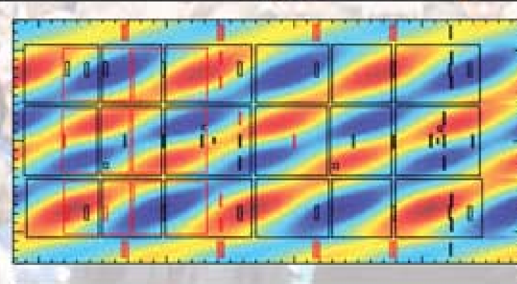
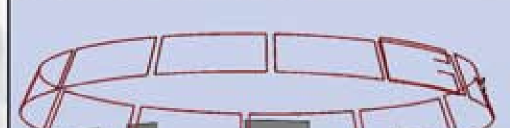
GA-A27526

THE DIII–D NATIONAL FUSION PROGRAM FIVE-YEAR PLAN 2014–2018

APRIL 2013





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GENERAL ATOMICS

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THE DIII-D NATIONAL FUSION PROGRAM FIVE-YEAR PLAN 2014–2018

by
PROJECT STAFF

Work prepared under the
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GENERAL ATOMICS PROJECT 30200
APRIL 2013

GENERAL ATOMICS

DISCLAIMER

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LIST OF ACRONYMS

0D	zero dimensional
1D	one dimensional
2D	two dimensional
3D	three dimensional
A-SSTR	Advanced Steady-State Test Reactor
ABB	Asea Brown Boveri
ABB1	Asea Brown Boveri transmitter #1
ABB2	Asea Brown Boveri transmitters #2
AC	alternating current
AE	Alfvén eigenmode
AGNOSTIC	in-situ ion beam analysis diagnostic (MIT)
AI	advanced inductive
ALARA	as low as reasonably achievable
ALCATOR C-Mod	MIT Tokamak (Boston, MA)
APS	American Physical Society
APS/DPP	American Physical Society/Division of Plasmas Physics
ARIES	Advanced Research Innovation and Evaluation Study
ARRA	American Recovery and Reinvestment Act
ASDEX-U	Axisymmetric Divertor Experiment Upgrade Tokamak (Germany)
ASIPP	Chinese Academy of Sciences, Institute of Plasma Physics (China)
AT	Advanced Tokamak
ATJ™	graphite (a product of GrafTech Inc. Ltd.)
AUG	ASDEX-U
AXUV	absolute extreme ultraviolet
BAAE	beta-induced acoustic Alfvén eigenmode
BES	beam emission spectroscopy
BGO	bismuth germanium oxide
BPX	Burning Plasma Experiment
C-C	carbon-carbon
C-Mod	ALCATOR C-Mod
CAMAC	computer automated measurement and control
CCFE	Culham Centre for Fusion Energy (UK)
CD	current drive
CEA	Commissariat à l'Énergie Atomique (Cadarache, France)
CECE	correlation electron cyclotron emission

LIST OF ACRONYMS (Cont.)

CEMM	Center for Extended MHD Modeling (SciDAC)
CER	charge-exchange recombination
CFC	carbon fiber composite
CP	center post
cPCI	compact peripheral component interface
CPES	Center for Plasma Edge Simulation (SciDAC)
CPI	Communications and Power Industries
CPS	cross-polarization scattering
CPU	central processing unit
CQ	current quench
CSPM	Center for the Study of Plasma Microturbulence (SciDAC)
CSPP	Cyber Security Program Plan
CSWPI	Center for Simulation of Wave-Plasma Interactions (SciDAC)
CTP	Co-operation on Tokamak Programmes
DBS	Doppler backscattering system
DEC	DIII-D Executive Committee
DEMO	DEMOnstration power plant
DEMO-CREST	Japanese Demonstration Power Plant Design
DiMES	Divertor Materials Evaluation System
DM	disruption mitigation
DMS	disruption mitigation system
DOE FES	Department of Energy, Fusion Energy Science
DT	deuterium-tritium
DTS	divertor Thomson scattering
EAST	Experimental Advanced Superconducting Tokamak
EC	electron cyclotron
ECC	Edge Coordinating Committee
ECCD	electron cyclotron current drive
ECE	electron cyclotron emission
ECEI	electron cyclotron emission imaging
ECH	electron cyclotron heating
ECPS	electron cyclotron power supply
EFC	error field correction
EFDA	European Fusion Development Agreement
EFDA-JET	European Fusion Development Agreement – Joint European Torus (England)
E-GAM	energetic-particle geodesic acoustic mode

LIST OF ACRONYMS (Cont.)

EH&S	Environmental, Health and Safety
EHO	edge harmonic oscillation
ELM	edge localized mode
EP	energetic particle
EPS	European Physical Society
EPSI	SciDAC-3 Center for Edge Physics Simulation
ESL	Edge Simulation Laboratory
ESnet	Energy Sciences Network
ETG	electron temperature gradient
EU	European Union
EUV	extreme ultraviolet
FCQ	fast current quench 1d analysis code
FDF	Fusion Development Facility
FDR	Final Design Review
FES	Fusion Energy Sciences
FESAC	Fusion Energy Sciences Advisory Committee
FFCC	Fusion Facilities Coordinating Committee
FIDA	fast ion D-alpha
FILD	fast ion loss detector
FIR	far infrared
FMIT	fusion materials irradiation test
FNSF	Fusion Nuclear Science Facility
FNSF-AT	Fusion Nuclear Science Facility – Advanced Tokamak
FSP	Fusion Simulation Program
FW	fast wave
GA	General Atomics
GAM	geodesic acoustic mode
GbE	gigabit Ethernet
GPI	gas puff imaging
GPU	graphical processing unit
GSEP	gyrokinetic simulation of energetic particle turbulence and transport
H-L transition	spontaneous transition from high confinement to low confinement
H&CD	heating and current drive
HBT-EP	high beta tokamak – extended pulse
HFS	high field side
HNBP	heavy neutral beam probe

LIST OF ACRONYMS (Cont.)

HPC	high performance computing
HTSS	hot tile surface station
HV	high voltage
HWA	Hazardous Work Authorization
HXR	hard x-ray
IAEA	International Atomic Energy Agency
IBA	ion beam analysis
IBS	ITER Baseline
ICH	ion cyclotron heating
ICRF	ion cyclotron radio frequency
ICRH	ion cyclotron resonance heating
IEA	International Energy Agency (Paris)
IEA IA	International Energy Agency Implementing Agreement
IGBT	insulated gate bipolar transistor
INPA	imaging neutral particle analyzer
IPEC	ideal perturbed equilibrium code
IPv6	internet protocol version 6
IR	infrared
IRTV	infrared television
ISM	integrated safety management
IT	information technology
ITB	internal transport barrier
ITER IO	ITER Organization
IO	ITER Organization
ITG	ion temperature gradient
ITPA	international tokamak physics activity
IWL	inner wall limited
JAEA	Japan Atomic Energy Agency
JAERI	Japan Atomic Energy Research Institute
JC3	Joint Cyber Security Coordination Center
JET	Joint European Torus (England)
JT-60U	Japan’s Tokamak-60 Upgrade
JT-60SA	Japan Tokamak-60 Super Advanced
KBM	kinetic ballooning mode
KSTAR	Korean Superconducting Tokamak Advanced Research
L-H transition	spontaneous transition from low confinement to high confinement

LIST OF ACRONYMS (Cont.)

LAN	local area network
LCO	limit cycle oscillation
LCS	local control station
LDAP	lightweight directory access protocol
LFS	low field side
LHCD	lower hybrid current drive
LHD	Large Helical Device (Toki, Gifu, Japan)
LHe	liquid helium
LIF	laser-induced fluorescence
LLNL	Lawrence Livermore National Laboratory
LN_2	liquid nitrogen
LPHP	long-pulse, high-performance
LQG	linear quadratic gaussian
LSN	lower single null
LTO	long torus opening (DIII-D)
MAST	Mega-Ampere Spherical Tokamak (UKAEA-Culham)
ME	magnetic energy
MFE	magnetic fusion energy
MFTF	Mirror Fusion Test Facility (Livermore, CA)
MG2	motor generator #2
MGI	massive gas injection
MHD	magnetohydrodynamic
MIR	microwave imaging reflectometer
MIT	Massachusetts Institute of Technology
MOU	memoranda of understanding
MPI	massive pellet injection (disruption mitigation)
MPI	message passing interface (computer processing)
MSE	motional Stark effect
MST	Madison Symmetric Torus (University of Wisconsin)
NAS	network-attached storage
NASA	National Aeronautics and Space Administration
NB	neutral beam
NBCD	neutral beam current drive
NBI	neutral beam injection
NPA	neutral particle analyzer
NRC	National Research Council

LIST OF ACRONYMS (Cont.)

NRMF	non-resonant magnetic field
NSF	National Science Foundation
NSTX	National Spherical Torus Experiment
NSTX-U	National Spherical Torus Experiment Upgrade
NTM	neoclassical tearing mode
NTV	neoclassical toroidal viscosity
NUF	National Undergraduate Fellowship
OANBI	off-axis neutral beam injection
ONFR	off-normal and fault response
ORNL	Oak Ridge National Laboratory (Tennessee)
OS	operating system
P/S	power supply
PAC	Program Advisory Committee
PB	peeling-ballooning
PCI	phase contrast imaging
Pd-MOS	palladium metal oxide semiconductor
PEGASUS	a small spherical torus experiment (University of Wisconsin)
PF	poloidal field
PFC	plasma facing component
PIC	particle-in-cell
PLC	programmable logic controller
PLUME	parallel flow impurity model
PMI	plasma material interaction
PoP	proof of principle
PPCS	European Power Plant Conceptual Study
PPPL	Princeton Plasma Physics Laboratory
PSI	plasma surface interaction
QH-mode	quiescent H-mode
QMB	quartz microbalance
R&D	research and development
RAM	random access memory
RC	research council
RCR	remote control room
RDI	rupture disk injection
RE	runaway electron
ReNeW	Research Needs Workshop

LIST OF ACRONYMS (Cont.)

rf	radio frequency
RFA	retarding field analyzer
RFP	reversed field pinch
RFX	Reversed Field Experiment (Padua, Italy)
RMP	resonant magnetic perturbation
RSAE	reversed shear Alfvén eigenmode
RWM	resistive wall mode
SA	switching amplifier
SBIR	Small Business Innovative Research
SC	superconducting
SciDAC	Scientific Discovery through Advanced Computing (project)
SCR	silicon controlled rectifier
SMBI	supersonic molecular beam injection
SNL	Sandia National Laboratory
SNLA	Sandia National Laboratory Albuquerque
SOL	scrape-off layer
SPA	switching power amplifier
SPI	shattered pellet injection
SPRED	survey, poor resolution, extended domain spectrometer
SST-1	Steady State Tokamak (India)
ST	spherical torus
STAC	Science and Technical Advisory Committee
Super-X	configuration with divertor strike point at large major radius
SWIM	Center for Simulation of Wave Particle Interaction with Magnetohydrodynamics (SciDAC)
SXR	soft x-ray
TAE	toroidicity-induced Alfvén eigenmode
TALIF	two-photon laser induced fluorescence
TBM	test blanket module
TCA	tile current array
TCV	Tokamak à Configuration Variable (Lausanne, Switzerland)
TE	thermal energy
TEM	trapped electron mode
TEXTOR	Torus Experiment for Technology Oriented Research (Jülich, FRG)
TF	toroidal field
TGLF	trapped gyro-landau fluid
TIP	tangential interferometer and polarimeter

LIST OF ACRONYMS (Cont.)

TM	tearing mode
TQ	thermal quench
TS	Thomson scattering
TTF	Transport Task Force
TTMP	transit time magnetic pumping
UCLA	University of California Los Angeles
UCSD	University of California San Diego
UF-CHERS	ultra-fast charge-exchange recombination spectroscopy
USBPO	U.S. Burning Plasma Organization
USC	User Service Center
USIPO	U.S. ITER Project Office
UV	ultraviolet
UVC	Universal Voltronics Corp.
VDE	vertical displacement event
VLT	Virtual Laboratory for Technology
VPN	virtual private network
VUD	vertical unstable disruptions
VV	vacuum vessel
W7-X	Wendelstein 7-X Stellarator (Greifswald, Germany)
WAN	wide area network
WEST	W Environment In Steady-State Tokamak (France)
Wiki	a web application that allows editing by users
XCS	x-ray crystal spectrometer

LIST OF COMPUTER CODES AND APPLICATIONS

CODE	PURPOSE
AE3D	Alfvén-eigenmode instabilities in 3D toroidal systems
AORSA RF	rf wave propagation and heating
ASCOT	guiding-center particle orbits
ATLAS	stochastic magnetic field topology
B2	2D edge transport simulation/analysis
B2/EIRENE	2D edge transport and neutral simulation/analysis package
BALOO	ideal MHD ballooning stability
BOUT	edge turbulence transport
BOUT++	C++ edge turbulence transport
C2	transport simulation
CAMINO	MHD ballooning stability
CERAUTO	automated CER analysis code
Condor	an open source queuing system for high throughput computing
CORSICA	transport simulation
CQL3D	3D quasi-linear evolution Fokker-Planck
CRONOS	transport simulation
CURRAY	rf ray tracing
D3	improved JavaScript library
DCON	ideal MHD stability
DEGAS	neutral transport
DIVIMP	edge/divertor impurity transport
DMZ	“science data DMZ”
E3D	3D Monte-Carlo heat transport code
EFIT	equilibrium reconstruction
EFIT3D	3D equilibrium reconstruction
EFITViewer	EFIT viewing tool
EGK	turbulence simulation
EIRENE	neutral transport
ELITE	edge MHD stability
EMC3	3D edge transport
EMC3-ERIENE	3D edge transport with neutrals
EPED	pedestal height and width model
EPED1	pedestal height and width model v1
ERO	3D Monte-Carlo edge impurity transport

LIST OF COMPUTER CODES AND APPLICATIONS (Cont.)

CODE	PURPOSE
FASTRANS	fast transport simulation
FCQ	disruption fast current quench simulation
FIDA	fast-ion D-alpha diagnostic
FIDASIM	fast-ion D-alpha simulation
GATO	ideal MHD stability
GEM	electromagnetic gyro-kinetic turbulent transport
GENE	gyro-kinetic turbulent transport
GENRAY	rf ray tracing
GKS	turbulent transport
GLF23	gyro-Landau fluid turbulent transport model
GS2	gyro-kinetic turbulent transport
GTC	gyro-kinetic turbulent transport
GTNEUT	neutral transport
GTS	gyro-kinetic tokamak turbulent simulation
GYRO	gyro-kinetic turbulent transport
HTTP	hypertext transfer protocol
IDL	scientific programming language
IMFIT	integrated modeling analysis tool
IPEC	ideal perturbed equilibrium
IPEC-NTV	IPEC neoclassical toroidal viscosity
ITMC-DYN	ion transport simulation in materials and compounds
JFIT	current distribution reconstruction
JOREK	3D MHD simulation
KPRAD	radiation dynamics
LIGKA	linear gyro-kinetic simulation with full orbits
M3D	3D MHD/two-fluid dynamics
M3D-C1	3D non-linear MHD/two-fluid simulation
M3D-K	hybrid 3D kinetic-MHD simulation
MAFOT	invariant manifold structure
MARS	linear extended MHD simulation
MARS-F	linear extended MHD simulation
MARS-K	hybrid drift-kinetic linear extended MHD
MARS-Q	quasi-linear extended MHD
MBC	MHD ballooning stability
MDSplus	data handling software system

LIST OF COMPUTER CODES AND APPLICATIONS (Cont.)

CODE	PURPOSE
MISK	Modifications to Ideal Stability by Kinetics
MIST	impurity transport
MM	multi-mode transport
Nagios®	computer monitoring system
NCLASS	neoclassical transport
NEO	drift-kinetic neoclassical transport
NFREYA	neutral beam deposition
NIMROD	3D nonlinear extended MHD simulation
NMA	resistive wall modes
NoSQL	not only structured query language
NOVA	linear energetic-particle instabilities
NOVA-K	linear kinetic energetic-particle Alfvén-eigenmode instabilities
NUBEAM	neutral beam deposition
OEDGE	edge/divertor interpretive modeling
OFMC	Monte-Carlo orbit following
OMFIT	integrated modeling tool
ONETWO	transport simulation/analysis
ORBIT	particle orbits
ORBIT-RF	rf particle orbits
PELLET	pellet ablation
PEST	ideal MHD stability
PEST3	resistive MHD stability
Protovis	JavaScript library
PTRANSP	transport simulation/analysis
Python	programming language
REDEP/WBC	erosion and redeposition
ReviewPlus	data viewing tool
RTEFIT	real-time EFIT equilibrium reconstruction
Snowflake	divertor configuration
SOLPS	edge transport simulation
SOLPS5	edge transport simulation
SOLPS5-EIRENE	edge transport simulation
SPIRAL	particle orbits
SQL	structured query language
STAR	computer computational cluster

LIST OF COMPUTER CODES AND APPLICATIONS (Cont.)

CODE	PURPOSE
Super-X	divertor configuration
SURFMN	Fourier analysis of magnetic topology
TAEFL	hybrid reduced-MHD gyro-fluid energetic-particle instabilities
TEMPEST	edge turbulence
TEQ	equilibrium solver
TGLF	trapped gyro-Landau fluid turbulent transport model
TGYRO	parallel steady-state gyro-kinetic transport analysis
TokSys	TOKamak SYStem control design/analysis
TOQ	equilibrium solver
TORAY	rf ray tracing
TORAY-GA	rf ray tracing
TORBEAM	electron cyclotron heating/current drive calculation
TORIC	rf wave modeling
TRANSP	transport analysis
3D	3D magnetic field line topology
TRIP3D	3D magnetic field line topology
TSC	tokamak simulation
UEDGE	edge simulation/analysis
V3FIT	3D equilibrium reconstruction
VALEN	3D conductor with linearized plasma MHD model for RWM feedback analysis
Venus	computational cluster
VMEC	3D equilibrium
Wiki	a web application that allows editing by users
XGC0	kinetic neoclassical edge transport
XGC1	kinetic turbulent edge transport
XHMGC	extended hybrid MHD-gyrokinetic energetic particle instabilities
XPTOR	transport simulation
ZIPFIT	between-shot profile analysis

1. PROGRAM MISSION, STRATEGY, UPGRADES AND IMPACT

1.1. OVERVIEW

The goal of fusion research is an attractive, long-term source of energy. The fuel supply for fusion is abundant (millions of years) and fusion energy generation emits no greenhouse gas. Successful development of fusion energy will greatly reduce the U.S dependence on foreign oil, reduce the impact of energy production on the environment, and help meet the energy needs of all mankind for centuries. Realizing this potential, the National Research Council (NRC) Burning Plasma Report states "Fusion energy holds the promise of providing a significant part of the world's long-term, environmentally acceptable energy supply." The world fusion program is now preparing for the burning plasma era as construction has started on a new major international fusion project ITER with the mission to "demonstrate the scientific and technological feasibility of fusion energy for peaceful purposes."

The DIII-D National Fusion Facility has played a key role in developing the physics basis for major aspects of the ITER design. The DIII-D Program Plan for 2014–2018 described here will provide critical research that informs remaining ITER design decisions and prepares the physics basis for ITER operation. This Program Plan is aligned closely with the high level vision for the U.S. fusion program for 2021 outlined by the Office of Science, Fusion Energy Sciences (FES) leadership (Table 1-1). Emphasis is placed on preparing for U.S. participation in ITER, developing the physics basis for next-step devices aimed at fusion nuclear science research [Fusion Nuclear Science Facility (FNSF)], and providing validated predictive tools for use on these future devices. Realization of this Program Plan is critical for the U.S. maintaining its leadership role in the fusion energy enterprise and preparing a new generation of fusion scientists to carry this leadership role into the burning plasma era.

Table 1-1
DIII-D Five-Year Plan Support of FES Vision for 2021

Element	FES Vision for 2021 (Synakowski, UFA Briefing, Nov. 2012)	DIII-D Five-Year Plan Strategy
ITER	"The U.S. has a strong research team hitting the ground on a completed ITER project … capable of asserting world leadership in burning plasma science."	Resolve critical ITER design issues, prepare validated physics basis for ITER operation, and train next generation of fusion scientists
Next-Step Devices	"The U.S. is prepared to move beyond conceptual design of a fusion nuclear science facility."	Provide physics basis of next-step devices by demonstrating potential of steady-state operation and developing innovative plasma-based heat flux/erosion control solutions
International Collaboration	"U.S. fusion research has successfully levered international research opportunities in long-pulse plasma control science, plasma-wall interactions, and 3D physics."	Leverage DIII-D unique capabilities and experience to enable U.S. exploitation of international devices (e.g., Long Pulse, High Performance initiative)
Predictive Validation	"The U.S. is a world leader in integrated computation, validated by experiments."	• Increase understanding of critical fusion issues via tight coupling with theory • Extend technical reach of device to "simulate" burning plasma conditions

The DIII-D National Fusion Facility is the pre-eminent magnetic fusion research facility in the U.S. with several capabilities that are unparalleled within the world fusion program. These capabilities have enabled numerous advances in the tokamak concept over the past two decades including the importance of plasma shaping, sustained operation near the ideal-wall pressure limit, and edge localized mode (ELM) suppression using non-axisymmetric coils (see Section 11 for a historical overview of DIII-D program). A major element of the Program Plan is to increase the technical reach of DIII-D to access conditions expected in future fusion energy systems while simultaneously enabling discovery of the underlying dynamics of performance-defining phenomena, testing of emerging theoretical concepts, and validation of state-of-the-art simulations of burning plasma conditions in preparation for ITER. This Program Plan will enable the U.S. fusion program to support the FES goals outlined in Table 1-1 through:

- Significant advances in the understanding of challenges posed by burning plasmas.
- Preparation of the physics basis for steady-state tokamak operation.
- Development of the 3D optimization of the tokamak concept.
- Elimination of the disruption risk for the tokamak.

DIII-D provides a national center to the U.S. fusion program for advancing physics and training scientists. Its leadership is derived from the expertise of the DIII-D National Research Team, comprised of individuals from multiple U.S. national laboratories, universities, and private industry as well as numerous international collaborators (see Section 8). This highly collaborative environment enables the DIII-D program to adapt quickly to ongoing program needs (as evidenced by its rapid response to an ITER request for testing the effects of a Test Blanket Module) and to tackle complex scientific issues through development of state-of-the-art measurement and theoretical tools. Conversely, DIII-D provides an exciting research platform for a wide spectrum of staff, ranging from a graduate student focused on testing a complex theoretical concept to large teams developing high performance regimes for long-pulse, superconducting devices including ITER. This synergy enables the DIII-D Program to address research gaps, needs, and opportunities as identified by the Fusion Energy Science Advisory Committee (FESAC) 2008 Priorities Panel Report and associated Research Needs Workshop (ReNeW) thrusts in a timely manner. As the largest magnetic fusion facility in the U.S., DIII-D is a critical asset not only in addressing these research needs but also in maintaining U.S. vitality in the fusion energy enterprise.

The DIII-D Program Plan for 2014–18 leverages the funding provided by FES through mutual investment by international partners in DIII-D upgrades that together will provide DIII-D with unique capabilities within the world program (see Section 9). This mutual investment will be targeted at DIII-D upgrades in which there is substantial interest on the part of international partners for DIII-D to provide proof-of-principle demonstration of critical aspects of their envisioned long-term programs. An example is a Long-Pulse, High-Performance initiative that first exploits DIII-D capabilities to determine the most attractive scenarios that can then be demonstrated in very long pulse (or steady-state) in new international superconducting devices. This international engagement in the DIII-D program will benefit the U.S. and world fusion programs by (1) enhancing international participation in the U.S. fusion program, providing critically needed manpower in high impact research areas; (2) providing the U.S. with a research platform that can be utilized to enhance increased U.S. participation on international devices; (3) accelerating the development of research programs on new international devices; and (4) establishing a framework for developing effective international scientific teams in preparation for ITER operations.

1.2. MISSION AND STRATEGY

The DIII-D mission is "***To establish the scientific basis for the optimization of the tokamak approach to fusion energy production.***" The DIII-D program is committed to carrying out excellent science, focused on innovation and optimization towards the goal of attractive fusion energy. This focus often translates into pursuing research to answer a specific R&D question for ITER. However, carrying out this research on solid scientific principle via theory-experiment interaction is the most effective means to resolve an R&D issue in a manner that translates readily to future devices. Hence, while the focus of an energy objective guides the proper science to pursue on DIII-D, excellence in science is the primary goal.

Through this science focus, the DIII-D program in 2014–2018 targets the development of a solid technical basis for successful operation of ITER and conceptual design of next-step devices such as FNSF while continuing to transform the prospects of fusion energy through new discoveries and innovative physics solutions. The DIII-D program strategy, depicted in Fig. 1-1, has two major objectives:

1. Provide access to and prepare for burning plasmas in ITER.
2. Prepare the path to fusion energy beyond ITER.

These objectives will be accomplished by providing scientists with the tools to advance the fundamental understanding and predictive capability of performance-defining physics phenomena, enabling the world fusion program to confidently transition into the burning plasma era.

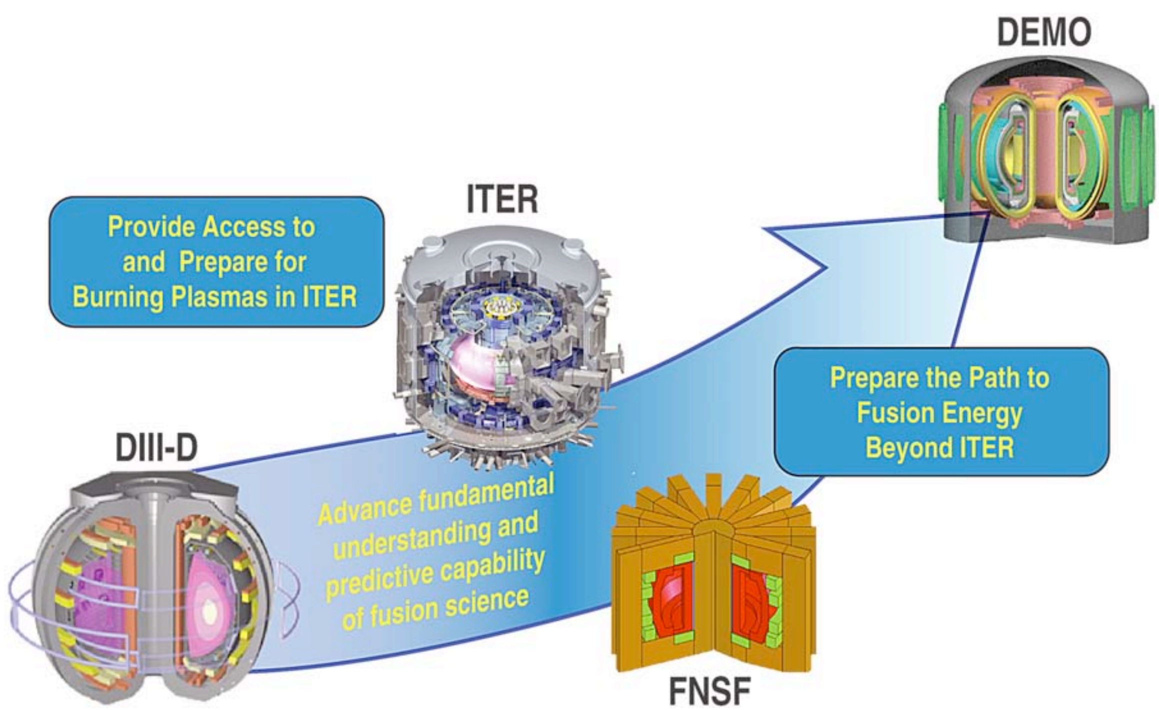

Fig. 1-1. DIII-D program strategy aims to provide basis for moving forward aggressively with fusion energy development.

Provide Access to and Prepare for Burning Plasma Conditions in ITER. ITER is the #1 priority of the U.S. Office of Science and FES. DIII-D is committed to ensuring ITER success and enabling U.S.

leadership in the burning plasma era. The Program Plan for 2014–2018 (shown in Fig. 1-2) recognizes that the time for impact on ITER design choices is drawing to a close and that preparing for ITER operation will now take center stage. Near-term activities will focus on resolving physics issues of remaining design decisions for disruption and ELM control on ITER. Successful implementation of these systems on ITER is critical, and DIII-D's contributions will provide the basis for U.S. leadership in these areas as ITER begins operations. As the ITER design is finalized, the research focus will shift to developing an improved physics basis for control and optimization of operating scenarios in the burning plasma regime in ITER. The key challenges are anticipating (and if necessary, overcoming) transport limitations in the burning plasma regime and validating instability control tools that are consistent with the ITER control toolbox. High priority will be placed on developing validated, predictive models for the key processes governing performance. These models will provide the U.S. fusion program with powerful analysis tools for use on ITER, enabling expedited execution of the ITER Research Plan through the simulated "design" of ITER discharge evolution as well as providing interpretive capabilities to better understand observed phenomena in ITER. In addition, DIII-D will serve as a test bed for qualifying diagnostics for which the U.S. has responsibility for providing for ITER. A key aspect of this research will be the training of the next generation of scientists tasked with gaining the most benefit from ITER operations. The breadth and complexity of the issues will provide graduate students and post-docs with leadership opportunities in the physics basis important for ITER's success while gaining experience in the large-team collaborative environment expected in ITER.

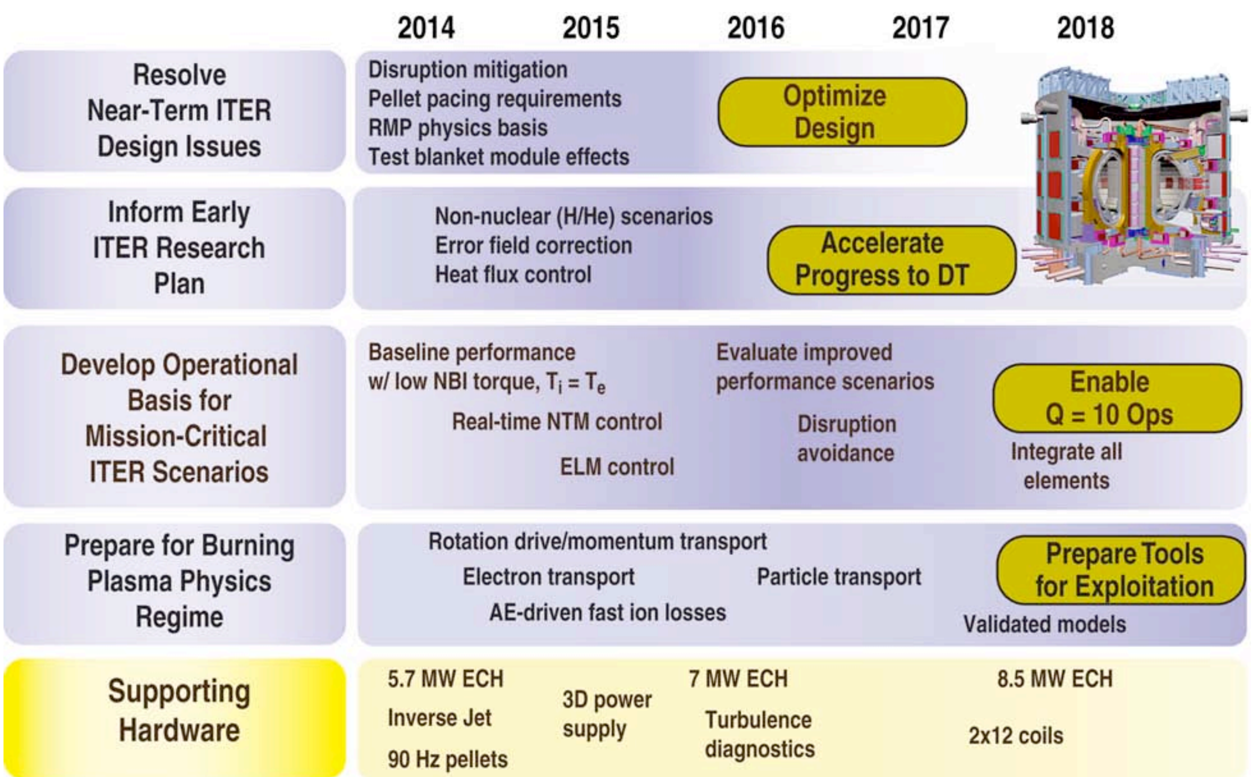

Fig. 1-2. Overview of the DIII-D 2014–2018 Research Plan in support of ITER.

Prepare the path to Fusion Energy beyond ITER. Looking beyond ITER on the path to fusion energy, FES has established a new program initiative — the Fusion Nuclear Science Program — aimed at resolving issues that bridge the gap between ITER and fusion power plant operation. A central element of this initiative is a FNSF to provide for nuclear testing of materials and components and closure of the tritium fuel cycle in a power plant environment. Such a facility will require high duty cycle and high power density operation and therefore demand significant improvements in the physics basis for steady-state operation and high heat flux handling beyond that necessary for ITER operation. The Program Plan targets these key areas (Fig. 1-3), providing the U.S. with capabilities to be the leader in this research worldwide. Taking advantage of existing capabilities, near-term research will focus on understanding the self-consistency between transport, stability, and current drive in the steady-state regime for durations exceeding the current relaxation time τ_R, the longest plasma physics time scale. Emphasis will be placed on developing and optimizing self-consistent, high-performance, steady-state core solutions for FNSF. This research program will extend U.S. leadership in this area and provide a compelling platform for exploiting U.S. expertise on new superconducting devices in China and Korea in addressing key issues such as steady-state control and the compatibility with acceptable wall materials. The Plan also outlines an aggressive program for new methods capable of providing adequate heat flux dispersal in an FNSF-class device, testing and characterization of new divertor geometries that are theoretically predicted to provide significant heat flux dispersal capabilities without significant impact on the core plasma. While no new divertor hardware is envisioned in the 2014–2018, this research should inform decisions on new hardware implementation in subsequent years.

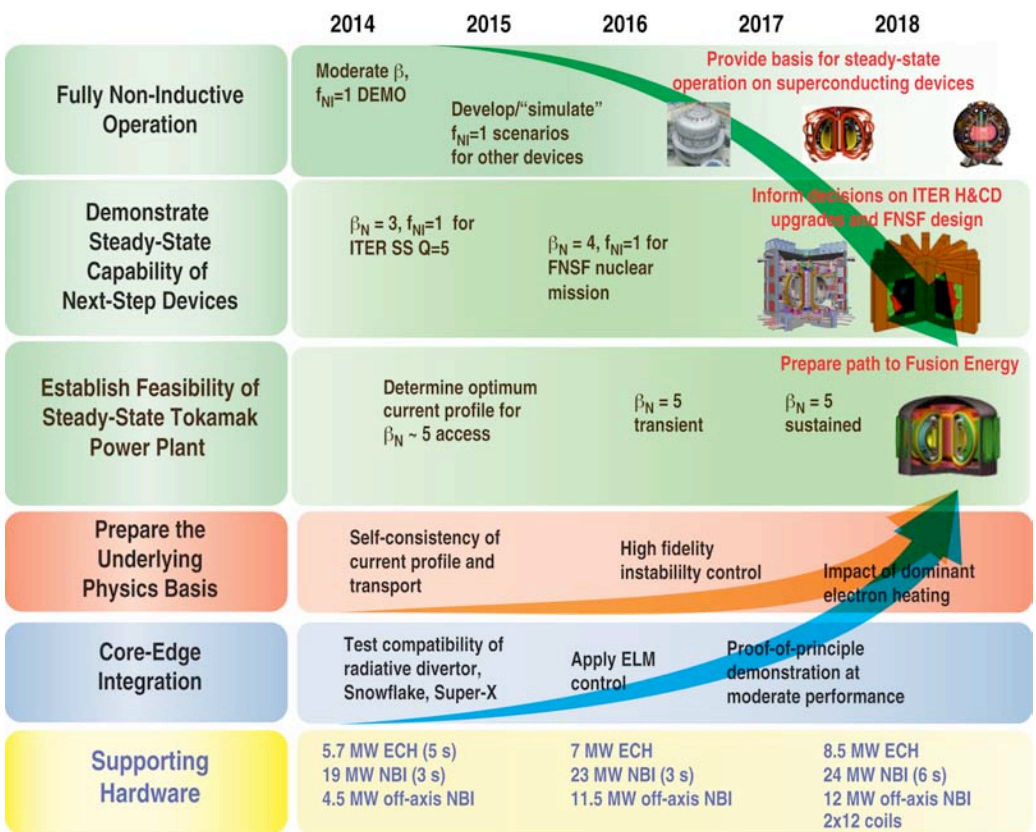

Fig. 1-3. Overview of DIII-D 2014–2018 Research Plan aimed at preparing the path to fusion energy.

Develop the scientific basis for the optimization of fusion energy. DIII-D's primary role in the fusion enterprise is to provide the fundamental scientific basis (or scientific building blocks) in making ITER and FNSF successful and preparing a clear path for the demonstration of fusion energy production in the future, as depicted in Fig. 1-4. These building blocks take on various forms. At the most basic level, DIII-D provides a platform for discovering, characterizing, and optimizing the key physical processes that govern transport, stability, current, 3D field effects, etc. Experiment-theory iteration and validation is a key aspect of this effort, which has long been a hallmark of the DIII-D program. This knowledge is then utilized to develop control tools for further scientific discovery and performance optimization. These capabilities are then brought together to enable development of regimes that are required for the success of ITER and FNSF. The key feature of this integration is the ability to produce conditions similar to those expected in a burning plasma device (e.g., $T_e/T_i \sim 1$, low torque input, low collisionality, high β). This approach will provide designers and researchers on future devices with simulation tools that can be used confidently and effectively on ITER and next-step devices, thereby reducing risk and improving productivity.

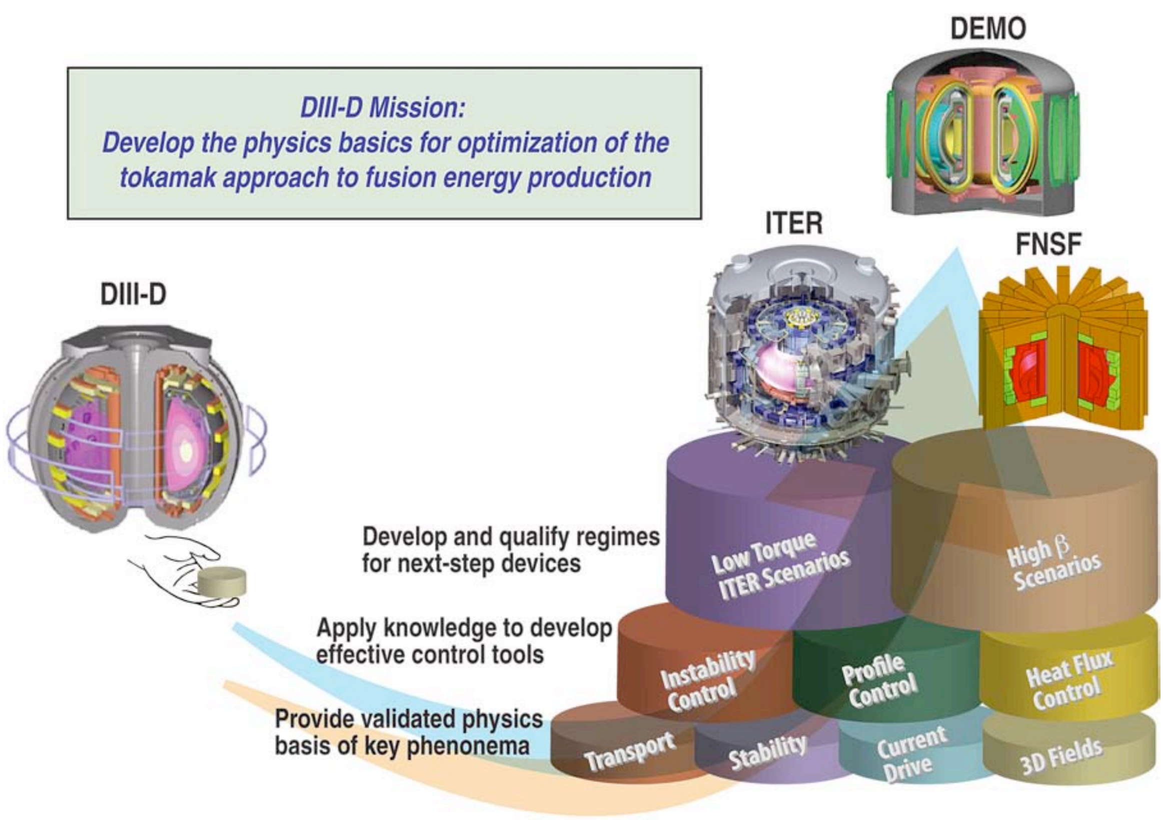

Fig. 1-4. DIII-D program's approach to providing the physics basis for optimization of the tokamak for fusion energy production.

1.3. PROGRAM STRUCTURE AND RESEARCH THRUSTS

DIII-D is committed to providing critical input that advances the world fusion program towards the realization of fusion energy. The DIII-D Research Plan is well aligned with the strategic objectives outlined by FES, with the activities carried out by three major research groups:

- The *Dynamics and Control* group will develop integrated operating scenarios for ITER and future devices incorporating areas of research such as scenario development, plasma control, stability, disruptions, and heating and current drive.
- The *Burning Plasma Physics* group will advance the understanding of critical physics phenomena expected in burning plasmas, including core transport and turbulence, L-H transition physics, and energetic particle research.
- The *Boundary & Pedestal* group will improve the physics basis and control solutions for the pedestal and boundary regions with emphasis placed on pedestal structure, ELM control, scrape-off-layer (SOL) physics, and plasma-material interactions.

The full research programs for these groups are outlined in Sections 2, 3, and 4. These programs provide an entry point for a large number of U.S. scientists into the DIII-D program, ensuring broad U.S. participation in developing the physics basis for ITER and future devices.

The Program Plan targets five research thrusts in which DIII-D can provide timely, high impact results over the next five years. These thrusts will resolve key physics issues on remaining ITER design decisions, enhance U.S. influence in the ongoing development of the ITER Research Plan, accelerate the program development of superconducting devices worldwide, and inform the conceptual design of next-step devices beyond ITER. These research thrusts are:

- Develop and qualify ELM control solutions for ITER.
- Meet the disruption challenge for ITER.
- Improve confidence in transport predictions for the burning plasma regime.
- Demonstrate the potential of high β, steady-state tokamak operation.
- Develop advanced heat dispersal techniques compatible with high core performance.

Each of these thrusts is a compelling area of scientific research in its own right. Their selection for DIII-D program emphasis are based on three considerations: their importance to the success of ITER and/or FNSF; their ability to resolve significant uncertainties remaining for ITER and/or FNSF; and DIII-D's unique or world-leading capabilities to address these uncertainties. The research planned for these thrusts over the 2014-18 time frame are described below along with the connection of these research areas with urgent ITER needs and recent FESAC reports tasked with delineating key research needs of the U.S. fusion program in advancing towards fusion energy realization.

Develop and qualify ELM control solutions for ITER. High-energy, repetitive losses due to edge instabilities known as edge localized modes (ELMs) pose a significant threat to internal component lifetime in ITER. While experiments have provided proof-of-principle demonstrations of a range of ELM control techniques, significant uncertainties still exist in the extrapolation of these techniques to ITER. DIII-D is the world leader in this research, having the demonstrated capability to suppress/mitigate ELMs with three ITER-relevant techniques: ELM mitigation using pellet pacing, ELM suppression via resonant magnetic perturbations (RMPs), and quiescent H-mode (QH-mode) operation. Unique ELM-control actuators that include multiple 3D coil sets and high frequency pellet injection enable these capabilities. Upgrades to the 3D coil power supply systems and the installation of a new internal 3D coil set will further augment these capabilities. The research plan to further develop the physics basis for utilizing these techniques for ELM control in ITER is shown in Fig. 1-5. Since proof-of-principle demonstrations have already been achieved for each of these techniques, emphasis will be placed on developing a validated physics basis for improved confidence in the extrapolation of these techniques to ITER. Specifically, research will validate models of the edge response (both magnetic and kinetic) to the application of RMPs, models of ELM triggering by small pellets, and theories of neoclassical toroidal viscosity (NTV) and edge harmonic oscillation (EHO) generation. A secondary focus of the research in these areas will be testing the compatibility of these techniques with anticipated conditions in ITER (e.g., low neutral beam torque, $q_{95} = 3.1$ in ITER shape, low pedestal collisionality). The net result of this research will be a validated physics basis on both the viability and the optimal implementation of each of these approaches in solving the ELM control issue for ITER.

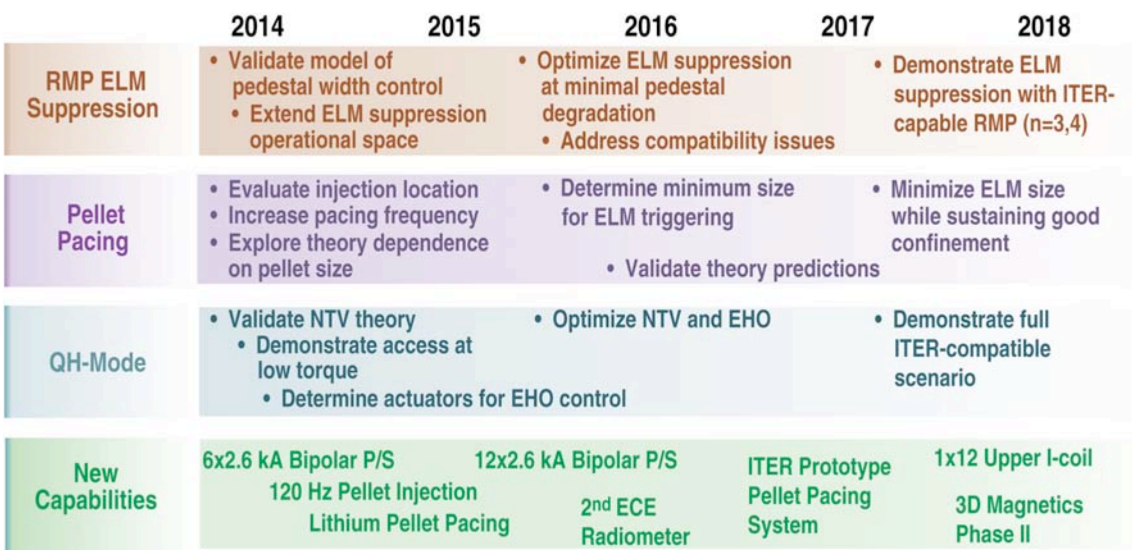

Fig. 1-5. Overview of DIII-D 2014–2018 Research Plan targeted at providing ELM control solutions for ITER.

This thrust directly supports near-term and mid-term priorities identified by the 2013 FESAC Priorities Panel, namely:

- *Near-term (1–2 years)*
  - Complete physical characterization of ELM suppression schemes.
- *Mid-term (3–5 years)*
  - Understand present ELM-free operation and develop operational modes that are compatible with ITER.

Meet the disruption challenge for ITER. Disruptions pose the single greatest threat for component damage in ITER as potential thermal heat loads, magnetic stresses, and runaway electron (RE) generation are all near the tolerable limit for the ITER design. While avoidance and mitigation techniques have been developed that show promise in reducing/eliminating the risk of such damage, there are large uncertainties on the use of these techniques in ITER due to the enormity of the scale difference between present-day devices and ITER (e.g., factor of 10^{10} in runaway avalanche gain). In addition, the U.S. has taken on the responsibility of delivering a disruption mitigation system (DMS) for ITER with a final design review due in 2016. DIII-D is the world leader in disruption avoidance and mitigation research, having several unique capabilities including an extensive set of instability control actuators, moderate size, and a suite of state-of-the-art diagnostics. This is augmented by a variety of disruption mitigation systems including massive gas injection (MGI), shattered pellet injection, and dust-filled shell pellets. The DIII-D Five-Year Research Plan in this area adopts a comprehensive approach with the goal of developing a multi-layer disruption protection system for ITER, as depicted in Fig. 1-6. Many elements of this approach have already been demonstrated individually – the most notable exception being a robust technique for rapid shutdown of ITER. For this reason, the five-year plan focuses heavily on testing the efficacy of a range of proposed techniques and then delivering a physics basis for the implementation of the best available techniques for ITER. Emphasis will be placed on RE control as this appears to be the most serious challenge faced by ITER and DIII-D capabilities most suited. Studies will also provide key information on disruption-induced thermal heat load and halo generation to guide design of ITER's DMS. DIII-D experiments will then tests prototype systems of the resulting ITER DMS concept. As the Plan progresses, increased emphasis is placed on integrating the full range of instability and disruption control into a disruption protection system, culminating with demonstrations that off-normal events can be handled robustly and safely in ITER.

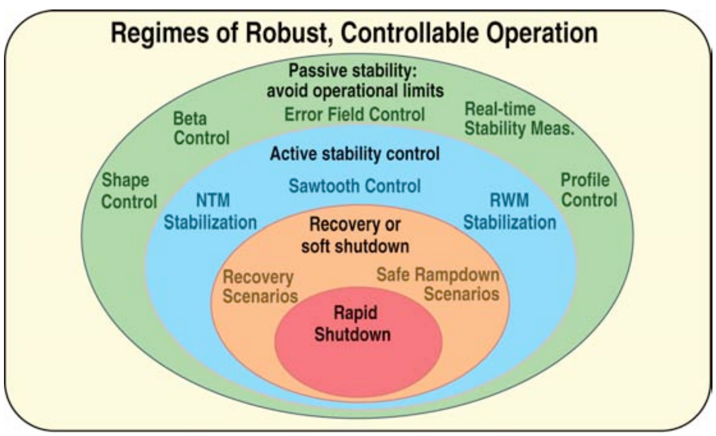

Fig. 1-6. DIII-D vision of multi-layer disruption solution for ITER.

This thrust directly supports near-term and mid-term priorities identified by the 2013 FESAC Priorities Panel, namely:

- *Near-term (1–2 years)*
  - — Understand the dynamics of REs in disruptions.
  - — Test and verify disruption mitigation approaches for required physical characteristics.
- *Mid-term (3–5 years)*
  - — Improve understanding and modeling of instabilities that lead to disruption for a range of operation scenarios.

— Examine the use of advanced tokamak (AT) control methods, e.g. pressure and current profile control, for disruption avoidance.
— Develop methods of disruption avoidance that are compatible with conditions in AT operation of ITER.

Improve confidence in transport predictions in the burning plasma regime. Success in Q=10, 500 MW operation in ITER is predicated on achieving good H-mode confinement; even a 10% reduction in thermal confinement from projected levels would make this objective quite challenging. While much has been learned with regard to turbulence-driven transport over the past two decades and the basis for ITER projections appears well founded, the burning plasma regime in ITER will present new challenges due to differences in the anticipated plasma conditions (e.g., $T_e \sim T_i$, dominant electron heating, low torque (rotation), high β, low collisionality). DIII-D has played a major role in improving the understanding of core and pedestal plasma transport in recent years, utilizing its state-of-the-art diagnostics to test linear and non-linear turbulence predictions developed by theorists worldwide. Yet, these comparisons have thus far been limited to narrow operational ranges that are somewhat disparate from those expected in ITER. Increased electron cyclotron heating (ECH) and enhancements in diagnostic capabilities on DIII-D will allow extension of these studies to ITER burning-plasma-relevant regimes, including H-mode with dominant electron heating and low torque. In the DIII-D Program Plan, emphasis is placed on the pedestal structure and core electron transport, particle transport, and rotation generation/momentum transport due to their importance in determining fusion power output in ITER. A key aspect of the DIII-D plan in this area is the tight coupling between theory, modeling, and experiment, as depicted in Fig. 1-7. Because of the large extrapolation from present-day devices, it is important to rely on theoretical guidance to identify the key physics that needs elucidation in improving the confidence of predictions in ITER. Experiments will then seek to utilize the extensive DIII-D turbulence and profile diagnostic set to produce a complete data set for testing and validating the simulation models. Through iterative improvements in theory, modeling, and measurement, the Plan will seek to deliver validated models that can be used reliably for ITER planning and exploitation.

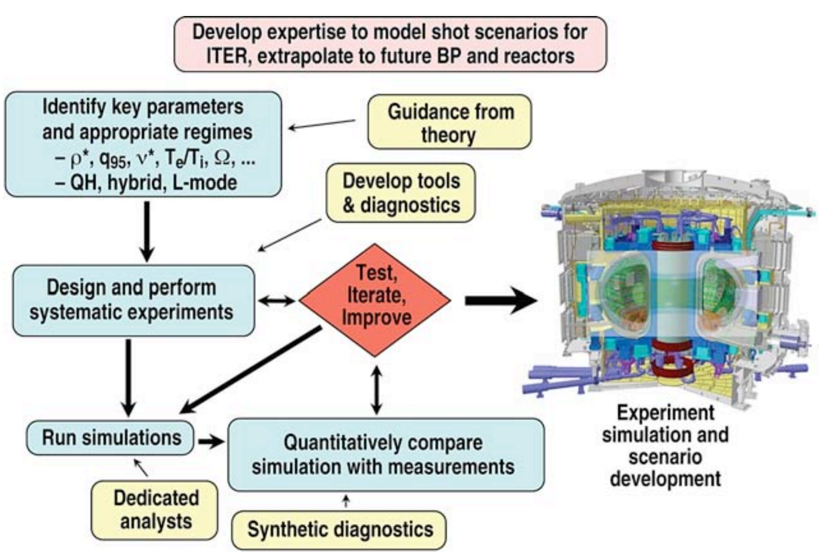

Fig. 1-7. Strong coupling of DIII-D experiments with theory will provide validated physics basis for ITER.

This thrust directly supports near-term and mid-term priorities identified by the 2013 FESAC Priorities Panel, namely:

- *Near-term (1–2 years)*
  - Develop a robust understanding of 3D edge pedestal physics and predictive capability for pedestal characteristics in tokamaks and stellarators.
  - Establish focused verification and validation (comparisons to data from experiments) programs to address specific case studies in high priority thrusts.
- *Mid-term (3–5 years)*
  - Develop improved predictive capability for L-H transition, core and edge transport and, plasma heating and fueling.

Demonstrate the potential of high β, steady-state tokamak operation. The promise of fusion beyond ITER hinges on the ability to produce high duty cycle, high gain scenarios capable of producing large amounts of fusion power over extended periods (preferably steady-state). Although research on various devices have shown glimpses of the possibility of steady-state operation, the ability to sustain high β (> 4%) operation for multiple current relaxation times has not yet been demonstrated. In particular, uncertainties still remain in the ability to operate at pressures approaching the ideal-wall stability limit with the self-consistency between the transport and current drive profiles, essential elements for steady-state operation. DIII-D is the world leader in this research, possessing an assortment of off-axis current drive tools [electron cyclotron current drive (ECCD) and neutral beam current drive (NBCD)] as well as sufficient power to produce high β plasmas for durations much longer than the current redistribution time. This gives researchers the capability to assess integrated, steady-state performance limits. Further upgrades to these capabilities as proposed in the Plan will enable DIII-D to explore, assess, and characterize regimes that project to steady-state operation in ITER (β_N ~ 3), FNSF (β_N ~4), and a demonstration power plant (DEMO) (β_N ~ 5) (Fig. 1-8). As β_N is increased towards the level envisioned for DEMO operation, the fraction of self-driven (i.e., bootstrap) current will increase to near 90%, placing increasing demands on the self-consistency of transport and current drive profiles. In this regime, DIII-D research will seek to validate and enable further development of transport models, especially with respect to the variation of energy, particle, and momentum transport with the current profile. In addition, real-time control of error field amplification, neoclassical tearing modes (NTMs), and resistive wall modes (RWMs) will become increasingly important and challenging, necessitating the development of advanced control methods and a more complete understanding of the physics mechanisms involved. This research will prepare the basis for an international long-pulse, high-performance initiative through the demonstration of the compatibility of these solutions with steady-state performance and metal walls on international devices. This research will exploit the capabilities highlighted by the 2013 FESAC Priorities Panel report which states "*Thanks to past investments in heating and current drive systems, as well as in diagnostics and control, U.S. facilities currently have world leading capability to make ground breaking contributions to steady-state research. The panel believes that this capability should be fully exploited, with an eye toward transfer of the knowledge gained to facilities with substantially longer pulses possible in superconducting, off-shore tokamaks*."

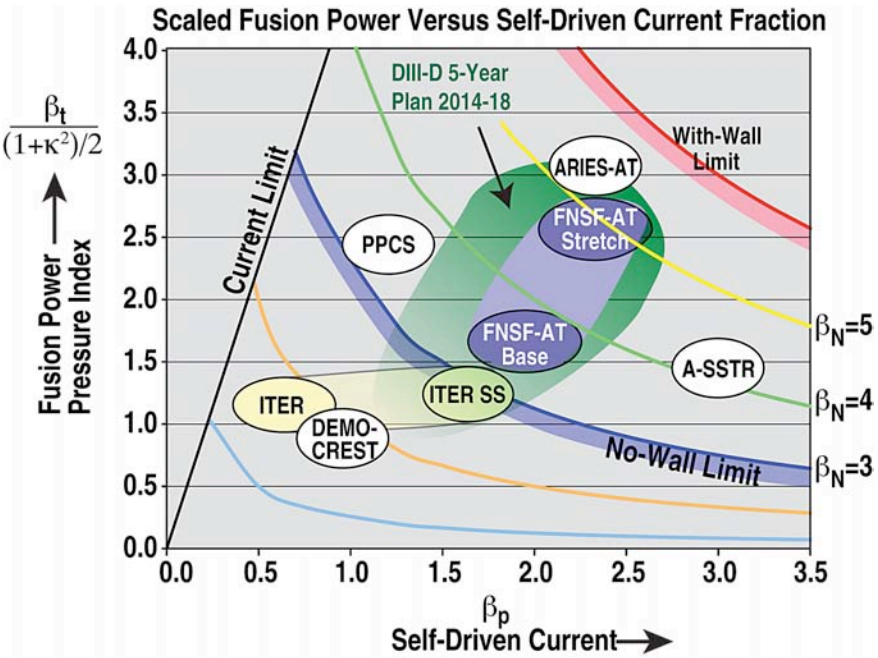

Fig. 1-8. DIII-D upgrades will provide capability to explore steady-state regimes for ITER and FNSF.

Develop advanced heat dispersal concepts for next-step devices compatible with high core performance. The realization of high fusion power density, steady-state core solutions consistent with the mission needs of next-step devices such as FNSF (and eventually DEMO) will place stringent requirements on the dispersal of the core heat efflux on the plasma facing surfaces. For example, the estimated divertor heat flux in FNSF and DEMO utilizing conventional, detached divertor operation will reach levels that are a factor of 2–3 higher than tolerable plasma facing material limits (~10 MW/m^2). Various methods have been proposed for increasing the heat flux footprint (e.g., double null, radiative mantle, radiative divertor, expanded divertor), with each method showing the capability to reduce the peak heat flux by over a factor of two. However, the compatibility of each of these methods with adequate core performance has not been established; therefore, there is considerable uncertainty in extrapolating the basis for these solutions to FNSF or DEMO. Taking advantage of DIII-D's comprehensive edge/divertor diagnostic set, flexible shaping capability, and demonstrated ability to produce core solutions of interest for FNSF and DEMO, research in the Five-Year Plan will seek to develop the physics basis for realizing a unified core-edge solution for steady-state high performance. A key consideration in this evaluation will be the self-consistency of the heat dispersal solution with obtaining adequate particle control to ensure the ability to achieve core density levels necessary for efficient non-inductive current drive. Research will focus on the compatibility of two approaches with good core performance—a radiating mantle to dissipate power before it reaches the divertor and advanced divertor geometries that both reduce the heat flux to the material surface of the divertor and modify the relation between the core and divertor operating densities to allow optimization of core and divertor operating point independently. Together with research devoted to improving the modeling capability of detached divertor operation, this program will provide the basis for divertor configuration modifications to enable full demonstration of the best solution *in the following five-year program period.*

1.4. DIII-D TEAM

This Research Plan is founded on the extensive expertise of the research staff that comprises the DIII-D Research Team, which includes experimentalists and theoreticians from universities, national laboratories, and private industry around the world (Fig. 1-9).

Fig. 1-9. A wide base of collaborations establishes a foundation for a strong DIII-D program.

Research Staff. The DIII-D Program is world renowned for its highly collaborative research program that engages collaborative staff at all levels of program management and execution (e.g., Fig. 10-1). The DIII-D on-site research staff consists of approximately 80 full-time Ph.D. scientists, which includes 32 Fellows of the American Physical Society and ten recipients of the Excellence in Plasma Physics Research Award. Over one-half of these scientists are from collaborating institutions. Approximately 350 researchers from around the world are active users of DIII-D data, and there were 443 authors on DIII-D papers in 2011–2012. These team members are from 83 institutions including:

- 39 Universities (26 U.S., 13 international)
- 34 National Laboratories (7 U.S., 27 international)
- 10 High Technology U.S. Companies

The extended research team includes over 30 more Fellows of the American Physical Society. DIII-D personnel also serve in high-level coordinating roles within the U.S. Burning Plasma Organization (USBPO) and the International Tokamak Physics Activity (ITPA).

Strong linkages between the DIII-D experimental program and theory/simulation [both at General Atomics (GA) and at collaborating institutions] greatly enrich the DIII-D program and contribute to the scientific excellence of the program. Significant off-site participation increases both the breadth and depth of the DIII-D research program. In addition, the DIII-D program is highly interactive with other fusion programs both domestically and internationally. This is evidenced by the large number of international scientists that participate in the DIII-D program as well as DIII-D participation in foreign experiments, many of these joint experiments facilitated by the International Energy Agency (IEA, Paris) and ITPA. More details on DIII-D international collaborations can be found in Section 9.

Graduate Students/Post-docs. DIII-D has an active program in educating both graduate students and post-docs. Over the past five years (2008–2012), 24 graduate students from 14 separate universities completed Ph.D. theses in which DIII-D experimental data played a prominent role. During this same time period, DIII-D graduate students have presented over 20 invited talks at scientific conferences and workshops in the U.S. and internationally. The quality of the graduate student research carried out on DIII-D is evidenced by several awards presented to graduate students in which DIII-D research was the central element of their research:

- Anne White (UCLA): 2009 Marshall Rosenbluth Doctoral Thesis Award
- Ben Tobias (UC Davis): 2012 UC Davis Allen G. Marr Prize for best dissertation in engineering
- Jon Hillescheim (UCLA): “High Commendations” for 2012 Itoh Prize

Post-doctoral research also plays a prominent role in the DIII-D Program. Over the past five years, 37 post-docs [supported by the Department of Energy (DOE) directly, General Atomics, or collaborating institutions] have conducted early career research on DIII-D. During this period, the scientific output of the post-doc program has been substantial with over 50 published papers and 30 invited talks at scientific conferences and workshops. In addition, several individuals have been awarded DOE Early Career Awards based on their post-doc research on DIII-D. Many of the post-docs trained at DIII-D have remained in the U.S. fusion program with several individuals now playing important programmatic roles.

The DIII-D Program Five-Year Plan seeks to significantly expand graduate student research on DIII-D through expansion of well-established university collaborations on DIII-D as well as development of new university collaborations that bring together the expertise of university research personnel with DIII-D capabilities. The proposed program would provide funding for 5 graduate students supported by GA subcontracts to universities and 10 graduate students funding directly by FES and the associated university. Additional experimental time is proposed (two weeks) to accommodate the associated experimental needs. The accomplished DIII-D team, the strong coupling to the GA Theory Group, excellent integration of all staff into the planning and execution of experiments, and a broad support structure provides an outstanding environment for graduate work. In addition, the DIII-D facility is accessible for students and faculty and can easily accommodate innovate ideas for diagnostics and hardware. Since this expansion in graduate students will require direct funding to universities by FES, this part of the proposal is included as a Program Option[1] rather than in the baseline proposal.

Governance. While the DIII-D program is operated by General Atomics for the U.S. Department of Energy's Fusion Energy Sciences Program, the management and program leadership is drawn from the broader DIII-D team through an effective and inclusive system of governance. The primary governance body is the DIII-D Executive Committee (DEC), which advises the DIII-D Program Director on matters of program planning, direction, budgets, and institutional issues. The DEC is comprised of the DIII-D division directors, and leaders for the major collaborating laboratories, and major collaborating universities. The DIII-D Program Advisory Committee (PAC), consisting of leaders and technical experts from other national and international fusion program, provides advice annually on the program plans and other major programmatic issues. The Research Council provides specific advice on the annual experimental plan and relative priority of experimental efforts within that plan. After major research emphases are chosen, experimental proposals are solicited from the entire International DIII-D Team at the Research Opportunities Forum. These proposals are discussed and further developed and prioritized in open meetings. Task Force Leaders and the standing physics area leaders present final research plans to the Research Council, and the Research Council provides advice on the program balance for the year. More details are provided in Section 10.

1.5. DIII-D FACILITY CAPABILITIES AND PROPOSED IMPROVEMENTS

The DIII-D National Fusion Facility has considerable experimental flexibility and extensive diagnostic instrumentation to measure the properties of high-temperature tokamak plasmas. This provides scientists worldwide with an experimental platform to push performance boundaries, resolve specific challenges for ITER and future devices, and advance the knowledge of fusion plasmas on a broad front. Existing capabilities of DIII-D include a highly flexible 2D shaping coil system to produce a wide variety of plasma shapes, flexible heating and current drive systems, three arrays of 3D-field perturbation coils located both inside and outside the vacuum vessel, multiple disruption quench systems, over 50 state-of-the-art diagnostic systems to examine plasma parameters, and an advanced digital control system for feedback control of the plasma. These capabilities have enabled several transformational discoveries including the importance of plasma shape on performance, ELM suppression using non-axisymmetric coils, and sustained operation near the ideal wall stability limit.

Further enhancements to these capabilities in 2014–2018 (Table 1-2) will enable U.S. researchers to address the fusion program's most urgent needs while also providing the possibility of new approaches that enhance the prospects for fusion energy. These enhancements, described in more detail in Section 5, include:

Increased Electron Cyclotron Heating and Current Drive. Torque-free, electron heating from alpha-particles will be a key distinguishing feature of burning plasma devices, resulting in significant changes to turbulence dynamics and associated transport from that experienced in present-day devices. Over a factor of 2 increase in absorbed EC heating to 8.5 MW will enable access to this physics in relevant high performance regimes characterized by dominant electron heating, low injected torque, low collisionality,

[1]Proposed elements that are included in the proposal for DOE informational purposes only.

and high β. The flexibility, precise deposition, and perturbative capabilities of the EC systems, combined with multiple profile and fluctuation diagnostics, will enable validation of turbulence transport models as T_e/T_i, ∇T_e, ∇T_i, and ExB shear are varied over a range spanning those expected in burning plasmas. In addition, this increase in EC power will provide new capabilities to explore off-axis current drive for steady-state AT research, localized current drive for stabilization of NTMs, and a wide range of scientific investigations in transport and stability control.

Table 1-2
DIII-D Capabilities will Provide Researchers with a Powerful Set of Experimental Tools for Carrying Out High-Quality, High Impact Fusion Science Research

Capability		2013	Proposed	Experimental Tool
Flexible Plasma Shaping		18 coils with 14 independently controllable	18 coils with 18 independently controllable	Single-null vs. double-null Low → High triangularity Conventional, Snowflake, Super-X divertor
Electron Cyclotron Heating and Current Drive		3.5 MW absorbed	8.5 MW absorbed	Dominant electron heating Current profile tailoring Instability control
Neutral Beam	Total/Duration	19 MW/3 s	24 MW/6 s	Sufficient power to probe β limits
	Co/Counter	14/5 MW	19/5 MW	Variable rotation/rotational shear
	Off-Axis NBI	4.5 MW	12 MW	Current profile control/sustainment
Ion Cyclotron Heating and Current Drive		3 MW, 90 MHz for 10 s	3 MW, 90 MHz for 10 s 0.8 MW, 500 MHz for 5 s	Dominant electron heating Energetic particle control Current profile sustainment
Enhanced 3D Capabilities	**Coils**	2x6 internal array 1x6 external array TBM mockup	2x12 internal array	Edge resonant perturbations to suppress ELMs Non-resonant perturbations for QH-mode at low torque Dynamic error field correction Resistive wall mode control
	Power Supplies	DC: 7 kA AC: +/- 4 kA 24 audio amps	DC: 10 kA AC: +/- 7 kA 48 audio amps	
Particle Exhaust		Three divertor cryopumps for low and high δ	Same	Density/collisionality control Increased current drive capability
All Carbon Wall		Operated at room temperature	Select tiles capable of high temp. operation	Erosion/migration/fuel retention of plasma facing surfaces at high temperature
Disruption Mitigators		Massive gas inj. Shattered pellets Shell pellets	Multiple location MGI Inverse-Jet Burst Disks	Tailor thermal quench radiation Runaway electron dissipation
Diagnostics		Extensive set of core, SOL, and divertor profile and fluctuation measurements	See Section 6 and tables in Sections 2–4	Validate state-of-the art models Enable high fidelity real-time control for scenario optimization

Increased Flexibility of Neutral Beam Injection. Realizing the promise of efficient, steady-state tokamak operation hinges on the ability to produce high β plasmas with self-consistent transport, stability, and bootstrap current profiles. Increased neutral beam power, deposition breadth, and duration (24 MW total, 11 MW off axis, 6 s) and ECCD will enable examination of the non-linear coupling of current drive, transport, and stability in fully non-inductive plasmas for a range of current profiles over multiple current redistribution timescales as well as the ability to probe the steady-state performance limits ($\beta_N \sim 5$) of the best candidates. Combining this additional heating power with the EC power upgrade will provide the capability to achieve P/R~20 MW/m, which will enable exploration of compatible exhaust mitigation solutions to test the principles of isolating a cold divertor plasma from the high performance fusion core.

Enhanced 3D Capabilities. Due to enhanced effects of 3D fields at high β and low rotation, optimizing 3D fields is critical to successful operation of ITER. Enhanced flexibility from a new 3D coil set and power supplies will enable tests of predicted ideal, resistive, kinetic, and neoclassical responses by varying the toroidal/poloidal spectrum, resonant vs. non-resonant fields, and radial localization. The DIII-D Program Plan provides for new power supplies capable of operating each of the above coil sets at its engineering current limits along with full rotation capability for perturbations with toroidal mode number n=1–2 [in partnership with Chinese Academy of Sciences, Institute of Plasma Physics (ASIPP)]. As the Plan progresses, the 2x6 off-midplane coils are replaced by a 2x12 coil set in a staged fashion, the upper 1x12 row in 2018 and the lower in 2019. This will provide the capability to apply n=1–6 perturbations along with full rotation capability of n=1–4 along with increased poloidal content flexibility to isolate physics mechanisms. Together, these new capabilities will provide unmatched capability for 3D optimization of the tokamak providing simultaneous error field correction, ELM suppression, RWM stabilization, and rotation without neutral beam injection.

High Frequency, Fast Wave Current Drive. Building on an idea suggested by V. Vdovin of the Russian Federation, recent simulations indicate the potential for efficient off-axis current drive using 500 MHz, "helicon" waves in high T_e plasmas. In collaboration with Russian scientists, this will be evaluated experimentally on DIII-D using a prototype 800-kW, klystron-based system coupled to the plasma via a traveling wave antenna. If successful, such an approach has the potential to transform the ability to drive significant off-axis current drive for current profile sustainment of high β_N scenarios in future devices such as FNSF.

Disruption Mitigators. A final design decision for the ITER Disruption Mitigation System (DMS) is presently scheduled for 2016 though prototyping and design finalization may continue for some time thereafter. DIII-D has multiple capabilities for delivering large quantities of material on time scales sufficient for mitigating disruptive effects including massive gas injection (MGI), shattered D_2 pellets, and shell pellets filled with low-Z material. New material injection capabilities (multiple-port MGI system, inverse-jet burst disk supplied by CEA-Cadarache) will enable the development of an improved physics basis for resolving key ITER physics issues on thermal quench symmetry/duration and runaway electron dissipation and control. Together with improved 3D diagnostics and non-linear modeling, these capabilities will enable tailoring of the plasma quench to better protect against disruptive events.

Diagnostics. DIII-D has a comprehensive diagnostic set which is essential for making progress in the understanding and control of fusion plasmas. A significant number of new diagnostics and upgrades to existing diagnostics aimed at addressing the most critical physics issues are included in the Program Plan. The highest priority diagnostics are shown in Fig. 1-10, and a more complete list is included in Section 6. Support is provided for installation and maintenance of five diagnostics that have recently been awarded DOE Diagnostic Grants by FES to university researchers for implementation on DIII-D. These include cross-polarization scattering (UCLA), microwave imaging reflectometer (UC Davis), phase contrast imaging (MIT), polarimeter (UCLA), and AGNOSTIC (MIT). Further enhancements to the diagnostic systems are prioritized based on the physics requirements and objectives of the research program. These include key diagnostics in advancing our understanding of energetic particle instabilities and their effect on fast particle transport [imaging neutral particle analyzer (INPA), fast ion loss detector (FILD)], plasma-material interactions (smart tile, heated tile, and AGNOSTIC), and runaway electrons (hard x-ray spectrometer).

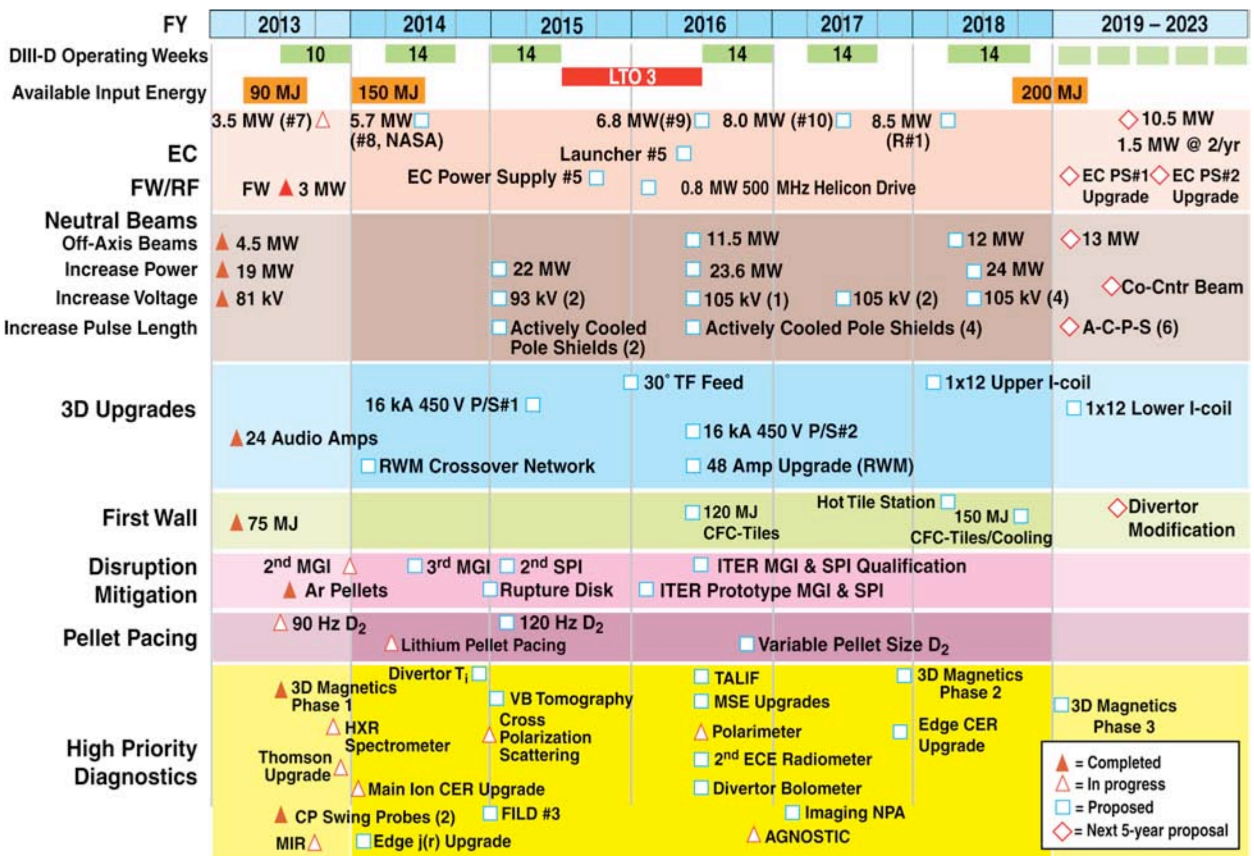

Fig. 1-10. The DIII-D National Facility Five-Year Plan 2014–2018. These capabilities will provide an excellent platform for fusion and plasma science, ITER support, and AT development for the next decade. The program enhancements shown beyond 2018 will further advance the program and we would plan to implement them as rapidly as funding allows. Symbols show dates when the item is available for experiments.

1.6. FACILITY OPERATIONS

The DIII-D Program Plan provides for 14 weeks of operation annually from 2014–2018. This level of operation yields sufficient utilization of the Facility to guarantee excellent scientific productivity of the Program while providing sufficient time for maintenance, diagnostic calibration, upgrades, and experimental planning. Some of the facility upgrades included in the plan require an extended maintenance period lasting approximately one year. To accommodate this, a schedule is envisioned in 2015/2016 similar to the 2010 and 2011 schedule, during which experiments were executed in early FY10, followed by a long maintenance period crossing the 2010/2011 fiscal year boundary with experiments executed during the last half of 2011. Sufficient resources to allow work to proceed on two shifts can shorten the duration of the upgrade period.

The DIII-D facility continually operates with a very large research backlog. From 2009–2013, four Research Opportunities Forums were held with the number of experiment proposals averaging over 450 per forum. Of these proposals, approximately 20% have been executed to date. The proposal contains a Program Option for an additional four weeks of operations a year to better accommodate this high demand. In addition to the direct consumables (i.e., electricity, helium gas, etc.), this level of operation will require increased staff to support adequate maintenance and the build-out of facility improvements in parallel with operations.

1.7. NATIONAL AND INTERNATIONAL LEADERSHIP

In addition to the scientific leadership that the DIII-D Program will provide through execution of this Program Plan, the DIII-D Program will play a key role of leadership and outreach to other U.S. and international groups including:

- Strong, active participation in coordinating international collaborations that leverage U.S. capabilities through the ITPA and IEA Cooperative Tokamak Program implementing agreement.
- Promoting and stimulating theory/model development and validation with the broader theory community through strong alliances with the U.S. Transport Task Force (TTF), Edge Coordinating Committee (ECC), the Scientific Discovery through Advanced Computing (SciDAC) theory efforts, and university theory groups across the U.S.
- Strengthening the role of universities in the U.S. fusion science program by increasing opportunities for graduate students and university research personnel.
- Active participation and leadership of the U.S. Burning Plasma Organization.
- Continued active role in evaluating and promoting new initiatives for the U.S. program.
- Participate in developing enabling technologies critical to the success of ITER.
- Outreach to the broader science community, communicating the excitement and progress of fusion energy science, making available data from well diagnosed high temperature plasmas and making the DIII-D facility available for non-fusion research as appropriate.

1.8. BENEFITS AND IMPACT OF RESEARCH

Research on DIII-D will provide significant benefits to the world fusion community while synergistically advancing FES goals in the pursuit of realizing fusion energy: success of ITER, FNSF conceptual design, enhanced international collaborations, and predictive modeling. In particular, DIII-D research will contribute significantly to the physics basis necessary to resolve remaining ITER design issues, enhance confidence in ITER achieving its Q=10 objective, prepare the physics basis for defining the path for fusion energy beyond ITER, and deliver validated predictive capability of performance-defining physics. At the same time, the Program Plan will deliver a world-class platform capable of significantly enhancing worldwide collaboration on key fusion science issues and provide a compelling framework for training a new generation of fusion scientists.

ITER Support. Over the five-year program period 2014–2018, DIII-D research will provide significant contributions to the U.S. effort on ITER including:

- Detailed physics information for decisions on critical ITER design issues including ELM control coils, rapid shutdown systems, etc.
- Enhanced confidence in predictive modeling of transport in the burning plasma conditions (e.g., T_e=T_i, low rotation, low collisionality).
- Validation of key physics models for projecting ITER performance, assistance in preparation of ITER experiments, and interpretation of ITER results.
- Validated long-pulse scenarios that satisfy ITER's high gain mission.
- Physics basis for steady-state operational scenarios on ITER.
- Demonstrated real-time control capabilities relevant for full range of ITER actuators and scenarios.
- Critical information for the design of ITER diagnostics.
- Demonstrated capability to respond quickly to ITER urgent issues (e.g., test blanket module tests).
- Training of scientific staff for the success of ITER, and for the U.S. to benefit from operation on ITER.

FNSF Conceptual Design. In the five-year program period, DIII-D research will benefit the FNSF conceptual design through:

- Proof-of-principle demonstration of high β, steady-state operation at performance levels consistent with FNSF mission requirements.
- Detailed physics basis of steady-state operation in conditions expected in FNSF (e.g., T_e=T_i, low rotation, high b) including self-consistency of transport, current drive, and stability.
- Demonstrated methodology for active profile and instability control at optimum performance levels.
- Innovative boundary solutions that achieve heat and particle control while maintaining high performance steady-state core plasmas.

International Collaborations. DIII-D's unique position in the international fusion program will enable the U.S. fusion program to gain significant benefit through:

- Mutual investment by international partners in new DIII-D capabilities.
- Leadership of a long-pulse initiative to demonstrate the promise of high gain scenarios for ITER and steady-state scenarios for next-step devices that first utilizes DIII-D capabilities to develop such scenarios followed by the demonstration of the compatibility of these solutions with steady-state performance and metal walls on international devices.
- Acceleration of the development of long-pulse scenarios on new superconducting devices to enable early research on steady-state control/sustainment and material issues.

Predictive Capability. Capitalizing on a key strength of the DIII-D program, the Five-Year Program Plan will advance the fundamental understanding and predictive capability on a broad front providing significant benefit to the fusion community including:

- Cutting-edge advances in understanding of key physical processes impacting fusion plasma performance.
- Validated, coupled physics models that describe complex plasma behavior sufficiently well for design and exploitation of future devices.
- Reduced physics models that can be used reliably for real-time profile control.
- Strong coupling with theoretical community that enables rapid adaptation to emerging understanding, potentially leading to transformational discoveries.

Through this Research Plan, the U.S. program will be enabled to remain at the forefront of fusion science, providing physics understanding and solutions that ensure the success of ITER and prepare the path to fusion energy development beyond ITER.

2. PLASMA DYNAMICS AND CONTROL

The achievement of burning plasma regimes suitable for fusion energy production represents one of the grand challenges of plasma physics. It requires not only a mastery of the dynamics of the burning plasma state in order to understand how to achieve the required performance, but also of the control techniques necessary to safely develop and maintain the plasma, and quench it when needed. Because the burning plasma state represents quite different and more demanding conditions than those accessed in devices to date, research is needed in present devices to resolve how future devices such as ITER will meet the required levels of performance and operational robustness with acceptable loads and device wear. This is vital to ensuring the success of ITER and a strong U.S. leadership role that capitalizes on its ITER investment. It is also crucial in determining a viable approach to steady-state burning facilities such as a Fusion Nuclear Science Facility (FNSF) and ultimately a power plant. This grand challenge — to develop the solutions and scientific basis for burning plasmas in future fusion devices — represents the primary focus setting the context for the DIII-D program in 2014–2018. The challenges for these future fusion devices are quite different from those in present facilities and provide the basis for the development and proposed upgrades for the DIII-D facility in the Program Plan, as summarized in Table 2-1 and discussed below.

Table 2-1
High Level Challenges for the Achievement of Burning Plasma Regimes for Fusion Energy

<table>
<tr><th>Challenge</th><th>Approach</th><th>Key Capability Improvements</th></tr>
<tr><td>Section 2.1 – Development of Inductive Scenarios for Burning Plasma Regimes
Help ensure ITER is successful in fulfilling its Q=10 mission by optimizing performance in burning plasma relevant regimes</td><td>Torque-free dominant electron heating and balanced neutral beam operation. Innovative diagnosis and perturbative experiments to resolve underlying physics.</td><td rowspan="5">Hardware upgrades:
• Electron cyclotron resonance heating (ECRH) upgrade for 8.5 MW plasma heating and current drive
• Increased neutral beam energy
• Second off-axis beam
• Advanced 3D coil set
• New poloidal field (PF) power supplies

Diagnostics:
• Improved turbulence, current profile and plasma termination diagnostics

Code development:
• Turbulence codes
• Advanced stability modeling
• Disruption simulation tools
• Expanded TokSys control design and simulation environment
• Integrate toward whole discharge simulation</td></tr>
<tr><td>Section 2.2 – Steady-State Scenario Development
Develop the means for fully non-inductive operation for FNSF and power plant</td><td>Off axis current drive and heating with increased heating power to reach high β configurations (above no-wall limit), consistent with confinement, pedestal and heat exhaust control.</td></tr>
<tr><td>Section 2.3 – Stability and Disruption Avoidance
Develop physics understanding of key instabilities and establish physics basis for their control</td><td>Perturbative studies to resolve stability boundaries. Active sensing and control with 3D fields. Profile manipulation. ECCD to control modes.</td></tr>
<tr><td>Section 2.4 - Disruption Characterization and Mitigation
Identify the means to safely quench the fusion plasma</td><td>Active control of thermal and current quench and runaway phase using mitigation tools, combined with sensitive diagnostics to measure critical processes and parameters.</td></tr>
<tr><td>Sections 2.5 – Control
Develop disruption-free control for ITER, FNSF, and DEMO</td><td>Design and apply model-based robust algorithms. Develop off-normal response algorithms to prevent disruption.</td></tr>
</table>

Development of Inductive Scenarios for Burning Plasma Regimes. Unlike present devices with high rotation and/or strong ion heating, a burning plasma will be dominantly heated through the electrons by the alpha particles and will have low rotation. This fundamentally changes the nature of the energy transport processes, likely leading to a different optimization of regimes from present devices. It is important to understand the dynamics of this optimization and its underlying physics in order to move rapidly toward realizing full performance in ITER and establish the requirements of an FNSF. Thus electron cyclotron heating (ECH) upgrades are proposed, which heat the electrons [like fusion alpha particles] and provide localized perturbative capabilities to explore the physics. These systems are now well-established and reliable tools on the DIII-D facility. Combined with neutral beam heating and balanced torque capabilities, this provides enormous flexibility to develop viable regimes and explore the underlying physics, which must also be combined with the other requisite control techniques for instabilities and edge localized modes (ELMs). High performance inductive research on DIII-D in burning plasma relevant conditions of low torque, dominant electron heating and low collisionality fits well into the worldwide program that has complementary capabilities, such as high density operation with metal walls [e.g., Germany's Axisymmetric Divertor Experiment Upgrade Tokamak (ASDEX-U) and the Joint European Torus (JET)].

Steady State. Beyond ITER, the key goal is to sustain fusion in "steady state" for quasi-continuous operation for research into fusion nuclear science and to prove the methods of a fusion power plant. This requires more advanced configurations that modify current and pressure distributions to enable the high levels of pressure, stability and confinement to be maintained. A second off axis neutral beam is proposed, as well as increases in beam energy, which modeling suggests will provide the flexibility required to access the high β scenarios necessary to explore this optimization. This is greatly augmented by the ECH upgrades, which can also drive localized current. The steady-state program proposed here will be unique in the world program. In particular, steady-state research is not being as aggressively targeted on the other large tokamaks, with ASDEX-U (AUG) and JET being primarily focused on understanding and optimizing performance with metal walls. However, as heating capabilities improve on the super-conducting devices like China's Experimental Advanced Superconducting Tokamak (EAST) and the Korean Superconducting Tokamak Advanced Research (KSTAR), steady-state solutions from DIII-D can be tested to true long-pulse steady-state conditions. Upgrades proposed for the National Spherical Torus Experiment Upgrade (NSTX-U) will allow complementary steady-state research to be conducted in a tight aspect ratio device, and when coupled with DIII-D research should inform the design of a next-step FNSF. In addition, parallel research on large stellarators such as Japan's Large Helical Device (LHD) and Germany's Wendelstein 7-X Stellarator (W7-X) will eventually allow for an evaluation of the most attractive steady-state fusion power plant.

Stability and Disruption Avoidance. These future directions also pose much greater stability challenges. Deleterious events such as tearing modes (TMs), ELMs or disruptions will be far less tolerable than in present facilities, while the parameters accessed potentially make the plasma more susceptible to these adverse events. In particular, low rotation in burning plasma devices increases susceptibility to tearing modes, which can be further exacerbated in the presence of three dimensional (3D) fields (naturally arising or used to control events such as ELMs). These issues imply an integrated program is needed to both identify and understand the susceptibilities, and develop the necessary means of control. This program will greatly benefit from increased flexibility in 3D fields, utilizing increased power supply capabilities to the existing 18 3D field coils in the early part of the Five Year Plan. Later in the plan, a new advanced coil will enable exploration and rotation of higher order toroidal harmonics, and inform how to optimize poloidal and toroidal composition of 3D fields to maximize beneficial effects [such as ELM control or neoclassical toroidal viscosity (NTV) rotation], while avoiding deleterious effects (such as locked modes). The proposed increases in ECH capability will also form a central part of this strategy, providing the localized current drive and profile modification to explore the full optimization of tearing mode control strategies for ITER and beyond.

Disruption Mitigation (DM). A strategy must be developed in the case of unplanned plasma termination or disruption. While a goal of the above programs must be to virtually eliminate these events, a fall back plan to safely quench the plasma is necessary. Unmitigated disruptions would lead to significant wear and the potential for damage in ITER and are virtually intolerable in a power plant. This challenge has three main constituents: (i) to spread the thermal loads sufficiently to avoid damage to the wall; (ii) to manage the current quench (CQ) to avoid excessive forces on the vessel components; (iii) to develop methods to prevent, or control and dissipate, the runaway beam arising from the current quench. While excellent progress has been made on the first two items, both at DIII-D and at other facilities, issues of radiation asymmetry remain of great concern. The complexity in achieving full-coverage diagnosis of the disruption implies a strong synergy for cross-machine comparison (e.g., AUG and JET) exists. For item (iii), the strategy remains unclear. DIII-D is now the premier facility in the world for exploring these issues, thanks in part to its forgiving carbon walls, which enable studies to be undertaken, but also to its range of mitigation and control systems, and its diagnostic excellence. Work in this Five Year Plan will focus on exploring the interaction of various quench systems with control approaches for position, shaping and 3D fields, to answer key physics questions and provide candidate solutions for ITER and beyond.

Control. As the world fusion community approaches the goal of achieving significantly self-heated plasmas in ITER, high performance plasma control plays an increasingly essential role. Achievement of the unprecedented levels of control reliability and performance demanded by ITER will require aggressive progress in both physics understanding specifically driven by control needs, and control science needed to provide ITER solutions. Disruption-free, robustly sustained operation of FNSF and a viable tokamak power plant will require an even greater level of reliability than ITER, with fewer actuator and sensor resources available. Control research is also critical for development of new algorithms to enable exploration and elucidation of new plasma physics frontiers in DIII-D and other operating devices. DIII-D leads the world in integrated plasma control, driven by the demands of advanced tokamak regimes and owing to its powerful and flexible plasma control system (PCS), a long history of control-level physics model development, and deep expertise in model-based design. The DIII-D PCS is shared by many operating devices worldwide, enabling a rich and synergistic sharing of resources to advance the field of control. Specific elements of the control research plan include advancement of profile control, active tearing mode suppression, emulation of integrated ITER control elements, robust regulation of proximity to stability boundaries, and off-normal event and fault response (ONFR) algorithms to prevent disruption.

The components of this program are described in the following sections. While issues directly associated with the dynamics and control of plasmas operating in fusion relevant conditions are discussed in Section 2, it should be noted that these same conditions set the requirements for work across the program, including anticipating the physics in burning plasma conditions in Section 3, and the development of a compatible boundary solution in Section 4.

This integrated program on the DIII-D facility will provide the basis to understand the design and optimization of the burning plasma state in future fusion devices, and the requirements and utilization of tokamak systems to control and safely manage the plasma in that state. The proposed upgrades will enable the facility to move forward to address this "grand challenge" by taking it to the parameters required to address and explore the new science of burning plasma devices. Together with the physics tools to resolve the underlying processes and optimizations for these future devices, DIII-D will keep the U.S. at the forefront of the field in the ITER era.

2.1. DEVELOPMENT OF INDUCTIVE SCENARIOS FOR BURNING PLASMA REGIMES

2.1.1. Challenges

The highest level goal of the Inductive Scenarios topical area is to help ensure ITER is successful in fulfilling its Q=10 mission. To achieve this, the research will focus on developing the best inductive scenarios that can be produced with ITER's expected capabilities and limitations, while minimizing risk to the ITER device and components. An essential aspect of this work involves developing and validating the physics basis for ITER Q=10 inductive scenarios to enable reliable extrapolation of the results from DIII-D to ITER, and to provide ITER the technical knowledge to operate candidate scenarios that meet its goals, including integration of the necessary control schemes. This should enable rapid progress to full performance on ITER, and avoid lengthy scenario development on ITER itself, while also providing design information for future fusion devices, including a nuclear test facility or a pulsed reactor.

The challenges in achieving these goals, the planned approaches to addressing them, and the necessary hardware upgrades are summarized in Table 2-2.

Table 2-2
Inductive Scenarios, Approaches and Upgrades

<table>
<tr><th>Challenge</th><th>Approach</th><th>Capability Improvements</th></tr>
<tr><td>Determine paths to high confinement and stability with low rotation and dominant electron heating to produce scenarios that fulfill ITER's Q=10 mission</td><td>• Utilize rotation control to optimize ExB shear
• Use current profile control to enhance stability and confinement
• Develop low torque electron heated scenarios with high fusion performance</td><td rowspan="4">Actuators:
• ECH power upgrade
• Off-axis NBI
• New power supplies for 3D coils
• Advanced 3D coil set

Diagnostics:
• Improved core Thomson scattering
• Increased spatial resolution of MSE

Codes:
• Time-dependent TGLF analysis
• GYRO with 3D fields and NTM physics
• IPEC-NTV, MARS-Q
• M3D-C1</td></tr>
<tr><td>Extend and enhance solutions to reduce risk to ITER operations</td><td>• Extend above approaches to achieve high performance at higher β_N and reduced I_p</td></tr>
<tr><td>Integrate the necessary control tools into high performance scenarios</td><td>• Simultaneously deploy NTM, ELM and heat flux control, together with disruption mitigation techniques, and investigate compatibility with high performance scenarios</td></tr>
<tr><td>Establish requirements for ITER to most effectively use its non-nuclear phase to prepare for burning plasma conditions</td><td>• Improve knowledge of L-H power threshold in He plasmas, and investigate techniques to reduce it
• Assess requirements for accessing regular type-I ELMing discharges
• Investigate compatibility of ELM suppression techniques in He plasmas</td></tr>
</table>

The standard "baseline" approach for ITER is to operate at moderate β_N and confinement and comparatively high plasma current. The β_N is limited in part to avoid triggering tearing modes, although even at these modest levels, tearing modes may still be problematic due to sawteeth. The potential exists on ITER to exploit more advanced scenarios, such as the advanced inductive (AI) plasma regime or quiescent H-mode (QH-mode), which offer the possibility to reach Q=10 with reduced risk to the device by operating at higher β_N with higher normalized confinement. A DIII-D goal is therefore to combine the favorable characteristics of the various scenarios to produce a solution with high normalized fusion performance in the anticipated ITER operating space (e.g., low torque access and operation; $T_e/T_i \sim 1$ with dominant electron heating; integrated off-normal recovery and disruption avoidance; ELM control; implementation of appropriate divertor solution; tearing mode and sawtooth control; compatibility with core fueling methods including pellets).

Demonstrating the existence of high performance inductive solutions is only one element of the research program. A critical and essential aspect of this work is developing a validated physics basis to ensure that the proposed inductive solutions can fulfill the needs of ITER. However, this in itself represents a challenge and an opportunity. For example, while DIII-D is well-suited to developing and adapting these scenarios to timescales of order the resistive time, it cannot test these solutions out to wall and plasma facing component (PFC) thermal equilibration timescale (10s to 100s of seconds). Moreover, experiments on JET and elsewhere have shown that a degree of adaption may be needed in going from a scenario developed with a carbon wall to a device with metal PFCs. Hence, an integral part of this plan should include testing these scenarios in long pulse superconducting (SC) devices with metal walls such as EAST and KSTAR.

Looking beyond this, the work in this area should inform the relative merits of an inductive versus steady state approach for a fusion reactor. Indeed, advanced scenarios may provide a path to an inductive solution that exceeds ITER's mission, with Q>10 or even ignition. One should therefore consider this research, by extension, a complement to the steady-state solution for a fusion reactor, where pulsed operation and the inherent thermal cycling are accepted in exchange for maximal fusion output, increased flexibility and reduced demands for scenario control. As the only tokamak that can routinely compare single and double null performance, DIII-D is ideally suited for supporting ITER's inductive needs as well as developing candidate operating modes for both FNSF and contributing to an assessment of the feasibility of a pulsed DEMOnstration power plant (DEMO).

2.1.2. Research Plan Overview

DIII-D is well positioned to pursue inductive scenario research and make key contributions to ensure the success of ITER and the broader fusion energy program. DIII-D can control important physics parameters with a sophisticated PCS and an extensive and highly flexible actuator set:

- Independent β_N and rotation control using co/counter neutral beam injection (NBI) and non-axisymmetric field.
- Control of T_e/T_i by changing heating from ions (NBI) to electrons (ECH).
- Current profile control using off-axis NBI (OANBI).
- ELM control with non-axisymmetric fields.
- Access to wide range of shapes (including ITER shape).

This allows DIII-D to produce ITER scenarios at relevant values of dimensionless parameters including collisionality, β, Mach number, and safety factor (although not necessarily representative of ITER plasma-wall interactions). The presence of a carbon wall allows for more freedom to explore performance boundaries with little risk to the tokamak. Figure 2-1 summarizes the timeline for the proposed research elements of the inductive scenario program.

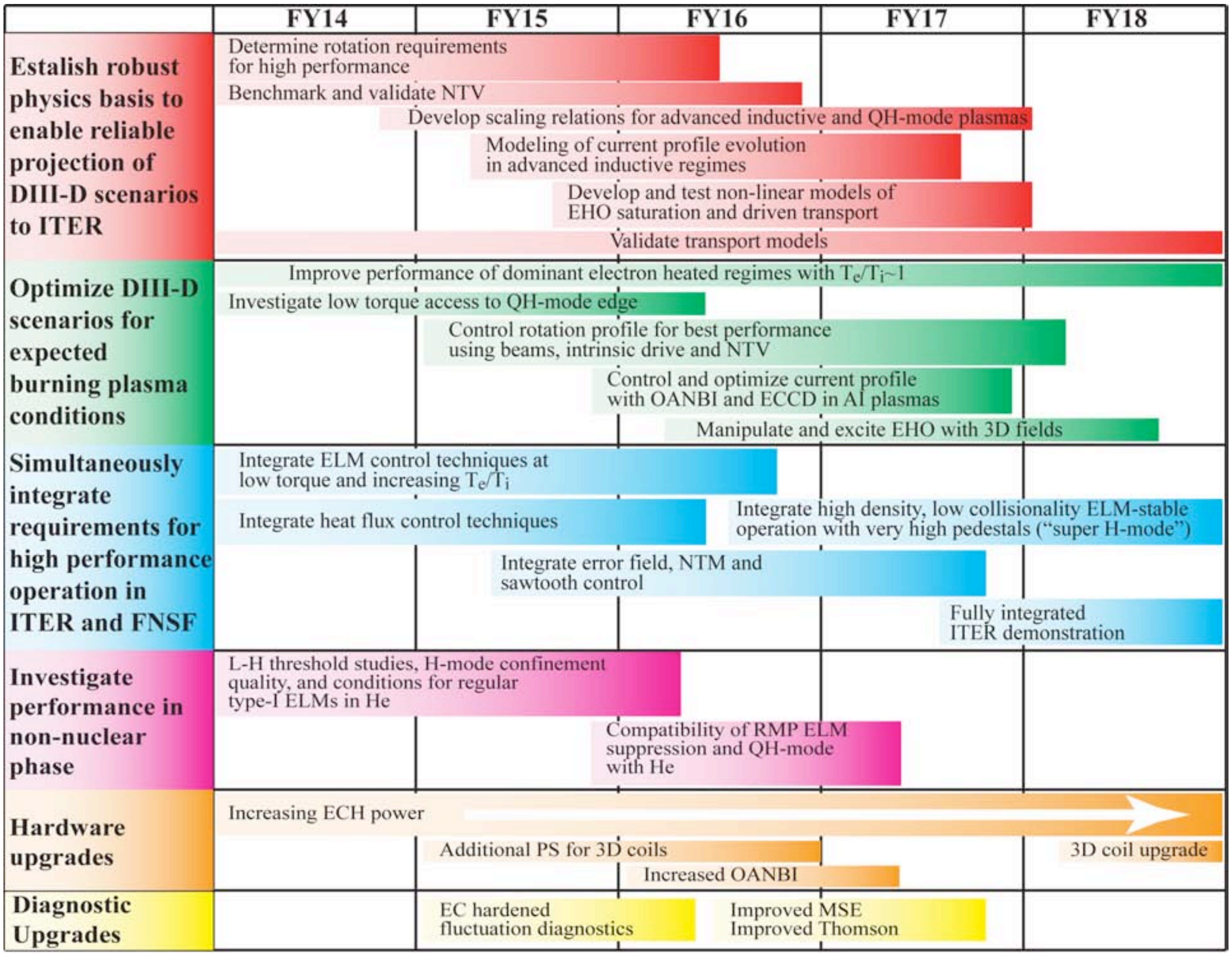

Fig. 2-1. FY14–FY18 program elements, hardware (upgrades).

2.1.3. Detailed Research Plan

The research goals in the inductive scenario area are primarily focused on optimizing performance while achieving maximal overlap with ITER and FNSF operating space. Where parameters cannot be simultaneously met on DIII-D, the physics basis for extrapolating the scenario toward ITER will also be strengthened. To this end, the performance of inductive scenarios, including stability and transport properties, will be evaluated as a function of key physics quantities (e.g., Mach number, T_e/T_i, collisionality vs. Greenwald fraction etc.).

The following subsections describe the key explorations, needed to improve the physics basis for confident extrapolation of DIII-D scenarios to future devices.

2.1.3.1. Optimization of Dominant Electron Heating Regimes. Burning plasmas will be heated primarily through the electron channel, both due to the self-heating from the alpha population, as well as increased direct electron heating from auxiliary systems. Hence, present experiments need to begin to assess the impact of electron heating on inductive scenarios, and, if necessary, re-optimize the scenarios for these more reactor relevant conditions. Already, prototype ITER baseline (IBS) discharges have been demonstrated using predominantly electron heating (Fig. 2-2), specifically with electron cyclotron heating

P_{ECH}=2.8 MW and NBI heating P_{NBI}=1 MW [Jackson 2013]. To date, these discharges have been limited to q_{95}~4.2; future work will aim at reducing this back toward the appropriate ITER value.

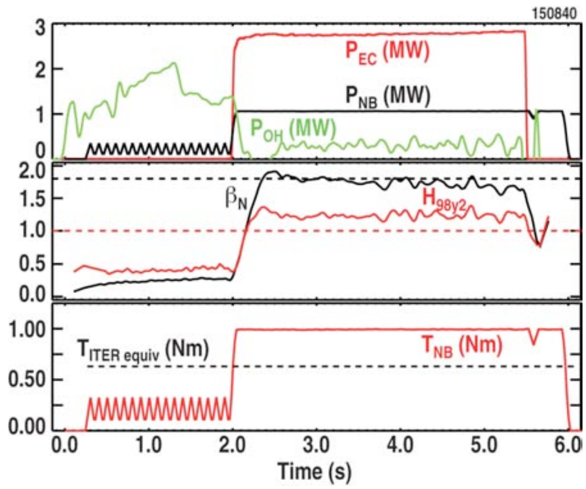

Fig. 2-2. Prototype ITER baseline discharge with dominant electron heating.

Scenario sensitivity and performance will be investigated as a function of T_e/T_i, using ECH power to supplement neutral beam heating. For the ITER baseline scenario, modeling shows 8.5 MW of ECH in DIII-D is sufficient to reach T_e/T_i>1.3 averaged across the profile at nominal toroidal field (TF) ~1.9 T, and allows a decoupling of the ions and electrons, with the ratio of the energy confinement time to the electron-ion equilibration time τ_e/τ_{ei} reduced from about 10 with current levels of ECH to about τ_e/τ_{ei}~0.5. This capability to study the impact of T_e/T_i in low collisionality plasmas will provide an excellent complement to facilities such as AUG and JET, where the temperatures are often equilibrated owing to high density as opposed to high electron heating. Up to 6 MW of electron heating is required to conduct modulation experiments at full field to investigate electron transport and stiffness. For higher β scenarios such as the advanced inductive/hybrid [Wade 2005], this level of ECH will allow operation with close to T_e/T_i~1 with minimal use of neutral beams, particularly if coupled with additional fast wave heating.

This increase in electron heating, in turn, allows a more thorough physics exploration of the transport mechanisms relevant to burning plasmas. For example, trapped gyro-Landau fluid (TGLF) code [Staebler 2005] modeling shows that the fraction of heat loss through the electron channel increases dramatically with electron heating, with only modest increases in the ions. Studies in AI plasmas have shown that an increase in the temperature ratio T_e/T_i from 0.65 to ~0.8 in the core reduces the confinement by approximately 15%. However, as Fig. 2-2 shows, good confinement can be achieved with significant electron heating. Adequate experience with electron heating and low torque in present devices is important to avoid potentially costly re-optimizations at the reactor scale.

2.1.3.2. Confinement Optimization with Low Torque. Although progress has been made on this goal, particularly the low torque aspects, there is still significant work required in this area, and hence it will continue to be a major emphasis of the DIII-D inductive research program. For the most part, low torque operation has been achieved using balanced NBI, and while the net torque achieved can be well controlled using such a technique and has been exploited extensively to expand operation into burning plasma relevant torque levels, it has the defect that the torque profile is not identically zero. For example, the profile from a co-beam tends to be slightly more peaked on axis than a counter beam, such that balanced injection typically has co-NBI in the core, and counter NBI in the edge, resulting in a degree of torque shear. The use of torque-free methods of heating, such as from the increasing levels of ECH throughout the course of the Five Year Plan, can help isolate the relevance of such subtleties. In total, up to 20 MW of approximately torque-free heating will be available for studying high beta scenarios in the burning plasma relevant regime of low torque when coupled with the existing balanced NBI capability. The ability to compare balanced torque input with inherently torque-free heating will be valuable in connecting work on purely rf-heated plasmas such as MIT's ALCATOR C-Mod (C-Mod) and Switzerland's Tokamak À Configuration Variable (TCV), with other devices which can vary the NBI torque, such as LHD and eventually Japan Tokamak-60 Super Advanced (JT-60SA).

Control of the rotation profile. Experiments on DIII-D will utilize balanced NBI and ECH for low torque heating, and will exploit non-axisymmetric magnetic fields to drive and control rotation independent of external momentum input. This will lead to improved understanding of how rotation influences performance.

Rotation requirements for high performance. In addition, the rotation requirements for high confinement, good stability and reliable ELM control will be established, which in turn will allow for designing scenarios with improved performance, by generating localized regions of *ExB* shear, for example. Determining such paths to recovering high confinement with low torque input is of particular importance to the AI regime, which has shown the most pronounced decrease in confinement as the rotation is reduced. A clear example of this is shown in Fig. 2-3, where the torque is ramped down with β feedback control in an AI plasma and the power demand increases significantly [Solomon 2013]. Despite the impact on confinement, recent experiments have confirmed that the scenario can be established without significant NBI torque, and that high β_N~3.1 and high normalized fusion performance can still be achieved (Fig. 2-4). A more modest impact on confinement is seen in ITER baseline scenario experiments.

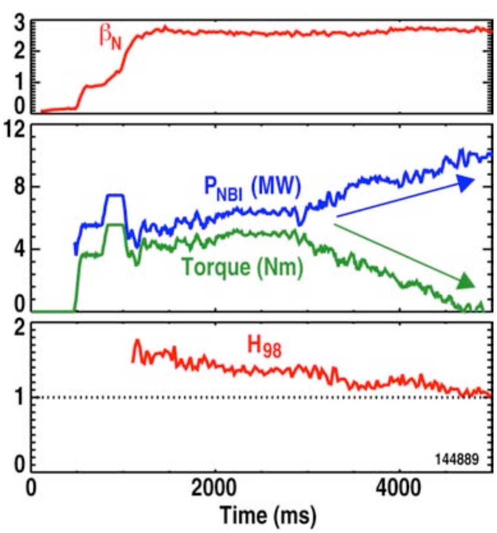

Fig. 2-3. A reduction in torque leads to a significant reduction in confinement in AI plasmas.

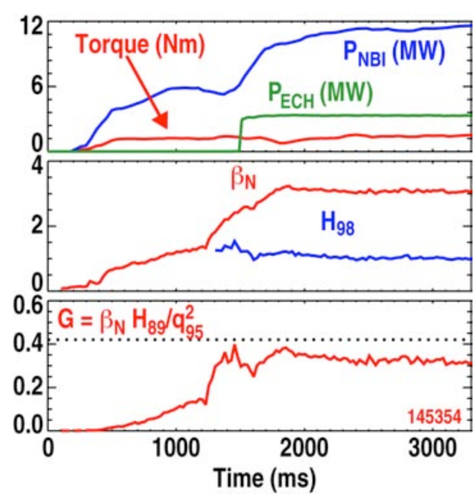

Fig. 2-4. High fusion performance at low torque.

Benchmark and validate NTV theory. Since 3D fields play an important role in rotation control, experiments will be conducted to further benchmark and validate NTV theory, particularly collisionality, beta and rotation dependences, to enable reliable projection of the associated torque to ITER (see also rotation physics, Section 3.4). Additional flexibility in controlling the 3D spectrum of the applied field, so as to vary the ratio of resonant and non-resonant components, will be valuable in allowing rotation control in scenarios with low external torque.

2.1.3.3. Integration of ELM Control. The periodic heat fluxes from ELMs presents an issue for the divertor and PFCs of ITER. It is expected that the heat flux from ELMs will have to be reduced by up to a factor of 50 to avoid premature destruction of the divertor. Hence, proposed inductive solutions for ITER need to be able to show compatibility with ELM control. Techniques to control ELMs include pellet pace making (to increase the frequency while reducing the peak heat fluxes), the use of resonant magnetic perturbations (RMPs) to suppress ELMs entirely, or operating in a regime that is inherently ELM stable (such as QH-mode or I-mode). Each of these ELM control techniques will be incorporated into candidate inductive scenarios, and the effect on fusion gain will be assessed, and where necessary, the application of these tools will be optimized to minimize any negative impact on performance. A recent example of RMP ELM suppression in the standard ITER baseline scenario is shown in Fig. 2-5. In this case, ELM suppression was achieved for approximately 45 τ_E and a few resistive times. So far, the use of electron cyclotron current drive (ECCD) for tearing mode control has been essential for this work, even in these all co-NBI discharges, since the addition of RMP results in a significant drag on the rotation which tends to destabilize tearing modes. The RMP in these ITER baseline (IBS) discharges also has a significant impact on confinement, which is exaggerated due to the use of additional electron cyclotron (EC) for mode control; however, $H_{(98,y2)}$~0.9 has still been achieved. It is expected that further optimization of the RMP fields will allow for higher performance.

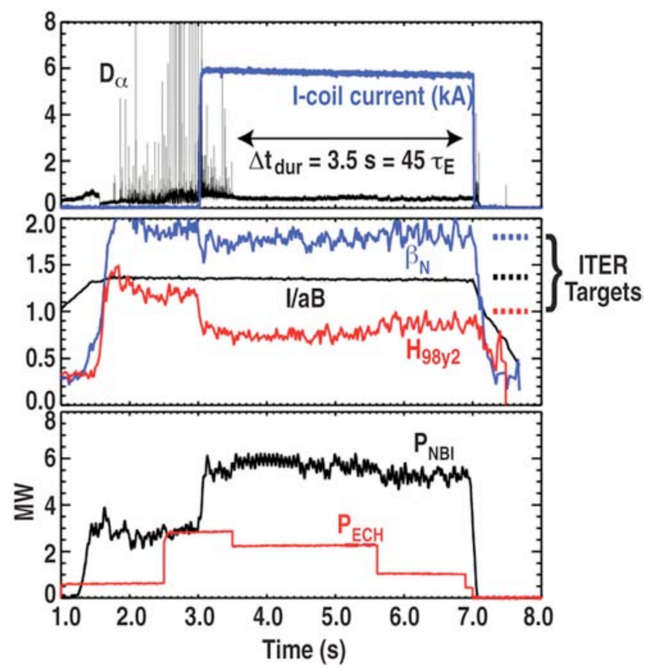

Fig. 2-5. RMP ELM suppression in ITER baseline.

QH-mode offers the possibility of operating in a state inherently free of ELMs and the associated pulsed heat fluxes, owing to an edge harmonic oscillation (EHO) that produces edge particle transport exceeding the time average pulses from ELMs [Burrell 2005]. It has been run for long durations up to 30 τ_E or approximately two current relaxation times, limited by the available NBI pulse length, and has also been studied on several devices, including JET, AUG and JT-60U. While transiently it has reached normalized fusion performance $G = \beta_N \mathrm{H}_{89} / q_{95}^2$ approaching the value needed for ITER (G~0.42) at relatively low levels of torque, as shown in Fig. 2-6, it has yet to be sustained at this level of performance. Extending this level of performance to more stationary conditions will be a critical first step in evaluating the use of a QH-mode edge for ELM control in ITER.

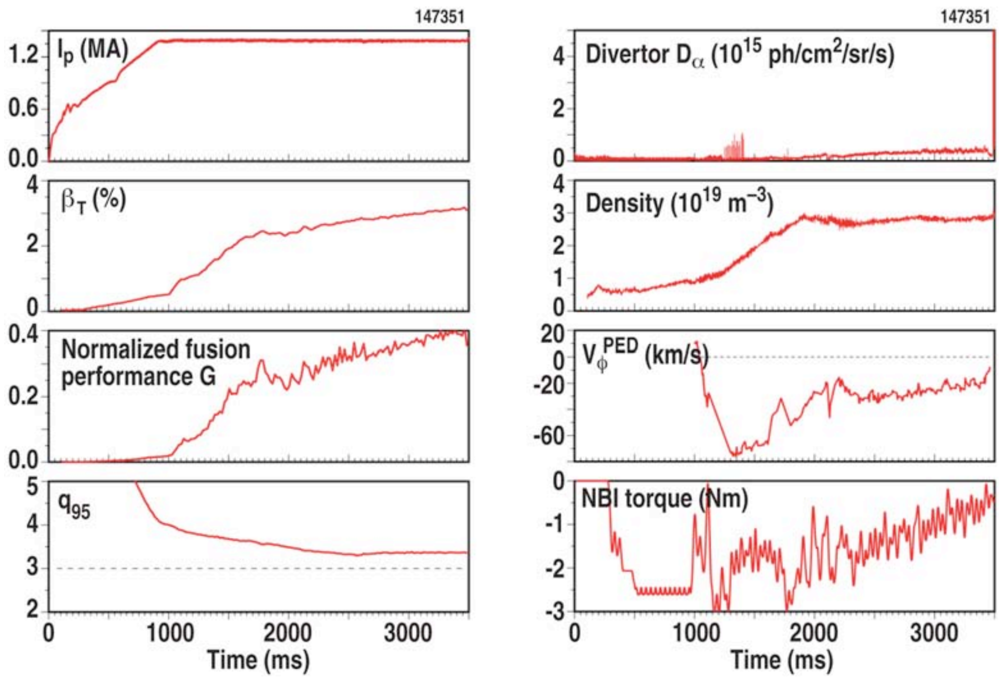

Fig. 2-6. Transient achievement of ITER-normalized fusion performance in QH-mode.

Validate ELM control techniques at low torque and T_e~T_i. Experiments on DIII-D will investigate the compatibility of ELM control techniques in low torque, dominant electron heated plasmas. Additional power supplies for the non-axisymmetric field coils will allow individual coils to be powered (allowing optimization of the error field while applying RMP), while an improved 3D coil set will allow for specific tailoring of the non-axisymmetric field for the desired purpose (e.g., resonant versus non-resonant field for RMP ELM suppression vs. QH-mode). With these new tools, the requirements of the field spectrum for low torque ELM suppressed states will be clarified.

Low torque access to QH-mode. Experiments will be conducted to determine the access conditions, particularly with respect to rotation and/or rotation shear, for establishing an EHO and QH-mode operation. In the past, QH-mode operation has typically been associated with very large levels of NBI torque, which made the scenario appear inaccessible to ITER. More recently, it has been demonstrated that QH-mode can be sustained at very low levels of NBI torque (e.g., Fig. 2-7), by using non-resonant magnetic fields (NRMFs) to provide the edge rotational shear [Garofalo 2011], albeit so far at higher q_{95}

and reduced normalized fusion performance (G~0.15). Although calculations using the EPED1 model and ELITE show that ITER will operate along the peeling boundary needed for QH-mode (Fig. 2-8), it is still not clear that QH-mode conditions can really be established in ITER. As a first step, this requires determining whether the NTV torque expected from the 3D coils on ITER can drive sufficient rotation shear to destabilize the EHO. Ideally, the NTV torque should be adequate at the L-H transition to allow a direct transition to QH-mode. If not, other ELM mitigation techniques (such as pellet pacing) may be needed for a short period before QH-mode is established.

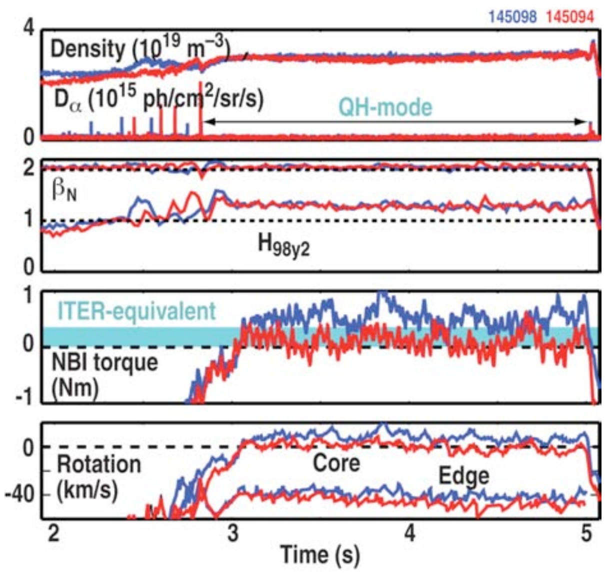

Fig. 2-7. QH-mode operation at low NBI torque.

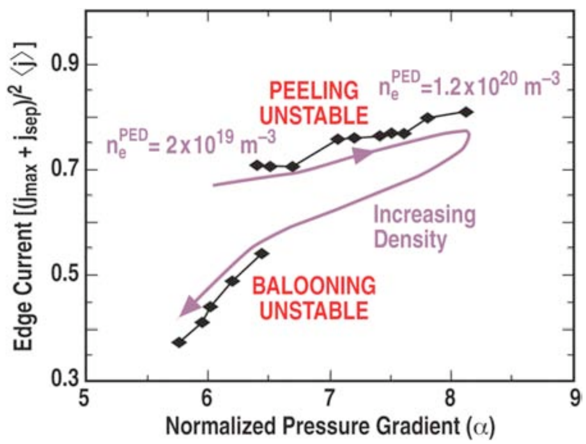

Fig. 2-8. ITER's pedestal calculated to be up against peeling limit as needed for QH-mode.

Manipulate EHO with 3D fields. New 3D coils will be exploited to externally excite the EHO and try to expand the QH-mode operating space, as well as enable mode number control of the EHO (which can be critical, since n=1 EHOs have a tendency to lock to the wall at low rotation). The audio amplifier upgrade will improve the capability of producing high frequency, high amplitude fields that are needed to explore this possibility.

Nonlinear models of EHO. Ultimately, to give confidence that QH-mode is compatible with ITER operation, a nonlinear model describing the saturation of the EHO will be developed. This will be used to evaluate the associated driven transport on DIII-D experiments, and to predict whether the EHO is destabilized on ITER and drives sufficient transport to prevent ELMs.

Super H-mode. An extension of QH-mode, dubbed "super H-mode" will be explored. It is thought that with strong shaping and a careful trajectory in density evolution, the peeling ballooning stability boundary can be extended to very high density and current. Such a solution would have a very high pedestal and high bootstrap current at the edge, and would simultaneously integrate high density and low collisionality operation, which together might represent a very attractive solution for high performance operation.

2.1.3.4. Integrated MHD Control. Disruptions have the potential to cause significant damage to internal components in ITER. Therefore, it is imperative that any proposed ITER scenario is resilient to disruptions, and, where necessary, that disruption avoidance and mitigation techniques can be employed. Obviously, this means maintaining a stable current profile, using both passive and active means of control as needed and inductive scenario research will focus on defining the requirements for, and access paths to such optimal current profiles. However, there is always the potential for off-normal events, and it is necessary to be able to be both detect and deal with such occurrences. Adequate detection will require accurate, real-time calculation of the proximity to a stability boundary that could lead to a disruption.

Integrate error field, neoclassical tearing mode (NTM) and sawtooth control. Experiments will be conducted to integrate high performance solutions with minimal disruptivity, by incorporating sophisticated error field control algorithms using the advanced 3D coil set, together with sawtooth mitigation and tearing mode control using active localized ECCD. The development of tools for off-normal events will be described in the stability and disruption avoidance section (Section 2.3), while the main effort in this research area will be on utilizing and adapting these tools as needed in high performance scenarios. The use, effectiveness and compatibility of such tools with candidate inductive scenarios will be evaluated against the criteria of maintaining adequate performance of a high fusion gain solution, while the general assessment of tearing stability will be conducted using codes such as PEST3 and NIMROD, ideally with improved spatial resolution of the current profile in the vicinity of low order rationals such as the q=2/1 and q=3/2 surfaces. Disruption mitigation techniques and non-disruptive soft-landing strategies will also be incorporated into the scenarios as the final fail-safe for off-normal evens (see disruption characterization and mitigation, Section 2.4).

These efforts will be enhanced by additional power supplies to run DIII-D's non-axisymmetric field coils, and faster, more flexible EC steering capability and faster system response. Additional ECH power is important when the ECH is required for multiple tasks at multiple locations (e.g., core heating, sawtooth control, 2/1 and 3/2 TM control), and also for use in specific measurement techniques (such as perturbative transport experiments). For example, simultaneous stabilization of the 2/1 and 3/2 TM in the IBS is estimated to require between 6–7 MW for ECCD (roughly double the present capability). Hence, an upgrade of ECH power will be extremely effective in addressing uncertainties in the physics models and extrapolation of DIII-D scenarios to future devices like ITER.

Current profile control. As noted earlier, achieving robust, disruption free operation is tightly coupled with achieving stable current profiles. Although NTM suppression has been demonstrated with very specific requirements for the localization of the ECCD, experiments have shown that NTM stability can be significantly improved even by changing the heating mix, presumably through changes to the conductivity profiles. Experiments will try to characterize and understand the mechanisms leading to such improved stability to NTMs. In addition, the q-profile is believed to strongly affect confinement, and hence control of the current profile may be an option for optimizing performance. Even though the ohmic current remains substantial in inductive scenarios, both ECCD and OANBI will be exploited to investigate the sensitivity of performance to the achieved current profile.

Modeling of current profile evolution. One particularly interesting scientific exploration involves understanding the evolution of the q-profile in AI plasmas. It is believed that the coupling of core NTMs with edge ELMs plays an important role in maintaining the broad current profile with q_{min} just above 1 associated with AI plasmas. However, one can suppress the NTM with ECCD and maintain the broad current profile using OANBI, allowing the evolution of the current profile to be investigated independent of NTM physics that can complicate transport studies. In addition, such studies will help develop and validate the understanding of the current profile evolution in advanced inductive plasmas and ensure such processes are applicable in ITER.

2.1.3.5. Investigation of Performance in Non-Activation Phase. The non-activation phase of ITER represents an important period to investigate some basic performance issues. Therefore, experiments will be conducted to evaluate the performance of candidate inductive scenarios in H and/or He plasmas. Such studies will focus on determining the access conditions to achieving robust, type-I ELMing discharges, including L-H power thresholds and transition physics, as well as exploring any hysteresis in the H-L back-transition (L-H threshold, Section 3.3).

Once the requirements are established for low rotation H-modes in H/He plasmas, the suite of ELM control techniques (particularly RMP ELM suppression and QH-mode operation) will be integrated and their compatibility with non-nuclear fuel will be investigated. This should indicate whether ITER can check out their ELM control schemes in the non-nuclear phase before the Q=10 D-T mission in the later years. More specifically, the study will define the parameter space over which such techniques can be expected to be effective in H/He plasmas. Recent experiments have shown that RMP ELM suppression can be obtained in plasmas with significant He fraction (~20%), provided that the overall collisionality is maintained similar to that required for ELM suppression in deuterium plasmas (Fig. 2-9). Similarly, the compatibility with DM techniques with helium operation will also be explored.

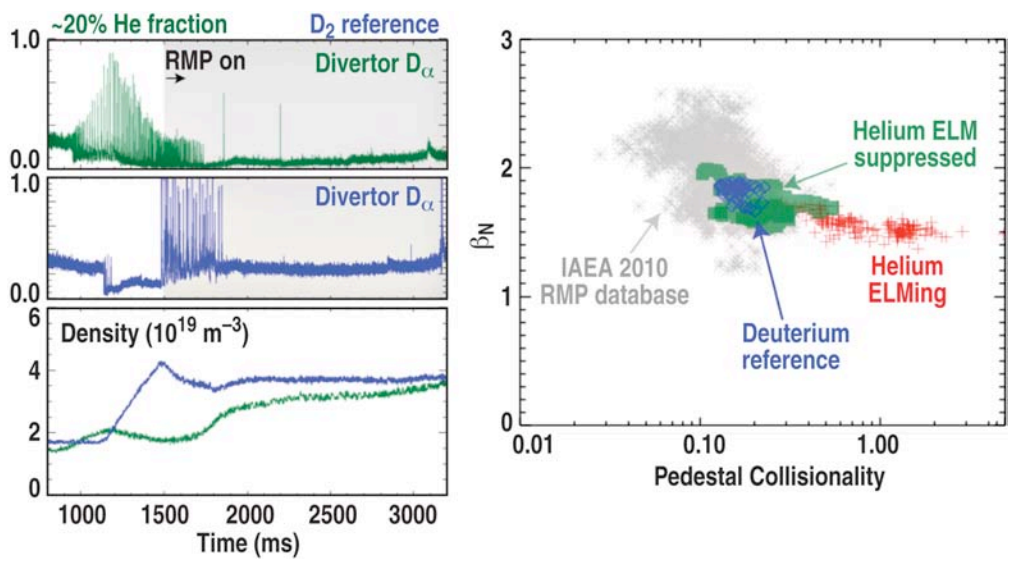

Fig. 2-9. RMP ELM suppression in plasma with 20% He fraction.

2.1.3.6. Improved Transport Understanding to Strengthen Physics Basis. The demonstration of integrated inductive scenarios is only a first step in the development of a solution for ITER. For the scenarios to be readily ported to future devices, an excellent physics basis is essential. An important aspect of performance projections comes back to an understanding of the underlying transport mechanisms. Therefore, more thorough transport studies will be undertaken to supplement and improve confidence in empirical scaling studies.

Validation of transport models. Kinetic profiles, together with heat, particle and momentum fluxes from perturbative transport experiments will be compared against transport model predictions from the full suite of transport codes including TGLF and GYRO. In addition, turbulence measurements will be compared against GYRO predictions where possible. (See Section 3.2 Transport and Turbulence.)

New improvements in TGLF allowing momentum transport and rotation profile predictions will be specifically tested in these scenarios, and used to project rotation profiles for the scenarios to ITER. These transport experiments are desirable not only to give additional confidence in the projections to ITER, but also to help illuminate the path for further optimization of the scenarios. As an example, if it is known that *E*x*B* shear is important in a specific location in the plasma to achieve improved performance, then effort can be spent in trying to craft the best-suited rotation profile (even if constrained that the overall rotation is low).

Develop scaling relations for advanced regime. As an intermediate step, empirical scaling relationships will continue to be developed, particularly for advanced scenarios. Scenarios with $H_{(98,y2)}$ significantly above one do not necessarily follow the standard IPB(98,y2) scaling law, and it needs to be established if more appropriate scaling laws might be applicable.

2.1.3.7. Integration of Heat Flux Control. It is recognized that even the continuous DC heat fluxes on ITER need to be controlled, and to this end, it is presently envisioned that a radiative divertor solution will be employed on ITER. Hence, we will investigate whether proposed inductive scenarios on DIII-D exhibit compatibility with a radiative divertor, or alternatively, demonstrate heat flux control using more novel methods such as the use of non-axisymmetric magnetic fields. More generally, this includes understanding how to initiate and terminate a radiative divertor, coupled with ELM control, consistent with entry to and exit from the burn phase. This, in turn, has a direct impact on the mix of heating systems suitable for entering burn on ITER and proceeding to the high performance Q=10 phase, where large excursions in the stored energy could lead to instabilities that need to be controlled during this sensitive stage of the evolution. Experiments on DIII-D will aim to qualify the physics requirements for ITER entering the burn phase using a radiative divertor (see also Section 4.1). This is an area that complements significant research on AUG, for example, with the DIII-D contribution addressing the low core collisionality parameter space.

2.1.3.8. Improvement Capabilities. To accomplish the goals described above in Section 2, several hardware and diagnostic improvements are required. Although DIII-D has produced several candidate high performance inductive scenarios, historically these have tended to be at relatively high levels of torque and high levels of direct ion heating and $T_i > T_e$. Both of these aspects represent significant differences in operating space compared with ITER and future burning plasmas. Consequently, improving the fidelity in these parameters is a required aspect of this program. Accounting for potential reduced confinement associated with reduced T_i/T_e and reduced rotation, it is anticipated that 8.5 MW of electron heating is needed for exploration of the standard baseline scenario at typical toroidal fields on DIII-D. For higher β_N scenarios such as the AI plasma regime, factors of two more power could be in principle be utilized, although it is anticipated that in this Five-Year Plan such scenarios can be operated at reduced field in order to get high β and dominant electron heating. Since many aspects of this work involve exploiting 3D magnetic fields, including QH-mode assisted by NRMF drive torques, RMP ELM suppression, and improved error field correction (EFC) algorithms, it is important to have more power supplies for the existing 3D coil sets, to allow the coils to be better utilized for multiple simultaneous purposes. An even more valuable option would be an improved 3D coil set to allow optimization of different aspects of the applied non-axisymmetric field (e.g., strong edge resonant field for RMP ELM suppression, with minimal non-resonant fields in the core to avoid unnecessary rotation braking). Other options that could benefit inductive scenario research include the capability to apply lithium for better wall conditioning, which may broaden the operating parameter space for both RMP ELM suppressed H-modes and QH-modes, and may be important for integration with a radiative divertor. In addition, faster steering of the EC mirrors to allow improved and faster feedback on fast growing modes in slowly rotating plasmas could be utilized.

These improvements in capabilities are summarized in Table 2-3, with the last two rows showing optional extensions that could be exploited if available.

Table 2-3
Proposed Hardware Upgrades and Associated New Physics Capabilities

Hardware Capability	New Physics
Increased low torque, electron heating (8.5 MW ECH)	Access to low torque dominant electron heated ITER baseline scenario at full field, and higher b scenarios at reduced field
Additional power supplies for 3D coil sets	Simultaneous use of improved EFC and/or NTV optimization and/or RMP application
Improved, more flexible 3D coil set	Ability to vary the ratio of resonant to non-resonant fields depending on application (e.g., edge NRMF with little resonant field for QH-mode, strong edge resonant with little core resonant or non-resonant for RMP ELM suppression)
Capability to apply lithium	Investigate methods of broadening QH-mode and RMP ELM suppressed operating space
Faster EC steering capability	Improved feedback control of modes

In addition to the above noted hardware improvement to the facility, improved diagnostic capability is also required as part of establishing the physics basis of the scenarios. Since a major element of the research plan is understanding the stability boundaries of the scenarios, a detailed knowledge of the current profile is essential, and to this end, improved spatial resolution of the current profile ($\lesssim$1 cm), especially near the q=2 surface and other low order rational surfaces, is critical in order to be able to properly characterize the tearing stability of candidate scenarios, and will also eventually be needed for real-time calculation of the stability and associated corrective actions when necessary. Associated with this is a need for improvements in the core electron density and electron temperature measurements to minimize ambiguities and uncertainties in kinetic EFITs. As these scenarios are moving toward low torque with dominant electron heating from ECH, it is important that microwave based diagnostics on DIII-D, including fluctuation diagnostics, be made “EC-hardened” so as to be routinely operated in scenario development experiments with significant EC power. These are summarized in Table 2-4.

Table 2-4
Improvements to Measurement Capability Required to Advance Physics Basis of Inductive Scenarios

Desired Measurement Capability	New Physics Possible	Possible Diagnostic
Improved spatial measurement of current profile (~1 cm)	Accurate assessment of tearing stability and benchmarking with codes	High resolution MSE or imaging MSE
Improved accuracy and reliability of core electron density and temperature	Remove uncertainties in kinetic EFIT reconstructions	Improved Thomson, reflectometry, …

A key aspect in improving the physics basis of the inductive scenarios is the validation of various models. Essential elements of this include transport model validation (e.g., GYRO and TGLF), benchmarking of NTV theory, and models of 3D response physics. These are summarized in Table 2-5.

Table 2-5
Code Development Plans for Validating the Physics Basis of Inductive Scenarios

Code Development	New Capability or Physics
GYRO including 3D fields and NTM physics models	Experimentally validate key dependences (e.g., T_e/T_i, rotation, collisionality, beta etc) in core transport physics models in high performance regimes
TGLF with momentum transport, integrated into time-dependent transport codes	Scenario development before experiments and post-experiment evaluation of performance
IPEC-NTV, MARS-Q	Evaluation and assessment of NTV torques
M3D-C1	Nonlinear EHO physics, NTV torque, 3D effects

2.1.4. Impact

The above research goals represent an essential step in assisting ITER meet its Q=10 mission, with the potential to lead to improved operating scenarios on ITER and on future burning plasma devices, including a possible pulsed tokamak DEMO. Paths to overcome confinement degradation associated with low rotation and increased T_e/T_i will be identified and exploited, and the investigations in H and He plasmas will enable ITER to effectively use its non-nuclear phase of operations. Successful completion of these research goals will lead to reduced risk to ITER operations and enable rapid progression to full Q=10 performance by avoiding time-consuming research in scenario development on ITER itself. The development of a complete and thorough physics basis of operating scenarios will ensure compatibility with proposed hardware and give confidence in the projections of future performance. Integration of the techniques for a full Q=10 scenario, from ramp up, entry into burn, high performance stationary phase and ramp down, together with the necessary control tools and off-normal even handling represents a critical step in addition to research elements pursued separately in other parts of the program. The longer term potential of this research is to improve regimes to future fusion devices such as FNSF, while exploring the feasibility and attractiveness of a pulsed tokamak as a fusion reactor in the future.

2.2. STEADY-STATE SCENARIO DEVELOPMENT

2.2.1. Challenges

A key mission of the DIII-D program is the development of the physics basis for fully noninductive steady-state operation at high plasma pressure. This work is strongly motivated by the anticipated improvements in reactor economy and reliability to be gained through operation in steady state and the increase in fusion gain with plasma pressure. Experiments are being conducted at DIII-D with the goal of producing discharges with all of the current driven noninductively ($f_{\rm NI}$=1) for duration greater than the resistive current decay time (τ_R) and the plasma pressure (as represented by its normalized values, β_N and β_T) at power plant relevant values. This work is yielding a predictive understanding of stability, transport and the requirements for heating and current drive systems for this type of discharge. This predictive capability can be used to ensure success of the ITER Q=5 steady-state mission and to design future burning plasma devices such as Fusion Nuclear Science Facility Advanced Tokamak (FNSF-AT) and a DEMO reactor.

The challenges in this work, the approach to addressing them, and the necessary improvement capabilities are summarized in Table 2-6.

2.2.2. Research Plan

2.2.2.1. Overview. The DIII-D steady-state research program has two primary goals for experimental operation during the proposal period: (1) development of fully noninductive ($f_{\rm NI}$=1) operation at reactor relevant β_T for at least twice the current relaxation time (τ_R), and (2) definition of parameter regimes in which stable operation at β_N=5 is possible. Ideally, this work will lead to a demonstration of $f_{\rm NI}$=1 operation at β_N=5. In addressing these goals, a range of discharge parameters will be studied in order to establish a predictive understanding of high β_N, fully noninductive operation that will enable the design of future tokamaks. Concurrently, research will also begin on the effect on steady-state operation of characteristic reactor conditions that are not typically present in current experiments: equal electron and ion temperatures, low toroidal rotation, and techniques used to control the heat flux to the wall.

The target parameters for fully noninductive discharges in DIII-D are motivated by projections for steady-state operation in ITER, FNSF-AT and a DEMO power plant. These devices are envisioned to operate at increasingly high values of β_N: 3.0–3.5 in ITER, 3.5–5 in FNSF-AT, and 4–5 or above in a DEMO power plant. This leads to the goal in the DIII-D program to demonstrate $f_{\rm NI}$=1 operation at β_N as high as 5, but also motivates studies at lower values of β_N. The benchmark parameter here is β_N because the fraction of the plasma current resulting from the bootstrap effect, $f_{\rm BS}$, increases with β_N and because β_N characterizes the stability limits to plasma pressure. Fusion gain, though, increases with plasma pressure, represented by the toroidal β, $\beta_T \propto \beta_N/q_{95}$ (q_{95} is the safety factor at the 95% flux surface). So an additional aim for DIII-D experiments is to reach power plant relevant β_T through simultaneous operation at high β_N and low q_{95}. There is a trade-off, however, because the noninductive current fractions, particularly $f_{\rm BS}$, increase with q_{95}. With the anticipated heating and current drive capability for the DIII-D facility, $f_{\rm NI}$=1 operation at $q_{95}\approx5$ is expected to be possible. The DIII-D pulse duration target, $2\tau_R$, is chosen to allow the discharge sufficient time to evolve close to the profiles expected in steady state. With the noninductive current density well aligned to the total current density, the inductive electric field will then be almost radially uniform.

Table 2-6
Challenges, Approach and Improvements for Steady-State Scenario Development

<table>
<tr><th>Challenge</th><th>Approach</th><th>Capability Improvements</th></tr>
<tr><td>Demonstrate fully noninductive discharge operation for multiple resistive current relaxation times at reactor relevant toroidal β</td><td>• Begin at higher q_{95}, where power requirements are reduced, and work down toward q_{95}=5 to approach power plant appropriate values of toroidal β
• Increase the plasma pressure until sufficient bootstrap current and externally driven current are obtained
• Study a range of broad to steeper pressure profiles to assess the trade-offs in bootstrap current fraction versus stability limits to pressure</td><td rowspan="4">Heating and current drive:
• ECCD power increased to 8.5 MW
• Second off-axis neutral beamline, 12 MW total off-axis capability
• Increased neutral beam power through operation at higher voltage: 19 MW co-injection, 24 MW total
• 6 s neutral beam full power pulse length

High β_N stability:
• Improved RWM feedback capabilities (crossover network)
• New 3D coil set

Measurements:
• Improved electron temperature and density profiles (Thomson, ECE)
• Midplane MSE profile with improvements in the outer half of the plasma
• Routine fast ion profile diagnostic (FIDA, INPA, FILD-3)

Predictive modeling and analysis:
• Improved transport models and predictive codes (TGLF, FASTRAN, PTRANSP)</td></tr>
<tr><td>Determine parameter regimes in which stable operation at β_N=5 is possible</td><td>• Utilize flexible heating and current drive systems to determine the optimum pressure and current profiles for access to high β_N
• Proceed in a staged approach to study scenarios with relevant β_N for ITER: ≈3, FNSF: ≈3.5–5, DEMO: ≈5
• Integrate β_N=5 with fully noninductive current generation</td></tr>
<tr><td>Develop a predictive understanding of steady-state operation to support ITER and enable the design of future devices such as FNSF-AT and a DEMO power plant</td><td>• Study potential scenarios through detailed tailoring of the current profile
• Compare candidates for minimum safety factor (≈1, ≈1.5, >2) and current profile shape (low and high internal inductance, varying shear profiles)
• Deploy comprehensive transport and turbulence diagnostics to study self-consistency of transport and current drive profiles</td></tr>
<tr><td>Maintain fully noninductive, high β_N conditions as toroidal rotation and electron to ion temperature ratio approach reactor relevant values</td><td>• Decrease toroidal rotation through use of counter-injection neutral beams, increase T_e/T_i with higher electron cyclotron and fast wave heating powers
• Assess the effect on transport, stability limits, external current drive, and bootstrap current fraction</td></tr>
</table>

In order to develop a predictive understanding of the physics of steady-state operation, the ability to access high β_N, f_{NI}=1 operation in four key discharge scenarios will be assessed. The four scenarios cover a wide range in the parameters that affect the physics of noninductively driven current and magnetohydrodynamic (MHD) stability at high β_N. This study of a broad range of parameters will enable detailed testing of physics models for use in the design of future devices. In three of the scenarios to be studied, access to high β_N while retaining stability to low toroidal mode number (n≥1) ideal instabilities is enabled through stabilization by a conducting vacuum vessel (VV) wall and, possibly, active stabilization coils.

The three scenarios are distinguished by the minimum value of the safety factor, q_{min}≈1, ≈1.5, or >2. Energy confinement, stability (for example, to ideal, tearing, Alfvén, and drift wave modes) and external current drive requirements depend on the value of q_{min} as well as the value of q_{95} and the detailed shape of the q profile including the magnetic shear profile. Therefore, a key part of the DIII-D program is to establish the physics of the trade-offs for steady-state operation as the q profile is varied from negative central shear to profiles with a broad region of uniform q to monotonically increasing q, all with a range of q_{min} and q_{95}. The fourth scenario to be studied has a relatively high value of the internal inductance, $\ell_i > 1$, resulting in confinement above the level typical of H-mode. The no-wall stability limit to n≥1 ideal instabilities scales with ℓ_i, so this scenario offers the possibility of stable operation at high β_N without the requirement for the presence of a stabilizing conducting wall or 3D active stabilization coils.

A key research goal is to validate the theoretical prediction that an approach to stable operation at β_N as high as 5 is to use a very broad current density profile that improves the effectiveness of the ideal-wall stabilization of low-*n* instabilities, as illustrated in Fig. 2-10 [Garofalo 2006]. The proposed heating and current drive upgrades have been selected, therefore, with a focus on off-axis current drive and sufficient heating power to reach the required plasma pressure. The target q profile used to design the required upgrades has $q_{min} > 2$ with q approximately uniform to normalized radius $\rho \approx 0.6$ where the peak in current density is located. To produce this q profile, a total of 8.5 MW ECCD will be used to drive current at $\rho \approx 0.6$. Additional off-axis current will be provided by a second neutral beamline modified for off-axis injection, and the necessary heating power to reach β_N=5 is expected with the additional capability to operate the off-axis neutral beams at voltages >100 kV. An extension of the maximum full-power neutral beam pulse length to 6 s will enable a 2 τ_R duration of the high β_N, f_{NI}=1 phase of the discharge. The proposed heating and current drive capability also has the flexibility in the radial profile of the externally driven current to allow the study of all four of the q profiles mentioned above.

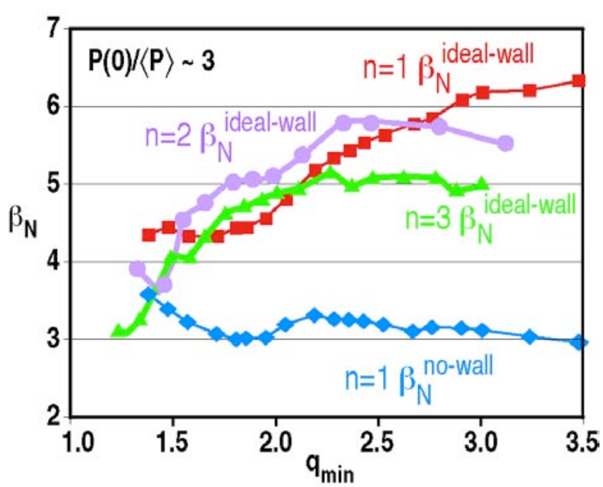

Fig. 2-10. Calculated β_N stability limit for ideal-wall and no-wall low-*n* instabilities as a function of q_{min} for fixed q_{95} and pressure profile. As q_{min} increases, so does the current density in the outer portion of the discharge, resulting in improved coupling to the stabilizing vacuum vessel wall and higher stability limits [Garofalo 2006].

The remainder of Section 2.2.2 describes the plan for research in the steady-state topical area. Figure 2-11 outlines the research program timeline and the enabling hardware. A description of the physics issues to be addressed (as briefly outlined in the table) is given in Section 2.2.2.2. Upgrades to the DIII-D hardware that are required in order to address the physics issues are described in Section 2.2.2.3.

	FY14	FY15	FY16	FY17	FY18
Demonstrate f_{NI}=1 for Multiple τ_R at Reactor Relevant q_{95}	• ITER shape, I/aB, ε • Identify ITER heating & current drive upgrade needs for f_{NI}=1 with Q=5, β_N≈3	• Develop scenarios for FNSF-AT Q≥2 steady state mission, β_N≈3.5–5		• Map operating space for f_{NI}=1, β_N>4 FNSF-AT & DEMO solutions • Refine ITER scenario using new tools	
Determine Parameter Regimes for Stable β_N=5 Operation		• Extend β_N=5 operation in "high-ℓ_i" scenario (q_{min}≈1)	• Access β_N=5 transiently in q_{min}>2 scenario		• Target f_{NI}=1 operation at β_N=5, q_{95}≈5 for advanced FNSF-AT & DEMO
Develop Predictive Understanding for Future Steady-State Devices	• Test potential scenarios with 1<q_{min} < 2.5 & identify the trade-offs to optimize stability, transport, current drive, & projected Q		• Expand parameter range for more complete model validation		
Increase Fidelity to Burning Plasma Conditions	• Test radiative divertor on f_{NI}=1 scenarios • Test advanced divertor geometry (snowflake, super-X)	• Compare FNSF-AT scenarios at lower torque		• Test ITER & FNSF-AT scenarios at low torque & high electron heating • ELM control with f_{NI}=1	
Enabling Hardware Capabilities	• 4.5 MW off-axis NBI • 4.4 MW coupled ECH • 19 MW total NBI (co- & counter-I_p) • 3 s NBI pulse length		• Upgrade to 11.5 MW off-axis NBI (2nd beamline) • 6 s NBI pulse length • 23 MW total NBI	• 3 MW FW • 24 MW total NBI	• 8.5 MW ECH • 3D coil upgrade

Fig. 2-11. FY14–FY18 GANTT chart: steady-state research timeline and hardware.

2.2.2.2. Detailed Research Plan. In this section, the key physics issues to be addressed are discussed along with the approach to the experiments. The section begins by highlighting the excellent capabilities of the DIII-D facility for the study of fully noninductive, high β_N discharges. Following that is a description of the approach to each of the research challenges that are outlined in Table 2-6.

The DIII-D Advantage for Steady-State Research. There is a unique opportunity to define the physics basis of steady-state operation through research on DIII-D. The DIII-D tokamak has the capability to produce a variety of discharge shapes, including the high elongation, high triangularity double-null divertor that has relatively high β_N stability limits and the single-null divertor shape planned for ITER. Pumping of divertor particle exhaust is in routine use in order to minimize the electron density n_e. The set of heating and current drive sources, including on-axis and off-axis neutral beams and gyrotrons for off-axis ECCD, has the flexibility to allow tailoring of the noninductive current profile to self-consistently match the target q profile. In order to study ITER and reactor-relevant conditions, neutral beams injected opposite to the direction of the plasma current provide the capability to reduce the toroidal rotation, and high gyrotron power will be available to increase T_e/T_i. An excellent set of diagnostics is available for measurement of the current density, temperature and density profiles and to characterize the fluctuations that affect plasma transport. The plasma control system has the flexibility required for implementation of algorithms for control of both global and local parameters.

The DIII-D program is already playing a global leadership role in research on steady-state, high β_N discharge scenarios. Discharges with $f_{\rm NI} \approx 1$ for duration $0.7\tau_R$ and β_N=3.7 have been demonstrated (Fig. 2-12) [Murakami 2006, Holcomb 2009]. An understanding of the physics of this type of discharge is being developed through studies of the scaling of confinement, transport, stability and $f_{\rm NI}$ with the discharge shape [Holcomb 2009], q profile [Ferron 2011a, Holcomb 2012a, Turco 2012] and toroidal field strength [Ferron 2011b]. The concept of increased β_N limits through broadening of the current density profile has been demonstrated in experiments with a B_T ramp, reaching β_T≈5% [Garofalo 2006]. In 2011, the capability to inject 5 MW of the neutral beam power off-axis became available. Off-axis beam injection has been used as a tool to allow the study of discharges with increased values of $q_{\min}$ (Fig. 2-13), with $q_{\min}$ sustained at values as high as 2.4, and to broaden the pressure profile to increase the calculated ideal MHD stability limit to β_N [Holcomb 2012b]. The capability to operate a partially inductively driven discharge ($f_{\rm NI}$=0.7) for $2\tau_R$ (3 s) at β_N=3.5 with $q_{\min}$=1.4 and an ITER-relevant value of the fusion gain parameter $\beta_N H_{89}/q_{95}^2 = 0.3$ through the use of off-axis beam injection has been demonstrated [Holcomb 2012b]. The DIII-D research program on advanced discharge scenarios has been carried out in close collaboration with similar programs on other devices such as JT-60U, JET and ASDEX-U. An overview of progress toward fully noninductive tokamak operation is given in [Luce 2011].

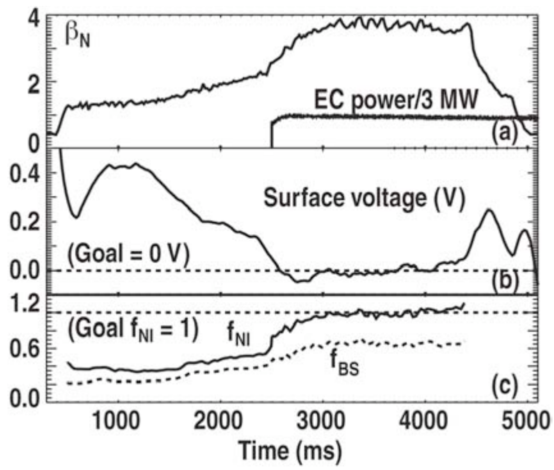

Fig. 2-12. Shape-optimized discharges with long pulse ECCD achieve high β_N, nearly fully noninductive conditions. (a) β_N and ECCD. (b) Measured surface loop voltage. (c) Calculated noninductive and bootstrap current fractions.

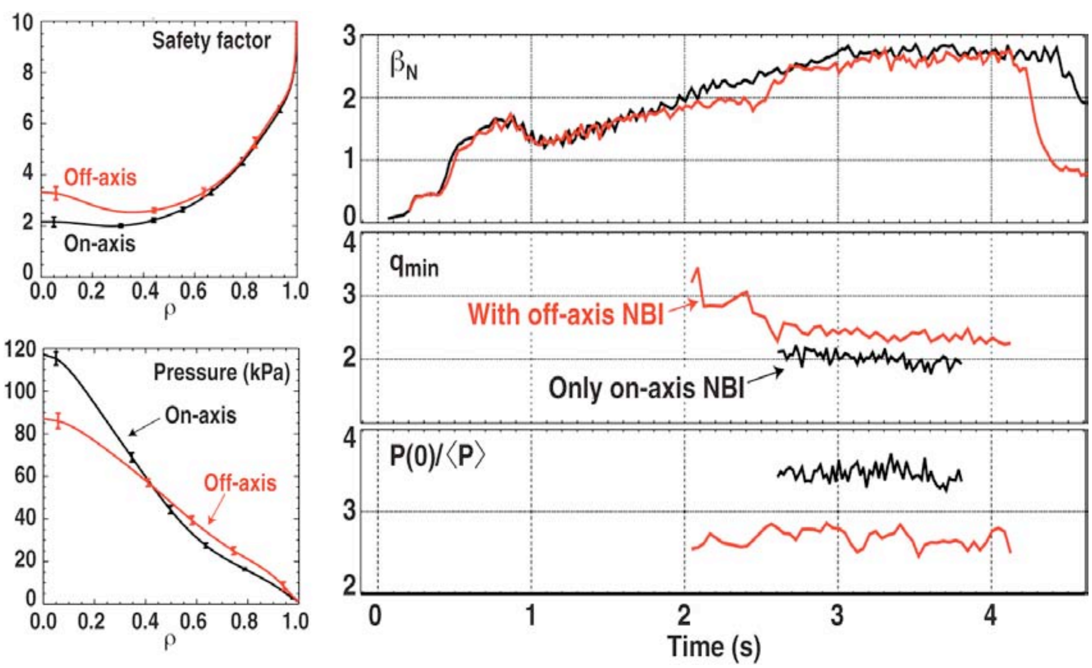

Fig. 2-13. Discharges can be operated with $q_{\min} > 2$ for the duration of the high β_N phase with off-axis neutral beam injection. Off-axis injection results in a broadened pressure profile.

Demonstration of Fully Noninductive Discharge Operation. Fully noninductive tokamak operation at reactor relevant β_T and f_{BS} for multiple τ_R has never been demonstrated. Previous experiments have achieved high f_{BS} and long pulse length but at reduced β_T. Thus, it remains to be proven that a solution at high β_T exists with stationary, self-consistent current and pressure profiles with zero toroidal loop voltage everywhere that is stable for duration greater than τ_R. This existence proof is a fundamental challenge for the DIII-D program.

The approach to this challenge will draw on previous experiments in DIII-D in which discharges with f_{NI} approaching 1 have been produced with relatively high q_{95}, primarily >6. These experiments took advantage of the favorable scaling of f_{NI} with q_{95} so that relatively low $\beta_N \approx 3.5$ and heating power were sufficient to achieve $f_{NI} > 0.8$. Experiments at the beginning of the proposal period will continue in this range of q_{95}, taking advantage of the first increments in neutral beam and gyrotron power. As the neutral beam and gyrotron power reach the full proposed values, $f_{NI}=1$ experiments will gradually transition to $q_{95} \approx 5$.

At a given q_{95}, in order to reach $f_{NI}=1$, the thermal β_N is increased to raise f_{BS} and the corresponding increase in the heating/current drive power simultaneously results in a higher fraction of externally driven current. Thus, at the beginning of the proposal period, the focus will be on increasing β_N from current values somewhat below 4 to values just above 4 in order to robustly achieve $f_{NI}=1$ at $q_{95} \approx 6$. The shape of the current density profile (and, correspondingly, the q profile) will be varied in order to maintain MHD stability. As additional gyrotron and neutral beam power becomes available, the focus will shift to achieving β_N closer to 5 in order to obtain fully noninductive operation at $q_{95} \approx 5$. The combination of the decrease in q_{95} and the increase in β_N will raise β_T from ≈3% to ≈5%.

The achieved f_{BS} depends on the pressure gradient profile at a given β_N, as does MHD stability. Higher f_{BS} can be obtained with steeper pressure gradients at the cost of reducing the β_N stability limit. The conditions that generate steeper pressure gradients, negative central shear profiles with an internal transport barrier, usually also have somewhat improved confinement. A discharge with relatively low β_N but with steep pressure profiles in order to obtain high f_{BS} is a current candidate for the steady-state Q=5 mission in ITER. Broad pressure profiles, such as those studied in DIII-D to date, and weak internal barrier type profiles will be compared to assess the trade-offs between bootstrap fraction, stability, and confinement for application to scenario designs for ITER, FNSF-AT and DEMO reactor type devices.

MHD stability, confinement, and bootstrap current density all depend on the discharge shape. The higher triangularity, close to double null shape characteristic of DIII-D steady-state scenario experiments [Holcomb 2009] will be compared to the single null divertor shape planned for ITER to determine how the ability to access $f_{NI}=1$ varies.

Access to $f_{NI}=1$ conditions at high β_N requires the stable evolution of the current, pressure and loop voltage profiles from the discharge breakdown to the point where the discharge reaches the uniform loop voltage profile of a stationary discharge. An increase of the maximum pulse length of the DIII-D heating and current drive sources will be utilized to study the evolution of the high β_N phase of the discharge for a duration of at least $2\tau_R$ so that conditions close to those of steady state are reached. At $\beta_N=5$, τ_R is anticipated to be ≈2.5 s. The planned upgrade to 6 s full power pulse length will allow the $2\tau_R$ duration, with sufficient energy remaining for formation of the discharge.

Increasingly sophisticated closed-loop control methods are under development for optimization of steady-state scenario discharges (Section 2.5). Closed-loop control will be studied as a means to enable reliable access to the fully noninductive regime during the discharge formation and for maintenance of the optimum current and pressure profiles during the high β_N, high f_{NI} phase of the discharge.

Parameter Regimes for Stable Access to β_N = 5. Operation at high values of β_N is motivated by the increase in fusion gain with β_T ($\propto \beta_N/q_{95}$) and the requirement for a value of q_{95} that is not too low in order to achieve sufficiently high f_{BS}. High Q power plant designs find operating points with β_N in the range of 5. Therefore, a challenge of the steady-state research program is to determine the range of current and pressure profiles and discharge shapes where stable operation at β_N=5 is possible.

The flexible DIII-D heating and current drive systems will be used to generate a range of q and pressure profiles. At each q profile, the stability limit to β_N will be determined through experiments and theoretical modeling.

The work will proceed in a staged approach as lower β_N operating points are envisioned for devices planned for operation before a DEMO reactor. Using the initially available neutral beam and ECCD power capability, ITER-relevant values of β_N≈3.0–3.5 will be studied. The q and pressure profiles that allow access to this range of β_N will be determined. These studies will include low gradient, broad pressure profiles and profiles with steeper gradients. Corresponding to this will be a study of a range of magnetic shear profiles. In each case, suitability for f_{NI}=1 operation will be assessed. As additional neutral beam and ECCD power becomes available, a similar range of q and pressure profiles will be tested for access to higher $\beta_N > 3.5$, appropriate for an FNSF-AT device. When the fully upgraded heating and current drive system is available, access to β_N approaching 5 can be tested in high f_{NI} discharges. Prior to that, access to β_N near 5 can be tested using reduced heating power and reduced B_T.

Stability limits will be studied in both the ITER single null divertor plasma shape and the optimized [Holcomb 2009], higher triangularity, double-null-type shape that is typical of DIII-D steady-state scenario discharge experiments.

A focus of the study of stable access to β_N=5 will be a discharge with a very broad current density profile. As an example, Fig. 2-14 shows the current density profiles in an equilibrium that is calculated to be stable at β_N≈5 and that can be produced using the proposed heating and current drive upgrades (Section 2.2.2.3). The broad current profile is created by ECCD at $\rho \approx 0.6$, the maximum deposition radius where reasonable current drive efficiency is available, off-axis neutral beam injection and the bootstrap current density resulting from the high value of β_N.

Further broadening of the current profile will be tested transiently using off-axis inductive current driven by a B_T rampdown. Decreasing the B_T rapidly induces a poloidal loop voltage that results in a net increase in the parallel current density, primarily in the outer half of the discharge. This will add to the current resulting from ECCD and neutral beam current drive as studied in previous experiments where β_T≈5% was achieved with high noninductive current fraction [Garofalo 2006]. With this transiently driven current, studies will be made of possible increases to the β_N stability limit resulting from broader current density profiles than will be possible in stationary conditions.

The high internal inductance scenario will also be studied for stable access to β_N=5. Previously [Strait 2009], operation at β_N up to 4.7 has been achieved with β_N>4 maintained for 1 s. The work will focus on increased β_N using the higher available neutral beam power, robust operation at reduced q_{95}, and maintenance of the high ℓ_i current density profile under stationary conditions.

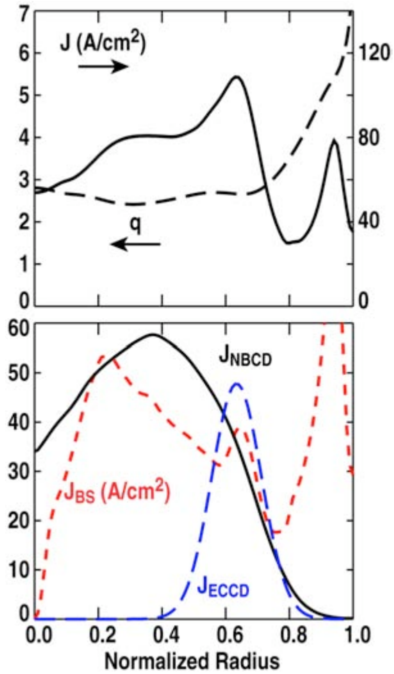

Fig. 2-14. Current density profiles in the β_N=5, fully noninductive solution that was found using the FASTRAN 1D model (Section 2.2.2.3). Here q_{95}=5.5.

Access to high values of β_N requires avoidance of all types of instabilities. The consistent, practical limit to operation has been found to be the n=1 or n=2 resistive tearing mode which can be classically destabilized as the ideal mode stability limit is approached. A key focus of stability studies during the proposal period will be to understand how to consistently avoid tearing instability. A particular challenge will be to reliably maintain stability as the current and pressure profiles evolve during the discharge formation and the high β_N phase. Use of the flexible heating and current drive sources available at DIII-D will allow modifications of the evolution of the pressure and current profiles for systematic studies of the influence on stability.

As studies of high β_N, high f_{NI} discharges with reduced rotation begin in the later years of this proposal period, the anticipated increased role of resistive wall modes (RWMs) will be assessed.

Fishbone modes have been observed with $q_{min} < 2$, resulting in fast particle loss and triggering of ELMs. The effect of fishbone modes on steady-state scenarios will continue to be examined.

A Predictive Understanding of Steady-State Operation. Data from experiments conducted to understand access to f_{NI}=1 and β_N approaching 5 will be compared to theoretical models. The ultimate goal is to arrive at a set of validated models for transport, stability, and current drive that will allow prediction of parameters in future devices. Key areas for study are the relationship between the q and pressure profiles and the resulting stability limits to pressure, the achievable bootstrap current fraction, the alignment of the profiles of the noninductive and total current profiles, the scaling of energy transport with the q profile and the heating method, and the optimum use of current drive and heating sources. Many of these relationships will be studied in isolation, but ultimately an understanding of all of these relationships must be integrated self-consistently to obtain high beta fully noninductive solutions.

Predictive capability requires a comprehensive understanding of a chain of causes and effects. For example: (i) the choice of actuators and target q profile has an effect on transport, (ii) transport affects the density and temperature profiles, (iii) bootstrap current and its alignment with the total current profile is sensitive to the density and temperature profile gradients. Obtaining this understanding requires the study of a wide range of q and pressure profiles at sufficiently high noninductive current fraction to identify the trends, trade-offs, incompatibilities, and useful compromises. Access to this wide range of q and pressure profiles will be possible using the flexible set of heating and current drive sources available at the DIII-D facility. These heating and current drive sources will be used to enable systematic scans in the current density and pressure profiles to facilitate a thorough validation of theoretical models.

Two fundamental types of discharge will be studied, one that requires the stabilizing effect of a conducting wall for high β_N stability and one that can be stable at $\beta_N \approx 5$ without wall stabilization. The wall stabilized cases are the low ℓ_i, elevated $q_{\min}$ scenario, with operation at $q_{\min} \approx 1.5$ and >2 considered separately, and a case with $q_{\min}$ near 1 based on the advanced inductive scenario. Wall stabilization in these cases may need to be supplemented by an external set of non-axisymmetric coils for feedback control of $n \geq 1$ pressure driven instabilities. The no-wall case has internal inductance $\ell_i > 1$ with $q_{\min}$ near 1, and is interesting because there is the possibility that non-axisymmetric, external feedback coils will not be needed for $n \geq 1$ stability. The key difference between these cases is the q (or current density) profile. A key research goal is to address the trade-offs in stability and noninductive current drive as $q_{\min}$ and the magnetic shear profile are varied.

The scenario based on the advanced inductive type discharge has $q_{\min}$ near 1 with ℓ_i higher than in the elevated $q_{\min}$ scenario, but still less than 1. There is a continuous 3/2 tearing mode that is thought to be responsible for a mechanism, not yet understood, that results in transport of current density away from the region near the axis. The concept for making this scenario run in steady state is to drive current as close to the axis as possible where current drive is efficient, and this current is self-consistently redistributed by the mechanism coupled to the tearing mode. The upcoming research program for this scenario will focus on gaining an understanding of the mechanism for the current density redistribution, the efficiency of current drive, the stability limits and the maximum achievable β_N, and the optimum combination of bootstrap current and externally driven current for $f_{\mathrm{NI}}=1$ operation. The upgrade in the available gyrotron power will be used for current drive near the axis in this case.

The challenge in the high internal inductance scenario [Strait 2009] is maintaining elevated values of ℓ_i with significant bootstrap current fraction, particularly because a large part of the bootstrap current density is located far off-axis in the H-mode pedestal region. The research objectives for a high ℓ_i discharge will focus on learning how to maintain a steady value of ℓ_i as far above 1 as possible, how to make high values of ℓ_i consistent with the bootstrap current profiles that will be produced at high β_N, the optimum way to utilize external current drive sources, stability at high β_N with particular focus on whether the presence of the vessel wall is required, and the transport properties at high ℓ_i.

In each type of discharge, a comprehensive set of fluctuation diagnostics will be employed to collect data to contribute to the understanding of thermal transport. Along with these measurements, profiles of temperature and density will be compared to the predictions of transport codes. The goal is to find a validated physics model for transport that is consistent with the experiment over the range of q and pressure profiles that is relevant to $f_{\mathrm{NI}}=1$ operation.

Parameters of experimental discharges will be routinely compared to resistive and ideal stability codes in order to validate their predictive capabilities.

Physics Basis of Heating and Current Drive. External heating and current drive are essential for fully noninductive current generation, so the research plan for f_{NI}=1 operation includes the study of outstanding issues in the fundamental physics of heating and current drive. This work will improve the ability to predict the performance of heating and current drive systems in future devices, particularly FNSF-AT which is anticipated to be a strongly driven device. An additional goal is to increase the flexibility of present and potential future heating and current drive systems on DIII-D to couple more power and drive more current where it is needed in steady-state scenario experiments.

Off-Axis Current Drive by Helicon Waves in the frequency range near 500 MHz is a possible high efficiency mechanism to broaden the current density profile in order to increase the β_N stability limit. Initial exploratory work on this current drive method is proposed. If successful, this would provide a valuable method to drive current off-axis in DIII-D and could also provide a means to support the desired current profile in FNSF-AT and a DEMO reactor, for which no fully suitable current drive technique has been identified. General Atomics' (GA) unique expertise in design, fabrication, and testing of high power traveling wave antennas would be employed to test this current drive technique (as described in Section 5.5.1.1), which is based on recent modeling work at the Kurchatov Institute. Plasmas with high electron β are needed in order for the current drive to take place off-axis, making DIII-D a highly suitable test vehicle for this process because of the availability of large electron heating power by the ECH system. Figure 2-15 shows the profiles of the driven current density and power deposition along with the wave propagation path for a calculation using DIII-D parameters.

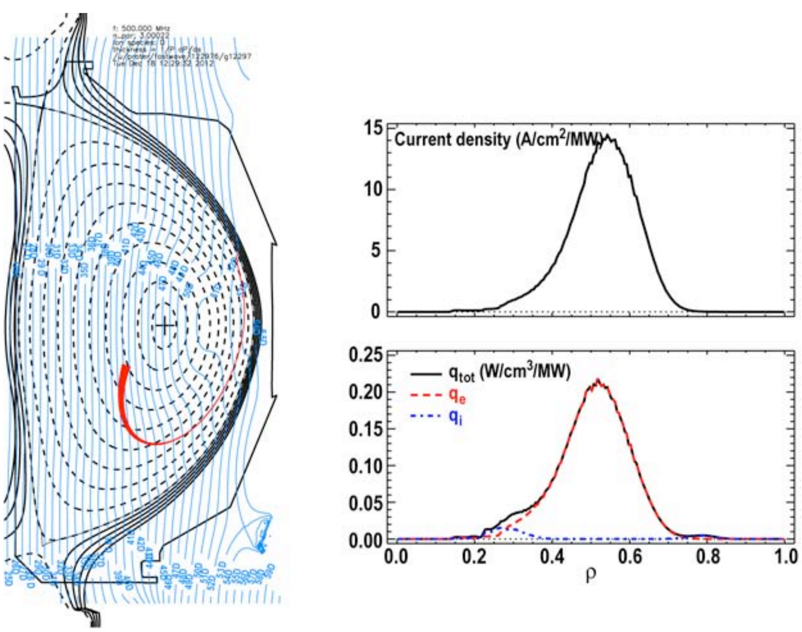

Fig. 2-15. Calculated current density per megawatt of input rf power, power deposition profiles and wave propagation path for 500 MHz waves in a plasma with DIII-D parameters. Blue contours are harmonics of the ion cyclotron resonance. The predicted efficiency of current drive is significantly higher than for off-axis ECCD.

Fast Wave Current Drive and Heating of Electrons can be a tool to achieve T_e=T_i and drive current near the axis where the bootstrap current density is low. Some of the most important issues to be studied are the following:

- Coupling of the power into an ELMing, H-mode discharge with low scrape off layer density.
- Use of the TOPICA code to develop antenna modifications to increase loading.
- Loss of coupled power that doesn't reach the core by direct observation of dissipation mechanisms.

Neutral Beam and Electron Cyclotron Heating and Current Drive. The following physics issues will be addressed:

- Efficiency models of off-axis neutral beam current drive when the current drive is far off-axis and/or with higher off-axis power than has been utilized to date, i.e. more than 5 MW.
- Experimental validation of the electron shielding model describing the neoclassical electron response to fast ions.
- Far off-axis electron cyclotron current drive to test models in the presence of strong electron trapping.

Increased Fidelity to Burning Plasma Conditions. The primary focus during this proposal period will be on the physics of high β_N, high noninductive fraction discharges using primarily high neutral beam power in the co-I_p direction supplemented by gyrotron power for electron cyclotron current drive. This type of heating and current drive source results in a plasma with significant toroidal rotation and $T_e < T_i$, features that will not be present in burning plasmas in upcoming devices beginning with ITER. Therefore, concurrently with this line of research, work will begin on the study of reduced toroidal rotation and increased T_e/T_i in high noninductive fraction, high β_N discharges. In addition, the issue of integration of the necessary core plasma parameters in steady-state scenario discharges with a solution for divertor heat flux handling will be addressed.

The increase in the total gyrotron power planned for availability during the proposal period will allow the study of high β_N discharges which are primarily electron-heated with low input torque. Fast wave electron heating and counter-I_p beam injection, to balance the torque from co-I_p neutral beam injection, will be used to supplement the gyrotron power for this purpose. In order to maintain high noninductive fractions, it will be necessary to explore these regimes at reduced current and higher q_{95}. This will result in discharges with reduced toroidal rotation and $T_e \approx T_i$, conditions close to those expected in a reactor, where the following physics issues can be addressed.

- What will be the overall change in confinement?
- With reduced *ExB* shear stabilization of ion temperature gradient (ITG) turbulence, and with $T_e/T_i \approx 1$, the ITG will be limited to a lower critical value. This may reduce the bootstrap current fraction if there is not another offsetting profile change.
- In high β_N, primarily electron heated plasmas, will the electron temperature profiles match those predicted by drift wave theory, or will other processes besides ITG, trapped electron mode (TEM) and electron temperature gradient (ETG) modes contribute to electron transport?
- Will tearing mode stability be reduced at lower rotation?

- As the rotation is decreased, will resistive wall modes become more important instabilities in steady-state scenario discharges?
- What will be the changes in the required error field correction coil currents at high β_N as the rotation is reduced?
- In high ℓ_i, high β_N discharges, will it be possible to maintain stability at low rotation as a partial demonstration of stability without the effect of the vacuum vessel wall?

The research plan for the study of the compatibility of high β_N, fully noninductive operation with techniques used to control the heat flux to the wall is described in detail in Section 4.1. The radiating mantle solution will be studied in order to quantify the response of high-performance core plasmas and to identify the impurity species that most effectively reduces the divertor power loading without serious degradation of the plasma performance. In addition, the physics basis for divertor geometry modifications (Super-X-like, Snowflake) will be explored in preparation for potential implementation at a later date. Methods for ELM mitigation or control such as by resonant magnetic fields or through pellet pacing will also be studied in order to determine their impact on the capability for fully noninductive operation (Section 4.4).

Collaborations. International collaborations (described in detail in Section 9) will continue to be a part of the DIII-D steady-state research program to improve validation of the physics basis of steady-state scenarios developed on DIII-D. This work would include scaling with ρ^* on JET and JT-60SA, operation with metal walls on JET, ASDEX-U and EAST and long pulse operation on EAST and KSTAR.

2.2.2.3. Improvement Capabilities. Stationary operation at f_{NI}=1 requires an exact balance between the heating and current drive requirements of the discharge. The externally selectable parameters, β_N, q_{95}, n_e, B_T, and the sources and profiles of the externally driven current, must be a self-consistent set that results in this required balance. Therefore, the external power requirements for the study of f_{NI}=1 discharges can vary, depending, for instance, on the choice of q_{95}. This will allow the study of fully noninductive discharges prior to the availability of the complete set of proposed power upgrades for DIII-D. The self-consistent solution for β_N=5 in a discharge with f_{NI}=1, though, will require relatively low q_{95} and relatively high heating and current drive powers. Therefore, the upgrades to the DIII-D heating and current drive capability that are proposed here are designed to meet the requirements of this discharge. At the same time, the heating and current drive sources will have the flexibility for the study of a wide range of q and pressure profiles, β_N and f_{NI}. These upgrades are summarized in Table 2-7.

The heating and current drive power upgrades proposed here each play a key role in production of a steady-state scenario discharge. In the highest β_N discharges, 8.5 MW ECCD will be used to provide externally driven current at a large radius in order to broaden the current density profile and increase coupling to the conducting vacuum vessel wall for MHD stability. At lower β_N and with varying q profile, the ECCD will be used to provide local current drive in order to properly align the noninductive and total current profiles and to tailor the current density profile for stability.

The fraction of the neutral beam power injected off-axis contributes to determining both the current density and pressure profiles. Both broader current and pressure profiles are desired for MHD stability at high β_N. This leads to the requirement for a second off-axis beamline in order to achieve the β_N=5 solution.

Table 2-7
Summary of Hardware Upgrades Proposed to Support the Steady-State Scenario Research Program

Hardware Upgrade	Physics Benefit
8.5 MW source gyrotron power	ECCD for steady-state scenario current drive, q profile tuning, T_e=T_i
Second off axis neutral beamline	Broader pressure profile for higher β_N limit, reduced on-axis NBCD for higher $q_{\min}$ and broader current profile
Increase beam voltage to >100 kV	Sufficient power to reach β_N = 4–5
6 s beam full power pulse length	$2\tau_R$ high β_N phase duration to approach a stationary state
3 MW fast wave power coupled to steady-state scenario discharges	On-axis electron heating for increased stored energy, T_e=T_i. On-axis current drive to fill in the bootstrap hole.
ELM control coils appropriate for q_{95} = 5–6	Tests of ELM stabilization in high $f_{\rm NI}$, high β_N discharges

The total injected beam power determines the plasma pressure, and thus β_N. An increase in the beam voltage to >100 kV is planned in order to have sufficient power available to reach β_N=5. The counter-injection beams can be used (on-axis) to provide additional heating power and to reduce the neutral-beam-driven current density near the axis. This aids both in reaching the target plasma pressure and in tuning the q profile.

In order to allow the discharge to be maintained at $f_{\rm NI}$=1 for duration up to $2\tau_R$, the full power pulse length capability for all of the neutral beam sources must be increased to 6 s.

Models of high noninductive current fraction discharges, both zero dimensional (0D) and one dimensional (1D), have been used to determine the required heating and current drive. The 0D model produces global values by extrapolating from the existing set of DIII-D high $f_{\rm NI}$ discharges without the use of a detailed energy transport coefficient model. The 1D transport code depends on the predictions of the TGLF model to produce local radius, profiles of T_e, T_i and the noninductive current densities. The models provided guidance to the hardware design process which resulted in an actual planned capability (Section 5) that differs slightly from what was assumed in the modeling described here.

Comparison of results from the two models is useful because each model has some limitations. The 0D model is useful to obtain an estimate of power requirements that do not depend on the validity of a local transport coefficient model, but there is uncertainty introduced when extrapolating to ECCD power significantly higher than in use presently and by the global confinement model used. In both the experiment and in the TGLF model, heating by ECCD power with off-axis deposition is inefficient in the present hot ion mode steady-state plasmas, with the primary role of the ECCD to drive current. Therefore, the increase in β_N to expect from an increase in ECCD power is not well known. The 1D transport code has the limitation that it depends on the validity of the TGLF model. In both models, there is uncertainty in the heating efficiency of the neutral beams that should be expected as a result of indications in the experiment of enhanced fast ion transport, particularly at high values of $q_{\min}$.

In the 0D model, the H_{98y2} confinement model is used to determine the power required to reach the target plasma pressure, and fits of the database to theory-based analytic models are used to determine the noninductive current drive fractions. The fitting coefficients implicitly include information on the characteristic temperature and density profile shapes in DIII-D discharges. Other parameters, such as the pressure peaking factor $f_p = P(0)/\langle P \rangle$ and H_{98} are chosen to be typical of the database. A model for the current density in the region near the axis (which assumes that all ECCD power is deposited off axis) is used to determine the fraction of the neutral-beam-driven current that must be off axis in order to achieve a given value of $q_{\min}$.

The 0D model provides an estimate of the heating power (which is assumed to be the same as the current drive power) that is required to achieve f_{NI}=1. Figure 2-16 shows the calculated heating power and β_N at the f_{NI}=1 operating point as a function of q_{95}. The f_{NI}=1 operating point is found by varying β_N with other model input parameters held fixed. This model indicates that 18–23 MW is required, with the highest power required at the lowest q_{95}. Because P_{ECCD} = 3 MW is the model input, the 0D model results should be interpreted as indicating that 15–20 MW beam power is required. The resulting value of β_N is between 4.2 and 4.7. The q profiles and pressure must be consistent with MHD stable operation at this β_N.

The 0D model can also be used to estimate the amount of the neutral beam power that must be injected off-axis in order to reduce the externally driven current near the axis sufficiently to reach a given value of $q_{\min}$ (Fig. 2-17). In the $q_{\min}\approx1.5$ scenario, the necessary amount of off-axis power is small, less than a few megawatts, even at low q_{95}. In order to reach $q_{\min}$=2.4 (the stable β_N=5 target found in the 1D model, below), approximately 12 MW of the neutral beam power must be injected off axis.

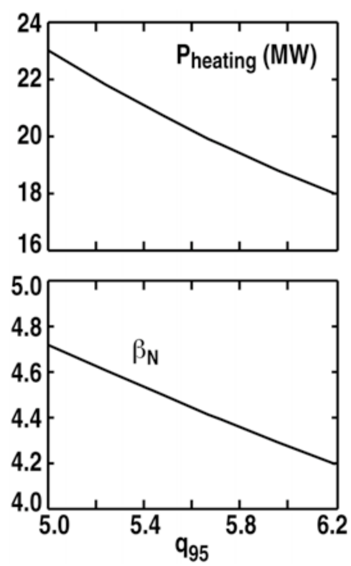

Fig. 2-16. Heating power required to reach f_{NI}=1 and the resulting β_N calculated using the 0D model. Model input parameters are: off-axis beam power 5 MW, $n_e = 4.7\times10^{19}$ m^{-3}, B_T = 1.75 T, f_p = 2.4, ECCD power 3.35 MW, ECCD deposition radius ρ = 0.45, H_{98} = 1.2.

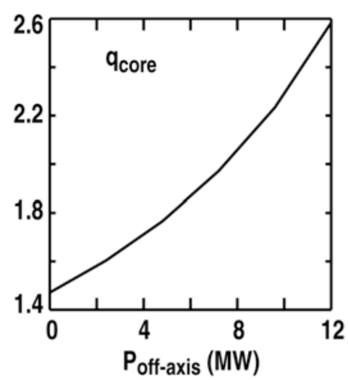

Fig. 2-17. The value of the safety factor averaged over the region 0.0 < ρ < 0.3 calculated using the 0D model. In the model, this value represents $q_{\min}$, with the assumption that $q(0) - q_{\min}$ is small. Model input parameters are: q_{95} = 5.5, n_e = 4.7×10^{19} m^{-3}, B_T = 1.75 T, f_p = 2.4, ECCD power 3.35 MW, ECCD deposition radius ρ = 0.45, H_{98} = 1.2.

The 1D transport code is used with the TGLF transport model to predict the electron and ion temperature profiles and the profiles of the bootstrap and externally driven current density. This approach gives results that are consistent with the 0D model, with the additional benefit of allowing detailed modeling of the current density profile. Deposition profiles for the externally driven current can be varied in order to determine the power requirements to produce a particular q profile. In addition, the code produces a self-consistent equilibrium that can be tested against ideal stability codes.

The 1D model has been used, in particular, to determine the detailed heating and current drive requirements for production of an MHD stable β_N=5 scenario. A stable solution was found by exploring the regime $q_{\min} > 2$ with $\rho_{q_{\min}}$ as large as possible. The electron density profile was taken from DIII-D discharge 147634, with the toroidal field set to 1.75 T where the capability to optimize the profile of electron cyclotron current drive in steady-state scenario discharges has been found to be the best. The plasma current is chosen so that q_{95}=5.5 and a small amount of anomalous fast ion diffusion is assumed, D_b = 0.3 m^2/s. The total available gyrotron power delivered to the plasma is set at 9 MW. The goal of the modeling has been to determine the effect of possible modifications to the DIII-D neutral beam heating configuration on discharge parameters at high f_{NI}. The role of the ECCD in this modeling is to provide current drive as far off-axis as is possible while still maintaining a reasonable current drive efficiency.

Combinations of three possibilities for modification of the neutral beam injection capability at DIII-D were considered using the 1D model: (a) add off-axis injection capability to an additional beamline in order to increase the MHD stability limit through broadened pressure and current profiles, (b) reorient the counter-injection beamline to provide additional co-injected power and (c) increase the maximum injection energy to increase the maximum available power.

Table 2-8 summarizes the transport limited β_N and the maximum stable β_N obtainable with combinations of these upgrades. This modeling was conducted to inform the choice of which upgrade options to pursue, and as such was performed before engineering analysis finalized the total powers. Nonetheless, given the uncertainties in the modeling, this table should be representative of the achievable parameters.

In the table, the transport limited value of β_N is that which is achievable when all of the neutral beam power is applied. With the off-axis beam power fixed at the maximum available, the on-axis beam power was varied to search for the MHD stability limit. The limiting value of β_N shown is the minimum of the ideal n=1, n=2 and n=3 limits calculated using the GATO ideal stability code with a conducting wall at the location of the DIII-D vacuum vessel. Two discharge shapes were tested, the optimized shape [Holcomb 2009] normally used for steady-state scenario experiments which couples well to the existing divertor structure for optimum exhaust pumping, and a higher elongation, balanced double-null shape.

With the 2012 neutral beam configuration (table first row), β_N=4 is the maximum value as limited by transport. This maximum value would only be stable in the stronger shape because of the relatively large pressure peaking factor [Ferron 2005] that results from the large on-axis beam power. The second row of the table considers the case where a second beamline (containing two beam sources) is configured for off-axis injection. This case has an increased β_N limit because of the reduced pressure peaking factor that results from moving some of the neutral beam power off-axis, but because the total neutral beam power has not increased, the transport limited β_N is still 4.0.

Table 2-8
Parameters of Model Equilibria Generated Assuming Various Combinations of Neutral Beam Heating and Current Drive Capability for DIII-D

	On-Axis Power (MW)	Off-Axis Power (MW)	$P(0)/\langle P \rangle$ (for higher κ case)	β_N (Transport Limited)	β_N Stability Limit	β_N Stability Limit (High κ)
Present NBI	10	5	2.9	4.0	3.6	4.5
Second OANB	5	10	2.6	4.0	4.0	4.9
Increased NBI power	14	7	3.1	5.2	3.7	4.4
8x co-I_p beams	15	5	3.2	4.8	3.6	4.2
2x OANB	7 (4 co-injection, 3 counter-injection)	11.5	2.7	4.5		4.8
2x OANB (stretch capability)	7	14	2.3	5.1	4.0	4.9

The bottom four rows of the table consider cases with an increase in the total neutral beam power. In the third row, the assumption is that there is still only one neutral beamline with off-axis capability but the maximum beam voltage for all sources is increased to increase the power. With the additional power, the transport limited β_N exceeds 5, but because there is still the same fraction of the power injected on-axis as in the present DIII-D configuration, the β_N limit is well below the transport limit. In the fourth row, additional co-I_p power is obtained by reconfiguring the present counter-injection beamline for co-injection. Again, the large fraction of power injected on-axis results in a pressure peaking factor that produces a relatively low β_N limit.

The fifth row of the table considers the combination of a second off-axis capable beamline with the voltage for both off-axis beamlines increased to 93 kV. This is the voltage anticipated to be technically most feasible during the first half of the proposed period. The increased beam power in this case results in a transport limited β_N=4.5 and stability limited β_N somewhat higher.

The final row of the table is the $\beta_N \approx 5$ solution. This case assumes that additional off-axis beam power is available at beam voltage 100 kV. The transport limited β_N increases to 5 and the stability limit increases as a result of a reduced pressure peaking factor. The q profile and the profiles of the various components of the current density are shown in Fig. 2-13.

The steady-state research program will also benefit from improvements in the DIII-D diagnostic capability. Interpretation of experimental results in high f_{NI} discharges depends on the capability to calculate the noninductive current density profiles from models. Therefore, measurements of the temperature and density profiles and the motional Stark effect (MSE) diagnostic measurement of the magnetic field pitch angle (for reconstruction of the current density profile) are essential and improvements to these diagnostics will contribute greatly to the research program. These profile measurements are also key to studies of transport. Table 2-9 summarizes the proposed diagnostic upgrades (discussed in Section 6) that are most relevant to the steady-state research program.

Table 2-9
Proposed Diagnostic Upgrades Most Relevant to the Steady-State Research Program

Diagnostic Upgrade	Physics Benefit
Improved Thomson scattering T_e and n_e measurements $\rho < 0.9$, particularly $\rho < 0.5$	Accurate T_e, n_e profiles are absolutely essential to evaluation of bootstrap current density, externally driven current density, transport, ideal stability analysis
Maintain capability to make MSE measurements at the midplane when the beam presently used for the MSE diagnostic is upgraded to allow for off-axis injection	MSE measurements at the midplane will give data over the full plasma radius, essential for accurate equilibrium reconstruction to obtain the current density profile
Improved MSE measurements for $\rho > 0.5$, Li-beam and other diagnostics for pedestal current density measurements	Understand physics of tearing mode stability over the full radius and bootstrap current in the pedestal region
Fast ion loss detector (FILD-3) for reverse B_T operation	Assess any difference between classical prediction of fast ion stored energy and NBCD and the experiment resulting from loss of fast ions

2.2.3. Impact

The understanding of the physics basis for fully noninductive operation at high β_N developed in DIII-D will enable the design of discharges for the Q=5 steady-state mission of ITER, and the design of future burning plasma tokamaks such as a Q≈3 tritium self-sufficient device (FNSF-AT), and a Q>10 demonstration reactor (DEMO). The DIII-D steady-state research program is well-positioned to demonstrate steady-state scenarios appropriate for all of these devices.

The specific plasma parameters for an f_{NI}=1 discharge in ITER have not yet been identified. So with the ability to produce a reduced scale copy of the planned ITER shape in DIII-D and a flexible set of heating and current drive systems, a wide range of potential discharge scenarios can be studied. The requirements for heating and current drive sources can be defined and compared to the planned ITER day 1 heating and current drive systems. The benefits of reasonable extensions of these initial ITER systems for completing the steady-state mission can be identified. The goal will be to simultaneously demonstrate f_{NI}=1 with the fusion gain parameter $H_{89}\beta_N/q_{95}^2 > 0.3$, the projected value for Q=5 in ITER. Comparisons of the necessary β_N to reach f_{NI}=1 and the necessary energy transport to what is projected to be possible in ITER will determine which discharge scenarios can satisfy the steady-state mission.

The design for an FNSF-AT device has not yet been established so DIII-D research can have a significant impact. Conceptually, FNSF-AT has significant external input power but without the use of neutral beams so that wall space can be devoted to tritium breeding blankets. Thus there will be no externally applied torque, a condition that experiments in DIII-D can model using balanced neutral beam injection, fast wave heating and electron cyclotron heating and current drive. The planned upgrade to the DIII-D gyrotron power capability will be a key enabler for these experiments. The various discharge concepts described in Section 2.2.2 will be tested under conditions with low toroidal rotation, T_e=T_i and with application of ELM and disruption avoidance techniques developed and tested in other parts of the DIII-D program (Sections 2.3 and 4.4).

The study of access to β_N=5 in an f_{NI}=1 steady-state discharge is primarily motivated by the anticipated reduction of the cost of electricity in a steady-state reactor as β_N is increased, as the fusion gain and the bootstrap current fraction both increase with β_N. The physics basis for stable fully noninductive operation in this range of β_N developed in DIII-D will be a key to validating designs for a DEMO power reactor.

2.3. STABILITY AND DISRUPTION AVOIDANCE

2.3.1. Challenge and Opportunity

Future burning plasmas must operate with both high performance and high reliability. High performance entails operation near stability limits, but high reliability implies a very low rate of instabilities. Instabilities that result in disruptions pose significant risks to ITER, as well as to next-step devices such as FNSF and fusion power plants, through the possibility of damage by electromagnetic forces and local heating [Hender 2007]. In addition, instabilities present a risk to the scientific program goals of ITER and the economic viability of a power plant owing to the potential loss of availability or the need to operate at reduced parameters.

The issue of plasma stability represents a challenge that must be addressed in the next 5 to 10 years for ITER's baseline, high fusion gain scenario.

Key issues for the ITER baseline include:

- Optimization of non-axisymmetric fields in order to minimize their deleterious effects (making the tokamak more two dimensional (2D) for example).
- Reliable avoidance or suppression of tearing modes, including control of sawteeth.

In a similar 5–10 year time frame, solutions must be developed for stable operation of ITER's steady-state scenario, and for the design of a high-β FNSF. Additional issues are:

- Maintain stability against kink modes in the wall-stabilized regime, through passive or active means.
- Monitor and correct a q-profile/j-profile that is approaching classical tearing instability.

In all cases, reliable means of detecting and avoiding stability boundaries are critical. In particular, instabilities that lead to disruptions must be avoided. If such instabilities are not controlled and thus are detected, *disruption avoidance* should automatically:

- "Snare and drag" tearing modes that would otherwise lock to the wall and disrupt.
- Recover the high performance *or* safely shut down the discharge.

The stability challenges, the approaches to address them, and the hardware upgrades needed to meet the demands are given in Table 2-10.

ITER, FNSF, and other burning plasmas will operate in regimes that have significant differences from most present tokamaks (Fig. 2-18). Unlike today's neutral beam-heated plasma, self-heated plasmas will experience much smaller torque, and consequently smaller rotation and rotation shear — both of which have stabilizing effects. For example, slower rotation can allow resistive penetration of non-axisymmetric (3D) fields, with island formation at rational surfaces. Steady-state tokamaks also require high normalized β, a regime where MHD instabilities become more likely owing to decreasing kink mode stability and increasing plasma "amplification" of external non-axisymmetric (3D) fields. Research in present devices must explore these regimes to the extent possible, and establish the scientific basis for prediction and improvement of the stability of ITER and future devices.

Table 2-10
Stability Challenges, Approaches to Address, Necessary Upgrades

Challenge	Approach	Capability Improvements
Minimize deleterious effects of complex error fields	Multi-coil, multi-mode error field correction, real-time feedback, utilize 3D diagnostics	Additional coils and power supplies, reduce intrinsic error field sources (TF feed)
Identify and avoid tearing mode stability boundaries	Real-time measure of evolving q-profile, q-profile control, magnetic sensing of tearing boundary	Higher radial resolution MSE, additional gyrotrons
Automated robust tearing mode and sawteeth control	Real-time tearing-sensing and feedback control of gyrotron power and their mirrors to m/n=3/2, 2/1 (ITER scenario), 5/2, 3/1 (in AT), and/or 1/1 sawteeth control, as well as q-profile control; synchronized modulation instead of cw EC where warranted	Increase EC power to 8.5 MW, oblique ECE for mode location/phasing
Maintain stability against resistive wall modes (kinks) in reactor relevant regimes	PCS RWM boundary warnings, magnetic probing and 3D diagnostics, feedback control of “slow” resistive wall mode	Faster ac power supplies, RWM cross-over network. Additional coils.
Disruption avoidance to avert the thermal quench and the need for disruption mitigation	Integrate above stability sensing control techniques to provide robust disruption avoidance; develop off-normal event control, such as “snare and drag” with n=1 rotating coil field with/without EC	As above

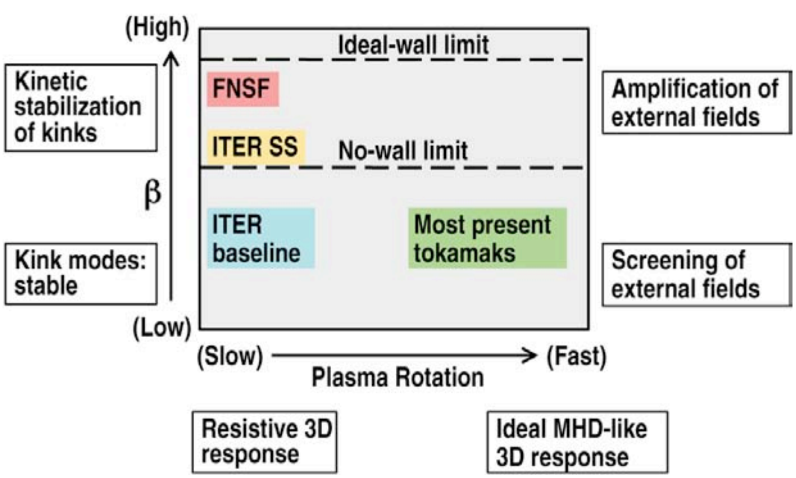

Fig. 2-18. Schematic diagram of regimes where 3D effects and non-ideal effects become important, vs. β and plasma rotation. The high-β, low-rotation regime where ITER and FNSF will operate differs from that of most present tokamaks.

DIII-D's Five-Year Plan focuses on developing a real-time control system capable of avoiding major instabilities and thereby preventing disruptions. A schematic of how a layered system should deal with this is shown in Fig. 2-19.

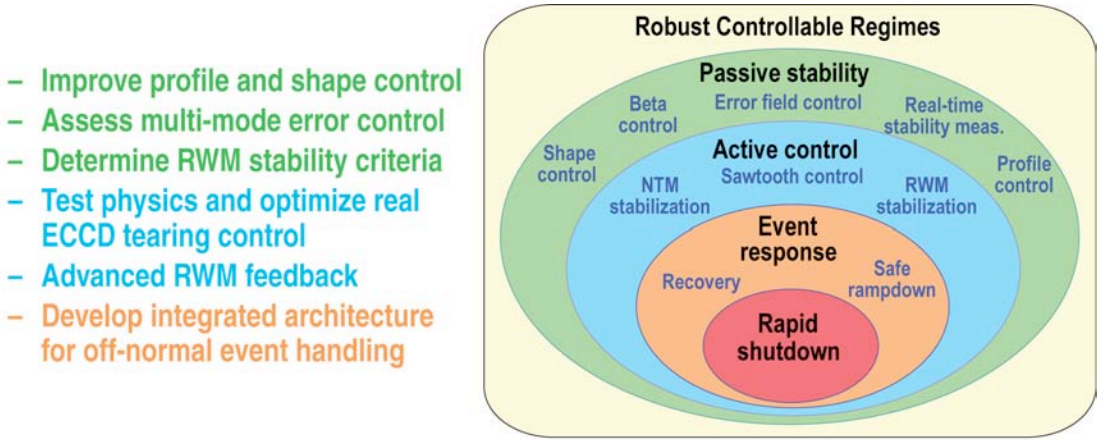

Fig. 2-19. Multi-layered plan in DIII-D shown for reducing the occurrence of disruptions, with the impact to prevent wear on ITER and enable its full physics program. Rapid shutdown plan is presented in the disruption mitigation Section 2.4.2.2.

2.3.2. Research Plan Overview

The DIII-D facility is well-suited to carry out stability research for future burning plasmas. DIII-D's extensive and often unique capabilities or combinations of resources include:

- Internal and external sets of non-axisymmetric coils that have made DIII-D a world leader in research on non-axisymmetric fields, and provided the basis for design of ITER's internal control coils.
- Unique mix of co- and counter-injected neutral beams, electron cyclotron resonant heating, and fast wave heating enables studies of the effect of external torque on plasma stability, including the low torque, electron-heated regime of a burning plasma.
- Capability of off-axis neutral beam injection enables studies of the effects of the fast ion velocity distribution on plasma stability, key to understanding kinetic effects in a burning plasma.
- New capability of real-time mirror steering for precise electron cyclotron resonant heating and current drive, similar to that of ITER, offers a wide range of possibilities for control of plasma stability, particularly when the effect of refraction is compensated for in real time (by implementing the code TORBEAM for example).
- Extensive set of diagnostics, including 2D internal imaging of plasma instabilities and new magnetic diagnostics for measuring non-axisymmetric effects, creates a unique opportunity for the detailed scientific studies necessary for extrapolation to burning plasmas.

The upgrades to coils and their power supplies, the electron cyclotron resonant heating and current drive system, and diagnostics in the next five years will greatly extend these capabilities. The stability elements and the new capabilities to successfully execute the elements are given in Fig. 2-20.

	2014	2015	2016	2017	2018	
Error fields	• Multi-mode error field correction with existing coils		• Reduce intrinsic error field		• Improve error field correction with new coils	
Tearing modes and sawteeth	• Augmentation of multi-mode multi-purpose gyrotron control • Real-time sawteeth control simultaneous with tearing mode control • Evolution and intervention of $\Delta'(t)$ towards unstable profile	• Implement TORBEAM for improved ECCD refraction correction		• Magnetic sensing of tearing boundary		
Kinks (RWMs)	• Improved feedback at low rotation		(n=2)	(n=3)	• Stabilize n>1 with feedback	
Disruption avoidance	• Integrate above elements into boundary warning and piggyback actions • Develop "piggyback control" if boundary found to be exceeded → dedicated tests					
New facility capabilities	• Fine structure MSE, oblique ECE, more and/or faster ac power supplies • Increasing number of gyrotrons →			• Ac probing coil and power supply	• New coils and power supplies, additional magnetics, 2nd off-axis beam	

Fig. 2-20. FY14–FY18 stability and disruption avoidance research plan.

2.3.3. Research Elements

DIII-D stability research is aimed at advancing the scientific understanding of plasma stability, and applying that understanding to help ensure reliable operation in ITER's baseline scenario and in steady-state scenarios for ITER and future devices. These goals will require the investigation of the underlying physics of tokamak stability as well as the development of schemes for instability detection and control. Once demonstrated in DIII-D, these elements together will allow extrapolation to stable operation of ITER and FNSF. To these ends, key elements of the research proposed for the next five years include:

- Understanding the interaction of static, non-axisymmetric fields with the tokamak plasma, and development of multi-harmonic, multi-coil error field correction.
- Understanding the physics of tearing mode stability at low and high β, and development of the physics basis for stability against tearing modes in low torque plasmas.
- Development of routine feedback control of neoclassical tearing modes and sawteeth (including multiple-mode control) in high performance plasmas.
- Understanding of the physics of resistive wall mode stability, including plasma rotation and kinetic effects.
- Development of resistive wall mode feedback control with advanced algorithms and improved coils and/or power supplies.
- Development of strategies for identification and avoidance of stability boundaries, and means for discharge recovery when a boundary has been crossed, in order to avoid disruptions.

The proposed research is described in more detail in Sections 2.3.3.1 through 2.3.3.6, while the impact of the research is discussed in Section 2.3.4. Section 2.3.5 summarizes the highest priority hardware and diagnostics upgrades.

2.3.3.1. Error Field Physics. The goal of error field research is to develop the scientific understanding of the effects of non-axisymmetric magnetic field errors, and to develop optimal methods of error field compensation using a limited number of correction coils [Reimerdes 2011a]. This research will contribute to the development of the best error field compensation strategies for ITER, using the external correction coils and possibly also the internal coils designed for control of ELMs. The research will also inform the specification of design tolerances for FNSF and other future devices in order to minimize error fields, as well as the design of compensation coils.

The role of the spatial spectra of the error field and compensation field represents the frontier of current research, and DIII-D efforts in the next five years will be focused in this area. To date, most research has concentrated on n=1 error field components that interact resonantly with weakly stable plasma modes, and that trigger tearing instabilities through this strong interaction. Experiments [Scoville 2004] and interpretive modeling [Park 2007] with varying poloidal spectrum of the correction field have shown that although optimal error field correction may actually increase the pitch-resonant component of the external field, it reduces the pitch-resonant harmonics within the plasma by reducing the kink mode-resonant response of the plasma [Lanctot 2011, Reimerdes 2011a]. This result seems to imply that error field correction should be insensitive to the detailed poloidal spectrum of the correction field, as long as the correction field has a component that couples to the weakly stable kink mode. However, recent results using artificially applied "error fields" suggest that this simple picture may be incomplete [Buttery 2011]. As shown in Fig. 2-21, compensation coils (here, the I-coils) can minimize the kink mode-resonant part of the error field (here, applied by the C-coils), even when the spatial spectra of the two fields are rather different. However, in that experiment the discharge performance (parameterized by the low-density threshold for locked modes) was not restored to its original value. This result suggests that other portions of the poloidal spectrum, where the optimized correction field may actually increase the net n=1 amplitude, also play a role, e.g. through non-resonant magnetic braking.

Compensation of error fields with toroidal mode numbers n>1 offers an opportunity to improve plasma performance that is, as yet, unexploited in DIII-D. In recent experiments, asymmetries in the response of the plasma to applied n=2 and n=3 fields show that there are intrinsic error fields with these values of n. Other experiments using DIII-D's Test Blanket Module (TBM) mockup [Schaffer 2011] have shown that although the plasma response is largest to n=1, compensation of n=1 alone is not always sufficient [Reimerdes 2012].

DIII-D is uniquely suited to investigate the effects of tailoring the 3D spatial spectrum of non-axisymmetric fields. The combination of C-coils plus two rows of I-coils allows 3-deg of freedom for variation of the poloidal spectrum. This capability allows investigation of the benefits of minimizing up to three regions of the poloidal spectrum, in contrast to the single region that was minimized in Fig. 2-20(d). The TBM mockup [Schaffer 2011] is a unique tool that can apply a very localized "error field" in order to study its effects and its compensation in ITER-like H-mode plasmas. In addition to compensation strategies, future research will investigate the physics of resonant and non-resonant drag by error fields, including validation of NTV theory for non-resonant torque.

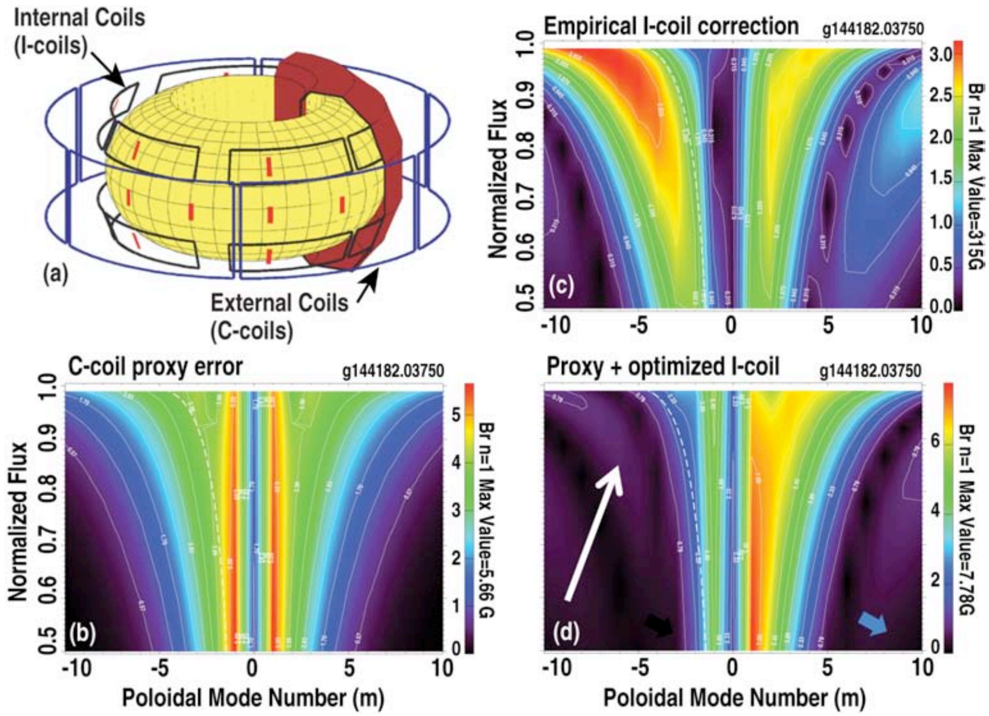

Fig. 2-21. (a) DIII-D's non-axisymmetric coils; and (b-d) calculated spatial spectra of magnetic perturbations applied by the coils, vs. poloidal mode number *m* (horizontal axis) and normalized flux as a radial coordinate (vertical axis). The dashed curve to the left indicates pitch resonance with the unperturbed field, $m=nq$. When the C-coil applies a large "proxy" error field (b), compensation by the I-coil (c) can minimize the net left-handed spectrum (d) at $m>nq$ (to the left of the dash line), where the strongest coupling to the kink mode is expected.

Additional power supplies for the I-coils and C-coils are critical for these studies, in order to test the full range of possible toroidal and poloidal spectra by powering each of the 18 coils independently to their full current capability. Even optimization of the poloidal spectrum for $n=1$ error field compensation requires nine independent circuits, and thus cannot be carried out with the present switching power amplifiers (SPAs) and C-supplies, which allow a maximum of only seven independent circuits at full current. As an example of the need for full-spectrum error field compensation, the localized toroidal field coil feed at 30 deg is known to be a significant source of broad toroidal mode number *n* error fields (with effective resonant $n=1$ for $q=2$ about $7\text{x}10^{-5}$ of the on-axis toroidal field). This error is located well off the midplane, producing an error with a large component of up-down anti-symmetry across the midplane, while the C-coils and I-coils, as presently operated, can only apply up-down symmetric compensation fields. As discussed below, research in resistive wall mode control can also take advantage of the upgraded power supplies, provided that they have sufficient bandwidth.

An upgrade to the number and spatial distribution of the non-axisymmetric coils will be extremely valuable in testing the effects of spatial spectra provided the corresponding power supply capability is installed. For example, doubling the number of coils in each row of the I-coil set will increase the range of toroidal mode numbers that can be applied from $n\leq3$ to $n\leq6$. At least as importantly, the additional coils will enable much better resolution of the physics of $n=2$ and $n=3$ error fields, by allowing continuous rotation of $n=3$ fields, and by allowing the application of $n=2$ fields without the large $n=4$ sideband that is unavoidable in the existing coil set.

New magnetic diagnostics to be installed in 2013 will be critical for these studies, enabling detailed measurements of the plasma response to non-axisymmetric fields for comparison to theoretical models. New active coils may dictate further upgrades to the magnetic diagnostics.

Minimization of intrinsic error fields [Luxon 2003] will benefit both scientific understanding and reliable operation of DIII-D. The toroidal field coil feed at 30 deg, a significant source of error fields, will be upgraded or compensated with a trim coil when the 30 deg beamline is modified for off-axis injection. (The corresponding feed at 210 deg was upgraded in 2006.) Other known sources of error (e.g. the radially shifted F7A coil) may also be addressed with local trim coils, an approach that could be tested initially with the TBM mockup.

2.3.3.2. Tearing Mode Physics. Research in tearing mode physics is aimed at understanding and predicting the stability of these important modes. This topic includes both low-β tearing modes where stability is dominated by the "classical" tearing mode index Δ', and also neoclassical tearing modes at higher β where the bootstrap current becomes important [La Haye 2006a, Gerhardt 2009]. Progress will help DIII-D and ITER to tailor the discharge, through passive or active means, to avoid the onset of classical tearing modes, and will solidify the scientific basis for the onset and stabilization of neoclassical tearing modes.

One focus of research in this area will be detailed measurements of perturbed quantities (helical magnetic field, temperature, density, plasma flow, etc.) across a tearing mode island. Such measurements have become possible through new and upgraded diagnostics (including imaging diagnostics [Yu 2009, Tobias 2011] and MSE measurements [Petty 2012]), and through the capability to control the rotation rate of the island with counter-injected neutral beams and electron cyclotron heating [Buttery 2008]. The results will allow validation of models for the dynamics and structure of magnetic islands, and will provide insight into the transport and flow effects that govern the nonlinear thresholds for onset and stabilization of neoclassical tearing modes.

Research will also investigate the evolution of the current profile and the tearing mode index Δ', with and without noninductive current drive, in order to predict the onset of tearing [Turco 2010]. Figure 2-22 shows an example where ECCD with narrow deposition did not prevent a tearing mode (perhaps through imprecise alignment with the q=2 surface) but the same power ECCD applied with a broad radial profile did avoid the tearing mode, probably through modification of the current density profile and Δ'. Experimental data will be provided to the new ITPA Joint Theoretical Activity (JA-1) to advance the theoretical understanding of shear flow effects on NTMs, i.e., how low rotation and/or low shear flow can make tearing less classically stable, a topic that needs validation. The capability to model, understand, and predict tearing stability will provide the basis for discharges that avoid the onset of tearing modes.

The use of active MHD spectroscopy to measure tearing mode stability will also be investigated. This technique has been demonstrated at very low frequency to provide a direct measurement of resistive wall mode (kink mode) stability [Reimerdes 2004]. Extension to the 1–25 kHz frequency range of tearing modes will allow continuous monitoring of tearing mode stability, and thus provide the potential for real-time warning of the approach to a tearing threshold.

Upgraded diagnostics will be critical for these studies. Most important is MSE measurements with higher spatial resolution, required for accurate determination of Δ' and the influence of ECCD with narrow deposition (whose full width half maximum is typically 0.06 in normalized minor radius for "search and suppress", to be discussed next). Additional toroidal locations of electron cyclotron emission imaging (ECEI) and/or radial ECE profiles will allow better measurements of island structure as would a new multi-channel oblique view (looking down and in) electron cyclotron emission (ECE) diagnostic.

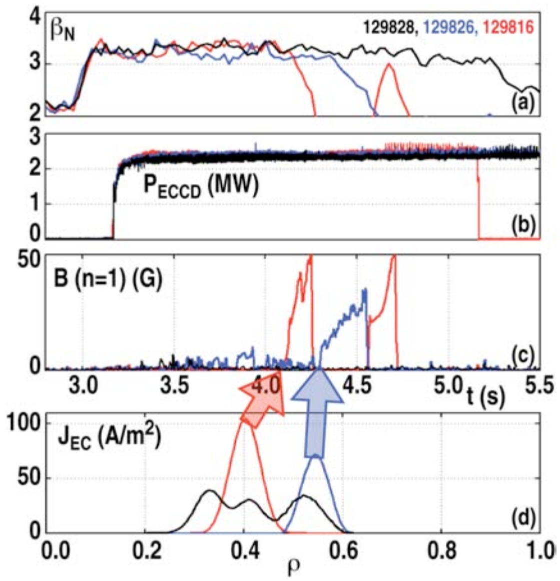

Fig. 2-22. Comparison of three discharges with varying ECCD deposition profiles, showing the time evolution of (a) normalized β, (b) ECCD power, and (c) amplitude of the n=1 tearing mode, as well as (d) the radial profile of EC-driven current density. The tearing mode is suppressed in the case with broad deposition (black curves) but not in the two cases with narrow deposition (red and blue curves).

MHD spectroscopy of tearing modes requires a dedicated antenna capable of operating in the 1–25 kHz frequency range. Such an antenna will need to be mounted well off the wall (or in a large port opening), in order to avoid the wall image current effect that limits the existing I-coils at high frequency — although the higher frequency capability of a new coil in a port opening comes at the expense of a broader spatial mode spectrum than that of the lower frequency I-coil.

2.3.3.3. Tearing Mode Control and Sawtooth Control. Research in the control of tearing modes and sawteeth is aimed at developing methods for accurate, prompt mitigation or suppression of these modes [La Haye 2006b, Prater 2007]. The research requires development of sophisticated control algorithms [Humphreys 2006], as well as validation of the scientific basis for active suppression. Tearing modes can lead to disruption or severe degradation of the discharge, and thus their control is essential to improve the reliability of operation in present facilities as well as in ITER and future devices. Comparison of the DIII-D control results with modeling – using discharges with the same shape and β as ITER and scaled torque equivalent to that of ITER – will provide the basis for extrapolation to ITER.

Much of the work will consist of optimizing control algorithms for the steerable ECCD mirrors [Kolemen 2012]. Different tracking schemes can eliminate the island after it appears (Fig. 2-23) or provide pre-emptive suppression (not shown here). Faster EC steering mirrors will allow prompt switching from one q-surface to another (1 to 2 for example). In general, these require real-time equilibrium analysis and real-time calculation of the EC wave path and deposition. While continuous ECCD can be effective, modulated ECCD (phased to the island rotation) can be more effective when an island is present, requiring less average power. For slowly rotating tearing modes, the control algorithms may also make use of the I-coils to control the island position relative to the current drive location and to inhibit wall locking. The ultimate goal is to integrate such schemes into DIII-D's standard control algorithms, making tearing mode control routine and reliable.

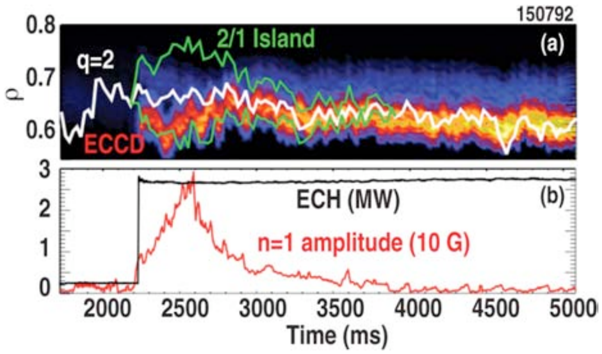

Fig. 2-23. A discharge where steerable mirror tracking of the q=2 surface allowed suppression of the 2/1 tearing mode, showing (a) radial positions of the q=2/1 surface and the ECCD, and (b) amplitude of the n=1 tearing mode and ECCD power. The n=1 mode is suppressed after the ECCD is aligned with the rational surface.

Sawtooth control is very closely related to tearing mode control. The goal is either to prevent sawteeth or to increase their frequency and reduce their amplitude to the point where they do not trigger NTMs [Chapman 2012b] (Fig. 2-24). The control issues are much the same as for tearing modes, and research will aim to establish the physics basis for sawtooth control, and to test real-time integrated control of sawteeth and tearing modes in ITER demonstration scenarios.

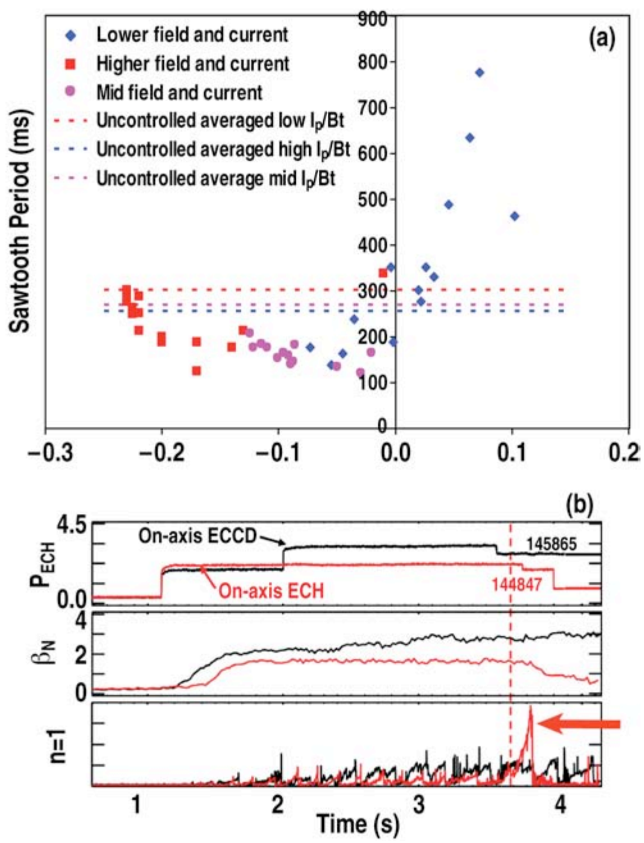

Fig. 2-24. (a) Sawtooth period vs. ECCD location relative to the q=1 radius. The period can be increased or decreased by more than a factor of two from the uncontrolled value. (b) Time evolution of discharges with different ECCD radii, showing EC power, normalized β, and amplitude of n=1 MHD activity. The case with ECCD inside the q=1 surface (black curves) has a reduced sawtooth period, and avoids triggering a 2/1 NTM despite higher β.

This work will benefit greatly from increased gyrotron power. Higher power will make it easier to stabilize tearing modes, and when integrated with multiple steerable mirrors, will allow stabilization of several modes (including sawteeth) simultaneously. A 16-channel upgrade to the oblique ECE diagnostic, from the present two channels would be valuable in detecting islands at the same poloidal location as the ECCD and with the same Doppler shifts.

2.3.3.4. Resistive Wall Mode Physics. The goal of research in resistive wall mode (RWM) physics is to develop a predictive understanding of the stability limits and damping mechanisms for these modes. ITER's steady-state scenario and future high performance devices such as FNSF are expected to operate in or near the wall-stabilized regime where RWMs may appear. DIII-D experiments have shown that the RWM often remains stable at β above the no-wall limit [Garofalo 2007, Reimerdes 2007]. Predictive RWM stability models incorporating the impact of kinetic, non-ideal MHD contributions are now mature [Liu 2008, Berkery 2010a, Chapman 2011]. Qualitative agreement between model predictions and rotation-dependence of the RWM marginal stability point in NSTX [Berkery 2010a] and the driven, stable RWM response in DIII-D [Reimerdes 2011a] has been obtained. However, additional predictions of the kinetic stability models, such as the stabilizing influence of energetic ions, have not yet been experimentally verified. A solid scientific basis for passive stability of RWMs without the need for control coils would have a significant impact on the design of future high β tokamaks.

Investigation of kinetic effects will be an important part of the research. In a departure from the original paradigm of a critical rotation threshold for RWM instability [Bondeson 1994], recent evaluations of the kinetic theory indicate that the passive stability depends on the interplay of plasma rotation with kinetic resonances involving both thermal and fast ions, leading to a non-monotonic dependence of the stability on rotation [Berkery 2010, Reimerdes 2011b]. Damping due to fast ions, including contributions from beam ions, ion cyclotron resonance heating (ICRH) heated ions, and fusion alpha particles is expected to play a significant role in determining the passive stability of ITER scenario four discharges [Chapman 2012a]. Preliminary experiments have provided support for these predictions [Reimerdes 2011b], and indicate that off-axis NBI has a measurable impact on RWM stability [Hanson 2012a] (Fig. 2-25). Future research will investigate the kinetic resonance in more detail, including the depen–dence on key parameters such as collisionality, T_e/T_i ratio, and fast ion velocity distribution function.

In addition, the coupling of stable RWMs to other modes such as ELMs and fishbones [Okabayashi 2011] will be studied, and the stability boundaries for multiple toroidal and poloidal modes will be investigated.

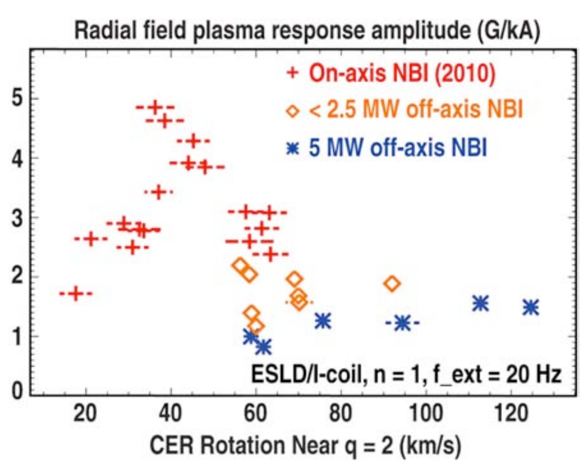

Fig. 2-25. Amplitude of plasma response to a rotating n=1 field applied for "MHD spectroscopy," plotted vs. toroidal rotation. The plasma becomes more stable to the RWM (smaller response) when a greater fraction of neutral beam power is applied off-axis.

These studies will be enhanced by the modification of a second beamline for off-axis injection, increasing the flexibility to vary the fast ion distribution function. A dedicated antenna for MHD spectroscopy will also be a valuable tool, making it possible to continuously probe RWM stability without compromising the use of the I-coil for other purposes such as error field compensation and ELM control. The new magnetic diagnostics to be installed in 2013, and any further upgrades for stationary modes, will be essential to identification of the least stable mode.

2.3.3.5. Resistive Wall Mode Control. Resistive wall mode control research is aimed at developing active feedback stabilization, to be used in cases where passive stability is not adequate [Strait 2004]. Active control is required when the RWM is unstable, and may also be required in stable cases where the RWM is so weakly damped that transients such as ELMs and fishbones can excite it to large amplitude [Okabayashi 2009]. The goal is to provide the basis for active RWM stabilization in ITER and other future devices, by developing and demonstrating RWM control algorithms that are validated against modeling.

A very closely related problem is that of feedback-driven "dynamic error field control" in which the response of a stable kink mode, driven by error fields, is used as input to the feedback system [In 2010]. Research in this area will develop the basis for reliable, automatic error field control in high-β plasmas.

DIII-D research in this area will focus on development and testing of improved feedback algorithms [Hanson 2009, In 2006]. Modeling predicts that with the use of a well-designed state-space controller, external coils can be as effective as internal coils for RWM stabilization (Fig. 2-26). A validated scientific basis for high-performance plasmas near the ideal-wall stability limit with only external control coils could have a significant impact on the design of future high performance tokamaks. Simultaneous feedback control of multiple RWMs (n=1 and n=2, for example) will be explored, and feedback-driven error field control will be developed further.

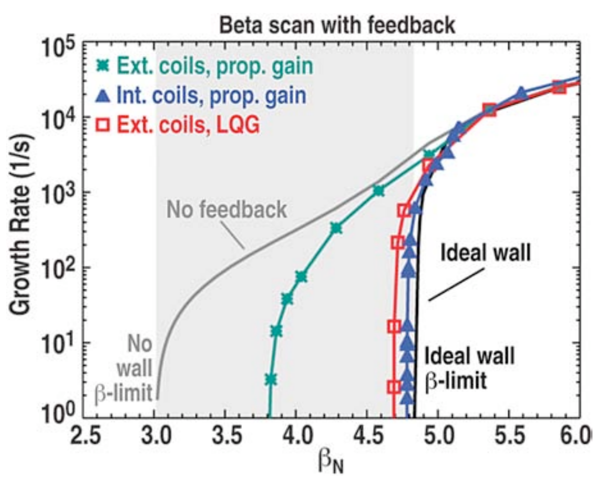

Fig. 2-26. RWM growth rate vs. normalized β, from modeling predictions by the VALEN code with different configurations of feedback control. External coils perform poorly with simple proportional gain, but a linear-quadratic-Gaussian (LQG) controller improves the stable β almost to the theoretical maximum (the ideal wall limit).

The goals of developing the basis for RWM control in ITER and evaluating advanced RWM control algorithms will benefit from upgraded power supplies for the active coils. For example, independent feedback control of the upper and lower I-coil sets would automatically match the spatial structure of the control coil response to that of the unstable mode, and thus reduce the likelihood that a mismatched response would drive secondary, marginally stable modes to large amplitude. In addition, model-based algorithms, such as the state-space controller are not restricted to a single array of coils, and can, in principle leverage all existing I- and C-coils simultaneously. Such independent control — at full current and with the necessary bandwidth of at least several kilohertz — requires additional power supplies beyond those currently available. Additional fast, high current supplies will also enable simultaneous RWM stabilization and multi-mode error field correction with the same coils. The new magnetic diagnostics to be installed in 2013 will provide more complete input to the feedback system.

2.3.3.6. Disruption Avoidance. In a very real sense, all of the stability research described here has the goal of avoiding disruptions. However, reliable avoidance of disruptions in routine operation will require integration of these results and others into a control system that can predict and respond to stability limits with very little operator intervention. The ultimate objective is to make control of the plasma's stability, by passive or active means, as routine and robust as axisymmetric shape control has become. The detection methods and control algorithms, supported by modeling, can be directly extended to ITER and other burning plasmas.

DIII-D research will explore real-time detection of stability limits before they are crossed. The use of real-time active MHD spectroscopy for controlled operation near a kink mode stability limit has already been demonstrated [Hanson 2012b] (Fig. 2-27), and will be extended to more routine use and to regimes of higher β above the no-wall stability limit. The plasma control system can already use MHD mode signals to shut down unstable discharges (the "dud detector"), and future research will develop improved, physics-based algorithms for early detection with a minimum of false positives. Planned research will also include development of paths for retreat from a detected stability limit, in order to maintain stability with minimal impact on the discharge performance.

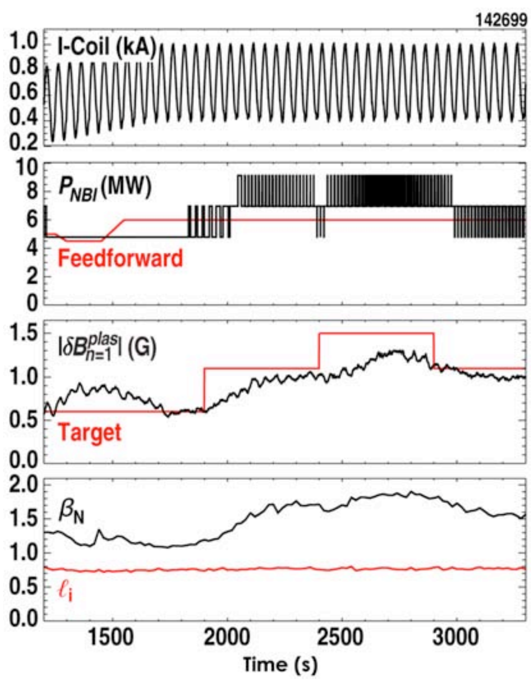

Fig. 2-27. Demonstration of feedback control based on real-time MHD spectroscopy, showing (a) current in the probing coil, (b) neutral beam power as the actuator, (c) measured n=1 plasma response to the probing field with the feedback target for this parameter, and (d) normalized β and internal inductance. As the feedback target is raised in two steps (c), the control system increases the neutral beam power and duty cycle (b), raising β (d) in order to achieve the requested plasma response amplitude (c). Similar control could reduce β in order to avoid large plasma response that indicates an impending instability.

The active control methods described above for error fields, NTMs, sawteeth, and RWMs will be employed to extend the stability limits, when operation near or beyond a passive stability limit is required. A key five-year plan objective is to develop active stabilization from an experiment to an operational tool.

For cases where an instability does occur, disruption avoidance research will investigate and develop “soft landing” solutions. These are techniques that allow the discharge’s thermal and magnetic energy (ME) to be brought down rapidly but in a controlled way, without a disruption and without the need to trigger the disruption mitigation system (DMS). (See Section 2.4.2.2 Disruption Mitigation and Runaway Avoidance.)

Integrated disruption avoidance will use the full tool kit described in earlier sections, and therefore many of the planned hardware upgrades are essential: upgraded power supplies and additional active coils for simultaneous error field correction and active control of RWMs and tearing modes, additional gyrotrons for profile control and NTM suppression, a dedicated MHD spectroscopy antenna for continuous sensing of stability limits, and upgraded diagnostics for better detection of instabilities.

2.3.4. Impact of Research

A stable plasma with a high β magnetic equilibrium that neither tears nor kinks is a prerequisite for the successful operation of a tokamak. Validation of predictive models includes: (1) what current density and safety factor profile combination is most tearing mode stable (to be maintained), and how is it affected by flow shear, and (2) how much plasma rotation is needed to passively stabilize resistive wall modes in regimes with anticipated kinetic effects ($T_e/T_i > 1$ in ITER for example). Recent advances in theoretical models have led to predictions that kinetic RWM stabilization will be marginally sufficient for ITER scenario 4 to meet its β target [Liu 2009, Berkery 2010, Chapman 2012a]. However, significant features of the theory, such as the contribution of fast ions to the stability, have yet to be experimentally verified. ITER, FNSF and DEMO will only be successful if disruptions are virtually completely avoided. The impact of the research described here will be threefold. First, the scientific understanding gained will help to ensure that ITER meets its fusion goals. DIII-D is well positioned to make major contributions to the scientific basis for error field compensation, prediction of resistive and ideal MHD stability limits, active control of sawteeth, suppression of NTMs, and active RWM control in ITER. Validated engineering solutions based on these scientific results will enable ITER to carry out its program without delays caused by damage due to disruptions, and without being hampered by excessively cautious operation to avoid disruptions.

In the longer term, robust solutions to the prevention of disruptions, with a scientific basis developed on DIII-D and validated on ITER, are probably a pre-requisite for the viability of future burning tokamak plasmas. Disruptions are perceived as a key weakness of tokamaks for fusion power, and rapid shutdown (“disruption mitigation”) is probably not feasible for devices larger than ITER. It is likely that a tokamak-based DEMO plant will only be built if the scientific and engineering communities are thoroughly convinced by experience on ITER that disruptions can be avoided with high reliability. DIII-D research will make critical scientific and engineering contributions toward the demonstration of robust avoidance of disruptions in ITER.

Finally, the research proposed here will improve the quality of DIII-D operation. Improved error field correction, improved profile control for stability, and reliable real-time detection of stability limits will increase the number and duration of useful discharges for other research. Active stabilization of NTMs and RWMs will allow robust operation in regimes of high fusion performance that would otherwise be transient or inaccessible.

2.3.5. Hardware and Diagnostic Requirements, Stability Codes to be Used

Tables 2-11 and 2-12 summarize the highest priority hardware and diagnostics upgrades for the research described here, in order of priority.

Table 2-11
Hardware Elements for Stability and Disruption Avoidance Research

Hardware Item	Physics Benefits
New power supplies for 3D coils: more channels, higher current	Physics of plasma response to 3D fields Improved error field correction Multi-mode RWM feedback control Simultaneous EFC and RWM feedback control
Faster steerable mirrors for all gyrotrons *(in progress)*	Shared profile control and NTM suppression NTM suppression at multiple rational surfaces
Increase EC power to 8.5 MW	Shared profile control and NTM suppression NTM suppression at multiple rational surfaces
New 3D coils	Wider spectrum for plasma response to 3D fields Improved error field correction
Reduction of intrinsic error field sources (TF feed)	More reliable operation Cleaner 3D field experiments Makes I-coil and C-coil available for other uses

Table 2-12
Diagnostics for Stability and Disruption Avoidance Research

Diagnostic Item	Physics Benefits
ECE diagnostics: • ECE imaging (2nd view) • ECE radial array (2nd view) • Oblique ECE	Detailed reconstruction of rotating mode structures Discriminate n=1 non-rotating mode structures Better island localization for ECCD stabilization
"3D" magnetic diagnostics *Phase 1 and Phase 2*	Resolution of n=3, 4 plasma response to RMP Detailed tests of plasma response vs. model predictions
High-resolution MSE	Resolve Δ' physics at tearing onset Measure Δ' modification by ECCD
Probe coil and supply (25 kHz) for active MHD spectroscopy	Continuous monitor of proximity to stability limits New tearing mode physics

Table 2-13 summarizes the highest priority stability codes to be used (as is, upgraded or developed) for the research described here. Latest theoretical predictive codes to be further advanced and/or use upgraded diagnostics are in red.

Table 2-13
Code Elements for Stability and Disruption Avoidance Research

Stability Code	Physics Benefits
SURFMN	Computes the non-axisymmetric fields of external coils or coil irregularities (and spectra) for comparison to that of equilibrium magnetic field
M3D-C1	Ideal MHD two-fluid stability code
MISK	Evaluates kinetic contributions to RWM stability
DCON	Evaluates eigenspectrum of ideal MHD perturbed energy (basis for both VALEN and IPEC)
VALEN	Resistive wall mode stability with realistic vacuum vessel, external coils, magnetic sensors, control algorithms for RWM stability
IPEC	Perturbed magnetic equilibrium for mode structure due to application of non-axisymmetric fields
PEST3 with finer MSE radial resolution used in EFIT	More reliable linear calculation of temporal trend in Δ' as profiles evolve, real time to be implemented
MARS, MARS-F, MARS-K	Linear and nonlinear MHD code with capability of adding rotation, kinetic effects
Real-time TORBEAM	Better refraction monitoring for more accurate alignment of ECCD on rational surfaces/islands

2.4. DISRUPTION CHARACTERIZATION AND MITIGATION

Disruption mitigation for reactor-regime tokamaks — ITER and beyond — poses a set of interconnected challenges that stem from the high levels of plasma current and plasma thermal and magnetic energies that achieving burning plasma operation entails. The Five-Year DIII-D Research Plan for Disruption Characterization and Mitigation focuses on providing physics understanding, predictive model development and timely physics and technology design guidance — initially by 2016 — for the ITER Disruption Mitigation System (DMS). Activities will focus on the understanding and meeting the three principal ITER disruption mitigation challenges:

- Thermal energy (TE) mitigation followed by current quench rate control.
- Avoidance or limitation of runaway electron (RE) avalanching.
- Runaway electron control and dissipation.

DIII-D is well positioned to study these issues owing to its capabilities to routinely withstand — without adverse consequences — the effects of elongated plasma disruptions with currents up to 2 MA, and its already demonstrated capabilities to repeatedly produce and benignly dissipate of up to 0.7 MA RE current. These capabilities, combined with diagnostic and injection system enhancements and disruption and runaway code and model development will provide a basis for ITER DMS selection and design and a unique test environment for DMS prototypes.

2.4.1. Disruption Mitigation Challenges

Table 2-14 summarizes the principal disruption mitigation challenges and highlights of the DIII-D Research Plan approaches and capabilities that will be used to address them.

Table 2-14
Disruption Mitigation Challenges, Approaches and Capabilities/Upgrades

Challenge	Approach(es)	Key Capabilities or Upgrades
TE mitigation, followed by CQ control • Protect divertor • Radiate TE benignly • Control radiation duration and symmetry • Control CQ rate	Massive gas injection (MGI) Massive pellet injection (MPI) Cryo-solid and/or shell pellet injection	MGI at second and third locations High-*Z* mini SPI or cryo-solid pellet Enhanced bolometry coverage Main chamber visible and IR view (PERISCOPE) 3D + *t* modeling Sequential MGI and/or SPI Variable SPI and/or shell MPI
Avoid or limit RE avalanching	<u>Super high n_e</u> ($>10^{22}$ m^{-3}) • Add 3D fields • After TQ injection	Improved solid-yield D_2 SPI Improved D_2 MGI or RDI Low-*Z* shell pellet RE seed and early loss diagnostics
Control and dissipate RE current and energy	High-*Z* gas injection • Pre-emptive (before TQ) • After CQ onset • With ITER-like passive + PF control	Existing + upgraded PF control ITER DM + RE control emulation CdTe array with inner-wall view EUV tangential x-ray camera BGO pulse-height HXR

2.4.2. Research Plan

The Five-Year Research Plan is staged and focused to address critical ITER needs by 2016. The plan recognizes the urgent need to provide data, physics understanding and validated predictive models in the three DMS-critical research topics (challenges) cited above. DIII-D is well positioned to do this owing to its disruption tolerance and RE control capabilities. In addition, DIII-D can produce a wide range of pre-disruption plasma configurations, including the standard ITER shape, and has passive and active equilibrium control that facilitates emulation of the expected dynamics of ITER disruptions and RE generation and loss events. These capabilities, combined with an extensive and growing array of 2D and 3D plasma and RE diagnostics position DIII-D to make a seminal contribution to disruption characterization and mitigation development for ITER and beyond. Figure 2-28 provides an overview of key research elements, capabilities and upgrades for the Five-Year Research Plan.

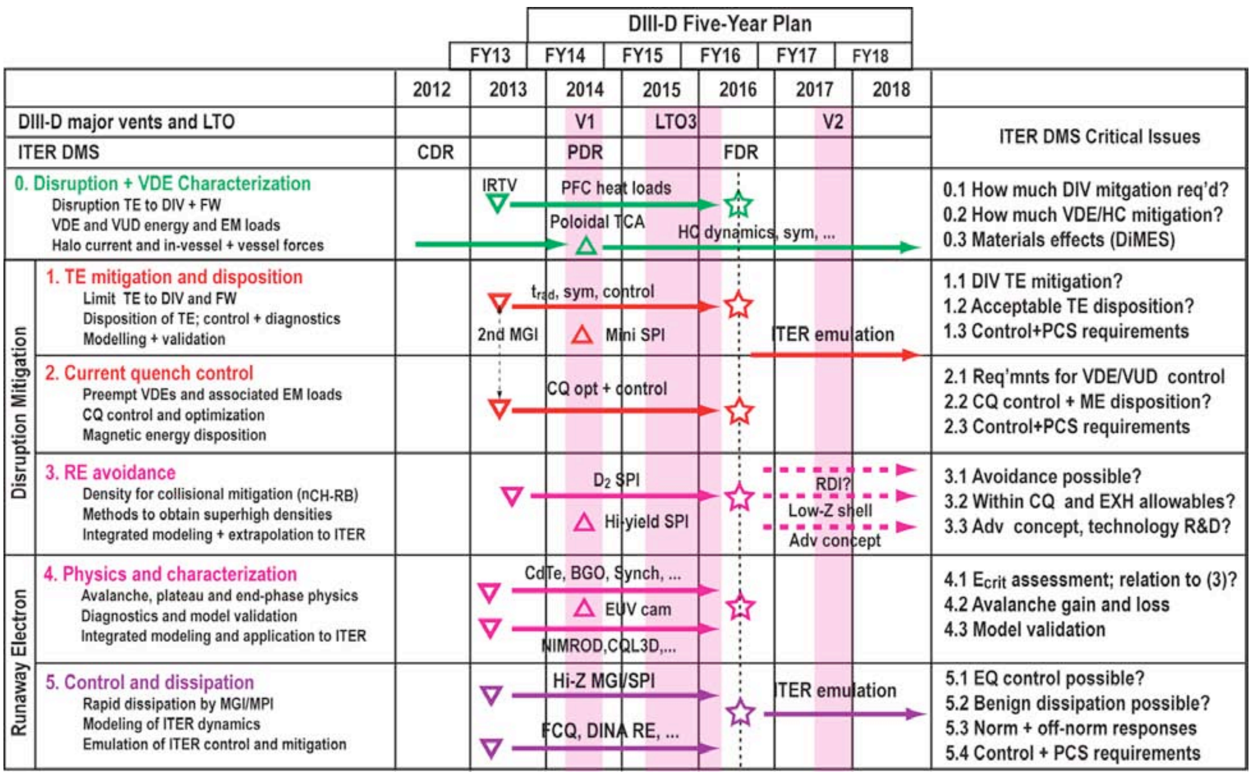

Fig. 2-28. Research plan for disruption characterization and mitigation.

Physics basis justifications and details of the various research topics and approaches follow in Sections 2.4.2.1–2.4.2.3. Presentation is organized in terms of three topics: (1) disruption characterization, (2) disruption mitigation, comprising TE mitigation and CQ control and pre-emptive RE avoidance, and (3) runaway characterization, control and dissipation. Concept testing of two innovative alternate injection concepts and possibilities for testing ITER prototype injection components is given in Section 2.4.2.4. Presentation of the major Research Plan resources — injection systems, diagnostics and code/models — follows in Section 2.4.3.

2.4.2.1. Research Plan for Disruption Characterization. Disruption characterization and the development of a predictive understanding of the causes, onset dynamics and consequences of disruptions remains a broad- and open-ended area of tokamak research. DIII-D characterization studies will focus on key data to support concept selection and functional requirements for the ITER DMS.

First Wall and Divertor Baffle Heat Loads. Characterization studies will focus on two topics: PFC heat loads from disruptions and vertical displacement events (VDEs) and halo currents and vessel forces owing to VDEs and vertically unstable disruptions (VUDs). Figure 2-29 shows VDE heat load data obtained during 2012 at ITER's request. The infrared data reveal unexpectedly high heat/energy loads on the inner first wall. These findings support setting requirements for VDE mitigation reaction time and VDE thermal energy mitigation efficacy of the ITER DMS. Refinement of these results and obtaining similar data for radial and vertically unstable disruptions with enhanced infrared camera (IRTV) viewing coverage will be pursued, starting in 2013. Halo currents and vessel forces are included in these studies.

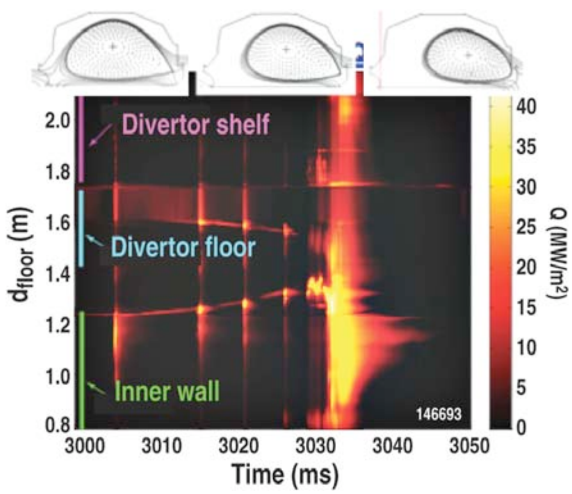

Fig. 2-29. VDE heat loads on the first wall.

These PFC energy deposition studies comprise part of the broader need to quantify and understand (extrapolate to ITER) the level of conducted and radiated heat loads in various types of disruptions, mitigated and unmitigated VDEs and massive gas injection/massive pellet injection (MGI/MPI)-initiated fast shutdowns. The wide-view IRTV and fast camera capabilities coming online in 2013 will advance these studies and will also contribute to quantifying magnitudes and locations (including peaking factors) of deposition from runaway electrons. Capabilities will also be available with Divertor Materials Evaluation System (DiMES) (Fig. 2-30) to measure material erosion and surface morphology changes from the full range of DIII-D disruption and disruption mitigation capabilities.

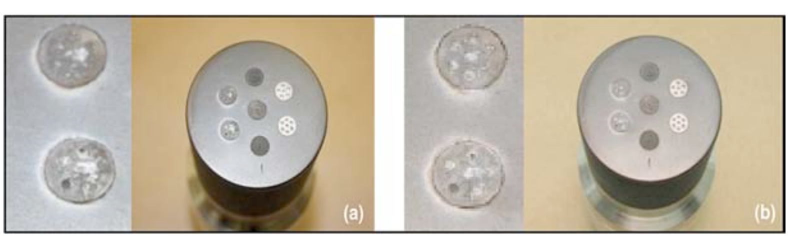

Fig. 2-30. DiMES button samples (insets) before and after exposure to Ar MGI.

2.4.2.2. Research Plan for Disruption Mitigation and Runaway Avoidance. The Plan addresses the three research elements needed to arrive at an integrated ITER DMS concept. These elements derive from the three critical objectives identified for the ITER DMS. The DMS must:

1. *Protect* the divertor PFC surfaces from direct deposition of ~350 MJ of plasma thermal energy
2. *Control* the rate of plasma current decay after thermal energy mitigation (*aka* divertor protection) to fall with a 50–150 ms decay time allowable
3. (a) *Avoid* generation of multi-mega-electron-volt REs and also, (b), provide an independent means to *benignly dissipate* runaway electrons produced by unmitigated disruptions or the action(s) of the DMS in effecting objectives (1) and (2)

A variety of mitigation technology concepts and modes of utilization in ITER are being considered by the ITER Organization, the U.S. ITER Project Office (responsible for providing the ITER DMS) and the international disruption mitigation research community. The Five-Year Research Plan focuses on the physics element research, technology development and testing, and model development and validation needed to arrive at an *integrated, safe and effective* ITER DMS design. Assessing ITER DMS concepts and function for the 2016 DMS Final Design Review (FDR) serves as the critical mid-term focus for the Plan.

As the narrative below explains, requirements (1) and (2) are sequential and are presently envisioned to be implemented in ITER by injection of moderate quantities of radiating impurities, e.g., neon or argon. Requirement (3a) is presently envisioned to proceed with similar pre-emptive injection of more massive quantities of deuterium, possibly supplemented with a weak admixture of higher-*Z* impurity to tailor (control) the radiation attributes. The common dependence on pre-emptive injection technologies – using either gas or pellet approaches, and the common need for [3(a)] strategies to also satisfy the control requirements for (1) and (2) makes them related sub-elements in the Disruption Mitigation Research Plan.

(1) Thermal Energy Mitigation. There are two requirements for benign mitigation of the ~350 MJ plasma thermal energy: (1) ≥ 90% of the energy must be diverted from direct impingement on the divertor PFC surfaces, and (2) the diverted thermal energy must be, more or less, uniformly spread over the first wall area in a way that avoids significant melting of the beryllium surface. The means proposed to do this in ITER is injection of radiating impurities and/or additional free electron density by MGI or alternately, by MPI. Successful TE mitigation by pure and mixed gas MGI, by high-*Z* killer pellet injection and by deuterium MPI [or shattered pellet injection (SPI)] has been demonstrated in DIII-D. There have also been demonstrations of MGI TE mitigation in many other tokamaks.

Accommodation of 350 MJ on the beryllium first wall in ITER sets stringent limits on the energy deposition time and the global peaking factor (peak to average) for the deposited energy (Fig. 2-31). The marginal square-pulse radiation time with fully uniform deposition is about 1 ms; this minimum time increases as the square of the peaking factor. Data from DIII-D and other tokamaks shows peaking factors (combined toroidal and poloidal) in the range of 2 to 5. Application to ITER indicates a corresponding radiation time requirement of 4–28 ms.

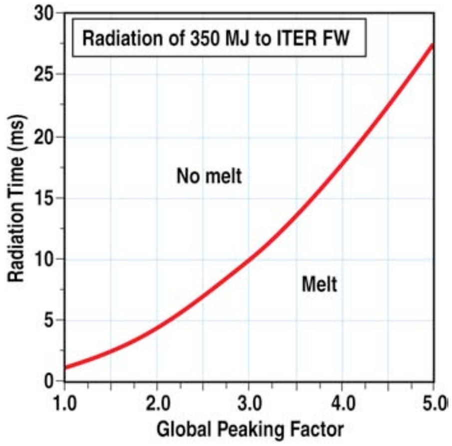

Fig. 2-31. Requirements for thermal energy deposit on the ITER first wall.

There are many still open physics basis questions about TE mitigation for ITER, including:

- How effectively can TE deposition to the divertor and baffle surfaces be limited?
- What will the thermal energy radiation time, time waveform and peaking factor(s) be?
- How will ME loss from thermal quench (TQ) contribute to radiation?
- How will TE and ME radiation partition among the pre-TQ, TQ and initial CQ phases?
- How will TE mitigation attributes be modified by the use of multiple injection locations and/or implementation of gas versus pellet delivery?
- What MGI/MPI preset and active control attributes will be needed, effective and safe for ITER?

The Five-Year Plan will focus on radiation time and peaking and the underlying physics basis of how gas- and pellet-injection delivered impurities and electron densities [local volume radiation rate scales as $n_e n_i L(Z)$, where Z denotes the atomic number of the radiating species] contribute to the distribution and timescale(s) of the FW surface heating. A second gas injection system (denoted as CERBERUS) will be added in the 135 R-2 port (Fig. 2-32). The 3-valve CERBERUS system, intended be used in conjunction with the existing 6-valve MEDUSA system, located at 15 R+1, will provide initial gas delivery to a flux line manifold that is poloidally opposite to the delivery from MEDUSA. Existing and enhanced soft x-ray (SXR), bolometric and IRTV diagnostics will be used to quantify the initial impurity delivery attributes and the timescale and toroidal and poloidal symmetries of the resulting in plasma radiation source and first wall energy/power depositions. Issues of valve timing and means for delivery synchronization and control will be assessed. The possibility of moving CERBERUS to the 135 R+1 port (120 deg from MEDUSA) and/or adding MGI valves at a third toroidal location in 2014 will be evaluated.

One of the key outcomes of this multiple location effort will be assessments of the inherent radiation source asymmetries owed to the MHD origin of the MGI mixing process and whether multiple injection locations and/or using deep penetrating SPI (MPI) injection can reduce these types of inherent asymmetries. The results will be compared with the radiation predictions of NIMROD 3D MHD modeling (see Fig. 2-33 and *Code Developments*), and also investigate whether externally applied 3D fields can affect or control the magnitude or toroidal phase of the radiation symmetry. The effect of multiple reconnection mixing events [Fig. 2-34(b) and also the P_{rad} precursor in Fig. 2-33] on divertor protection and radiation symmetry, duration and partitioning will also be assessed.

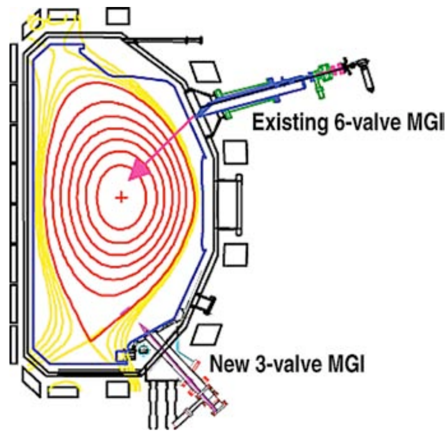

Fig. 2-32. Second MGI system will allow tests of two-location injections.

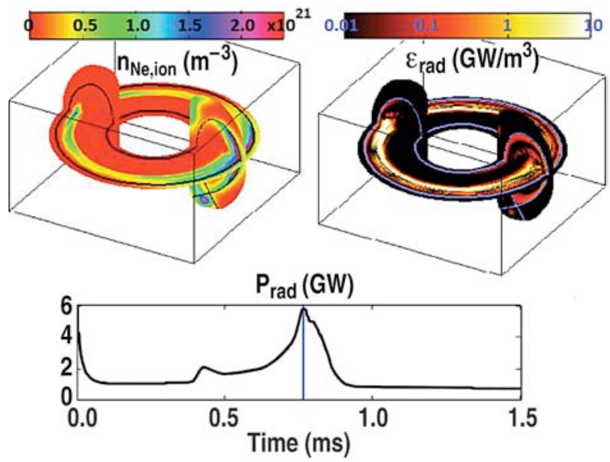

Fig. 2-33. NIMROD 3D MHD modeling of DIII-D thermal energy radiation from MGI. Note the precursor reconnection event at ~ 0.4 ms.

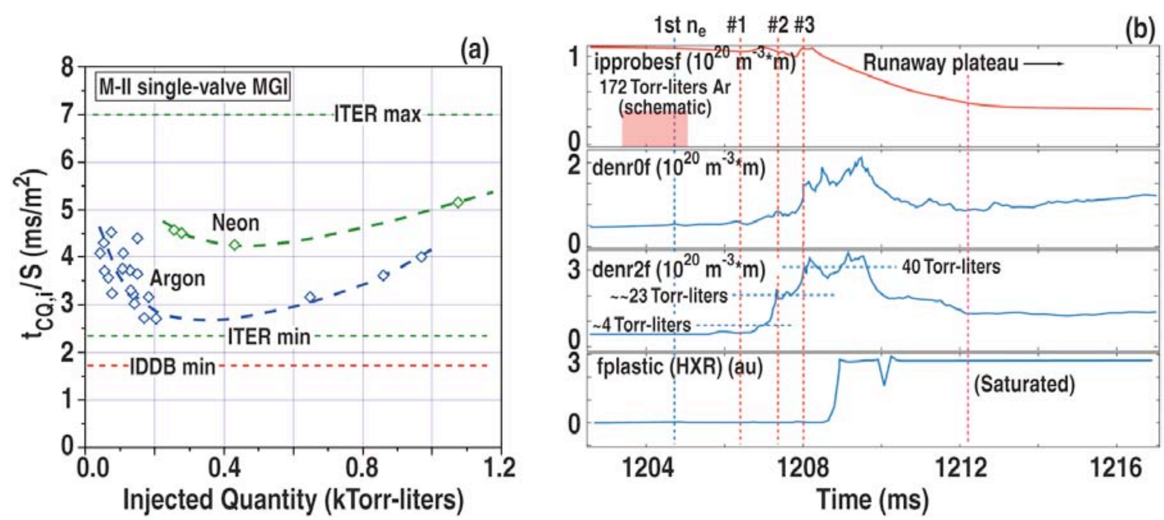

Fig. 2-34. (a) CQ control and variance with low-quantity argon MGI. (b) Multiple reconnections and RE generation with low-quantity argon MGI.

Injection of micron-size boron dust particles by *shell pellet delivery* (see *Alternate Injection Methods*, below) or with a dust-loaded rupture disk injector (*ibid*) is expected to prove a localized in situ source of impurities. Hence dust injection may provide a method to assess the toroidal and poloidal transport and radiation dynamics of centrally deposited impurities.

(2) Current Quench Dynamics and Control. ITER has guidelines for allowable plasma current decay times. Minimum and maximum times are respectively 50 and 150 ms. These are for routine/repetitive 15 MA disruptions or MGI/MPI fast shutdowns. Current decays with less than 35 ms decay time "shall not occur", and the number of events with quench times in the range of 35–50 ms will need to be strictly limited.

The impurity and free-electron delivery used for TE mitigation provides a minimum basis for the current decay rate. Present understanding is that supplemental impurity or electron injection (after TE mitigation) can be used to *enhance, but not reduce*, current decay rates. Hence the challenge for ITER mitigation design is to arrive at a concept that satisfies the TE constraints *without* foreclosing being able to subsequently satisfy the current decay control constraints. The focus of the Five-Year Research Plan will be on finding and eventually emulating an *integrated disruption mitigation (DM) scenario* for ITER that satisfies both requirements.

Studies in 2012 used low-quantity argon and neon injection to obtain area-normalized current decay times (t_{CQ}/S, where S is the poloidal cross-section area) that fall within the ITER requirement of $2.3 \leq t_{CQ}/S \leq 7$ ms/m^2. These results demonstrate control capability, (Fig. 2-33), albeit with strong sensitivity to the amount of injected gas and significant same quantity variance. The presence of at least two sequential MHD mixing events (evidenced by two I_p spikes in the current waveform) is seen these single-valve examples. Experiments beginning in 2013 will revisit these studies with improved valve control, a wider range of pure and mixed (e.g., D_2 + Ne) gases and comparisons of single and multiple location and single-valve versus multiple-valve gas delivery. Continuation in 2014 and after will focus on integrated scenario development and optimization using multiple valves and possibly also using mixed sequential injection techniques, e.g., a small Ar pellet followed by MGI for final current decay control. These DM scenario development experiments will also provide valuable model validating data for extrapolating DIII-D results to ITER.

(3) Runaway Electron Avoidance. The inherent propensity of reactor-scale tokamaks in general and of ITER in particular to Coulomb-avalanche converting a large fraction (~80%) of their pre-disruption plasma current to ~20 MeV RE current is widely recognized. The principal method proposed for *avoiding* such conversion in ITER is pre-emptive injection of sufficient impurity and/or hydrogen density to achieve a free-electron density ~5×10^{22} m^{-3}. At this *super-high* free-electron density (or at an equivalent free + bound density obtained with high-Z injection), the classical *e-e* collisional drag is theoretically sufficient to inhibit Coulomb avalanche growth and onset of RE conversion. The magnitude of the required density follows from the Connor-Hastie critical electric field E_{crit} (V/m) $\approx 0.1 n_e(10^{20}$ m$^3)$ and the empirical observation that the fastest current decays observed in present tokamaks and predicted for ITER typically yield a peak current decay E of about 50 V/m.

Attempts to achieve free or free+bound electron densities of this super high magnitude in ASDEX-U and DIII-D have so far fallen well short of this critical density (aka "Rosenbluth density") goal. The shortfall comes in part owing to lack of sufficient gas delivery capability, in part owing to lack of efficient assimilation of the injected gas, and in part owing to indications that injected/ionized gas is not always well retained during the plasma current decay. In addition, the current decay rates obtained in ASDEX-U and DIII-D with high quantity high-Z injection invariably fall at or below the ITER lower allowable of 2.3 ms/m^2. Hence using high-Z injection to obtain super high densities in ITER will be proscribed.

It is possible that the anomalous RE seed losses or alternately, the critical electric field enhancement relative to the classic Connor-Hastie estimate observed in DIII-D RE plateau experiments (see *RE Physics and Characterization*, below) may translate into a corresponding reduction in the critical density for CQ avalanche suppression. Such a reduction would reduce gas injection and exhaust requirements; whether it (reduced density) would be enough to skirt the ITER CQ limitation noted above remains to be assessed.

The runaway avoidance studies proposed in the DIII-D Five-Year Plan will focus on the feasibility of using *massive deuterium injection*, delivered via SPI, to achieve high free-electron densities and study the particle confinement attributes during the resulting fast current decays. SPI has so far achieved at current quench onset densities of up to 2x10^{21} m^{-3}, and good retention of the added density during the subsequent current decay is observed (Fig. 2-35).

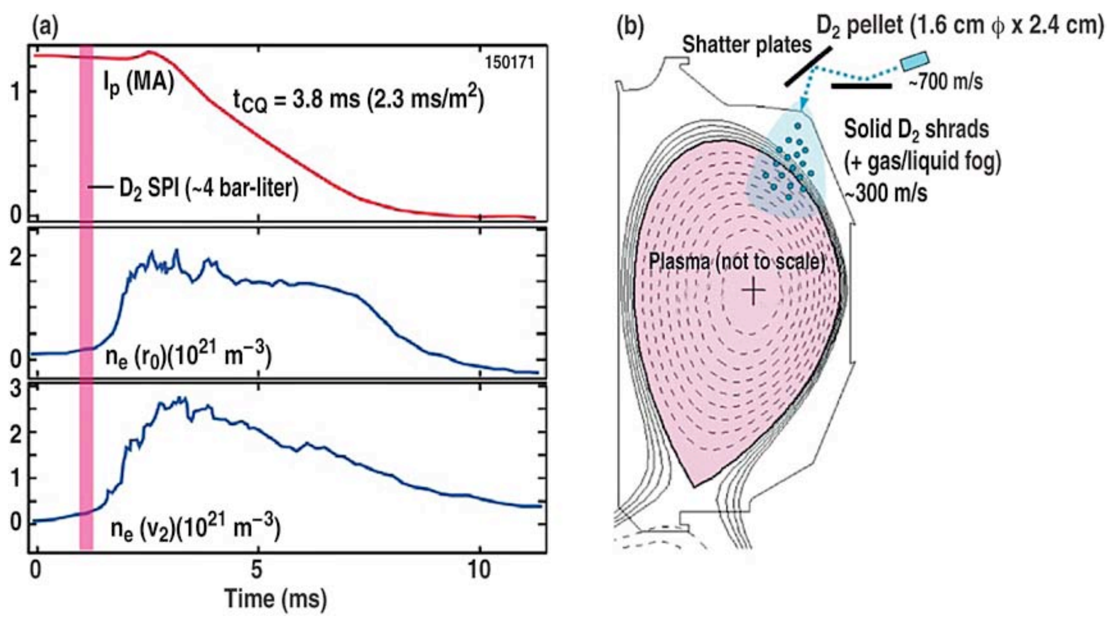

Fig. 2-35. (a) High density D_2 SPI. (b) SPI with double-bounce shatter plates.

Higher SPI assimilation may reduce ITER D_2 exhaust loads to acceptable levels. Hence it is planned to replace the present double-bounce SPI shatter plate assembly with an alternate bent-nozzle concept — now in development — to test whether improved solid yield and shatter stream collimation can raise the ~20% limitation on SPI assimilation seen to date. Experiments with variable shatter pellet size and incident velocity will also elucidate how shattered pellet injection and penetration and assimilation and SPI radiation duration and symmetry will scale to ITER. Finally, modeling of SPI attributes for plasmas without carbon impurities (which presently set the too-fast-for-ITER CQ rate seen in DIII-D) will be needed to assess SPI implementation and attributes for ITER.

2.4.2.3. Research Plan for Runaway Physics, Control and Dissipation. Experiments and model development to clarify the physics basis for runaway electron generation, growth and ultimate loss and dissipation in ITER-like disruption and fast shutdown scenarios will comprise a second major focus of the Five-Year Plan R&D. The results from this physics-oriented study will provide critical inputs for the ITER DMS, including:

- Estimates of the density needed for pre-emptive MGI/MPI avalanche suppression (see above).
- Understanding and modeling bases for RE seed generation, avalanche growth and loss.
- Strategies and ITER-relevant methods for benignly dissipating multi-MA RE currents generated by disruptions or by low-quantity MGI/MPI deployed for TE+CQ mitigation.
- Prediction for ITER RE avalanche generation and loss to PFC surfaces during normal and off-normal disruption and DMS-action scenarios.

Need for RE Mitigation. It is likely that the low-quantity high-*Z* DM scenarios mandated by ITER constraints on thermal energy disposition and current decay rate will result in copious RE generation. Hence ITER should expect multi-MA RE generation and *must* have an independent means to control and benignly dissipate the high RE currents — up to 12 MA — to be expected following an unmitigated disruption or low-quantity MGI/MPI.

The Five-Year Research Plan will address this critical RE mitigation need in two ways:

1. Development of physics basis understanding and validated models, and
2. Development and test in DIII-D of ITER-deployable post-emptive RE control and dissipation methods.

Here *"post-emptive"* denotes scenarios and methods where action is (can be) taken after initial onset of plasma current decay and RE growth. The division between physics basis studies and mitigation method development and test is artificial in the two presentations that follow, but helpful to understand how the Research Plan activities will contribute to ITER's RE mitigation needs.

Runaway Generation and Physics. Understanding of the basis for RE generation, avalanche growth and confinement and dissipation following disruption or pellet- or gas-injection is to date largely theoretical and limited in DIII-D and similar experiments owing to inability to explicitly measure the initial RE seed source and/or early nascent RE losses. Hence, for example, the key premise of avalanche growth rate, $\gamma_I = I_{RE}^{-1} dI_{RE}/dt \approx e/mc \ \ln\Lambda^{-1} \ (E - E_{crit})$ remains to be directly verified in the initial strong avalanche regime, where $E >> E_{crit}$ is ~50 V/m, and predicted growth rates are in excess of 100 s^{-1}. RE current growth rates of this magnitude are routinely observed in DIII-D and other tokamaks, so the basic presence of the avalanche process is not in doubt. But quantitative verification remains elusive. The following steps will be taken to address this verification need:

1. Vary and control the RE seed formation rate by varying Ar pellet injection and/or high-*Z* gas injection properties.
2. Measure RE avalanche growth rate using an extreme ultraviolet (EUV) imaging system and CdTe and hard x-ray (HXR) detectors to assess seed and avalanche dynamics.

3. Assess the role of MHD activity during and immediately after pellet/gas injection in enhancing nascent RE losses.

To better understand these experimental results, 2D and 3D (NIMROD) MHD/RE growth+loss models will be developed and applied, which self-consistently include thermal and RE current dynamics, MHD island overlap and self-consistent equilibrium evolution during the avalanche growth phase. A synthetic diagnostic methodology for interpreting EUV and synchrotron emission imaging and HXR data will be developed and applied. Predictive utilization of this modeling will support extrapolation to ITER of the post-emptive RE mitigation methods we will test in DIII-D.

The study of RE loss in the quasi-stationary *current plateau phase* that follows completion of avalanche growth will be continued. In this phase, the experimentally inferred magnitudes of $(E - E_{crit})$ are ~1 V/m, so only slow RE current growth or decay is to be expected. However, plateau-phase data in DIII-D shows faster decay and slower growth than predicted by a classical Connor-Hastie + Rosenbluth-Putvinski model. The offset linear shift of the γ_I-$[E–E_{crit}]$ data shows presence of anomalous losses, indicative of additional loss processes and/or higher than expected E_{crit}. There are indications that the RE channel equilibrium configuration, RE and thermal current density profiles and in- and ex-channel density profiles and composition may still be evolving, even in 600 ms duration constant current stationary plateaus (Fig. 2-36). These evolutions appear to affect the anomaly magnitude(s) and raise the interesting physics question of whether avalanche-equilibrated plateaus can ever reach a fully stationary equilibrium condition.

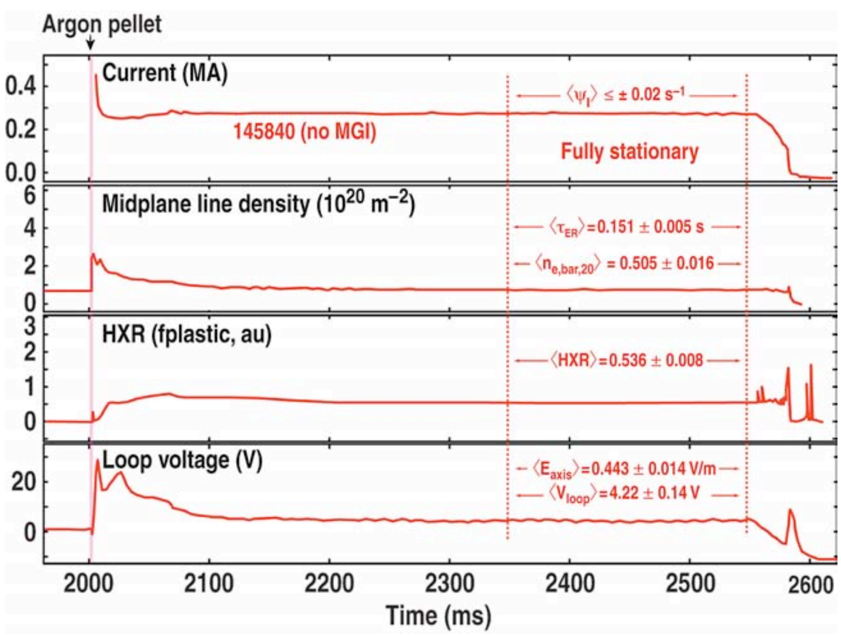

Fig. 2-36. Long duration RE plateau, with nearly stationary current, voltage and density.

Plateau studies during the Five-Year Plan will focus on obtaining more complete understanding of these observations and what they imply for RE dissipation in ITER. The source of RE plateau anomalous loss terms will be investigated using a CdTe EUV imaging array and an in-vessel scintillator probe to identify whether the anomalous losses arise from enhanced loss on the inner wall or enhanced outward losses owed to drift orbits. The RE plateau current channel profile will be measured by comparison of SXR emission profiles with modeling and compare this current profile with magnetic reconstruction data obtained with JFIT and a RE-cognizant EFIT. Finally, measurements of the RE distribution function will be improved. This will be done with a combination of visible synchrotron emission, CdTe array, and HXR energy sensing detectors, with the observations from these diagnostics being compared with the predictions of the CQL3D Fokker-Planck code.

Dissipation of RE Plateau Current. Experimental studies, conducted in 2009–2012, of the effect of post-emptive injection of noble gases into the RE channel demonstrated the ability of high-Z (neon or argon) gas injection to enhance in-channel electron density, HXR emission and rate of RE current decay. In contrast, injection of deuterium or helium enhances density, whilst *reducing* HXR emission and rate of RE current decay. These observations plus DIII-D's unique capabilities to control the RE channel equilibrium and interaction with the inner wall limiter will allow us to use controlled injection of small quantities of low-Z and high-Z gas into an already stationary RE plateau to assess the effect of modifying the in-channel composition and density. Again, comparison of these steady-state plateau injection and dissipation results with predictive models will provide a basis for applying them to ITER.

Rapid Post-Emptive RE Dissipation. ITER needs a robust means for post-emptive RE dissipation. The RE-MGI results obtained in DIII-D comprise prototype examples of how high-Z gas injection can provide this capability for ITER. Further pursuit of these experiments and associated model development during the course of the Five-Year Plan will provide information for ITER runaway mitigation scenario design and also validating data to assess the ITER needs for ancillary equilibrium control during gas injection RE shutdowns. These models will also provide estimates of the expected magnitude and location of dissipated RE kinetic and magnetic energies and improved understanding of how much of the RE channel ME (up to ~250 MJ in ITER) will be converted to PFC-deposited RE kinetic energy.

Figure 2-37 shows three examples of fast RE current dissipation obtained in DIII-D, respectively with pre-emptive Ar killer pellet injection, with post-emptive Ne gas injection into an established RE plateau, and with pre-emptive (before CQ onset) Ar MGI. While the vertically unstable equilibrium evolution of the ITER-like discharge 137611 case differs from the vertically stable inner wall limiter contraction dynamics of the gas injected 142732 and 150468 examples, all of the examples demonstrate benign RE energy dissipation [without detectable plasma material interaction (PMI)] and, taken in combination, the basis for realizing a *minimal control* ITER RE mitigation scenario.

Experiments with rapid RE dissipation during the Five-Year Plan will proceed by (1) understanding the physics basis of high-Z gas injection with vertically stable inner wall limiter target plasmas, and (2) extending the gas injection rapid shutdown techniques to vertically unstable lower single-null (LSN) targets like 137611. With regard to the latter, the 2012 success with using high quantity Ar MGI to generate a 670 kA RE current starting with a 1.2 MA inner-wall limited (IWL) thermal current target raises the prospect that this method can be used with a 1.5 MA ITER-like LSN thermal plasma to emulate (and benignly dissipate) an ITER-like 1-MA RE conversion example.

2.4.2.4. Alternate Injection Methods. Two innovative alternate gas/particle delivery concepts will be pursued during the course of the Five-Year Plan activities. The first alternate method is *shell pellet injection*. Here a payload of micron diameter boron dust contained in a thin 100 μm x 1 cm o.d.

polystyrene plastic shell will be injected into a neutral beam-heated target plasma. Ablation calculations indicate that the shell will burn through as the pellet reaches the q=2 flux surface, thereby releasing the dust in the plasma core. The resulting internal delivery of finely divided dust payload is expected to provide a rapid thermal energy and current shutdown, with expectation that assimilation/retention of the boron will be higher than with MGI or MPI delivery. A proof-of-principle test of the method is planned for 2014. The results are also expected to contribute to the understanding of in-plasma density/impurity ionization and transport following deep penetration delivery.

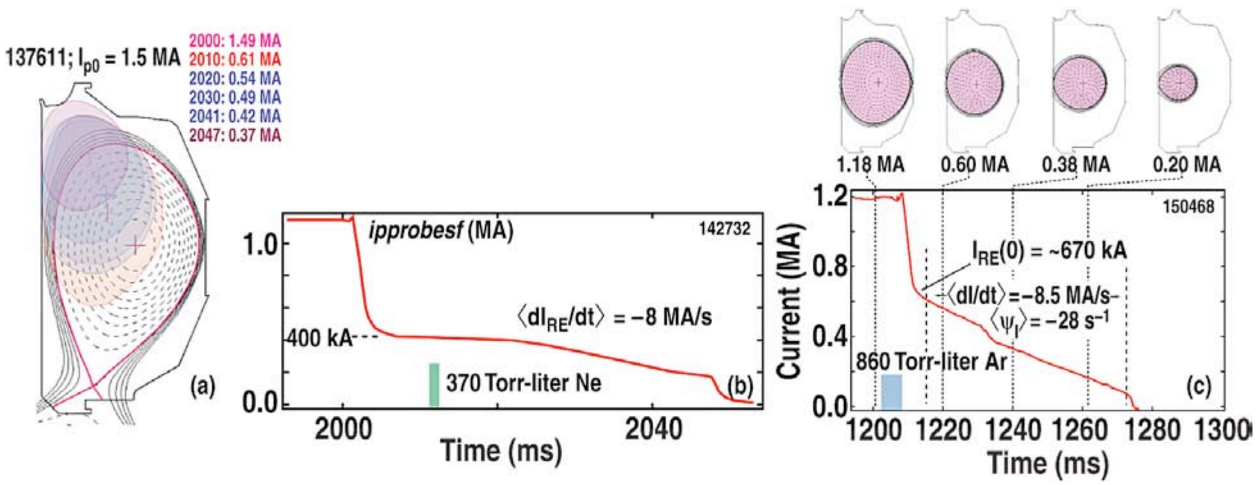

Fig. 2-37. Fast RE shutdowns with (a) LSN and (b), (c) IWL targets.

The second alternate delivery scheme that can be tested during the Five-Year Plan *is* *__rupture disk injection (RDI)__*. Here, opening of a rupture disk-sealed gas cartridge will produce a high-flow, high-pressure gas exit stream that can, if the rupture disk end of the cartridge is located close to the plasma surface, penetrate significantly beyond the plasma scrape-off layer. Expectations are that this may increase gas assimilation efficiency and facilitate the attainment of the super high free-electron densities needed for RE avoidance. For ITER, a rupture disk cartridge concept might provide a close-coupled short-pulse/high-ram pressure alternate to conventional remote valve MGI. For DIII-D, a rupture disk injector would provide a low cost means of assessing the MGI benefits of co-location of the exit stream close to the plasma surface and tests whether increased gas kinetic pressure (ρv^2) improves assimilation and other valve MGI attributes. Penetration and plasma interaction data can be compared with models already developed for ITER. As with SPI and shell pellet injection studies, critical assessment of radiation time scales and peaking factors will comprise a key part of the RDI studies. Discussions have been initiated with Commissariat à l'Énergie Atomique (CEA), Cadarache, France (Tore Supra) on possible RDI experiment and modeling collaboration.

Rupture disk injection of a dust-load gas stream could also provide a test as an alternate (micro) pellet delivery means and could be useful as an exploratory impurity injection diagnostic method.

Various **advanced concepts** — ranging from rail gun pellet launchers to high-mass plasma jets — have been proposed as possible solutions or improvements for ITER and reactor tokamak disruption mitigation. Possibilities for testing such concepts in DIII-D can be assessed during the course of the Five-

Year Research Plan. Other prototypes of candidate ITER injection systems can also be tested — scaled to DIII-D injection requirements.

2.4.2.5. Research Plan Resources and Schedule. New and improved injection systems, new and upgraded diagnostics and an expanded suite of data analysis and modeling codes are required over the course of the Five-Year Research Plan. Key additions and utilizations have already been cited in the three detailed research plans presented above. A program schedule oriented presentation follows here:

1. **Injection hardware developments and improvements.** In 2013, two major new hardware installations are being implemented:

   - An *argon pellet pipe gun injector* with changeable barrel size and variable pellet velocity.
   - A *second 3-valve MGI system* located on the lower R-2 135 deg port.

   These installations will respectively support renewed RE development and plateau study experiments and ITER-like controlled MGI experiments with two poloidally separated injection locations.

   Argon Pellet Injector. A test of the pipe gun prototype in 2012 revealed the need to add a pellet punch to improve launch reliability and the need for additional pellet size, integrity and velocity diagnostics. These will be added and tested in 2013. The upgraded injector will be relocated to avoid having to use a velocity limiting S-bend guide tube to direct the pellet into the torus. Whether the injector can be modified to allow neon as well as argon pellet injection is also being evaluated.

   Second MGI System. The 3-valve CERBERUS system at 135 R-2 will use the same solenoid-actuated fast valves as the existing 6-valve MEDUSA system at 15 R+1. The two systems will provide a wide range of capabilities to assess MGI efficacy and radiation symmetry with well-controlled short-pulse injection of D_2, mixed and high-Z noble gases. The feasibility of gas injection system gas supply and control upgrades is being examined, with a goal of allowing parallel or sequential injection of 1, 2 or possibly 3 different gas species and/or combination pellet and MGI experiments. Ways to improve injected-quantity diagnostic accuracy and/or valve drive pulse repeatability for injection of small (ITER-like) gas quantities are also being explored. These upgrades are being developed and installed beginning in 2013 and continuing into 2014.

   The deuterium shattered pellet injector will be upgraded with an alternate “bent-nozzle” breaker assembly intended to provide a higher solid-to-gas shatter ratio and collimated exit stream. Laboratory assessments of the performance are in progress. An examination of whether a pellet-ejection punch can be added to the shattered pellet injector to improve before-shatter pellet integrity and reliability is also being conducted. Finally, the need to develop and install a “mini-SPI” is being assessed. The reduced-size SPI system, optimized to produce low-quantity neon and argon pellets, is intended to provide the MPI ITER-like equivalent of the present low-quantity MGI capabilities.

   A prototype large shell pellet injection system was tested in 2012 and will be improved and relocated to an mid-plane or R±1 port to provide better straight-in entry into the plasma and better diagnostic views of pellet entry and ablation. The possible need for a mid-sized pellet design and launcher is being evaluated. This will allow for assessing shell pellet injection with ITER-like injected payloads.

Possibilities for adding a rupture disk injection system will continue to be examined. Requirements for the system are still in study, but tentatively include multi-cartridge (six minimum) with electrical triggering, no vacuum break cartridge reload, a port with midplane access plus close to plasma surface capability and coordination with fast camera and other diagnostic view(s). Using a rupture disk injector with dust entrainment is also under consideration. Timing of any rupture disk addition will likely be in or after 2016. Possibilities for collaboration with CEA Cadarache for such additions are being explored.

Table 2-15 summarizes the injection and control additions. Organization is by category of application and does not indicate program priority.

Table 2-15
Disruption Characterization and Mitigation – Injection and Control

System	Application	Results + Comments
1. 135 R-2 fast valves (3)	DM with two MGI locations	Plume physics, radiation duration and symmetry, CQ control, test alternate (poloidal) position for ITER, ….
2. 3rd MGI location at 255 R+1	DM with three equally spaced MGI locations.	Emulation of ITER concept (with second MGI moved to 135 R+1)
3. Mini-SPI (high-Z) or midi cryo-solid pellet(s)	DM with ITER-like neon quantity	Penetration and transport physics, radiation duration and symmetry, CQ control, comparison to MGI
4. Improved D_2 SPI breaker	Super-high n_e,	Penetration and assimilation, radiation duration and symmetry, CQ rates with high-efficiency MPI
6. Large shell pellet	Micro-solid delivery concept, sized to obtain high density	Proof-of-Principle (PoP) demonstration of central delivery of low-Z (e.g., boron) ”dust”; shell ablation and dust ablation/ionization/transport/assimilation, radiation duration and symmetry with central ‘dust’ delivery
7. Midi shell pellet	DM-size delivery of boron dust	Ditto, for DM-equivalent quantity of boron or similar low-Z species
8. Rupture disk array	High ρv^2 gas jet	High-pressure jet penetration and assimilation; alternate means to achieve super-high n_e. Options for DIII-D implementation and utilization under study.
9. Rupture disk + dust	Dust delivery means	Ditto. Demonstration of gas-jet “dust” injection as an alternate micro-solid delivery means

2. **Diagnostic development and improvements.** Five major new diagnostic additions will be implemented to support Five-Year Plan research:

- *Fast total radiated power bolometry,* with four viewing locations uniformly spaced around the torus, will be added to complement the existing fast bolometer/SXR arrays at 90 and 210 deg. Details of how/where this AUVX diode system will be installed are presently being evaluated. The intent is to have the new full-toroidal-coverage system available for FY14 radiation symmetry experiments.

- *Fast infrared and visible camera imaging capabilities* will be added to the already-installed in-vessel periscopic viewing system. These new capabilities will facilitate a wide variety of disruption studies, including better characterization of main-chamber VDE heat loads and wide-view imaging of disruption, MGI/MPI and RE interactions with the main chamber PFC surfaces.
- *Tangential viewing capabilities of the two fast camera systems* will be upgraded with four-way image splitters to allow simultaneous imaging of disruption mitigation and RE experiments in multiple impurity radiation and synchrotron emission passbands. This multi-band fast imaging will also support obtaining pellet injection ablation and impurity plume propagation data to validate predictive models for ITER. An agile fast capture survey spectroscopy system will also be implemented, which is optimized to assess visible bremsstrahlung emission from RE plateau discharges.
- *A main-chamber viewing CdTe array* will be installed in 2013. This will allow imaging of x-ray emission in the 100 keV energy regime to assess runaway electrons losses. A *main chamber EUV (~0.1–1 keV) imaging system* optimized to study runaway electron seed generation and avalanche growth during the initial current decay phase will be installed in 2014.
- *A poloidal viewing visible bremsstrahlung array* optimized to provide fast density measurements during high density D_2 MGI and SPI experiments will be installed in 2014. The improved high density capabilities of the four-channel tri-color interferometer will also be exploited during the SPI RE avoidance experiments planned to begin in 2014.

Upgrades to existing diagnostics will also support enhanced disruption and RE experiments and data acquisition. Pulse height spectroscopy will be added to the existing multi-detector bismuth germanium oxide (BGO) HXR system. This addition will allow assessment of the RE energy distribution function. In the same vein, a broadband visible survey spectrometer will be added to facilitate better dynamic measurements of the visible synchrotron radiation continuum from steady-state and fast shutdown RE plateau discharges. The possible addition of a scintillator tip on the fast insertable midplane probe is being assessed to allow measurements of drift orbit losses of RE electrons at the large major radius side of RE channels.

It is planned to continue to add and expand the poloidal and toroidal coverage of the first-wall tile current array (TCA) monitor system and add Hiro-current monitors to look for the presence of these in-vessel current flows. On-vessel accelerometers will also be installed to assess the vertical and radial symmetry of vacuum vessel response to disruptions and VDEs. These additions will facilitate enhanced ability to characterize halo currents and vessel EM loadings from VDEs, VUDs and pellet and gas injection fast shutdowns. Table 2-16 summarizes the diagnostic plan. Organization is by category of application and does not indicate program priority.

3. **Code development and utilization (analysis)**. The plan is to develop, utilize and upgrade data analysis and modeling capabilities for disruption and runaway electron studies. The use of a fast current quench (FCQ) 1D dynamic model of impurity radiation and RE source + gain/loss will be expanded. This general purpose model has already proved successful in modeling a number of DIII-D results and ITER simulations, including simulated effects of very short-pulse gas injection

(as from a rupture disk). Synthetic diagnostic simulation capabilities will be added to this and the other simulation models described below to facilitate using FCQ to interpret experimental data.

It is proposed to develop a DINA-type 2D dynamic equilibrium code with a self-consistent RE physics model included. This will assist in interpreting the complex 2D evolutions seen during RE current channel formation and control. The plan is to include an explicit runaway equilibrium in the EFIT data analysis model and the real-time RTEFIT equilibrium control model. The reconstructions and pressure and current profile data from these codes will be compared with FCQ and DINA-RE simulations.

Table 2-16
Disruption Characterization and Mitigation – Diagnostic Additions + Upgrades

Diagnostic	Measurement	Application(s) and Schedule
1. Toroidal AXUV bolometry array (~4 azimuths)	Thermal radiation from native + injected impurities	Radiation duration and asymmetries (peaking factors) from D_2 and/or impurity injection; upgrade to 3 or 4 toroidal azimuths in 2014
2. 4-way splitter for fast camera(s)	Multi-band visible emission (toroidal + IWL views)	Impurity ablation plume, RE synchrotron and line emission source identification, first-wall PMI assessments; test in 2013
3. Main-chamber visible and IR camera view (PERISCOPE)	Visible and IR emission	PFC and FW heat loads + PMI from D, VDE, DM, RE; initial wide-view tests in 2013; possible upgrade to faster IR camera in 2014
4. HXR scintillators with pulse-height counting	HXR intensity + energy distribution	HXR and inferred RE energy distribution(s); feasibility test in 2013, expand to full multi-detector coverage in 2014 or 2015
5. Main-chamber CdTe array	~100 keV HXR emission from IWL	RE losses to IWL and RE loss instabilities; prototype test in 2013, additional systems
9. Adjustable view slits on charge exchange recombination (CER) spectrometers	Ion temperature	T_i during disruption and/or MGI/MPI CQs
10. Poloidal visible-bremsstrahlung array	Local electron density	Density transport during super-high-density D_2 SPI or shell pellet injection
11. CO_2 polarimeter	Line-average n_e	n_e from SPI or shell pellets. Test of ITER prototype polarimeter
12. Improve TS for DC+DM	Main plasma T_e *and* n_e	$T_e(r,t)$ and $n_e(r,t)$ during TQ and CQ
13. Expand TCA poloidal coverage	Halo current in VV tiles	Poloidal distribution of halo currents; toroidal symmetry and rotation of halo currents
14. Hiro current monitors	Local currents in VV	Hiro currents during disruption and MGI/MPI
15. Vessel accelerometers	VV motion	Vessel force dynamics and asymmetries

The development of a parallel flow impurity model (PLUME) will continue, with immediate focus on modeling pellet ablation plume expansion and radiation loads associated with localized pellet or gas injection.

For longer-term predictive modeling, NIMROD resistive MHD code modeling of disruptions and disruption mitigation and runaway generation and loss experiments will continue to be applied and enhanced to allow self-consistent disruption mitigation modeling from onset of gas/pellet injection to end of thermal and RE current decay. With regard to modeling of MGI, recent NIMROD results (Fig. 2-32) are already beginning to provide insight as to how impurity source location(s) and toroidal and poloidal distributions (e.g., MGI valve locations) affect gas assimilation and symmetry of the resulting radiation source. NIMROD simulations have also provided insight about how MHD activity arising from pellet and gas injection may affect RE seed losses and subsequent avalanche development. The long-term goal for NIMROD application will be to provide a validated 3D MHD basis for predicting disruption and RE electron mitigation attributes for ITER.

Finally, CQL3D Fokker-Planck modeling of runaway electron energy distribution and avalanche dynamics during both the highly dynamic conditions encountered during RE generation and loss/shutdown and also in quasi-stationary plateaus will be resumed. Coupling the NIMROD and CQL3D models for data interpretation and ITER prediction will be explored.

Table 2-17 summarizes the code and modeling plan.

Table 2-17
Disruption Characterization and Mitigation – Codes and Modeling

Code or Model	Key Features or Physics	Application(s)
1. FCQ 1D	General-purpose scoping model for pellet, MGI and SPI/shell deposition, radiation effect, RE generation and loss, with self-consistent current profile dynamics	Dynamic modeling of pellet, MGI and MPI scenarios. Design and optimization for DIII-D and ITER implementation. Model upgrades to reflect emerging DIII-D and ITER concepts and test articles can be incorporated as required
2. 2D dynamic equilibrium with halo currents and REs	DINA or equivalent, with self-consistent halo current and RE avalanche and loss models	VDE, VUD and RE data analysis and projection to ITER
3. RE-EFIT	EFIT with explicit RE equilibrium	RE equilibrium data analysis and real-time RE equilibrium control
4. Parallel flow/impurity plume model	Local 3D + *t* pellet or MGI/SPI impurity dynamics	Initial impurity delivery and propagation, radiation source and FW effect
5. NIMROD 3D MHD	Resistive MHD with pellet/MGI/SPI delivery models + self-consistent RE gain/loss included as required	First-principles modeling of onset and effect of ”MHD mixing”+ resulting radiation dynamics + asymmetries and ensuing RE growth/loss.
6. CQL3D	Fokker-Planck electron distribution function	RE distribution function dynamics, interpretation of HXR spectrum data, prediction of avalanche gain/loss in plateau and rapid-dissipation regimes

2.4.3. Impact

The Five-Year Research Plan for Disruption Characterization and Mitigation will provide timely R&D support, initially by the middle of 2016, for finalization of the design of the ITER DMS. Plan activities following the DMS Final Design Review (FDR) and the DIII-D Long Torus Opening (LTO) will allow for further studies and optimization of ITER disruption and runaway electron mitigation strategies and for possible tests of ITER prototype hardware and control methods. Opportunities to assess alternate/innovative injection methods for ITER will be available. The Research Plan will also provide selected ITER-specific and generic disruption characterization data to support development of a disruption-aware approach to initial ITER plasma operation and DMS deployment. Finally, the experimental data, science understandings and improvements in predictive modeling obtained during the Plan will provide a sound basis for assessing disruption characteristics and mitigation strategies and future R&D for more ambitious fusion power development experiments such as FNSF and a tokamak-based DEMO.

2.5. PLASMA CONTROL

2.5.1. Challenges

Plasma control research is the field through which physics understanding is transformed into effective solutions for robust operation of ITER, FNSF, and DEMO reactors. Advanced control will ensure that disruptions do not occur in a power reactor. Control solutions serve to integrate the requirements for high performance scenarios, core-edge compatibility, plasma stability, and disruption avoidance and mitigation [Humphreys 2007]. ITER will demand control performance and reliability far beyond that required by presently operating devices, yet with significantly more constraints on control actuators and diagnostics [Gribov 2007, Hawryluk 2009]. Advanced tokamak regimes, characterized by operation beyond various open loop stability limits, are particularly demanding of control advancements, and continue to drive DIII-D to maintain its leadership role in plasma control [Ferron 2002, Humphreys 2003]. Future FNSF and DEMO reactors will require still more reliability than ITER, likely operating in AT regimes with even stronger cost constraints and higher reliability requirements [Jardin 2006, Chan 2010]. The DIII-D control research program will advance the critical control science needed, both driving and applying the physics understanding from other research areas to develop and demonstrate viable operational solutions for the DIII-D experimental program itself, for ITER, and for a robust and reliable disruption-free advanced tokamak reactor. In order to fulfill these missions, control research will require more than basic physics understanding from other areas of study. Realization of a robustly sustained burning plasma requires *specific* physics knowledge driven by this practical mission, and also requires the advancement of control science in areas which extend significantly beyond the scope of plasma physics alone. The key scientific questions to be addressed by the DIII-D control research program are summarized in Table 2-18, along with the research approach and key resources required.

Table 2-18
Key High-Level Control Research Questions and Approaches 2014–2018

Key Scientific Questions	Approach	Hardware/Software Upgrades
Can high fidelity model-based control algorithms be deployed in ITER without significant empirical tuning?	Develop and validate control-level models, design/apply model-based algorithms, quantify performance without tuning	Dedicated PCS hardware and software implementing ITER PCS architecture
What control elements and interconnections are essential for integrated control in ITER?	Demonstrate individual ITER control algorithms and integrated solutions with ITER emulation in DIII-D	New power supplies to enable emulation of ITER PF coil operation
What control methods are essential for advanced tokamaks to operate robustly disruption-free?	Develop and quantify high robustness control with low disruptivity, including off-normal response algorithms that prevent disruption	Finite state machine software and PCS infrastructure; new PCS computers for real-time execution of predictive codes
What advanced control solutions will best enable and accelerate the DIII-D physics program?	Apply cutting edge control research to achieve and sustain plasma regimes, elucidate physics	Continual upgrade of the TokSys control analysis and design environment

2.5.2. Research Plan

2.5.2.1. Overview. The DIII-D control research program in 2014–2018 is organized around four high-level goals:

- Develop and demonstrate effective model-based control with minimal tuning for ITER.
- Develop and demonstrate integrated ITER control solutions.
- Develop and demonstrate methods for robust disruption-free advanced tokamak control.
- Develop control solutions to support DIII-D experimental physics goals.

The first program goal is to develop the model-based approach to control design to establish the capability of this approach to provide control algorithms that perform with high reliability without the need for tuning. This effort is principally driven by the need to establish sufficiently high performance control in ITER without using machine time to develop control algorithms. ITER will have limited operational time available for control development, and will not be tolerant to large numbers of control failures that would be produced during such an empirical tuning process [Gribov 2007]. This research area will include developing and advancing control-level models for many control processes, including MHD instabilities, divertor operation, and plasma current profile response. Once validated, models such as these will be used to design appropriate control algorithms, and the pre-tuning performance will be evaluated to quantify the applicability of the approach.

The second program goal is to demonstrate a substantial fraction of the integrated ITER control solution [Humphreys 2007]. This entails development and study of ITER-specific control algorithms for individual control goals, implementing and studying key aspects of ITER PCS architecture, and producing integrated algorithms that address ITER control requirements.

The third program goal will focus on key research elements to enable robust control capable of sustained disruption-free operation of advanced tokamaks. This research area will focus on developing methods for quantifying and guaranteeing high performance control to a specified level of reliability (ultimately that required by power plants) [Humphreys 2009]. In addition to developing quantified high reliability control under nominal plasma scenario operating conditions, this research area will include development of control responses that will prevent disruption even under off-normal and fault conditions.

The fourth program goal involves control research to support the general DIII-D experimental physics program. This research area will include model-based profile control to enable precise execution and sustainment of desired plasma regimes, and deployment of tearing mode stabilization algorithms as a general tool for experiments in which growth of such modes is undesirable [Walker 2008, Ou 2007, La Haye 2006a].

Figure 2-38 illustrates the broad control research program schedule, including key program elements and upgrades. Blue milestone markers represent DIII-D experimental routine use, red markers represent key ITER results, and green markers represent key disruption free steady-state results.

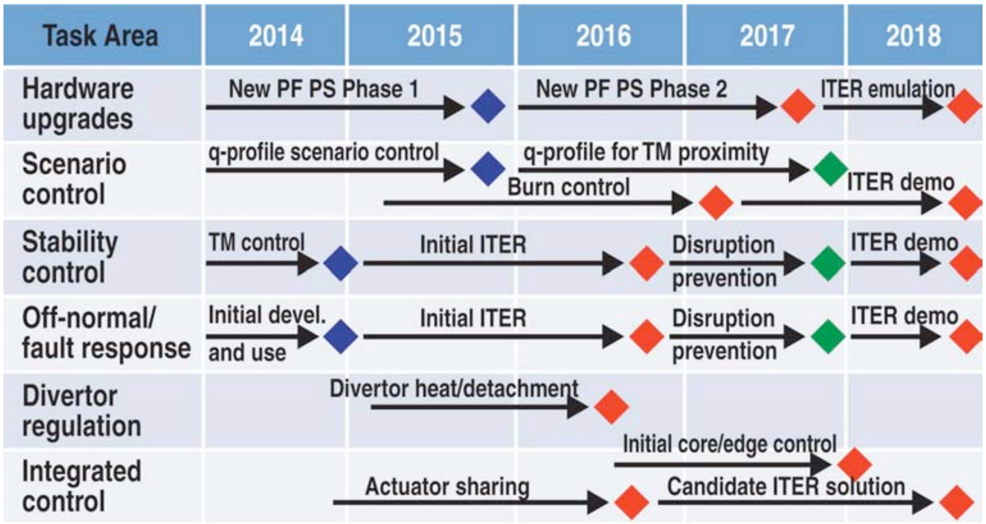

Fig. 2-38. Schedule for execution of key control research task areas 2014–2018.

2.5.2.2. Detailed Research Plan

Model-Based control design for minimal tuning in ITER. This program goal focuses primarily on development of the ITER reference *model-based* approach to control design. This control design process, illustrated in Fig. 2-39, includes control-level model derivation based on physics understanding, design of control algorithms based on mathematical techniques with quantifiable robustness, verification of performance in simulation, experimental study of control performance, and validation or revision of the relevant control physics elements. Control physics here includes plasma and system dynamic behavior models, models of plasma response to actuators and actuators to commands, response and use of diagnostics for relevant plasma conditions, and emergent dynamics for closed loop systems. Typically the models required for effective algorithm design and deployment with minimal need for tuning are quite different from the basic physics understanding that results from exploratory experimental and theoretical efforts. Models for control design often require a description of dynamic plasma responses that are not recognized in the absence of control considerations. However, although higher fidelity of physical representation leads to better control performance, the use of sophisticated control mathematics can often compensate for limited accuracy in control-level models and produce excellent performance. ITER will require (and has specified) use of the model-based plasma control process to design, verify, and validate all aspects of control prior to execution to maximize confidence in control and physics performance and extract maximum value from discharges. The DIII-D research program has long pioneered this approach, and will apply it to ITER scenarios in this period, as well as to many other areas of control. Model-based control is also integral to the other control research areas. The principal activities in this research program will include derivation or construction of control-level models for design of algorithms for operating point and stability control. The principal outcome of the research will be evaluations of achievable control performance in key areas without the use of empirical tuning. Key milestones of this research activity will include construction of control-level models, and design and evaluation of performance for resulting model-based control algorithms to achieve:

- Shape control for ITER targets using the fiducial ITER gap parameters and the DIII-D isoflux boundary control scheme.

- Plasma current profile control in ITER and steady-state targets.
- Divertor regulation in ITER targets.

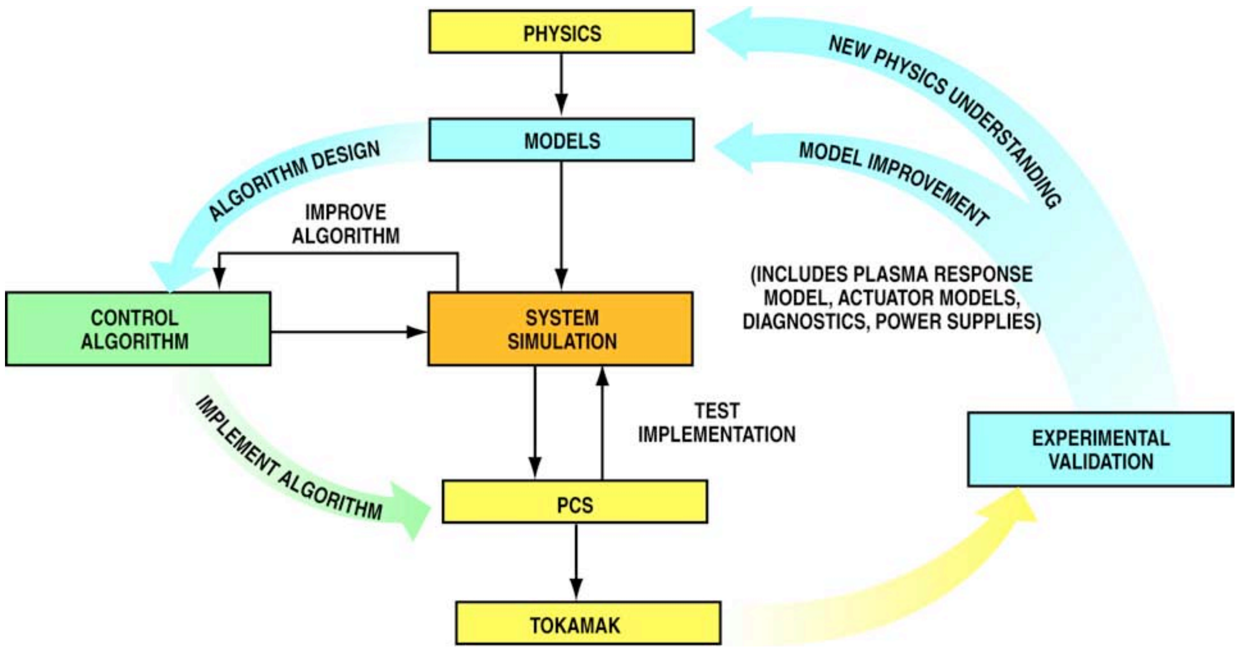

Fig. 2-39. Model-based control design process uses validated physics-based models to construct control algorithms, and verifies control system performance against detailed simulations prior to operational use.

Integrated ITER control solutions. The integrated ITER control program goal focuses primarily on the development and study of ITER-specific control algorithms to determine which approaches will best control ITER discharges, and to determine the degree of integration needed among individual algorithms to achieve ITER performance goals. This program will apply model-based design to integrated ITER control scenarios in this period, including progressively integrated emulation of the ITER coil configuration, tearing mode control, RMP/ELM suppression, demonstration of ITER-required levels of controllability without tuning, relevant off-normal responses, and relevant stability, profile, divertor, and burn control algorithms. All of these algorithms will therefore entail model-based design to a substantial degree, so that the program effort will include research to develop and quantify sufficiently accurate *integrated* models for ITER control design, as well as evaluation of algorithm approaches themselves, and evaluation of multi-algorithm or multiple control goal integration approaches. Many of the integrated plasma control solutions specific to ITER will be combined in the second half of the proposed research plan in order to demonstrate key aspects of the ITER PCS and operational control approach functioning together. ITER scenario discharges will be produced in DIII-D with the PCS and coil configuration operated in ITER emulation mode, while employing ITER reference control schemes and selected aspects of ITER PCS architecture. These experiments will make use of new power supplies (see upgrades below) in order to enable nearly or completely independent operation of the shaping coils.

This research effort will include:

- Study of ITER shape control using emulation of the ITER coil configuration.
- Development of ITER-relevant integrated current profile operating point regulation and active tearing mode control.
- Radiative divertor control integrated with core confinement and RMP/ELM control.
- Initial demonstration of ITER-required levels of controllability without tuning, relevant off-normal responses, and relevant shape, stability, profile, divertor, and burn control algorithms.
- Experimental validation of ITER approaches for actuator sharing (e.g. dynamic gyrotron allocation for profile control and tearing mode suppression).
- Experimental validation of ITER off-normal response architecture and algorithms (e.g. responses to loss of key heating systems, imminent onset of tearing instability, or actual growth of a tearing island with onset of locking).

Robust disruption-free control. The robust disruption-free control program goal will focus particularly on developing control solutions with quantifiable performance to ensure robust operating scenarios, even in the rare event of system and plasma faults. As in the case of the integrated ITER control program goal, this program goal relies heavily on model-based control, with a similar need for control-oriented physics research. This research program will depend critically on research to determine general controllability boundaries and regulate proximity of the operating point to these boundaries in real-time, fundamental methods for quantifying controllability, and actuator sharing solutions. Several of these areas are synergistic with and overlap the ITER control program (e.g. ITER-relevant off-normal event response algorithms and tearing mode solutions).

Because a key goal of this program is establishing the achievability of disruption-free operation in advanced tokamak regimes, robust control for operation near or beyond various stability limits must be a significant focus of the effort. Thus, this element of the control research program will continue to focus on developing and demonstrating methods for robust stabilization of nonideal MHD instabilities such as tearing modes (via locally applied and dynamically regulated electron cyclotron current drive) and resistive wall modes. The 2014–2018 period will feature emphasis on tearing mode stability control integrated with regulation of degree of instability, quantifying robustness of mode suppression, commissioning of a reliable PCS tearing mode control tool for DIII-D experiments, and demonstration of elements of an integrated ITER solution. This will include continuation of the successful active tearing mode suppression control research path, as well as a new focus on regulating proximity to the controllability boundary for tearing modes. Controllability boundary proximity regulation will likely require substantial increase in understanding of tearing mode stability (research expected to be done primarily in the stability physics topical area), as well as advances in diagnostics for real time determination of the relative stability. Specific control research will be required to transform the detailed physics understanding into control-level models amenable to both design and real-time algorithm execution. Validation of such models will enable high confidence extrapolation to FNSF and DEMO.

All practical engineered systems, including both ITER and future reactors, have a finite probability of fault occurrence. Achievement of sustained, sufficiently disruption-free operation of a tokamak reactor will require off-normal event and fault response (ONFR) solutions that enable both performance recovery (where possible) and effective action for disruption prevention (where recovery is not possible). Research required to develop effective ONFR solutions includes predictors and detectors for the relevant off-normal/fault conditions, scenarios for recovery or safe rapid shutdown, and robust algorithms to execute these scenarios. A key research goal is to achieve minimal complexity for maximal effectiveness in such algorithms. As in the case of stability control systems, quantifying the performance of ONFR solutions is important for establishing the viability of such approaches extrapolated to long pulse and reactor operation.

Achieving the ultimate goal of true disruption-free operation will require a strong focus on quantifiable, high confidence control performance. This in turn requires a continuing research program in robust control algorithm design. Robust controller designs must be found for both passively stable dynamic aspects of plasma scenario operating points (e.g. global characteristics such as plasma beta, as well as local or profile characteristics such as current density or rotation profiles) and potentially unstable plasma dynamics (e.g. burn state and MHD instabilities). In addition, methods must be determined for quantifying the probability of loss of control for all relevant instabilities, particularly those with high disruption potential (e.g. axisymmetric stability, tearing modes, and resistive wall modes). This entails a large and specific control mathematics research effort, which is closely coupled with physics-based modeling and experimental assessment of relevant controllability probability distribution functions.

Specific research efforts under the robust disruption-free control program goal will therefore include:

- Development of control-level models for tearing mode onset as a function of current and pressure profile characteristics combined with seeding phenomena.
- Advancement of control-level models for current profile control, tracking the progressive expansion of DIII-D heating and current drive systems, and incorporating coupled effects such as radiative divertor regulation.
- Study and identification of control mathematics algorithm design methods for quantifiable reliability in control of profiles, plasma instabilities, and off-normal responses.
- Design and experimental validation of profile control (or related plasma state control) algorithms for tearing mode stability and regulation of the proximity to the tearing mode controllability boundary.
- Development of a general theory for quantifying controllability and performance reliability for plasma instability control, and application to tearing and resistive wall modes.
- Design and experimental validation of quantifiably robust active tearing mode suppression algorithms using ECH/ECCD.
- Design of specific off-normal event response scenarios and algorithms, including tearing mode rotation and phase control ("locked mode avoidance").
- Application of controllability theory to general ONFR algorithms to quantify reliability, with experimental validation of performance and robustness.

Control research for DIII-D experimental physics. In order to support its aggressive advanced tokamak mission and exploit its wide range of flexibility in plasma targets, the DIII-D experimental physics program demands the highest performance advanced control among all operating devices. Much of the control research performed on DIII-D directly supports these physics needs, while synergistically providing solutions to present and next generation long pulse devices including ITER, EAST, and KSTAR. Control research resulting in supporting and routine experimental use in DIII-D experiments high reliability TM suppression, flexible model-based current profile control, powerful new ONFR architecture for flexible scenario/algorithm development and implementation, and model-based design of control algorithms for novel configurations and regimes such as Snowflake and Super-X divertors.

It should be noted that the DIII-D control research program is strongly dependent on and tightly coupled with the scenarios, stability, and other physics research programs. For example, new physics understanding to enable much of the model generation needed to execute the control research will originate in these other areas. Conversely, the control research program can serve as a powerful guide to establish priorities and quantified requirements on the output of these other physics areas. For example, while particular actuator schemes and some constraints on their use will be determined under the disruption physics research area, disruption mitigation scenarios and relevant control algorithms for their execution falls within the off-normal control research area.

2.5.2.3. Capability Improvements. To accomplish the goals described above, several hardware improvements are required. These are summarized in Table 2-19.

Table 2-19
Hardware Improvements

Hardware Capability	New Control Research Enabled
Phase 1 (2014–2015): Two 6 kA insulated gate bipolar transistor (IGBT) based DC/chopper integrated supplies	Increasing robust operating space for DIII-D equilibria; improved emulation of ITER (and other SC device) PF coil configurations
Phase 2 (2016–2017): 6x600 V/6 kA IGBT-based supplies, 4x1200 V/12 kA IGBT-based supplies	Full emulation of ITER (and other SC tokamak) PF coil configurations
Additional DIII-D PCS computers	Research on and demonstration of ITER PCS architectural and algorithmic design choices
Specialized computer hardware, software, and infrastructure for real-time parallel processing capability	Development and demonstration of ITER-essential Faster Than Real-Time Simulation

2.5.3. Impact

The DIII-D control research program will prepare solutions for many aspects of ITER operation, including high robustness to achieve the specified scenarios with minimal disruptivity, while maximizing the physics output of experiments. Many of the control science results and direct solutions expected will be essential to the success of the ITER mission. As the leading tokamak in the world in the areas of both advanced tokamak scenarios and control, DIII-D will play a leading role in establishing the robust disruption-free control basis for FNSF and DEMO, and will thereby establish many of the realistic requirements for designs of these devices. These results will contribute significantly to demonstrating the viability of the tokamak for energy production.

This research program will have significant impacts on ITER, including development and validation of model-based control algorithms applicable to ITER and demonstrated in high-fidelity ITER scenarios on DIII-D. These will provide a basis for the actual algorithms to be deployed in the ITER PCS. Similarly, effective off-normal event handling algorithms and scenarios based on validated physics models will form a basis for many parts of the ITER PCS Exception Handling system. Demonstration of an initial cut at the integrated ITER PCS solution will provide a crucial benchmark for readiness of these ITER PCS algorithms, and help identify gaps that will need further research before operation of various stages of the ITER Research Plan. Data and quantifiable reliability of these solutions will establish the level of disruptivity to be realistically expected in ITER, and will quantify the ability of control solutions to accomplish rapid hard shutdown scenarios while mitigating damage.

2.6 REFERENCES FOR SECTION 2

[Berkery 2010] J.W. Berkery et al., Phys. Plasmas 17, 082504 (2010).

[Berkery 2010a] J.W. Berkery et al., Phys. Rev. Lett. **104**, 035003 (2010).

[Bondeson 1994] A. Bondeson and D.J. Ward, Phys. Rev. Lett. **72**, 2709 (1994).

[Burrell 2005] K.H. Burrell et al., Phys. Plasmas **12**, 056121 (2005).

[Buttery 2008] R.J. Buttery et al., Phys. Plasmas **15**, 056115 (2008).

[Buttery 2011] R.J. Buttery et al., Phys. Plasmas **19**, 056111 (2012).

[Chan 2010] V.S. Chan et al., Fusion Sci. Technol. **57**, 66 (2010).

[Chapman 2011] I.T. Chapman et al., Plasma Phys. Control. Fusion **53**, 065022 (2011).

[Chapman 2012a] I.T. Chapman et al., Phys. Plasmas **19**, 052502 (2012).

[Chapman 2012b] I.T. Chapman et al., Nucl. Fusion **52**, 063006 (2012).

[Ferron 2002] J.R. Ferron et al., "Progress Toward Sustained High-Performance Advanced Tokamak Discharges in DIII-D," Proc. 29th Plasma Physics and Controlled Fusion Conf., Montreux, Switzerland, 2002, Vol. 26B (European Physical Society, Paris, France) paper P1.060.

[Ferron2005] J.R. Ferron, Phys. Plasmas **12**, 056126 (2005).

[Ferron 2011a] J.R. Ferron et al., Nucl. Fusion **51**, 063026 (2011).

[Ferron 2011b] J.R. Ferron et al., Nucl. Fusion **51**, 113007 (2011).

[Garofalo 2006] A.M. Garofalo, Phys. Plasmas **13**, 056110 (2006).

[Garofalo 2007] A.M. Garofalo, Nucl. Fusion **47**, 1121 (2007).

[Garofalo 2011] A.M. Garofalo et al., Nucl. Fusion **51**, 083018 (2011).

[Gerhardt 2009] S.P. Gerhardt et al., Nucl. Fusion **49**, 032003 (2009).

[Gribov 2007] Yu. Gribov et al., Nucl. Fusion **47**, S385 (2007).

[Hanson 2009] J.M. Hanson et al., Phys. Plasmas **16**, 056112 (2009).

[Hanson 2012a] J.M. Hanson et al., "Probing Resistive Wall Mode Stability Using Off-axis NBI," Proc. 24th IAEA Fusion Energy Conf., San Diego, California, October 8–13, 2012, Paper EX/P4-27

[Hanson 2012b] J.M. Hanson et al., Nucl. Fusion **52**, 013003 (2012).

[Hawryluk 2009] R.J. Hawryluk et al., Nucl. Fusion **49**, 065012 (2009).

[Hender 2007] T.C. Hender et al., Nucl. Fusion **47**, S128 (2007).

[Holcomb 2009] C.T. Holcomb et al., Phys. Plasmas **16**, 056166 (2009).

[Holcomb 2012a] C.T. Holcomb et al., Phys. Plasmas **19**, 032501 (2012).

[Holcomb 2012b] C.T. Holcomb et al., "Fully Noninductive Scenario Development in DIII-D Using New Off-Axis Neutral Beam Injection Capability," Proc. 24th IAEA Fusion Energy Conf., San Diego, California, October 8–13, 2012, Paper EX/1-05.

[Humphreys 2003] D.A. Humphreys et al., "Integrated Plasma Control for Advanced Tokamaks," Proc. 20th IEEE Symp. on Fusion Engineering, San Diego, CA, 2003, (Institute of Electrical and Electronics Engineers, Inc., Piscataway, NJ) page 20.

[Humphreys 2006] D.A. Humphreys et al., Phys. Plasmas **13**, 056113 (2006).

[Humphreys 2007] D.A. Humphreys et al., Fusion Engin. Design **83**, 193 (2008).

[Humphreys 2009] D.A. Humphreys et al., Nucl. Fusion **49**, 115003 (2009).

[In 2006] Y. In et al., Phys. Plasmas **13**, 062512 (2006).

[In 2010] Y. In et al., Nucl. Fusion **50**, 042001 (2010).

[Jackson 2013] G.L. Jackson et al., "Long-Pulse Stability Limits of ITER Baseline Scenario" Proc. 24th IAEA Fusion Energy Conf., San Diego, California, October 8–13, 2012, Paper EX/P2-08.

[Jardin 2006] S.C. Jardin et al., Fusion Engin. Design **80**, 25 (2006)

[Kolemen 2012] E. Kolemen et al., Bull. Am. Phys. Soc. **57**, 350 (2012).

[La Haye 2006a] R.J. La Haye, Phys. Plasmas **13**, 055501 (2006).

[La Haye 2006b] R.J. La Haye et al., Phys. Plasmas **13**, 056113 (2006).

[Lanctot 2011] M.J. Lanctot et al., Phys. Plasmas **18**, 056121 (2011).

[Liu 2008] Y. Liu et al., Phys Plasmas **15**, 112503 (2008).

[Liu 2009] Y. Liu et al., Nucl. Fusion **49**, 035004 (2009).

[Luce 2011] T.C. Luce et al., Phys. Plasmas **18**, 030501 (2011).

[Luxon 2003] J.L. Luxon et al., Nucl. Fusion **43**, 1813 (2003).

[Murakami2006] M. Murakami et al., Phys. Plasmas **13**, 056106 (2006).

[Okabayashi 2009] M. Okabayashi et al., Nucl. Fusion **49**, 125003 (2009).

[Okabayashi 2011] M. Okabayashi et al., Phys. Plasmas **18**, 056112 (2011).

[Ou 2007] Y. Ou et al., Fusion Engin. Design **82**, 1153 (2007).

[Park 2007] J.K. Park et al., Phys. Rev. Lett. **99**, 195003 (2007).

[Petty 2012] C.C. Petty et al., Nucl. Fusion **52**, 013011 (2012).

[Prater 2007] R. Prater et al., Nucl. Fusion **47**, 371 (2007).

[Reimerdes 2004] H. Reimerdes et al., Phys. Rev. Lett. **93**, 135002 (2004).

[Reimerdes 2007] H. Reimerdes et al., Phys. Rev. Lett. **98**, 055001 (2007).

[Reimerdes 2011a] H. Reimerdes et al., Fusion Sci. Technol. **59**, 572 (2011).

[Reimerdes 2011b] H. Reimerdes et al., Phys. Rev. Lett. **106**, 215002 (2011).

[Reimerdes 2012] H. Reimerdes et al., "Rotation Braking and Error Field Correction of the Test Blanket Module Induced Magnetic Field Error in ITER," Proc. 24th IAEA Fusion Energy Conf., San Diego, California, October 8–13, 2012, Paper EX/P4-09.

[Schaffer 2011] M.J. Schaffer et al., Nucl. Fusion **51**, 103028 (2011).

[Scoville 2004] J.T. Scoville and R.J. La Haye, Bull. Am. Phys. Soc. **49**, 263 (2004).

[Solomon 2013] W.M. Solomon et al., "Access and Sustained High Performance in Advanced Inductive Discharges With ITER-Relevant Low Torque," Proc. 24th IAEA Fusion Energy Conf., San Diego, California, October 8–13, 2012, Paper EX/P2-01.

[Staebler 2005] G.M. Staebler et al., Phys. Plasmas **12**, 102508 (2005)

[Strait 2004] E. J. Strait et al., Phys. Plasmas **11**, 2505 (2004).

[Strait2009] E.J. Strait, Nucl. Fusion **49**, 104008 (2009).

[Tobias 2011] B.J. Tobias et al., Phys. Plasmas **18**, 056107 (2011).

[Turco 2010] F. Turco and T.C. Luce, Nucl. Fusion **50**, 095010 (2010).

[Turco2012] F. Turco et al., Phys. Plasmas **19**, 122506 (2012).

[Wade 2005] M.R. Wade et al., Nucl. Fusion **45**, 407 (2005).

[Walker 2008] M.L. Walker et al, "Open and Emerging Control Problems in Tokamak Plasma Control," Proc. 47th IEEE Conf. on Decision and Control, Cancun, Mexico, 2008, p. 3125.

[Yu 2009] J.H. Yu et al., Phys. Plasmas **16**, 056114 (2009).

3. BURNING PLASMA PHYSICS IN DIII-D

The promise of fusion is predicated on generating sufficient alpha particle heating to sustain the fusion process with minimal external heating. The resulting ‘burning plasma’ will involve highly non-linear processes that must be understood to optimize performance in such devices. The primary goals of Burning Plasma Physics research in DIII-D are to advance the predictive capability for critical physics phenomena, and to explore complex behavior in the highly nonlinear burning plasma environment. Particular emphasis will be placed on the validation of comprehensive physics models in the areas of transport and energetic particles (EPs). High priority is given to understanding the underlying physical mechanisms that produce the observed phenomena. This knowledge will provide new insights into complicated processes of matter in the high temperature state, and contribute to the design and successful operation of future fusion devices. DIII-D is well positioned to contribute to this physics knowledge with a flexible set of control tools, an extensive operating space, and a comprehensive diagnostic set capable of providing both spatial and temporal information during plasma experiments. DIII-D’s strong connections to the theoretical and experimental communities both in the U.S. and internationally will enable the program to adapt quickly to the latest developments in fusion research worldwide and investigate pertinent issues for ITER.

The research planned for 2014–2018 covers issues that have critical impact on the prospects of fusion energy in the following areas:

- Energetic particles
- Core transport and turbulence
- Low-to-high (L-H) transition
- Rotation Physics

The above topics are closely connected, and this is taken into account in this research plan. Turbulent transport studies include not only the anomalous cross-field diffusion of particles, energy and momentum, but also the effects of turbulence on intrinsic rotation, and possibly poloidal rotation and energetic particles. Zonal flows driven by plasma turbulence are believed to play an important role in the L-H transition, and L-mode transport establishes the edge conditions immediately prior to the L-H transition. Additionally, edge transport may contribute to the physics of edge localized mode (ELM)-suppressed regimes.

Burning plasma physics research will make important contributions to the main DIII-D research thrusts over the next five years. The thrust to “improve confidence in transport predictions in the burning plasma regime” is well supported by the research described in Sections 3.2.2.1 through 3.2.2.3. In addition, transport issues are important to the thrust to “demonstrate the potential of high β, steady-state tokamak operation” as discussed in Section 3.2.2.4, as well as to the thrust to “develop advanced heat dispersal concepts for next-step devices” as discussed in Section 3.2.2.5. Finally, research on three dimensional (3D) fields in the energetic particles (Section 3.1.2.2) and transport (Sections 3.2.2.4, 3.2.2.5 and 3.4.2.2) will support the goals of the thrust to “develop and qualify ELM control solutions for ITER”.

A new frontier in fusion science is emerging that is exemplified by the use of detailed experimental measurements in the validation of predictions from simulation codes. These codes employ state-of-the-art theoretical descriptions of fundamental plasma behavior. Key research themes in the Burning Plasma

Physics areas, as shown in Table 3-1, are defined according to this exciting and relevant frontier. Particular emphasis will be placed on important research topics for which DIII-D has unique capabilities. Once validated, these simulation codes will serve as a key resource in utilizing the knowledge gained from the physics research program to design future burning plasma experiments and operational scenarios. The research themes in Table 3-1 will adapt to the new experimental discoveries and theoretical developments that are advanced as the full research program unfolds.

Table 3-1
Burning Plasma Physics Research Objectives for 2014–2018

Topical Science Area	Research Theme	Research Objectives
Energetic Particles	Model Validation	• Validate integrated suite of nonlinear models, especially in regards to instability-driven fast ion transport
	3D Field Effects	• Assess impact of 3D magnetic fields on fast ion confinement in ITER and future devices
	Control	• Reduce or exploit fast ion instabilities to improve burning plasma performance
Turbulence and Transport	Transport in burning plasma regimes	• Investigate and understand transport mechanisms and turbulence behavior in "reactor-relevant" conditions • Study coupling between various transport channels • Validate transport simulations from core to edge
	Transport during current ramp-up and ramp-down	• Resolve L-mode 'turbulence and transport' shortfall • Validate models of T_e and q profile evolution in ITER-like conditions • Connect L-H transition models with L-mode transport models of edge turbulence and transport
	3D Field Effects	• Characterize 3D-field driven turbulence and transport • Determine its role in RMP ELM-suppression and density pump-out • Determine influence of q_{95} on 3D-driven turbulence
	Advanced and improved-confinement regimes	• Transport predictions for high-β, steady-state scenarios • Validate transport physics in ELM-suppressed regimes • Develop improved-confinement regimes with low torque injection
	Turbulence Characterization	• Understand physics of driving instability modes, nonlinear dynamics and internal energy transfer • Test theory-based models by measuring all relevant fluctuating fields
Plasma Rotation	Intrinsic Rotation	• Understand scaling with plasma size • Clarify role of edge intrinsic rotation layer
	NTV and Magnetic Torques	• Investigate means to manipulate and control rotation profile in future burning plasmas • Obtain quantitative understanding of NTV torque
	Poloidal Rotation	• Improve quantitative understanding of poloidal rotation
	Momentum Transport	• Continue to develop predictive model of momentum transport
L-H Transition	Identify Trigger for L-H Transition	• Non-linear energy transfer from turbulence to sheared flows in edge • Identify characteristic changes in edge turbulence and flows across transition
	Physics-Based Model of L-H Power Threshold	• Connect to L-mode turbulence and transport • Understand scaling with n, B, m_i, V_ϕ, q, 3D fields
	Techniques to Lower Power Threshold	• Pellet-induced transitions • Geometry effects

The ability to control and diagnose plasma properties with high spatial and temporal resolution is a key enabling feature of DIII-D research in these areas. The electron cyclotron heating (ECH) power upgrade is an important component of the Burning Plasma Physics plan as it allows greater control of plasma instabilities [both turbulent and magnetohydrodynamic (MHD)], better matching of reactor relevant conditions, and enables transient transport measurements. Other flexible tools, such as the 3D coil set and on/off-axis co/counter neutral beam injection (NBI), will allow DIII-D to enhance its program to control instabilities and transport (both thermal and fast ion). The plasma control system (PCS) on DIII-D is able to dynamically control global parameters such as the plasma shape, density, and β, as well as dynamically control local values of the current density, toroidal rotation and temperatures. These control capabilities allow scientists to isolate plasma parameters, thereby enabling the elucidation of the important physical processes. Diagnostic innovation (Section 6) will continue to be a high priority for the DIII-D program as new measurements naturally lead to new physics ideas, some of which will become transformational breakthroughs. State-of-the-art measurements of plasma profiles are needed to continuously advance our fundamental science understanding, mainly by testing the best-available theoretical model.

3.1. ENERGETIC PARTICLES

3.1.1. Challenges

The goal of the DIII-D energetic particle (EP) research program is to provide the scientific basis for fast ion physics in future burning plasma devices. Its extensive diagnostic set makes DIII-D the premier toroidal device in the world for providing high-quality data that rigorously test theoretical models and simulation codes. DIII-D also has a compelling plan to use a diverse array of 3D magnetic coils to optimize the tokamak concept, thus making DIII-D the ideal device to study the effects of 3D fields on fast ion transport. This includes the test blanket module (TBM) coil that is a unique research element for DIII-D. Table 3-2 summarizes the challenges, the approach to addressing them, and the necessary hardware upgrades.

Table 3-2
Energetic Particles Development

<table>
<tr><th>Challenge</th><th>Approach</th><th>New Capabilities</th></tr>
<tr><td>Experimentally validate an integrated suite of models through multi-institutional collaboration for predicting instability driven fast ion transport and its consequences in ITER and beyond</td><td>Build on recent successes and present understanding of linear mode properties and transport. Separate problem into fundamental components
• Basic mode properties (structure, frequency)
• Linear stability (drive, damping)
• Nonlinear dynamics (saturation/amplitude, chirping, bursting, mode coupling)
• Induced fast ion transport and loss
Initially one piece at a time, then move to integrated, self-consistent description</td><td rowspan="3">Actuators
• Advanced 3D coil set
• Increased beam power/voltage
• Second off-axis neutral beam
• Increased ECH power
• Large amplitude/ bandwidth coil

Measurement/Diagnostic
• 2nd ECE, PCI upgrade for toroidal mode number measurement
• INPA
• Full D_α spectrum measurements
• FILD-3
• IR periscope
• B-polarimeter, CPS, 3D magnetics

Analysis (see Table 3-6)
• F(v) inversion tools
• Non-perturbative EP codes with non-Maxwellian
• 3D equilibrium codes
• Massively parallel EP follower</td></tr>
<tr><td>Predict the impact of 3D fields on fast ion confinement in ITER and future devices with emphasis on loss</td><td>• Investigate impact on confined, lost, and promptly lost fast ions
• Survey of effects and initial modeling.
– n-spectrum
– L-mode, H-mode
– Resonant, non-resonant fields
– Plasma response vs. vacuum description
• Validation of models over a range of conditions
• Synergistic effects between 3D fields and MHD</td></tr>
<tr><td>Gain capability to control and potentially exploit fast-ion instabilities and EP transport in DIII-D with goal of improved performance in future BP devices</td><td>• Actuator development (OANB, ECH, beatwave, rotation…) will emphasize modeling and predictive use of tools developed in other two EP areas
• Implementation and testing of actuators
• Avoid and mitigate instabilities
• Begin to exploit instabilities and EP transport for improved performance.
• Integrate into AT scenarios</td></tr>
</table>

Future burning plasma experiments like ITER will have a variety of fast ion populations, including 3.5 MeV alphas, 1 MeV beam ions and tail ions generated by ion cyclotron heating (ICH). These energetic particles play critical roles in heating, current drive, momentum input, and plasma stability, making their successful confinement essential in a fusion reactor. Achieving adequate confinement, however, is faced with several challenges; these particles can excite a variety of instabilities and are subject to several transport mechanisms, including that from these EP instabilities as well as from imposed 3D magnetic fields (due to ELM-suppression coils or test blanket modules for example). Fast ion transport and loss can reduce fusion performance as well as cause localized heating and damage of first wall components. Consequently, developing validated models that describe these interactions, along with control techniques to suppress or exploit these effects, is critical for extrapolating to ITER and beyond.

Collaborations. The study of energetic particle instabilities is highly collaborative, and national and international cooperation are essential to the success of the validation program. The experimental team on DIII-D includes scientists from UC Irvine, Princeton Plasma Physics Laboratory (PPPL), Garching and General Atomics (GA). A strong experimental collaboration has also been formed between DIII-D and Axisymmetric Divertor Experiment Upgrade (ASDEX-Upgrade) in this field, with annual exchange of personnel. Cross-machine comparisons have also begun with National Spherical Torus Experiment (NSTX) and Joint European Torus (JET). DIII-D experimental results are compared with simulation codes developed by the two Scientific Discovery Through Advanced Computing (SciDAC) Energetic Particle centers, as well as many international research teams. Within the last year, DIII-D EP results have been analyzed by codes developed at the following institutions: PPPL, UC Irvine, U. Colorado, GA, Oak Ridge National Laboratory (ORNL), Frascati, Ukraine, Danish Technical University, Culham Centre for Fusion Energy (CCFE), Helsinki, Japan Atomic Energy Agency (JAEA) and Garching. DIII-D scientists have leading positions in the EP group in the U.S. Burning Plasma Organization (USPBO) and Transport Task Force (TTF). Internationally, personnel who represent the U.S. in the International Tokamak Physics Activity (ITPA) distribute important DIII-D cases to the international energetic-particle modeling community.

3.1.2. Research Plan

Overview. The DIII-D Energetic Particle research program aims to utilize its flexible facilities, advanced diagnostics and strong theory-experiment coupling to develop a comprehensive understanding of fast ion transport in fusion plasmas. The emphasis in the next five years will be on model validation for the prediction, avoidance, consequence, and potentially exploitation, of EP instabilities in ITER and Fusion Nuclear Science Facility (FNSF). In the 2014–2018 time frame, an ambitious program also will be started to gain the capability to control fast ion instabilities and energetic particle transport with the goal of improved performance in future burning plasma devices. The control work will leverage new hardware and diagnostics for DIII-D, discussed in Section 3.1.2.3, including increased electron cyclotron heating/electron cyclotron current drive (ECH/ECCD) power to allow DIII-D researchers to modify the local fast ion slowing down, control magnetic shear, and alter T_e/T_i, thus modifying drive, damping, and the nature of many different instabilities. An approximate timeline for these various elements is given in Fig. 3-1.

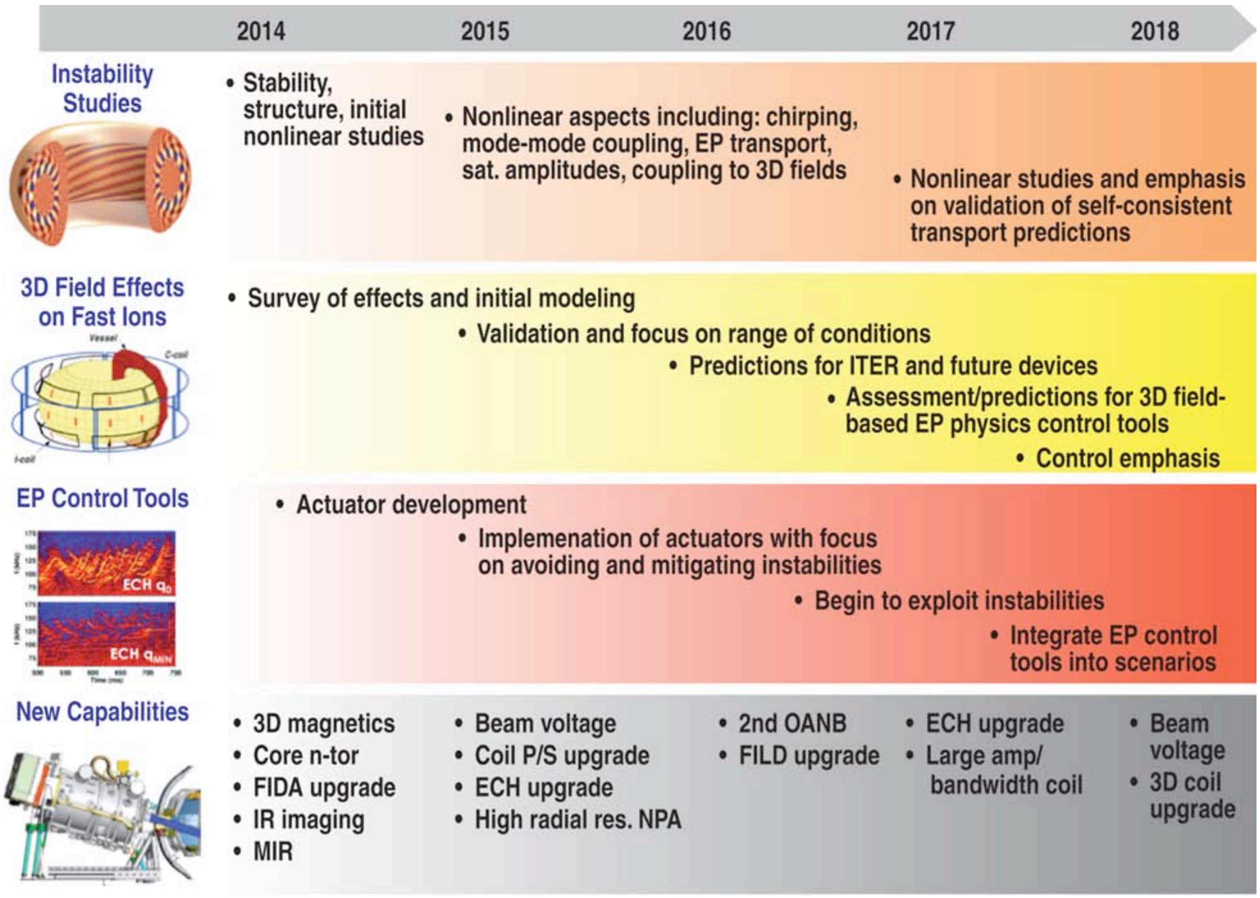

Fig. 3-1. Energetic particles program elements, hardware, diagnostics.

Timeliness. Developing validated models for EP behavior and techniques for avoiding potentially deleterious effects is crucial to optimizing the tokamak approach to fusion. With two currently funded Department of Energy (DOE) SciDAC centers focused on developing validated codes that can predict fast-ion instabilities and their consequences in ITER, the U.S. is poised to make major progress in this area in the next five years. DIII-D is the lead device for validation efforts undertaken by these two centers. Through targeted experiments, close theory/experiment coupling, and diagnostic improvements, DIII-D will continue to improve the level and accuracy of these validation studies. The result will be an improved understanding of the underlying physics, more reliable projections and interpretation of future experiments, as well as more strategic targeted experiments that maximize the potential information gain.

Detailed Research Plan. There are three main research elements: instability studies, 3D field effects on fast ions, and energetic particle or instability control. All elements rely heavily on modeling and are intrinsically linked to validation of models.

3.1.2.1. Instability Studies. The purpose of this research element is to experimentally validate an integrated suite of models, through a multi-institution collaboration, for predicting instability-driven fast ion transport and its consequences in ITER and beyond. Energetic particle experiments on DIII-D will address fast ion transport due to a large range of instabilities relevant to burning plasmas, from short wavelength high-n drift wave turbulence to n=0 energetic-particle geodesic acoustic modes (E-GAMs).

Typical instabilities include sawteeth, tearing modes, fishbones, E-GAMs, and a variety of Alfvén eigenmodes (AEs). All have been observed to cause fast ion transport. Ultimately, these studies must produce a predictive ability for determining the level of transport expected based on the instabilities that are present. In the last five years, much progress has been made on understanding the linear properties of the EP driven instabilities present in DIII-D plasmas, as well as the level of fast ion transport that can be expected from them. In the next five years, DIII-D EP instability studies will address key issues for ITER and future devices, building on recent successes and focusing on details of the fast ion distribution function, nonlinear evolution of the instabilities/transport, and an ambitious program to control these instabilities.

The process of testing and validating a suite of energetic particle models must address all hierarchical levels (sometimes called the "primacy hierarchy") of the models, beginning with fundamental constituents and ending in fast-ion transport predictions. As a representative example, the elements for testing the Alfvén eigenmode aspect of DIII-D energetic particle research are listed in Table 3-3. In the previous five years, much attention has been focused on the basic mode properties and induced fast ion transport and loss. Core diagnostics on DIII-D such as electron cyclotron emission (ECE), electron cyclotron emission imaging (ECEI) and beam emissions spectroscopy (BES) provide unprecedented resolution of code structure. Several codes are now able to reproduce the measured eigenmode structure and frequency [VanZeeland 2006, Spong 2012]. An example is shown in Fig. 3-2, where the predicted electron temperature perturbations from an n=3 reversed shear Alfvén eigenmode (RSAE) from three different simulation codes is favorably compared to measurements from ECEI on DIII-D [Spong 2012]. The red box in the simulations using the TAEFL code shows the region of the ECEI measurement. During AE activity on DIII-D, fast-ion D-alpha (FIDA) measurements show a large central depletion of fast ions (up to 50%) [Heidbrink 2007], and the fast ion loss detectors (FILDs) show losses of ions [VanZeeland 2011, Pace 2011]. Using these experimentally identified modes, fast ion transport calculations can also reproduce the measured impact these modes have on the fast ion population (both redistribution and loss) [White 2010, VanZeeland 2011]. This capability by itself is not adequately predictive, however, since the eigenmodes and amplitudes used in the calculations are determined by experiment. Much of the progress in understanding basic mode properties has been fueled by diagnostic advancements and by creation of two SciDAC Energetic Particle centers (discussed in "collaborations" section).

Table 3-3
Primacy Hierarchy for Validation of Alfvén Eigenmode Transport Models

Primacy Hierarchy	Observables	Agent/Mechanism	New Diagnostic
Basic mode properties	Polarization, structure, frequency		2nd ECE and PCI upgrade, MIR, two-axis magnetic probes, B-polarimetry, CPS
Linear stability	Drive, threshold, damping	EP spatial gradient, velocity anisotropy	Full FIDA spectrum, INPA array
Nonlinear dynamics	Amplitude saturation, chirping, bursting, mode coupling	Wave-wave, wave-particle interaction	MIR, full FIDA spectrum, INPA array, FILD-3
Transport	Distribution function, redistribution, loss	Cross-phase, relaxation	FILD-3, IR periscope, full FIDA spectrum, INPA array

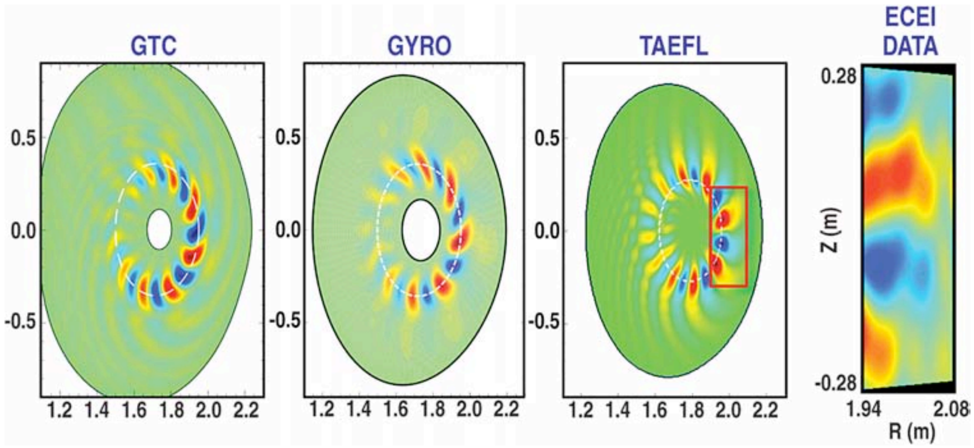

Fig. 3-2. Comparison of electron temperature perturbations for a n=3 RSAE calculated by three simulations codes with the measured T_e perturbation from ECEI on DIII-D.

Work in the next five years will focus on furthering this understanding and modeling capability to include validated models for eigenmode linear stability and nonlinear dynamics; both are critical elements for a fully predictive self-consistent model of AE induced transport in future burning plasmas. Several fast particle instabilities are important in tokamaks across a wide range of spatiotemporal scales. Attention will focus on the Alfvén instabilities that are the most relevant for ITER and FNSF, such as the toroidicity-induced Alfvén eigenmode (TAE) and RSAE. Other energetic particle instabilities of importance to DIII-D are the E-GAM and the beta-induced acoustic Alfvén eigenmode (BAAE), which exist at much lower frequencies. The flexibility of the DIII-D facility accommodates a wide range of experiments that test the underlying dependencies, especially access to burning plasma relevant regimes and beam injection velocities that exceed the Alfvén velocity at low B_T values. Readily altered parameters of importance in energetic particle theory include the following:

- Fast-ion distribution function, which is controlled by the co/counter/on-axis/off-axis neutral beam (NB) mixture and by perpendicular acceleration of the fast ions through fast wave (FW) heating. An example of this is given in Fig. 3-3, where the change in AE stability by going from on to off-axis NBI is shown.
- Field strength and increased beam voltage, which alters the ratio of fast-ion speed to the Alfvén speed as well as fast ion gyroradius.
- Increased ECH/ECCD power, which can modify the local fast ion slowing down, magnetic shear, and alter T_e/T_i, thus modifying drive, damping and the nature of many different instabilities.
- Plasma shaping, which alters the damping and existence of Alfvén eigenmodes in linear theory.
- The q profile, which strongly influences the Alfvén gap structure and the resulting eigenmodes.

This flexibility is invaluable for comparative experiments between facilities. For example, by using the appropriate mixture of heating systems, DIII-D is able to closely match all possible NSTX parameters except for major radius, which differs by a factor-of-two between the devices. With recent advances in EP diagnostics on both devices, new comparative experiments between the devices will provide a rigorous test of the theoretical models.

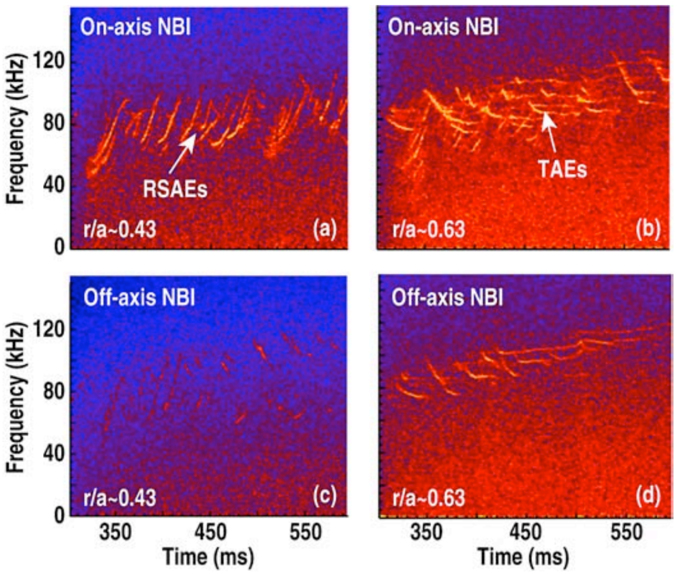

Fig. 3-3. ECE spectrograms at two different radii (r/a~0.43 and r/a~0.63) for DIII-D discharge 146076 on-axis injection (a,b), and 146077 off-axis injection (c,d). These data show the AE stability is significantly altered by off-axis injection, with RSAEs disappearing in regions where the fast ion gradient is weakened [compare (a) and (c)]. TAEs remain unstable at larger radius where gradients are expected to be similar to those from on-axis injection [compare (b) and (d)].

To arrive at a validated suite of models for instability induced transport, a variety of experiments or general studies are planned that address key elements of the problem as well as leverage new DIII-D capabilities. The research approach for EP Instability studies over the next five years will be broken into three stages:

- Stability, structure, initial nonlinear studies.
- Non-linear aspects including: chirping, mode-mode coupling, EP transport, saturated mode amplitudes, coupling to 3D fields.
- Validation of self-consistent non-linear transport predictions in a range of conditions from L-mode to advanced tokamak (AT) high performance plasmas.

DIII-D EP instability experiments in these areas will contribute to three separate ITPA joint experiments: EP-2 (fast ion loss and redistribution from localized AEs), EP-4 [effect of dynamical friction (drag) at resonance on nonlinear AE evolution], and EP-7 (the impact of localized ECH on AE activity), and much of the validation work will be carried out as ITPA activities.

New diagnostics for 2014–2018, shown in Fig. 3-1, will provide critical information for instability studies, such as the addition of toroidally displaced ECE measurements to determine the toroidal mode number of instabilities in the core. The basic mode structure of internal magnetic fluctuations will be probed for the first time on DIII-D using B polarimetry and cross polarization scattering (CPS). Also, the future focus on stability and nonlinear dynamics will require detailed measurements of the fast ion distribution function as stability and nonlinear behavior are very sensitive to details of the distribution function. The beam ion distribution function is highly anisotropic in velocity space, as shown in Fig. 3-4. Both diagnostics and codes need to be upgraded to include these effects. It is planned to convert all of the FIDA channels to measure the full D_α spectrum, resulting in an integrated modeling of confined fast ions that has been demonstrated to produce superior measurements [Grierson 2012] (Fig. 3-5). Additionally, an imaging neutral particle analyzer (INPA) system with high radial resolution is planned that will measure a localized region of fast ion velocity space at many spatial locations. New numerical tools will be developed to invert the fast ion distribution function from the expanded set of measurements. The inversion algorithm will exploit new formulas that relate FIDA spectra to the fast-ion distribution function [Salewski 2012]. Ultimately, a Bayesian framework that incorporates all of the fast-ion diagnostics with their various weightings in phase space is envisioned.

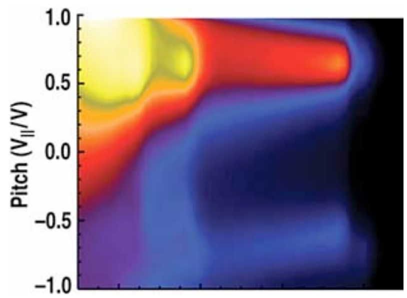

Fig. 3-4. Beam ion distribution function as modeled by TRANSP.

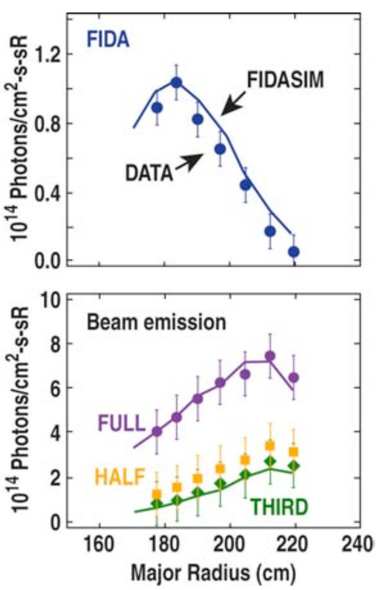

Fig. 3-5. Comparison of confined beam ions measured by the full D_α spectrum with the FIDASIM simulation code.

In the next five years DIII-D EP instability studies will address key issues for ITER and future devices, and will build on recent successes that have already allowed a detailed understanding of EP driven instabilities and their induced transport by focusing on details of the fast ion distribution function, nonlinear evolution of the instabilities/transport, and ambitious program to control these instabilities.

3.1.2.2. 3D Field Effects on Fast Ions. The goal of this research element is to measure, understand and be able to predict the impact of 3D magnetic fields on fast ion confinement in ITER and future burning plasma devices. Non-axisymmetric magnetic fields in tokamaks, such as those from ELM coils or TBM, can significantly alter fast ion confinement. For example, simulations show ELM mitigation coils can induce up to 5% loss of NB ions in ITER [Shinohara 2011]. Magnetic field ripple from the finite number of toroidal field coils and the TBM in ITER will also increase fast ion losses [Spong 2011]. Additionally, 3D fields can increase energetic particle losses from core MHD that would otherwise only cause internal redistribution [Shinohara 2011]. In the last five years, DIII-D research related to the impact of 3D fields on fast ion confinement focused primarily on TBM-induced EP losses and recently, in close collaboration with ASDEX-Upgrade, initial exploratory experiments probing I-coil induced losses have begun. In the next five years, a major focus will be the development and validation of efficient reliable tools to calculate 3D field-induced losses (which can be computationally intensive) and to use these tools to understand losses from I-coil and C-coil perturbations. These tools will then be used to predict the expected level of fast ion losses in ITER and future devices when 3D fields are applied, for example, to mitigate ELMs. The flexibility of the DIII-D device makes it an ideal environment for these studies. On DIII-D, the non-axisymmetric magnetic fields produced by the (internal) I-coil and (external) C-coil will be the main tool used to understand the effects of 3D fields on fast ion confinement. From a validation standpoint, the I/C-coil array is extremely well suited to this problem due to its flexibility. The current I/C-coil array can create static magnetic perturbations with toroidal mode numbers up to n=3, and rotating perturbations with toroidal mode numbers up to n=2. An advanced 3D coil set is planned that increases the number of coils from 6 to 12 and doubles the maximum toroidal mode numbers. The ability to rotate the perturbations is particularly valuable for physics experiments as it allows the 3D loss patterns to be rotated past the toroidally localized fast ion loss detectors, as well as past the toroidally localized beams (i.e., impacts prompt loss). Figure 3-6 shows preliminary data obtained in 2011 where the measured fast ion loss signal oscillates due to the application of rotating n=2 I-coil fields. An additional tool is the TBM coil that can be inserted into a midplane port on DIII-D to reproduce the non-axisymmetric magnetic fields created by the test blanket module on ITER. Figure 3-7 shows how infrared (IR) thermal imaging can be used to measure the increase in the heat flux deposited on tiles near the TBM due to fast ion losses; this data can be compared to models.

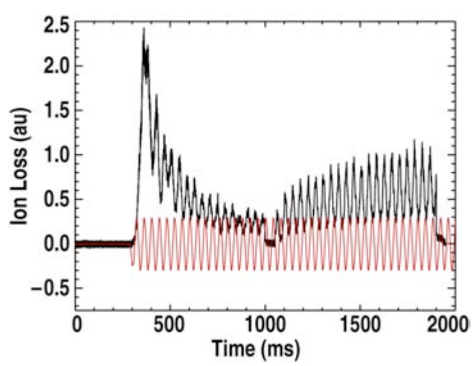

Fig. 3-6. Time history of fast ion losses measured by FILD (black) driven by a rotating n=2 field generated by the I-coil (red) on DIII-D.

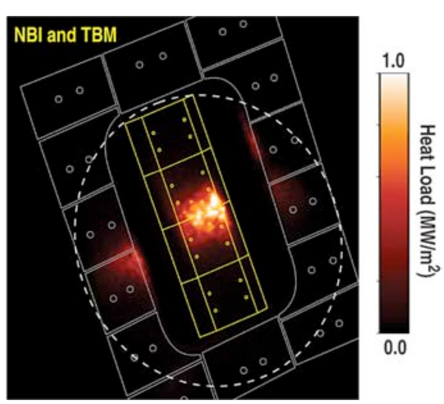

Fig. 3-7. Infrared imaging of heat deposition on TBM tile by fast ions when the coil is energized.

The research plans for 3D field effects on fast ions over the next five years will be broken into three stages:

- Survey of effects and initial modeling. While resonant magnetic perturbation (RMP) experiments have been a major program emphasis for several years, experiments investigating fast ion loss due to these perturbations are just beginning. Thus, initial experiments will focus on providing a survey of the observable effects.
- Validation of models over a range of conditions, leading to projections.
- Using 3D field effects for active control of energetic particles.

Experiments in this area are the subject of an ITPA joint experiment (EP-6) and will include studies of the scaling with toroidal mode number, perturbation strength, coil phasing, vacuum vs. plasma response, etc. There is also a strong synergy between these 3D field effect studies and the experiments led by the RMP ELM control task force, and the energetic particle studies plan to make use of the extensive modeling capabilities developed by the task force.

Experiments will be supported by a range of analysis tools similar to the recent TBM analysis effort led by Kramer [Kramer 2012], in which codes from PPPL, ORNL, JAEA and Aalto Univ. were employed with a variety of physics models. Full orbit following will be carried out in the presence of fields that include the calculated plasma response. Several codes are currently available for this aspect of the problem or are being developed, including M3D-C1, VMEC, and 3D EFIT. In addition to the inclusion of plasma response with fields calculated to the vessel wall, the capability to model beam birth profiles that properly account for perturbed 3D kinetic profiles will be essential. From the preliminary data obtained thus far (Fig. 3-6), it is becoming apparent that one of the largest effects that applied 3D fields have on fast ion losses in DIII-D is a modification of prompt beam ion loss. To model this, fast ion birth profiles will have to be calculated that include the perturbed profiles properly.

These 3D field fast ion experiments will be supported by recently installed diagnostics as well as future upgrades. Thermal imaging allows the fast ion losses to be monitored over a large region of the outer wall, and a wide field-of-view visible/infrared periscope will provide enhanced coverage to look for thermal loads due to lost fast ions. To complement thermal imaging, additional FILDs are planned that have excellent energy/pitch angle resolution. Installing a toroidal and poloidal FILD array will provide details of the 3D loss patterns with large bandwidth that will constrain modeling and provide additional details of loss mechanisms. Additionally, recent experiments have demonstrated that FIDA light is emitted by fast ions that traverse the high neutral density region at the plasma edge [Heidbrink 2011]. The light is measured by FIDA spectrometers and by detectors that employ bandpass filters. Application of this new diagnostic technique will provide additional information about the fast-ion losses induced by 3D fields.

In the next five years, 3D fields research carried out by the DIII-D EP group will allow researchers to predict with confidence the impact of 3D magnetic fields on fast ion confinement/loss in ITER and future burning plasma devices.

3.1.2.3. Control of Instabilities. The purpose of this research is to gain the capability to control and potentially exploit fast ion instabilities and energetic particle transport on DIII-D. Energetic particle control research will use the physics understanding gained in the instability and 3D field effect studies to form the basis for energetic particle physics control tools. If instability-induced transport is shown to be significant in future devices, or if 3D fields are demonstrated to affect EP instabilities and fast ion transport, several questions arise:

- What can be done to avoid (or induce if desired) these instabilities?
- If they occur, what can be done to mitigate the impact?
- Can instabilities be used to improve performance?

Presently, there are not many EP instability relevant control tools (some will be described in the following section), fewer yet have been shown to be a robust or are thoroughly understood. Answering these questions represents a long term vision and may require extensive exploration, both experimentally and numerically. DIII-D is poised to make significant progress in this area over the next five years.

There are promising examples that serve as a starting point for the long term goal of EP instability control. As an example of AE avoidance, localized ECH in DIII-D experiments has been shown to have a dramatic effect on RSAE stability [VanZeeland 2008]. When ECH is deposited near the mode location, RSAEs can be effectively stabilized (Fig. 3-8) with a significant reduction in fast ion transport. Experimentally, ECH modification of AEs and AE control techniques, in general, are the topic of a newly proposed ITPA joint experiment (EP-7) to be led by DIII-D. Another example of a promising starting point is the change in the EP stability and drive between on-axis and off-axis NBI, as shown in Fig. 3-3. Highlighting the fundamental physics aspect of this problem is a result from the Columbia dipole, where a small amount of radio frequency (rf) power was found to scatter EPs out of resonance, suppressing frequency chirping and eliminating large bursts [Maslovsky 2003]. This motivates the search on DIII-D to find analogous techniques to eliminate damaging bursts of lost alphas in a reactor. In addition to instability avoidance, there is another branch of control research that tries to turn EP instabilities to our advantage. For example, experiments on DIII-D found that AEs in low current discharges can redistribute fast ions and broaden the neutral beam current drive (NBCD) profile, which elevated $q(0) > 2$ [Wong 2005]. This suggests the possibility of using instability-driven redistribution of alpha particles to control the safety factor profile if the instability can move particles selectively from trapped to co-passing orbits, or select between co-passing and counter-passing alphas.

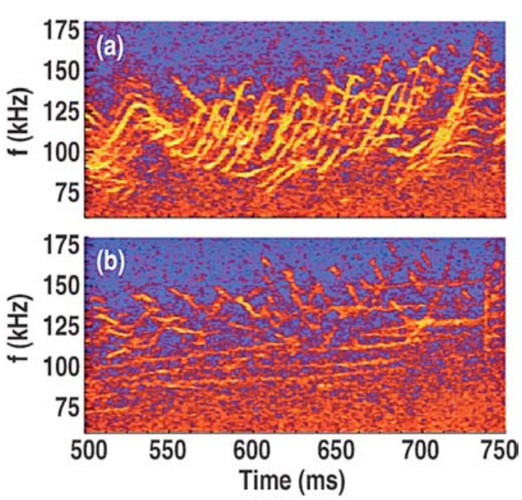

Fig. 3-8. Example of ECH modification of RSAE stability. (a) ECH applied near magnetic axis. (b) ECH applied near q_{min}.

Future experiments will explore new regions of parameter space in search of undiscovered transformative effects, as well as search for and implement actuators that can significantly alter the drive, damping, and nonlinear behavior of EP modes. Broadly, experiments in the control aspect of DIII-D EP research over the next five years will be organized as follows.

- Actuator identification and development.
- Implementation of actuators to avoid and mitigate instabilities.
- Exploitation of instabilities and EP transport for improved performance. Eventually integrate into AT scenarios.

Initial actuator identification and development experiments will be based on selecting tools that are capable of providing a macroscopic perturbation to the plasma with a plausible physical reason for altering the target instabilities. Ideally, these experiments will be guided by simulation. Examples of these types of actuators are listed below.

1. ECH/ECCD offers a targeted means of altering fast ion slowing down, T_e/T_i, electron distribution function, pressure and current profile. These elements will in turn change instability drive, mode existence and damping.
2. Rotation shear – by changing the plasma rotation profile with varied beams or coil induced torques, the Alfvénic continuum Doppler shift can be varied resulting in increased or decreased interaction with the continuum, thus changing mode damping.
3. Beatwaves formed by injection of two or more radio frequencies separated by local eigenmode resonances can be used to drive AEs. Also, as in Columbia dipole experiments, this option of rf injection can change mode nonlinear saturation and dynamics by scattering ions in/out of resonance.
4. On/off axis beam mix can be used to change fast ion spatial gradients and alter mode drive in a targeted way.
5. Applied 3D fields can be applied to increase fast ion transport in regions of phase space responsible for mode drive or to reduce spatial gradients.

Actually beginning to use these actuators to avoid and mitigate instabilities will largely be guided by modeling. Once an actuator has been identified, modeling will be used to plan targeted experiments aimed at validating the understanding of that particular actuator. For example, the reason for ECH stabilization of RSAEs is not presently known (and the actual cause is likely a combination of effects), but recent modeling advances will be applied to the problem. These simulation tools treat all of the relevant damping, changes to the drive, and eigenmodes themselves self-consistently (e.g., GTC and GYRO which employ non-perturbative fast ions). These tools will be used to predict unexplored regimes where ECH has not been used and those will form the basis for the next experiments in this area. Eventually, the goal is to apply these tools to scenarios where they can be used to improve performance.

Capabilities and Improvements. To accomplish the goals described in this section, upgraded control tools are crucial, as summarized in Table 3-4. The first two are considered essential requirements, while the last two are highly desirable.

Table 3-4
New Control Tools for EP Studies on DIII-D

Control Tool	Parameter Being Controlled	Purpose
Higher power ECH	Electron temperature and distribution function, local magnetic shear	Stabilize/modify AE modes (such as RSAE)
Advanced 3D-coils	Helical magnetic field perturbations	Induce orbit stochasticity for energetic particles, rotate perturbations with toroidal mode numbers up to n=4
Second off-axis neutral beam, higher injection energy	Fast ion density profile, ion distribution function	Alter AE drive
RF beatwaves options	AE waves, ion distribution function	Mode excitation, alter nonlinear dynamics by altering effective collision frequency of fast ions

In addition to these control tool upgrades, improved diagnostic capability is also required to achieve the physics goals of the EP research program, as seen in Table 3-5. An essential upgrade is an improved measurement of the core-localized toroidal mode number. Toroidal mode numbers are currently obtained from Mirnov coil arrays, but core-localized Alfvén modes are often barely detectable on the magnetics. This presents a significant source of uncertainty in modeling of experiments. An array of toroidally displaced ECE radiometers or CO_2 interferometers will successfully address this challenge. A new INPA will provide radially resolved measurements of confined fast ions that are very localized in phase space to help reconstruction of the fast ion distribution function. The INPA provides localized measurements in velocity space in order to determine which class of particles exchanges energy with the waves. A diagnostic upgrade that is crucial for 3D field studies is a toroidal and poloidal array of FILDs to provide details of the 3D loss patterns with large bandwidth. The high bandwidth edge-loss detectors and neutron scintillator signals are needed to search for wave-particle couplings, as well as for direct evidence of fast-ion transport. Another improvement will be to convert the vertical-viewing FIDA channels to a similar design as for the “main ion” charge-exchange recombination (CER) system. This will allow the full D_α spectrum to be analyzed for each chord, providing many constraints on the determination of the fast ion content and beam deposition. This will result in a more accurate measurement of the fast-ion density profile on every beam-heated discharge and will provide additional information about the velocity distribution on selected discharges. FIDA is the principal diagnostic for measurement of fast-ion transport by the instabilities. The recently installed periscope to measure IR and vertical images over a large area of the outer wall will provide enhanced coverage to look for thermal loads due to fast ion losses.

Energetic particle research on DIII-D has an emphasis on the validation of models used for the prediction, avoidance, consequence, and potentially exploitation, of EP instabilities in ITER and FNSF. A list of the codes that will be used in the 2014–2018 period are their purpose is shown in Table 3-6.

Table 3-5
Physics Enabled by New Diagnostics for EP Research

Desired Measurement Capability	New Physics Enabled	Proposed Diagnostic
AE toroidal mode number	Better mode identification in model validation	2nd ECE and PCI upgrade
Wave polarization	Better mode identification in model validation	2-axis magnetic probes
Internal magnetic fluctuations	Distinguish electrostatic instabilities from electromagnetic modes	B fluctuations from polarimetry, CPS
Structure of density fluctuations	Better mode identification, search for wave-wave interactions, zonal flows associated with wave couplings	Microwave imaging reflectometry (MIR)
Fast ion radial profile, ion distribution function	Improved radial resolution of confined ion redistribution, wave-particle couplings, phase space engineering	INPA, enhanced FIDA with full D_α spectrum
Toroidal/poloidal location of lost fast ions, energy/pitch angle of lost fast ions	3D field effects, wave-particle couplings, fast ion radial displacements, improvement determination of fast ion loss	IR periscope, FILD-3
Non-axisymmetric magnetic fields	3D field effects	3D magnetics

Table 3-6
Codes Used for EP Research

Code	Key Physics/Purpose
GTC, GYRO, GEM, LIGKA	Gyrokinetic – EP instability drive/damping/structure, thermal and EP fluxes, interaction with turbulence
TAEFL	Gyrofluid – AE instabilities
M3D-K, MEGA, XHMGC	Kinetic/MHD hybrid – EP studies including AEs, Fishbones, E-GAM
M3D-C1	Two fluid MHD – 3D fields
NOVA/NOVA-K, AE3D	Ideal MHD + kinetic extension – AE instabilities
SPIRAL, OFMC, ASCOT, ORBIT	Full orbit and/or guiding center following in axisymmetric and non-axisymmetric fields
FIDASIM	FIDA diagnostic simulation
TRANSP	Transport analysis including heating from EPs and detailed calculations of fast ion distribution function
Distribution function inversion	Tool to invert fast ion measurements to obtain confined distribution function

3.1.3. Impact

Through a focused experimental effort that effectively utilizes several planned device capabilities, DIII-D energetic particles research over the next five years will greatly enhance the ability to predict EP transport from instabilities and 3D fields in future burning plasma experiments as well as potentially control or even exploit EP driven instabilities. These results will be made possible due to DIII-D's great flexibility in its heating sources and plasma conditions, the best fluctuation diagnostics in the world, excellent motional Stark effect (MSE), and competitive fast-ion diagnostics. Also, an important factor in achieving these goals is DIII-D's role as the lead device for validation efforts undertaken by the two U.S. SciDAC centers focused on developing validated codes that can predict fast-ion instabilities and their consequences in ITER, as well as the DIII-D EP groups' involvement and leadership in international collaborations, such as high-profile ITPA experiments focusing on understanding nonlinear aspects of AEs, fast ion transport, and also control of EP instabilities. The tools developed through these experiments and validation efforts will help the development of scenarios for ITER and FNSF that minimize the negative consequences of EP transport, maximize performance, and avoid potential scenarios that can damage device integrity through excessive loss of fast particles. Further, the results of these studies will help the U.S. fusion community to interpret, understand, and maximize the utility of our participation in other EP experiments worldwide.

3.2. TURBULENCE AND TRANSPORT

The long-term goal of this research area is a predictive understanding of transport embodied in a suite of well-tested modeling codes. The transport effects are difficult to calculate accurately because they are the result, in most cases, of turbulent processes. In spite of the difficulty, advances in theoretical understanding and computational capability over the last decade has led to steady improvements in our ability to accurately calculate turbulent transport effects.

3.2.1. Challenges

The primary goal of turbulence and transport research is to develop a predictive capability that can be used to guide and optimize experiments on DIII-D but on ITER and FNSF as well. The critical transport issues, the approach to addressing them and the necessary hardware upgrades are summarized in Table 3-7. To accomplish this goal, transport understanding needs to be advanced in burning plasma regimes, including different ITER scenarios such as ELM-suppressed and steady-state regimes with non-monotonic safety factor profiles, and the simulation boundary conditions need to be moved to the plasma edge (e.g., the top of the H-mode pedestal). It is also important to be able to model the current ramp-up and ramp-down phases in ITER for discharge design purposes.

Table 3-7
Critical Transport Issues to be Resolved, Methods for Achieving Solutions and Required Instrumentation and Hardware

Challenge	Approach	Capability Improvements
Validate transport models for operation and optimization of burning plasma regimes: • T_e~T_i, low torque • Extend from core to pedestal • Boundary solution compatibility	Obtain comprehensive fluctuation and profile measurements in systematic scans of critical dimensionless transport parameters extending to burning plasma regimes, including baseline scenarios; perform multi-level comparisons with simulations, including fluctuations, transport and profiles	**Actuators:** • Fast perturbative particle injection: rapid pellets, supersonic gas jets • High-frequency, higher-current internal-coil power supplies option • High power ECH • Second off-axis beam • Advanced 3D coils **Measurements:** • New and improved fluctuation diagnostics (B polarimeter, CPS, UF-CHERS option, HNBP option, 2nd DBS option) **Codes:** • GYRO, TGLF, GEM, GTC, XGC1, GENE, BOUT++
Determine *q*-profile dependence of transport in order to optimize advanced scenarios	Vary *q*-profile and magnetic shear via current ramp, ECCD and off-axis NBCD in advanced scenarios, and measure turbulence and transport response; include NTV-driven rotation, stiffness reduction, and radiative impurity effects for *q*-profile optimization.	
Resolve the role of fundamental turbulence behavior and dynamics behind the “edge transport shortfall” conundrum	Measure fluctuation behavior, nonlinear dynamics through advanced measurements and higher-order analysis techniques to directly and quantitatively compare with simulation to identify missing instabilities or saturation processes in simulations	
Understand the effects of heat dispersal concepts on core transport	Study effect of 3D fields on turbulence and particle transport, control impurity accumulation through particle transport, determine effect of edge magnetic shear on core transport, and test role of pedestal height on transport stiffness	

Transport research in the burning plasma era aims to develop validated simulations for ITER and other burning plasma experiments for discharge design and performance optimization. It is likely that all discharges in ITER will need to be simulated beforehand to ensure safe and efficient operation, and this requires (among other things) an accurate transport model. Also full transport modeling is needed to project present-day scenarios to ITER and to optimize the performance of both high fusion gain and steady-state regimes. Parameter regimes of interest are comparable ion and electron temperatures, low torque injection, low collisionality, moderate to high beta, and varying safety factor profiles. The ECH power upgrade to 8.5 MW injected is crucial to achieving the burning plasma regime. The successful validation of theory-based transport models will be a critical contribution of the U.S. to the world fusion program that will build upon our strengths in diagnostics, heating and current drive, control and advanced simulations. This will also position the U.S. to exploit further advances in transport science gained during ITER operation that will improve future fusion reactor designs.

The transport model validation approach on DIII-D utilizes a primacy hierarchy that addresses multiple spatial and temporal levels. For example, an experiment will test theory by simultaneously comparing the underlying dynamics (e.g., turbulence), local fluxes (e.g., transport), and plasma profiles (e.g., T_e, T_i). This approach determines whether agreement, or lack thereof, with a theory-based transport model is systematic (multiple channels, a range of spatiotemporal scales) or is limited to certain areas. Turbulence modes span a substantial range of spatial scales, have different impacts on various plasma fields (density, temperature, etc.) and contribute different amounts to the various transport channels. The overall level of transport in fusion plasmas is set by the interaction between the turbulence drives and the various stabilization mechanisms. Understanding those interactions (at all relevant scale lengths), testing the simulations of those interactions, and understanding this nonlinearly saturated state is the long term goal of transport research.

The challenge of predicting transport is sufficiently complex that no one machine or research team can tackle the whole problem by itself. Different tokamaks have different diagnostic sets and different heating and current drive systems, and thus have different opportunities when pursuing transport studies. Taken together, the tokamaks in the U.S. and abroad can provide a wider range of tests than can any one machine, leading to more definitive experiments when the resources are combined. For example, experiments testing the effects of aspect ratio are possible by combining data from DIII-D and NSTX. Experiments testing the dependence on relative gyroradius (ρ*) can cover a significantly broader range when data from DIII-D and JET are combined. Furthermore, with the maturing of simulation and transport models in various institutions, intensive interactions of DIII-D experimentalists with the international community of theorists and modelers will improve, and possibly speed up, the transport validation process.

A significant advance in transport understanding in the next five years can come from determining fluctuating fields that are currently not measured on DIII-D. This includes internal magnetic fluctuations that can be determined using a cross polarization scattering (CPS) diagnostic or B polarimetry, and plasma potential (ϕ) fluctuations that can be determined using a heavy ion diagnostic, such as the optional heavy neutral beam probe (HNBP). This will be a huge advancement in transport validation studies as all the local turbulent fluctuations can be tested against predictions, not just their effect on the plasma profiles.

3.2.2. Research

Overview. The goal of transport studies in the Burning Plasma Physics area is to test, challenge, and validate the basic science in well-diagnosed and well-analyzed plasmas, to extend this work to more challenging advanced scenarios, and finally to predict the transport for actual scenarios in ITER and FNSF. The program will emphasize the use of nonlinear transport simulations to make testable predictions that will aid in the design of experiments, with attention given to measurements with advanced fluctuation diagnostics. A summary of the transport program elements is shown in Fig. 3-9. The study of the burning plasma regime will be greatly aided by increasing the injected ECH power to 8.5 MW (which can alter the instability drive), and co/counter NBI as well as a second off-axis beamline will allow the torque density profile to be varied to study rotational (i.e., *ExB* shear) effects. DIII-D has a unique strength with its complement of advanced turbulence diagnostics that measure several fluctuating quantities across a wide wavenumber and spatial range, allowing for a more quantitative and comprehensive comparisons to simulation and can provide more detailed examination when experiment and simulation do not agree.

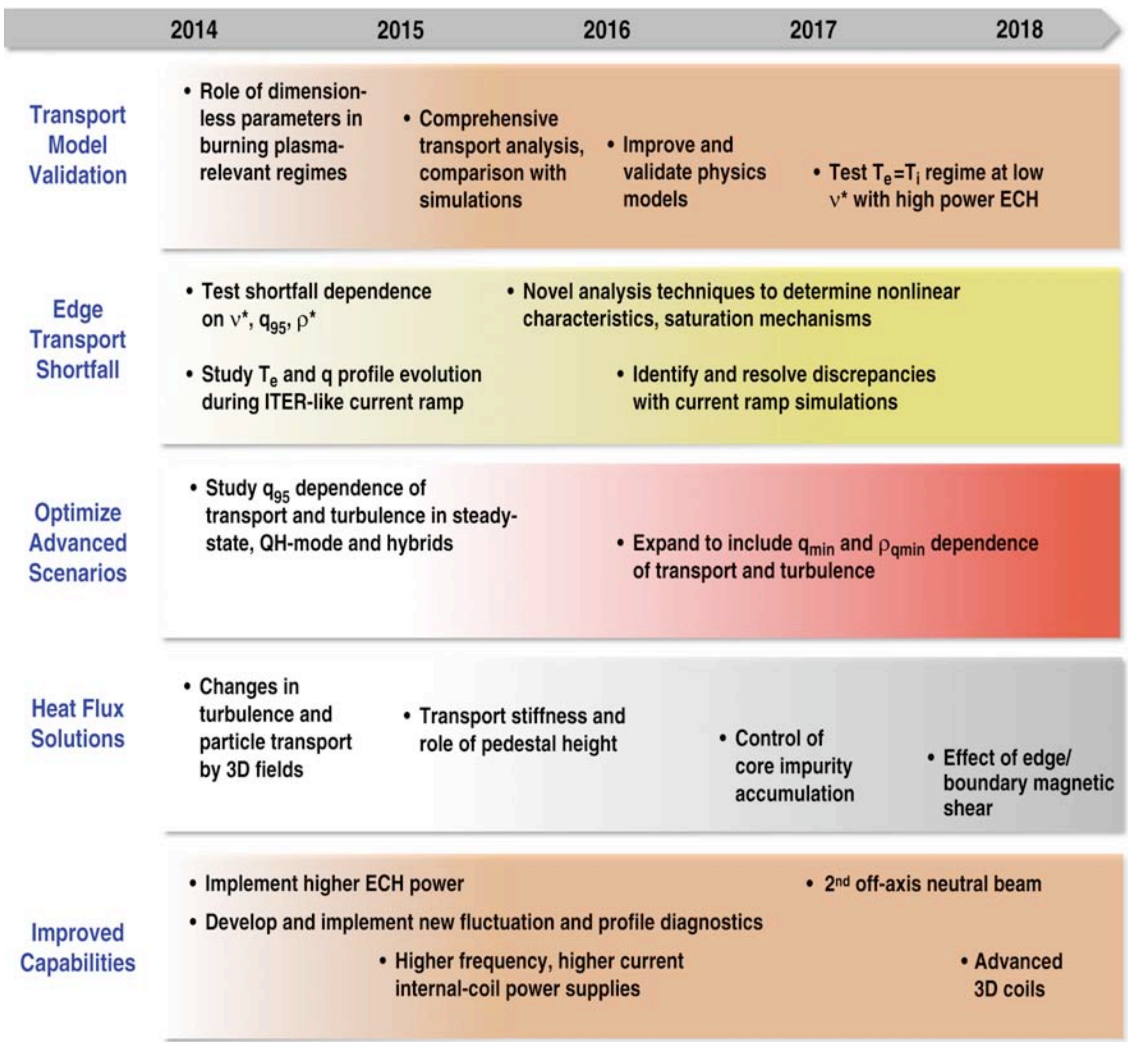

Fig. 3-9. Transport program elements, hardware, diagnostics.

A standard suite of analysis codes will be used for essentially all transport experiments. This includes EFIT for equilibrium reconstructions, integrated profile analysis codes like IMFIT and OMFIT, and the power-balance transport codes ONETWO and TRANSP. In addition, many transport experiments will benefit from measurements of the perturbative (or transient) transport from modulations in the heat source or particle source.

Detailed Research Plan. There are six main research elements: transport model validation in "reactor relevant" conditions, dimensionless parameter scans, transport during current ramp-up and ramp-down, improved confinement regimes, transport in plasmas with divertor heat flux solutions, and fundamental turbulence investigations. All elements have a strong emphasis on comparison with simulation codes.

3.2.2.1. Transport Model Validation in Reactor Relevant Conditions. A new area of emphasis in the DIII-D research program during 2014–2018 will be transport investigation and model validation in H-mode reactor relevant conditions. Table 3-8 shows the main characteristics of reactor relevant conditions and what their impact will be on transport. Experiments on DIII-D will use strong electron heating (primarily from ECH) and balanced-NBI to study H-mode plasmas with T_e~T_i and low injected torque, and compare and contrast these results with co-NBI cases. The experiments will look for changes in turbulence, heat transport, particle transport, poloidal and toroidal rotation, profile stiffness and critical gradients as reactor relevant conditions are approached. Additionally, the physics of intrinsic rotation will be investigated, such as the energetic particle contribution, as well as the effects of impurity injection and main-ion dilution on transport in reactor relevant conditions. These measurements will be compared to theory-based transport models and simulations such as GYRO, TGYRO, GS2, GEM, GTC, GENE, XGC1, BOUT, TGLF and MM. To process the large number of simulations needed for this transport validation task, additional analysts will be needed; these are the experts versed in experimental aspects who run transport simulations, implement synthetic diagnostics, and perform quantitative comparisons of simulation and measurement. The code validation work will take the form of continual model testing and improvement.

Table 3-8
Unique Transport Features of Burning Plasmas

Characteristic	Impact on Transport
T_e~T_i, strong electron heating	Instability drive (ITG/TEM/ETG)
Low torque, low V_ϕ	ω_{ExB}, low-k suppression
Low collisionality	Instability drive (ITG/TEM/ETG)
Energetic particle population	Turbulence interaction/drive
ELM-mitigation/suppression	RMP increases turbulence and transport
Stiffness of core profiles	Strongly affects fusion gain

The experimental plan for transport model validation over the next five years includes:

- Perform integrated experiments in burning plasma regimes: T_e~T_i, low rotation, low ν*.
- Test ion-channel profile stiffness in H-mode plasmas by examining the relation between T_i fluctuations and the variation in turbulent flux with ion temperature gradient (ITG).
- Test electron-channel profile stiffness in H-mode plasmas using high-power off-axis ECH to strongly vary electron temperature gradient (ETG).
- Determine if plasmas with electron temperature gradient below trapped electron mode (TEM) threshold have inward electron heat pinch.
- Study intrinsic rotation with dominant ECH at high β.
- Demonstrate validated simulations across a wide parameter range.
- Incorporate new multi-field (n, T, V, ϕ, B) turbulence diagnostics into validation tests.

A large advancement in transport model validation would come from measurements of all the fluctuating fields, including the cross-phases [White 2010]. An example of validating the electron density-temperature cross-power spectrum and cross-phase is shown in Fig. 3-10. The current diagnostic set on DIII-D can measure fluctuations in n, T_e, T_i, and V_ϕ, although some of these diagnostics have a limited number of spatial channels, limited wavenumber coverage, and limited sensitivity. The most important unmeasured fluctuating field is the plasma potential (ϕ), and there is an exciting proposal to remedy this by adding a heavy ion diagnostic to DIII-D, such as the optional HNBP. In principle this would allow a determination of the electrostatic turbulent flux in DIII-D via calculation using the measured fluctuations and cross-phases, which would be a great advancement in transport model validation. Additionally, testing of electromagnetic modes would require measurements of the fluctuating magnetic field using B polarimetry and/or CPS. Existing diagnostics such as ultra-fast charge-exchange recombination spectroscopy (UF-CHERS), correlation electron cyclotron emission (CECE) and BES would benefit from additional spatial channels to improve our ability to validate gyrokinetic calculations of turbulence.

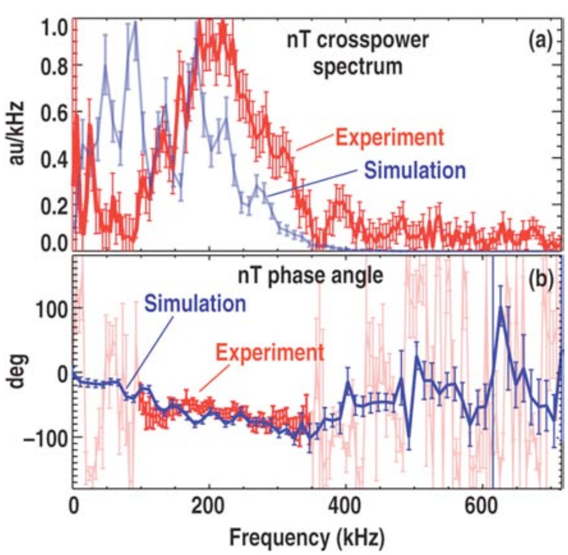

Fig. 3-10. (a) Cross-power spectrum and (b) cross-phase angle of electron density and temperature fluctuations measured on DIII-D for an L-mode plasma. Synthetic diagnostic predictions taken from a GYRO simulation are also shown.

To achieve reactor relevant conditions on DIII-D requires a large increase in direct electron heating power without core fueling or torque injection, which simulates alpha heating in burning plasmas. Figure 3-11 shows that 3–4 MW of direct electron heating is needed on DIII-D to obtain T_e~T_i in ITER-like baseline plasmas with β_N=1.7 and low rotation; additional direct electron heating power will allow the $T_e > T_i$ regime to be explored. The upgrade of injected ECH power to 8.5 MW, combined with up to 3 MW of FW direct electron heating, will allow the achievement of T_e~T_i in high-β plasmas that are relevant to steady-state power plant operation. A key physics result in the 2014–2018 period is understanding why certain regimes on DIII-D observe a strong decrease in confinement with the addition of direct electron heating power and, ideally, develop methods to mitigate this effect. An optional x-ray crystal spectrometer would allow measurements of the toroidal velocity and T_i in plasmas with only rf heating [Ince-Cushman 2008].

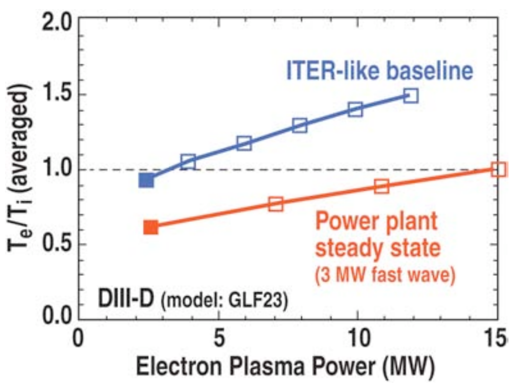

Fig. 3-11. Predicted ratio of the volume-average electron and ion temperatures, determined using the GLF23 transport model, as a function of the direct electron heating power (ECH and FW). The blue curve is for an ITER-like baseline case with β_N=1.7, while the red curve is for a fully non-inductive case with β_N=3.7.

3.2.2.2. Dimensionless Parameter Scans in Burning Plasma Regimes. The projection of transport results in scenarios on present-day tokamaks requires an extrapolation in one or more dimensionless parameters [Petty 2008]. The experimental plans for dimensionless parameter scans over the next five years includes:

- Perform scaling experiments in burning plasma regimes with single parameter focus.
- Perform scaling experiments in integrated fashion where multiple parameters are varied to project transport to ITER conditions (example: ρ* and ν* together).
- Perform relevant simulations to validate parameter scaling of transport models.

A comprehensive approach of studying multiple transport channels will be undertaken, including particle, momentum, ion energy and electron energy. Particle transport studies will be tied to understanding particle removal in burning plasma scenarios. Separating the ion and electron thermal diffusivities requires decoupling of the ion and electron temperatures, which can be accomplished with sufficiently large ECH power (> 7 MW) as shown in Fig. 3-12 for an ITER-like baseline discharge on DIII-D. Note that transport decoupling does not mean $T_e \neq T_i$. In fact, it is possible to have low collisionality plasmas with T_e=T_i and decoupled electron/ion transport channels as decoupling means that the electron-ion exchange power does not dominate the power flow. Understanding the effect of T_e/T_i on transport in DIII-D has important physics and programmatic implications, and a key result will be to finds means to sustain high confinement in strongly electron heated regimes.

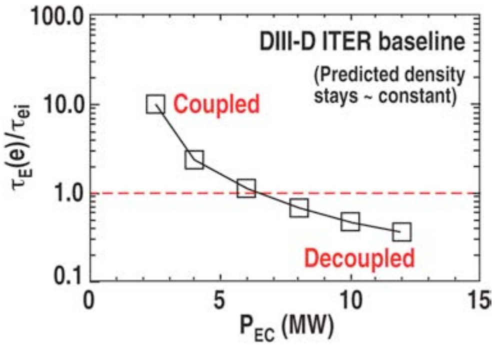

Fig. 3-12. Calculated strength of electron-ion coupling as a function of ECH power.

Single dimensionless parameter scans are also an outstanding way to test theoretical models. Besides having a much smaller value of the relative gyroradius (ρ^*), the burning plasma regime will likely have smaller collisionality (ν^*) and Mach no. (i.e., normalized rotation), and perhaps different values of the fast-ion β. Therefore, experiments on DIII-D will study the integrated effects of changes in the dimensionless parameters between present-day values and the ITER values. During these systematic parameter scans, full fluctuation documentation should be done for comparison with gyrokinetic codes.

A list of important dimensionless parameters that can effect the extrapolation of transport from DIII-D to the burning plasma regime is given in Table 3-9. Experiments on DIII-D will study the change in transport between strongly rotating plasmas with co-NBI and the more ITER-relevant low torque cases that can be generated on DIII-D using balanced-NBI and ECH. Another important quantity is the collisionality, the expected ITER value for which lies at the lower end of the DIII-D range. Interestingly, GYRO predicts that particle transport is sensitive to ν^* at ultralow values. International studies have found that the peaking of the density profile depends on ν^* [Angioni 2005], but it is unclear whether DIII-D observes this effect. This will be explored by measuring particle transport during ν^* scans, primarily using modulated D gas puffs or a single He gas puff [Baker 2000].

Table 3-9
Important Dimensionless Parameters for Extrapolating Transport to Burning Plasmas

Characteristic	Impact on Transport
Low Mach no.	ω_{ExB}, low-k suppression
Low ν^*	Flow damping, instability drive
Small ρ^*	Bohm/gyroBohm extrapolation
High β	New instabilities (e.g., micro-tearing modes)
q, s	Safety factor profile varies widely between different scenarios, strong turbulence and transport dependence

Another critically important dimensionless parameter for projecting transport of integrated scenarios to the burning plasma regime is ρ^* [Petty 1995]. The relative gyroradius dependence of transport has the largest influence on the projected confinement in ITER as the extrapolation is large (approximately a factor of 7) and the scaling is strong [$\Omega\tau \propto (\rho^*)^{-3}$ for gyroBohm-like scaling]. Other dimensionless parameter scalings to be studied include the β dependence, which can effect profile stiffness and the onset of new instabilities such as micro-tearing modes, and the q dependence, which can alter the confinement in difference scenarios that have reverse magnetic shear, weak shear, or zero shear. Micro-tearing modes, which give rise to magnetic field fluctuations that can be measured by polarimetry or CPS, have been of interest lately as this instability may explain the degradation of confinement at high β and high ν^* in some tokamaks [Vermare 2008].

Dimensionless parameter scaling experiments would benefit from improved measurements of the plasma profiles. An upgraded Thomson scattering system will improve measurements of the core electron density and temperature profiles. An option to upgrade the density profile reflectometer for higher frequencies will enable higher density measurements. Upgrades to make fast density measurements or a fast ECE system would improve the quality of transport perturbation experiments. Another improvement for edge profile measurement can come from the addition of an edge main-ion CER system. For particle transport experiments, a better method of controlling the injection rate of particles is desired. Hardware improvements on DIII-D for perturbative particle fueling include small, rapidly injected pellets and supersonic gas jets.

3.2.2.3. Transport During Current Ramp-Up and Ramp-Down. Many critical processes take place during the current ramp-up and ramp-down that will play a role in determining the success of ITER. These processes include the current profile evolution, the L-H transition, and the avoidance of major disruptions. Current transport models show significant deficiencies in modeling the T_e and q evolution during the L-mode ramp-up phase [Casper 2011], which is a crucial issue for implementing adequate power supply and poloidal field control. Therefore, it is important to validate our theory-based transport models during the startup/shutdown phases of the discharge, including testing in L-mode plasmas. The experimental plans for investigating the ramp-up/down and L-mode shortfall topics over the next five years includes:

- Examine L-mode shortfall conundrum via tests of low temperature, high q_{95}, high ν^*. Is this due to breakdown of gyrokinetic ordering?
- Validate predictions of ITER startup/shutdown via integrated experiments and simulations.
- Connect L-mode transport models to L-H power threshold scaling from turbulence and shear flows.

An optional HNBP diagnostic to measure fluctuations in the plasma potential, and B polarimetry and CPS to measure fluctuations in the magnetic field, can help resolve the edge transport shortfall issue as these will constrain critical parameters for transport that are currently unknown on DIII-D. High power ECH will be useful for controlling the electron temperature to vary the current profile evolution during startup/shutdown.

Experiments on DIII-D during the 2014–2018 period will compare tokamak discharge modeling, which incorporates theory-based transport models, with the measured T_e and q profiles, as well as the normalized inductance, to allow the determination of the ohmic supply requirements for ITER operation. The electron temperature is the single most important parameter for model testing during the current ramp-up as it governs the current profile evolution. Additionally, these experiments will compare the full fluctuation measurements with gyrokinetic codes in ITER-like ramp-up and ramp-down conditions to determine whether simulations capture the underlying turbulent characteristics, such as gyroBohm-like scaling. This approach of stressing the primacy hierarchy will give confidence that any correct predictions of global parameters (such as the normalized inductance) is due to getting the local processes correct.

One conundrum that needs to be resolved is the L-mode "turbulence and transport shortfall" of simulation codes in the edge regions [Holland 2009]. The basic and reproducible problem in comparing L-mode experiments to theory-based gyrokinetic models, either continuum or particle-in-cell (PIC), is that they under-predict both turbulence amplitudes and transport levels for $\rho > 0.7$ typically, as seen in Fig. 3-13. The fact that turbulence and transport are under predicted by the same amount suggests that the transport shortfall is due to predicting turbulence that is too weak, and that the problem is not due to a non-turbulent transport mechanism like paleoclassical [Callen 2007]. Experiments on DIII-D will study the dependence of the shortfall on edge plasma parameters such as n, T, ν^*, q, s and ExB shear; new measurements and analysis suggest that GYRO may overestimate the impact of local shear on turbulence, leading to underestimated transport [Shafer 2012]. We will also investigate whether the edge turbulence/ transport shortfall is strictly an L-mode phenomenon or whether it can occur in H-mode as well. When comparing the experimental profiles and fluxes to models, importance will be given to distinguishing variations in the code predictions (e.g., differences between GYRO and GENE predictions) in addition to determining possible deficiencies in the physics embodied in the codes.

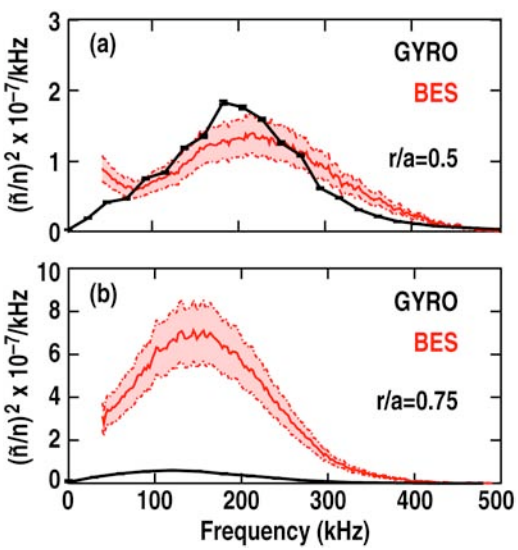

Fig. 3-13. Comparison of BES-measured and GYRO-synthetic density fluctuation power spectra for L-mode plasmas on DIII-D at (a) ρ=0.5 and (b) ρ=0.75. A significant shortfall in the simulated turbulence is seen at the larger radius.

3.2.2.4. Regimes with Improved-Confinement. Advanced modes of tokamak operation aim to achieve both high stability and high confinement [Petty 2000]. There is a practical upper limit to confinement improvement as the external heating power cannot be less than the current drive power for steady-state operation, but even so high confinement factors of $H_{98y2} \approx 1.6$ are desired. In this section, we will discuss methods for confinement improvement, as seen in Table 3-10. Additionally, the local transport coefficients determine the plasma profiles, which in turn determine the bootstrap current profile. Thus, an accurate transport model is needed to predict and optimize the bootstrap current profile in advanced modes. One desired outcome of this research is the development of transport simulation tools that can be utilized to design advanced, integrated experiments on DIII-D.

Table 3-10
Transport Issues for Various ITER Scenarios

Scenario	Transport Issues
ITER baseline scenario	Understand core transport and extrapolate to ITER
QH-mode	Understand core transport and extrapolate to ITER
Low-rotation NRMF-driven QH-mode	Optimize high-shear edge region while maintaining low global rotation
I-mode	Can we achieve high energy confinement with low particle confinement?
Hybrid	• Can high confinement be recovered at low injected torque? • Understand variability of electron thermal transport. Role of ETG mode and effect of density peaking.
Advanced steady-state scenarios	• q-profile, shear and shape effects • Effect of off-axis current drive (ECCD, NBCD) • Electromagnetic effects at high β • Impurity accumulation

The experimental plans for transport studies in advanced scenarios over the next five years include:

- Utilize quiescent H-mode (QH-mode) to study transport with dominant electron heating and little fast ion content.
- Determine role of edge *ExB* shear and edge harmonic oscillation (EHO) in optimizing particle and thermal transport in QH-mode.
- General validation of neoclassical toroidal viscosity (NTV) theory.
- Understand difference between edge heat and particle barriers for I-mode and extend theory-based transport models to edge region.
- Perform integrated tests with dominant ECH in high β, steady-state scenarios. Look for evidence of electromagnetic effects.
- Examine whether density peaking at low ν^* can suppress ETG modes and improve electron transport.
- Detailed studies of dependence of transport on q and s profiles.
- Connect impurity accumulation projections to validated particle transport studies.
- Test new confinement control concepts.

Previous work on QH-mode has shown that TGLF and GYRO transport predictions are sensitive to main-ion dilution by the beam ions [Holland 2011], so the extrapolation of core transport to ITER needs to be studied. Also a new mode of operation for QH-mode uses NTV from non-axisymmetric fields to create a large *ExB* flow shear in the edge despite having little global rotation [Garofalo 2011]. This edge shear effect should be further optimized in QH-mode to increase confinement with low injected torque from beams. On ALCATOR C-Mod, a new I-mode scenario has been developed with an edge heat transport barrier without an edge particle barrier [Hubbard 2011]. DIII-D experiments should determine whether the I-mode is reproducible and what advantages it may have over other ITER scenarios like

ELM-suppressed H-mode. To make a big advance in improved confinement regimes, DIII-D needs to explore new control options that may directly influence turbulence in a positive manner.

Advanced scenarios meant for steady-state operation have a number of interesting transport issues. Perhaps the main issue is optimization of the safety factor profile; the q profile is highly variable owing to the high bootstrap current fraction and strong off-axis ECCD and NBCD. Particle removal is important in steady-state scenarios, and impurity accumulation in improved confinement scenarios is always a concern as it lowers the fusion gain, thus particle transport experiments on DIII-D will study issues. Also at high β, electromagnetic effects may have a larger effect on transport than for some of the lower β scenarios in Table 3-10. Micro-tearing modes, which can be destabilized at high β and ν^* and for flat density profiles, have been identified as a possible source of beta degradation of confinement [Vermare 2008]. Therefore, a new window for investigating electromagnetic turbulence is desired for the study of high-β plasmas. DIII-D has recently installed a single-channel Faraday rotation polarimeter that may be able to measure magnetic field fluctuations; it is desired to increase the sensitivity of the polarimeter and perhaps add additional chords looking at different regions of the plasma. Also a cross polarization scattering diagnostic can be integrated into the Doppler backscattering system (DBS) system, allowing internal magnetic fluctuations to be measured. The B fluctuations measured by these diagnostics, and the associated β dependence of transport, will be compared to gyrokinetic simulations including finite β effects. To obtain high β regimes over a wider range of plasma conditions, especially higher magnetic fields, upgrades to the neutral beam energy and power are needed.

3.2.2.5. Effect on Core Transport of Proposed Divertor Heat Flux Solutions. It is generally believed that special remediation is required in H-mode plasmas on ITER to reduce the divertor heat flux to acceptable levels for the envisioned first wall materials [ITER 1999]. Table 3-11 lists the main lines of research being undertaken on DIII-D to either eliminate ELMs or to spread the heat flux over a larger area. These proposed divertor heat flux solutions can have a significant effect (positive or negative) on core transport, which need to be studied. The experimental plans for transport in plasmas with reduced divertor heat fluxes over the next five years includes:

- Tests of transport stiffness and role of pedestal height.
- Changes in turbulence and particle transport induced by 3D fields.
- Control of impurity accumulation through particle transport studies.
- Validation of NTV theory.
- Effect of edge/boundary magnetic shear on core transport.

Experiments on DIII-D will study methods to use particle transport to keep the core impurity levels low while keeping the edge impurity levels high enough to radiate the desired amount of power. Additionally, radiation removes heat flux directly from the electron channel, which may reduce the electron temperature in the pedestal region. If transport is stiff, then a low pedestal temperature will propagate into the core, resulting in a low temperature (and low confinement) throughout the plasma. On the other hand, various tokamak experiments have observed improved confinement during impurity injection [Messiaen 1996, McKee 2000], so it may be possible that a radiative mantle can be beneficial to transport.

Table 3-11
Divertor Heat Flux Solutions Being Explored on DIII-D

Heat Flux Solution	Impact on Transport
Radiative mantle	• Impurity accumulation • Depressed pedestal T_e • Improved confinement
Snowflake or Super-X divertors	• Changes in edge magnetic shear
RMP ELM suppression	• Direct turbulence response to non-axisymmetric fields • Islands • Torques (resonant and non-resonant) • Density pump-out
ELM pellet pacing	• Density control • Depressed pedestal β_N

Other schemes to reduce the peak divertor heat flux are tied to ELM mitigation or suppression, and experiments on DIII-D should optimize these configurations to improve transport, perhaps through the edge magnetic shear. For example, it has been clearly identified that radial magnetic fields used to suppress ELMs [Evans 2008] significantly increase turbulence, as show in Fig. 3-14, as well as particle and thermal transport. With the flexibility that comes with an advanced 3D coil set, experiments will strive to find a RMP configuration that suppresses ELMs with a minimal (negative) impact on core transport. Particle transport is an important issue for ELM pellet pacing studies as the plasma density needs to be controlled despite the strong fueling, and it is conceivable that pellet pacing could be combined with 3D fields to increase the particle transport. However, a high ELM frequency can depress the pedestal pressure, which can propagate inwards as a low core pressure if transport is stiff.

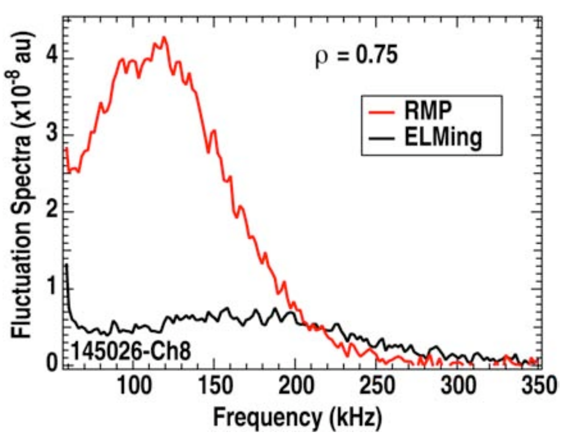

Fig. 3-14. Density fluctuation spectra measured by BES for an ELMing H-mode case (black) and an ELM-suppressed RMP case (red).

3.2.2.6. Fundamental Turbulence Investigations. A comprehensive understanding of plasma turbulence is a crucial component of plasma transport, and a long-term goal of this research is the development of a predictive capability for future burning plasma experiments. Turbulence interacts with and affects pressure and rotation profiles in a complex, highly nonlinear way. Important processes include pressure gradients (i.e., instability drive), internal energy transfer, nonlinear mode saturation, sheared *ExB* flows, and turbulence-zonal flow-geodesic acoustic mode (GAM) interactions [Tynan 2009].

The experimental plans for fundamental turbulence studies over the next five years include:

- Implement advanced diagnostics, multi-field (n, T, V, ϕ, B) turbulence measurements.
- Fundamental tests of turbulence physics.
- Turbulent flux validation.

The major emphasis in the 2014–2018 period will be the validation of sophisticated nonlinear 3D simulations, such as GYRO, GTC, and GEM and associated transport models (GLF23, TGLF). The nonlinear simulations have advanced to the point where all of the relevant physics is believed to be included, and simulations of realistic plasmas with actual geometry and measured profiles can be performed. The goal is to quantitatively compare fluctuation characteristics between simulations and measurements. These characteristics will first include fluctuation spectra, amplitudes, radial and poloidal correlation length, and wavenumber spectra for multiple fluctuating fields across much of the minor radius of the plasma, and to do these for multiple fluctuating fields. This is an ongoing line of research that steadily increases in sophistication as simulations and diagnostics improve. In the past, the advent of new diagnostic techniques (such as correlation ECE [White 2008]) opened new areas for theory/experiment comparison that were quickly used to study new physics [White 2010]. In the coming years on DIII-D, new diagnostics to measure magnetic field fluctuations and possibly plasma potential fluctuations should lead to similar new physics results.

Turbulence characterization and simulation comparison will rely on systematic dedicated experiments to measure the important quantities and vary critical parameters. Generally, relatively simple plasmas (low to moderate β, standard shapes, quasi-stationary) are especially fruitful for turbulence studies. Dimensionless scaling experiments such as those described in Section 3.2.2.2 provide a particularly successful method for performing experimental scans in a systematic fashion that will be useful for simulation comparison. To perform these experimental scans, one dimensionless parameter will be varied while other dimensionless quantities are held constant, requiring careful control over density, temperature, and other profiles.

The study of fundamental turbulence is diagnostic driven, and the DIII-D program has continually developed the tools needed for intensive, definitive comparison of transport theory and experiment. A list of current turbulence diagnostics on DIII-D is given in Table 3-12, and a picture of their relative locations in DIII-D is shown in Fig. 3-15. While this is already an impressive suite, future plans call for new diagnostics to be installed to measure additional fluctuating fields that contribute to the turbulent fluxes. One recently added capability is UF-CHERS, which measures fluctuations in the carbon impurity ion temperature and toroidal rotation [Uzun-Kaymak 2012].

Investigation of turbulence characteristics can be improved by the ability to measure all of the fluctuating fields on DIII-D, and over as large a range of wavenumbers as possible. The main gap in our diagnostic ability is the lack of a plasma potential fluctuation and magnetic fields fluctuation measurements. The edge pedestal radial electron field can be measured at high time resolution using an optional HNBP, and this diagnostic also may be able to measure potential fluctuations in the plasma edge. For testing the electromagnetic branch, the sensitivity of a Faraday rotation polarimeter will need to be increased to measure broadband magnetic field fluctuations. Additionally, cross polarization scattering will be incorporated into the DBS system on DIII-D to measure internal magnetic fluctuations. Other optional diagnostic upgrades are additional spatial locations for T_e and T_i fluctuations and upgrades to BES and DBS.

Table 3-12
Currently Available Fluctuation Diagnostics and their Basic Measurement Capabilities

Diagnostic	Measures	Wavenumber Range
BES	Multipoint (2D) density fluctuations, v_θ	Low-*k*
CO_2 interferometer	Line-integrated n_e fluctuations	Low-*k*
Correlation ECE	T_e fluctuations	Low-*k*
Correlation reflectometer	Radial correlations lengths at multiple radii	
Doppler reflectometer	Density fluctuations, v_θ	Low-*k* to medium-*k*
Far infrared (FIR) scattering	Density fluctuations	Low-*k* to high-*k*
PCI	Density fluctuations	High-*k*
Reciprocating Langmuir probes	n_e T_e, potential fluctuations in edge/SOL	
UF-CHERS	T_i and v_ϕ fluctuations	Low-*k*
ECE imaging	T_e fluctuations	Low-*k*

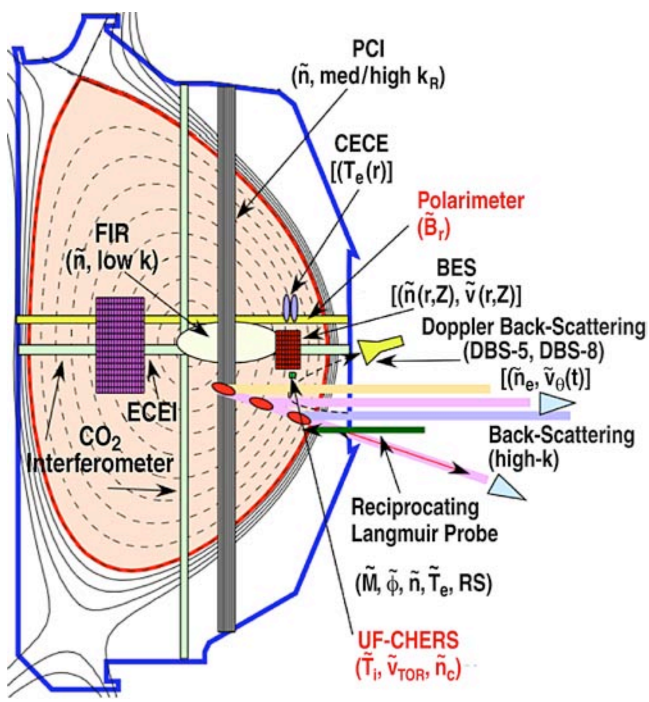

Fig. 3-15. Locations of turbulence diagnostics on DIII-D.

In order to perform these comparisons, synthetic diagnostics that model the performance of actual diagnostics is required. These synthetic diagnostics relate the output of simulations, which typically have high spatial resolution and no added noise sources, to measurements via application of transfer functions, thus simulating actual measurements including finite spatial and time resolution. In addition to these first order spectral characteristics it will be very important to compare higher-order nonlinear characteristics of the turbulence, such as bi-spectral properties, internal energy transfer, and zonal flow generation. These parameters are typically more difficult to measure due to their increased sensitivity to noise in the measurements and reliance on multipoint measurements, but will provide a more credible comparison with simulations since they more directly probe the nonlinear physics inherent to turbulence in a magnetically confined plasma.

DIII-D has several transport control tools, described in Table 3-13, that significantly enhance the experimental capabilities for studying turbulence and its dependence on plasma parameters. These tools allow for well-characterized systematic experiments to examine turbulence as a function of the key parameters that affect turbulence and turbulent transport. The electron cyclotron (EC) systems can be used to vary the safety factor profile and magnetic shear as well as directly heat electrons to vary T_e/T_i. The toroidal rotation and flow shear can be altered by switching between co- and balanced-NBI (the rf systems also heat without injecting torque). Off-axis NBI also strongly affects the torque deposition profile in the plasma core. Finally, it has been shown previously that non-axisymmetric fields can directly affect plasma turbulence [McKee 2012]. Experiments have found that after turn-on of the 3D coils the turbulence appears to increase before the plasma profiles change, suggesting that turbulence is responding to the change in magnetic topology.

Table 3-13
Control Tools for Turbulence Studies

Plasma Quantity to be Controlled	Tool to be Used
Safety factor/magnetic shear	ECCD, FWCD, off-axis NBCD
Toroidal rotation/flow shear	NBI (co or counter injection), NTV from internal and external coils
Electron-to-ion temperature ratio	ECH, FW option
Non-axisymmetric fields	Internal and external coils

Capabilities and Improvements. The new heating and control systems on DIII-D listed in Table 3-14 will allow for well-characterized systematic experiments to examine turbulent transport as a function of the key parameters. Higher power ECH, up to 8.5 MW injected, will be crucial to achieving the burning plasma regime of T_e~T_i and low injected torque, and will allow larger scans of the electron temperature gradient and higher electron energy fluxes. A more extensive use of transient transport (i.e., ECH modulation) experiments will allow us to further distinguish between the effects of diffusion and thermal pinches. The addition of a second off-axis beamline will allow greater ability to study transport in high-β plasmas with shallow temperature/density/rotation scale lengths (owing to the strong off-axis deposition of heat, particles and torque). An advanced 3D coil set will be good for scientific studies of the effect of non-axisymmetric fields on transport, in particular particle transport, and will be beneficial to studies of NTV torque and can help optimize the edge *ExB* shear for confinement improvement in low NBI torque plasmas. The hardware upgrades in Table 3-14 are listed in priority order for transport experiments, with higher power ECH being an essential requirement and the other three being highly desirable.

Table 3-14
Hardware Upgrades for Transport Studies

Hardware capability	New physics
Higher power ECH	Wider range of burning plasma conditions with T_e~T_i and low injected torque, current profile control
Second off-axis beam	Control of temperature/density/rotation scale lengths
Advanced 3D coil set	Finer control of NTV torque, effect of non-axisymmetric fields on transport
Neutral beam energy/power upgrade	High-beta regimes

Fluctuations arising from plasma turbulence occur in a number of parameters and cover a wide range in wavenumber space. Adequately diagnosing them requires the development and deployment of multiple additional fluctuation diagnostics at DIII-D. The currently available and planned fluctuation diagnostics on DIII-D are listed in Table 3-15. The wavenumbers covered by the various diagnostics ranges from long-wavelength range, thought to dominate much of turbulent transport, through the short-wavelength range, thought to contribute most directly to electron thermal transport. Current diagnostics measure fluctuating fields in n, T_e and V_θ, with some initial T_i and V_ϕ measurements. Many upgrades are planned in these areas, including greater sensitivity, more channels, and extension to the plasma edge/SOL. For example, intermediate-k density fluctuations and poloidal flow in the SOL can be measured using an optional 33–50 GHz DBS system which would complement the current core system and could extend core measurements to lower B_T. Also a poloidally aligned high-k backscattering system would complement the existing radial-k backscattering system, allowing us to study asymmetries in the fluctuation spectrum. While the current CECE diagnostic has observed important turbulent phenomena, such as a critical gradient threshold in the electron temperature (Fig. 3-16), it needs to have increased spatial coverage and increased sensitivity to study H-mode plasmas.

Exciting new diagnostic proposals are aimed at measuring fluctuations in the plasma potential and magnetic field. The ϕ measurement can be made using an optional heavy neutral beam probe in the outer regions and pedestal. Either a cross polarization scattering diagnostic or a Faraday rotation polarimeter, such as the 288 GHz R0 polarimeter recently installed on DIII-D, can measure B fluctuations to investigate electromagnetic turbulence in high β regimes. Arguably, the fluctuation diagnostic set on DIII-D is the most comprehensive in the world fusion program, and continued new developments and expansions will further enhance capabilities and performance.

Transport research on DIII-D has a strong emphasis on comparison with simulation codes. A list of codes that will be used in the 2014–2018 period and their purpose are shown in Table 3-16.

Table 3-15
Diagnostic Improvements for Transport Studies

Scientific Objective	Physics Measurement	Diagnostic Technique
Recent Upgrades:		
Understanding role of turbulence in transport	Electron temperature fluctuations	ECE-I
	Ion temperature and toroidal velocity fluctuations, n_i-T_i cross-phase measurement	UF-CHERS
Improved profile measurements for more stringent tests of transport models	Full radius plasma rotation measurement for study of rotation structure	CER measurements at locations with $R<R_{axis}$
	Edge current density profile for stability, L-to-H transition, and pedestal studies	Lithium beam polarimetry system and development of edge MSE analysis to separate E_{rad} and j(r)
	Edge electron temperature and density profile for L-to-H transition and pedestal studies	High spatial resolution for edge Thomson scattering (TS)
	Main ion (deuteron) density and rotation measurements for improved understanding of rotation	CER measurements of D_α spectrum (main ion CER)
New measurements using extensions of present techniques:		
Understanding role of turbulence in transport	Ion temperature and toroidal velocity fluctuations, n_i-T_i cross-phase measurement	Expanded (multi-point) UF-CHERS option, lithium beam upgrade
	Density fluctuations and turbulent eddy velocities, toroidal mode number	MIR
	Electron temperature fluctuations	Broader spatial coverage and increased sensitivity for CECE
	Plasma potential fluctuations, n-ϕ cross-phase measurement	HNBP option, BES velocimetry
	Internal magnetic fluctuation measurements to determine if magnetic fluctuations drive transport	Higher sensitivity and more chords for Faraday rotation polarimeter, CPS
	High-k turbulence	Poloidally aligned backscattering, PCI upgrade
	Edge/pedestal turbulence studies	High spatial resolution BES option, 2nd DBS option, ECE-I option
Improved profile measurements for more stringent tests of transport models	Main ion (deuteron) density and rotation measurements in edge/pedestal region	Edge CER measurements of D_α spectrum (R=2.2 m to 2.32 m)
	Edge radial electric field well	Edge CER measurements of carbon option
	Perturbative transport measurements	Monostatic upgraded profile reflectometer, 2nd reflectometer option, fast ECE system
	Core electron density and temperature	Upgraded Thomson scattering
	Measure T_i and toroidal rotation during rf-only heating	XCS option
New measurements which require new techniques:		
Understanding role of turbulence in transport	2D neutral deuterium density measurements	TBD

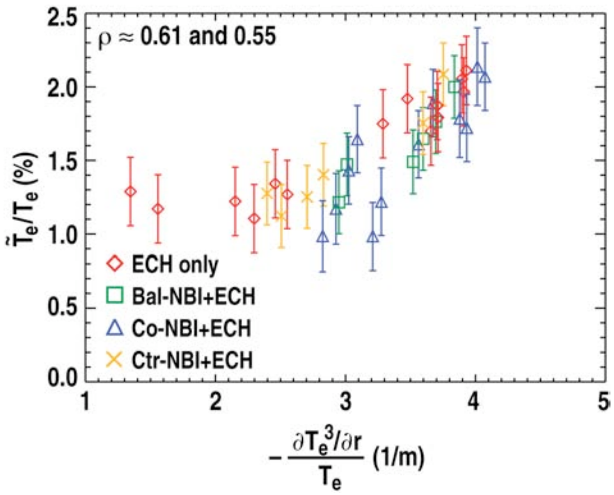

Fig. 3-16. First observation of a turbulent threshold in the electron temperature gradient made by CECE in an L-mode plasma on DIII-D.

Table 3-16
U.S. Codes Used for Transport Research

Code	Purpose
NCLASS	Neoclassical transport predictions via semi-analytic model
NEO	Neoclassical transport predictions via direct solution of drift-kinetic equations
GYRO	Local and global nonlinear gyrokinetic simulations (Eularian continuum) of core turbulence and transport
GS2	Local nonlinear gyrokinetic simulations (Eularian continuum) of core turbulence and transport
GLF23	Quasi-linear gyrofluid core transport model
TGLF	Advanced quasi-linear gyrofluid core transport model; successor of GLF23
GEM	Local and global nonlinear simulations (particle-in-cell) of core turbulence and transport
GTC/GTS	Global nonlinear gyrokinetic simulations (particle-in-cell) of core turbulence and transport
XGC1	Global nonlinear gyrokinetic simulations (particle-in-cell) of core and edge turbulence and transport; “full-f” but adiabatic electrons
BOUT++	Braginskii fluid simulation of turbulence and transport in edge, separatrix and scrape-off layer (SOL) region
TGYRO	Steady-state core transport solver (predicts core profiles using TGLF or GYRO)
TRINITY	Steady-state core transport solver (predicts core profiles using GS2)
PTRANSP	Time-dependant core transport solver (predicts core profiles using GLF23 or TGLF)
ONETWO-GCNMP	Time-dependant core transport solver (predicts core profiles using GLF23 or TGLF)

Note: core = can only run on closed flux surfaces. In principle, any of the core-only codes can be run in pedestal region. Opinions vary as to whether they should.

3.2.3. Impact

The DIII-D research plan on transport and turbulence has made major contributions to sophisticated theory/experiment comparisons, and will continue to have important consequences for future burning plasma experiments:

- Validating transport models in reactor-relevant regimes is essential for developing experimental plans to meet ITER's goals and for maximizing the scientific benefit garnered from participation in ITER.
- Extending transport models to the plasma edge (i.e., top of H-mode pedestal) will give greater predictive ability, including plasmas in which divertor heat flux solutions have been implemented.
- Understanding transport in advanced regimes, including non-monotonic q profiles and at high β, will guide the optimization of steady-state scenarios on DIII-D, ITER and FNSF.
- Complete knowledge of plasma turbulence may allow us to tailor transport to control the density profiles for fuel ions and impurities.
- Being able to predict the evolution of the electron temperature and current profile during current ramp-up and ramp-down will allow one to determine operational requirements for ITER beforehand.

Improving the ITER experimental program using predictive models is a valuable goal of the DIII-D transport efforts. Optimizing confinement in reactor relevant conditions will not only benefit ITER but also help the U.S. design other burning plasma devices such as FNSF. This will build upon the U.S. strengths in diagnostics, heating, control and advanced simulations, and enable the training of young scientists. The importance of achieving this goal before the start of ITER operations justifies an increased emphasis on transport research in the near term, while in the longer term this will put the U.S. in a leadership position in the ITER program.

3.3. L-H TRANSITION

The long-term goal of this DIII-D research is to develop a physics-based model of the low-to-high (L-H) transition power threshold to enable reliable predictions of auxiliary heating power required to access H-mode in ITER and FNSF and potentially develop techniques to lower the H-mode power threshold.

3.3.1. Challenges

The goals for L-H transition research on DIII-D are linked to the importance of obtaining H-mode in ITER and FNSF. Understanding the L-H transition physics is important for three reasons: (1) risk mitigation – wanting to be ahead of the curve if ITER has more difficulty than anticipated obtaining H-mode access, (2) discharge simulation – the timings of the L-H transition and high-to-low (H-L) transition during the plasma current ramp up and ramp down phases are crucial in developing scenarios for ITER, and (3) optimization of H-mode access in ITER and FNSF, i.e., reducing the power threshold requirement. The challenges for L-H transition physics and power threshold scaling, the approach to addressing them, and the necessary hardware and diagnostic upgrades are summarized in Table 3-17.

Table 3-17
High Level L-H Transition Physics and Scaling Problems to be Resolved, Methods for Achieving Solutions, and Required Instrumentation and Hardware

Challenge	Approach	Capability Improvements
Determine the relationship and interdependence of local turbulence characteristics, plasma profiles, and gradients near the L-H transition	Identify dominant edge instabilities; investigate comprehensively how the dynamics of equilibrium *ExB* and zonal flows (inc. GAM), turbulence characteristics, and energy transfer evolve from L-mode, across the L-H transition to early H-mode as a function of local edge parameters	**Actuators:** • 3D coil upgrades • Increased ECH power • Fast perturbative particle injection: rapid pellets, supersonic gas jets **Measurements:** • New and improved fluctuation diagnostics: B-polarimeter, CPS, UF-CHERS option, 2nd ECE, 2nd DBS option, HNBP option • Fast reciprocating probe-based T_e, B, T_i, and plasma potential fluctuation measurements • Density profile reflectometer upgrade • Main ion CER upgrade • Lithium beam upgrade **Codes:** • Testing and comparisons with BOUT++, XGC1
Determine the L-H trigger mechanism	Test the model of turbulence-driven zonal flow as trigger in various regimes, emphasizing limit-cycle oscillations, and ITER-like configurations; consider and evaluate equilibrium *ExB* shear and other mechanisms	
Understand the P_{LH} scalings based on local edge plasma and turbulence parameters	Perform experiments varying relevant local parameters such as density, ν^*, q_{95}, rotation as well as magnetic configuration, shape and applied 3D fields	
Develop methods and gain physics understanding on how to improve H-mode access	Develop and evaluate innovative techniques to vary (and reduce) P_{LH}, such as pellet-injection, shaping, and rotation control.	
Understand H-L back transitions, power hysteresis, and how to achieve safe discharge termination	Explore control of timing and duration of the H-L back-transition via gradual power ramp-down, shape evolution, RMP fields, and induced limit-cycle-oscillations	

There is extensive literature on the global parameters that can influence the power threshold for the L-to-H transition [Ryter 1996, Martin 2008], most of which are listed in Table 3-18. It is clear from the large number of factors that influence the L-H transition that simple scaling relations cannot capture the physics taking place. As a result, recent research on this topic has focused more on understanding the underlying nature of the L-H transition, such as the role of turbulence-generated zonal flows on the transition [Diamond 2005] and Reynolds stress [Kim 2003], and the conditions needed for the equilibrium *ExB* shear to grow strong enough to suppress the L-mode edge turbulence. Research on this topic supports the development of a physics-based model, to be implemented in nonlinear edge simulations using codes like BOUT++, that utilizes the specific trigger mechanism(s) and edge transport to enable reliable predictions for the L-H and H-L power thresholds in ITER and other future devices.

Table 3-18
Parameters that Can Control the H-Mode Power Threshold

• Plasma density
• Toroidal magnetic field strength
• Ion ∇B drift direction relative to X-point
• Plasma cleanliness/fueling
• Plasma geometry in the vicinity of the divertor (or limiter)
• Plasma species (H, D, T, He)
• RMPs (non-axisymmetric magnetic fields)
• Plasma shape (e.g., surface area)
• Plasma-wall gaps
• Plasma current ramp rate
• Sawteeth trigger
• Toroidal rotation (i.e., co/counter beam mix)

While a crucial question is how much heating capability must ITER have to access H-modes in deuterium/tritium plasmas, it is also valuable to know what will be the H-mode power threshold for pure hydrogen and helium plasmas for the early non-nuclear phase of ITER operation. An additional issue or concern for ITER is predicting when the L-H transition will occur during the current ramp-up and when the H-L transition will occur during the current ramp-down; this causes rapid changes in plasma inductance which can impact the poloidal field supply requirements to maintain safe operation.

DIII-D is an ideal device to study the physics of the L-to-H trigger and transition because of the excellent suite of edge diagnostics, the flexibility to alter the parameters listed in Table 3-18 and the strong collaboration between experimentalists and theorists. The comprehensive set of edge fluctuation diagnostics listed in Table 3-17 will be critical in studying the transition trigger mechanism(s). For example, variations in the edge turbulence will be thoroughly investigated during changes in the machine control parameters that can influence the H-mode power threshold. Additionally, new actuators, such as fast perturbative particle injection, will give greater control of the L-H power threshold. Finally, the DIII-D experimentalists will establish connections with H-mode theory and modeling groups to develop

L-H (and H-L) models with quantitative predictions, which can be assessed through comparisons with local edge measurements (both profiles and turbulence) at the transition.

3.3.2. Research Plan

Overview. Owing to the important roles of plasma turbulence and edge barriers, research on the L-H transition is integrated with transport research in the Burning Plasma Physics area of DIII-D. A summary of the research plan in L-H transition physics for the period 2014–2018 is found in Fig. 3-17. Over this period, experiments on DIII-D will make a strong push towards a local physics understanding by working to identify the nature of the L-H transition trigger and the physics mechanisms responsible for the scaling of the L-H power threshold with density, magnetic field strength, magnetic geometry, ion mass, toroidal rotation and safety factor. An important component of the trigger physics is to determine the dynamics of the nonlinear energy transfer from plasma turbulence to zonal flows over a range of plasma conditions, including how this may eventually lead to edge turbulence suppression. This will require a detailed understanding of L-mode turbulence and transport (discussed in Section 3.2.2.3) as the edge plasma parameters just prior to the transition are governed by L-mode physics. Additionally, the role of equilibrium flows, neutrals and ion orbit loss will be studied.

Detailed Research Plan. During the 2014–2018 period, there will be three main research elements: identifying the "trigger" mechanism for the L-H transition, creating a physics-based model for the power threshold, and developing methods to substantially improve access to the H-mode. This program requires close cooperation between experimentalists on DIII-D and H-mode theory and modeling groups.

3.3.2.1. Identify Trigger for L-H Transition. A clear understanding of the mechanism(s) that trigger the L-H transition will not only aid in the development of a physics-based model, but it may also help us develop techniques to lower the power threshold. Specifically the roles of zonal flow and equilibrium *ExB* shear in triggering the L-H transition needs to be determined, which should lead to the development of models that can be tested. Experiments on this topic during the next five years include:

- Identify characteristic changes of turbulent eddies across transition (radial/poloidal extent/correlation, size distribution, avalanche characteristics, non-Gaussian statistics).
- Directly measure Reynolds stress gradient non-linear energy transfer from turbulence spectrum to flows using DIII-D midplane reciprocating probe and/or BES.
- Investigate role of equilibrium and zonal flow shear in trigger dynamics at low and high collisionality. Determine if trigger mechanism changes between low and high collisionality.
- Identify physics mechanism responsible for non-monotonic scaling of L-H transition power with density.
- Investigate spatiotemporal evolution of turbulence and flows during H-L back transitions.

A prominent model for the L-H transition in high temperature plasmas is that zonal flows, generated from the turbulence via the Reynolds stress, have to overcome damping by ion-ion collisions in order to produce sufficiently strong shear to initiate a local turbulence quench [Kim 2003]. Recent experiments in DIII-D have studied L-H transitions preceded by zonal flow limit cycle oscillations (LCOs) [Schmitz 2012] as seen in Fig. 3-18. If the energy transfer rate from the turbulence spectrum to the zonal flow is directly determined, by a reciprocating probe or other method, then the zonal flow damping rate can be extracted from the LCO period. The transition power threshold may directly depend on this quantity. The experimental approach is to obtain simultaneously the Reynolds stress and non-linear energy transfer to the zonal flow from reciprocating probe data and measure the electric field, *ExB* flow shear and turbulence amplitude via Doppler backscattering and BES across the radial electric field well during the LCO. This data set will be taken across a wide range of L-mode target densities to achieve the largest possible variation in ion-ion collisionality.

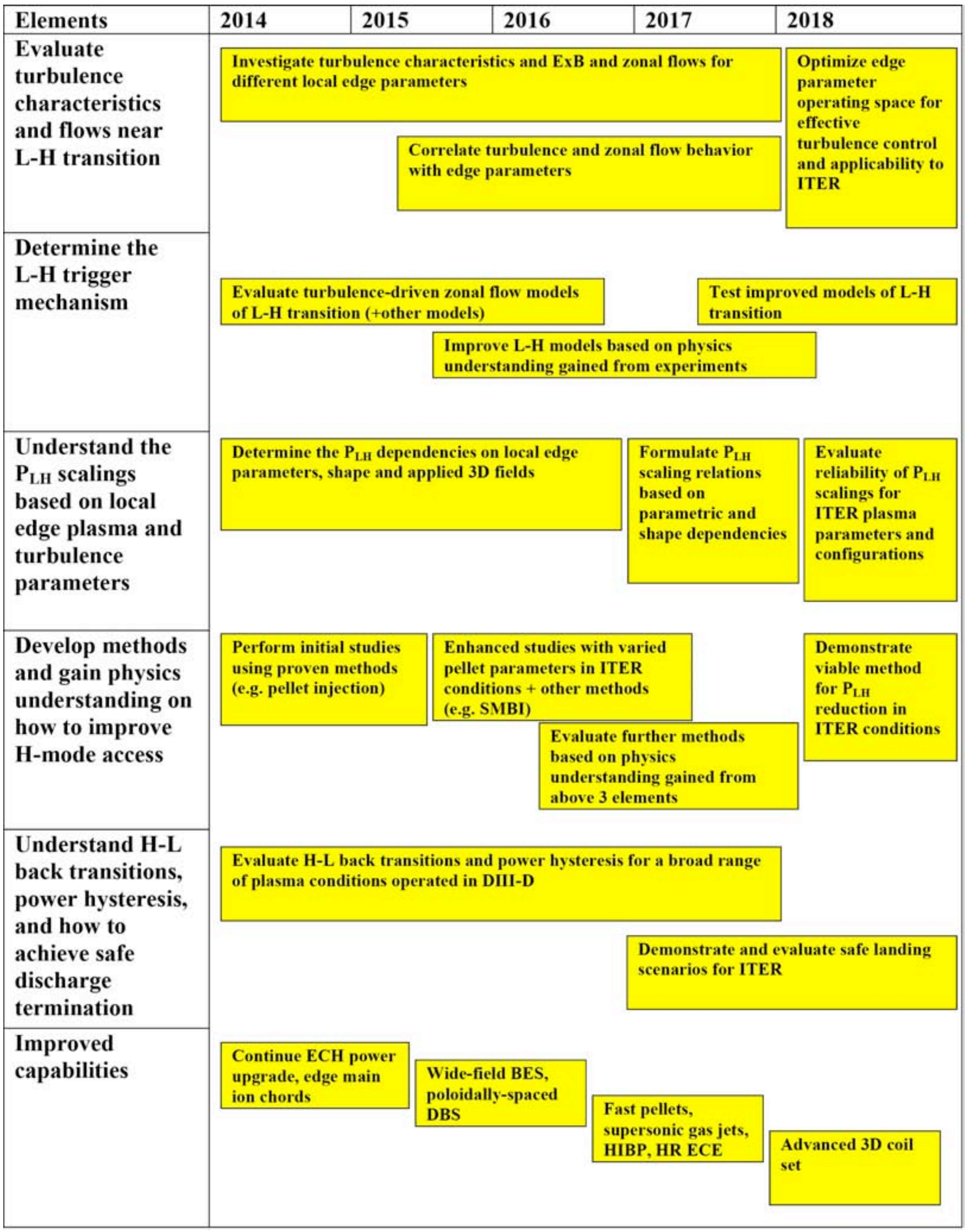

Fig. 3-17. L-H transition elements, hardware, diagnostics.

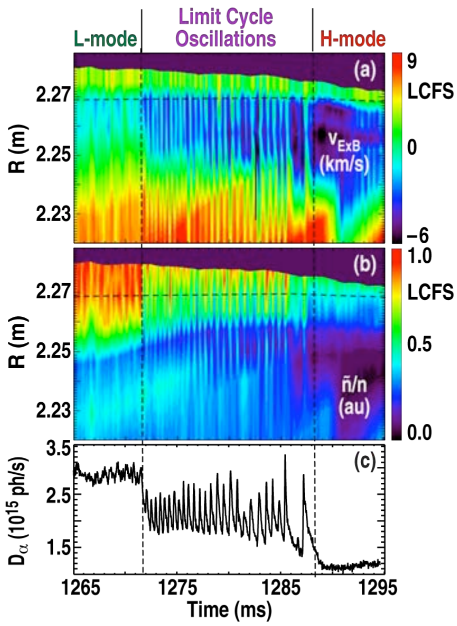

Fig. 3-18. Limit-cycle oscillations during the transition from L-mode to H-mode. (a) *ExB* flow velocity and (b) density fluctuations measured by the Doppler backscattering system (DBS). (c) Divertor D_α emission.

A crucial measurement for understanding the H-mode trigger dynamics is the turbulence correlation length, which needs to be measured with good spatiotemporal resolution and, preferably, good wavenumber resolution as well. This can be accomplished on DIII-D by the BES density fluctuation measurement and by adding the optional DBS measurement at a different radial and poloidal location. A poloidal array of DBS measurements would have the benefit of allowing the poloidal turbulence correlation length to be determined. It would also be beneficial to add a measurement of magnetic field fluctuations in the plasma edge to look for electromagnetic turbulence contributions to the L-H transition.

3.3.2.2. Physics-Based Model of L-H Power Threshold. One of our goals over the 2014–2018 period is to make significant advances in the long-term objective of developing a physics-based model of the power threshold that will allow us to make confident projections to ITER, FNSF and other burning plasma devices. Specifically, the model should predict the L-H threshold power to a similar accuracy as core transport models predict the heat flux. Initially the local parameter dependences can be determined empirically, but ultimately this should lead to the development of theory-based models. The data needed to build such a model will be obtained by

- High spatiotemporal resolution mapping of the *ExB* flows and turbulence evolution across the L-H transition using BES and DBS.
- High time resolution measurements of the density profile evolution from profile reflectometry.
- Documenting correlation between transition power threshold and measured flow/turbulence dynamics during scans of the density, magnetic field strength, ion mass, toroidal rotation, 3D fields and safety factor.
- Quantitatively comparing the measured turbulence decorrelation rates with shearing rates.

Efforts should be made to examine the relationships between the L-H transition theories and models dependent on local parameters to the global parameter scalings, such as with density and magnetic fields.

As the edge parameters at the instant of transition to H-mode are actually determined by L-mode physics, the edge transport shortfall in L-mode (Section 3.2.2.3) is a hindrance to developing a physics-based model of the L-H power threshold, which is one reason why there continues to be an emphasis on understanding L-mode transport on DIII-D.

A number of general models have been developed that describe aspects of the L-H transition. These invoke the action of zonal flows and/or GAMs interacting with ambient turbulence, suppressing the turbulence, and thus triggering the transition [Miki 2010, Miki 2012, Kim 2003]. To test these models, and put the physics concepts on a more quantitative basis, important features of the turbulence, zonal flow, GAM, and equilibrium flows will be compared as the plasma evolves from far away from the H-mode, to near the H-mode, and then across the transition itself. In addition, it is important for these models to be implemented in nonlinear simulations of the edge, such as the BOUT++ code [Dudson 2009]. One area of focus will be to examine the transfer of energy from ambient, higher frequency turbulence, into zonal flows and/or GAMs, and how this process is affected by heat flux, plasma parameters, gradients, and equilibrium flows. Measurements obtained with Langmuir probes, BES and DBS will allow for extraction of these key energy flow features, which can then be compared with simulations.

A key variable that strongly affects the H-mode threshold power is the plasma shape (as shown in Fig. 3-19), and experiments on DIII-D will study the microphysics behind the impact of plasma shaping and divertor geometry on L-H transition physics. A starting point will be the known influence of plasma shape on the turbulence drive, the radial profile of self-generated and equilibrium *ExB* flows, and the turbulent eddy topology and propagation [Fenzi 2005]. The divertor geometry also influences neutral recycling and probably (indirectly) flow damping, as well as drifts in the SOL and their coupling to the confined closed field-line plasma.

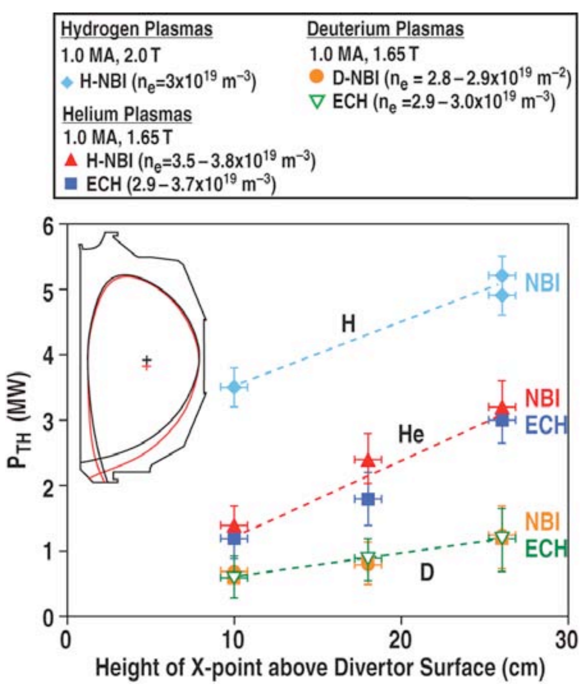

Fig. 3-19. The H-mode power threshold as a function of the height of the lower X-point with respect to the lower divertor surface for H, D and He plasmas and different auxiliary heating schemes. The density values in brackets correspond to the range of L-mode densities used in the scan.

The creation and testing of theory-based models of the H-mode power threshold will be aided by improved measurements of the edge profiles, including density, temperature, rotation and the radial electric field. The high spatial resolution Thomson scattering (TS) system will improve the measured n_e and T_e profiles in the edge. Adding new edge CER channels in the region R=2.20–2.32 m to measure the D_α spectrum will allow the deuterium density, temperature and rotation to be determined. Better determination of the edge E_r well can be accomplished several ways. The edge CER upgrade option includes additional poloidal and toroidal rotation measurements using carbon that will double the spatial range where high spatial resolution E_r measurements are made (covering the same R=2.20–2.32 m range as the D_α measurement). The optional HNBP will allow high-resolution spatiotemporal measurements of the E_r well inside the separatrix. The high DBS radial resolution allows dynamically tracking/mapping the formation of the velocity shear layer. Also the pitch angle measurements from the lithium beam system and edge MSE can be analyzed to determine the current density profile in the edge. Improved ability to control external factors that influence the H-mode threshold power, such as the RMP spectrum or the injected torque (Fig. 3-20), will also be useful for L-H threshold studies.

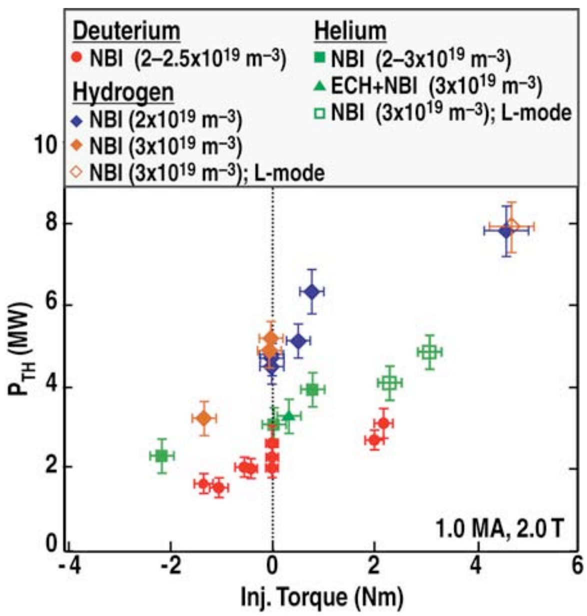

Fig. 3-20. The net power required to access the H-mode as a function of the injected torque for various target densities and heating methods for hydrogen, deuterium and helium. The target (i.e., L-mode) densities are indicated in parenthesis. The open symbols denote discharges that failed to transition to H-mode at the applied power.

3.3.2.3. Techniques to Lower Threshold Power. An important deliverable of this research is the development of new techniques to lower the H-mode threshold power, especially for burning plasma devices like ITER and FNSF that will have limited auxiliary heating power (relative to the size). The goal is to use the physics knowledge gained to plan experiments to determine both the means and the optimization of methods that can significantly (>30%) reduce the power requirements to access H-mode plasmas. Some techniques may come directly from the physics experiments described in the previous two sections. Other methods not yet discussed will be explored include:

- Fast perturbative particle injection, such as from pellets or supersonic gas jets.
- Optimize techniques that have a strong effect on threshold (e.g., divertor geometry effects).

Pellet-induced H-mode transitions have been shown to decrease the H-mode power threshold by 30%–40% for a given set of conditions [Gohil 2011]. Also, H-mode power threshold is strongly affected by certain plasma configurations, such as the magnetic geometry in the vicinity of the divertor.

As experiments in DIII-D have shown that the H-mode threshold power decreases as one shifts from co-NBI to balanced-NBI [Gohil 2010], the application of ECH power can be used to determine if the H-mode threshold power is lower than that derived from NBI-dominated databases in reactor-relevant conditions. In addition, this threshold dependence on rotation could be related to underlying changes in the edge turbulence and zonal flow properties that favored the transition at lower injected torque [McKee 2009], suggesting that the macroscopic scaling behavior can be correlated with edge turbulence properties.

Capabilities and Improvements. Control tools that can affect the H-mode threshold power are desired, both from the point of view of testing our understanding of the L-H transition physics and because they reproduce processes relevant to burning plasmas devices. For example, DIII-D has shown previously that the H-mode threshold power depends on the injected torque [Gohil 2010]. As ITER will have a high moment of inertia, and thus will likely rotate with a small Mach number, it is useful on DIII-D to study the L-H transition physics in plasmas with little injected torque. The planned increase in ECH power, and the ability to steer the power deposition, will accomplish this. The ability to control the edge density gradient using fast pellet injection is an important tool for lowering the threshold power. Additionally, machines like ITER may use RMP to suppress ELMs for reasons of divertor heat flux reduction [Evans 2004, Evans 2008], but RMP can also increase the H-mode threshold power. To accomplish the goals described in this section, upgraded control tools are crucial, as summarized in Table 3-19. The first two are considered essential requirements, while the last one is highly desirable.

Table 3-19
New Control Tools for L-H Studies on DIII-D

Hardware Capability	New Physics
Higher power ECH	Effect of torque/rotation on transition
Fast pellet injection	Effect of edge density gradient on threshold power
Advanced 3D-coils	Helical magnetic field perturbations

There are several planned upgrades to the DIII-D diagnostic set that will benefit research on the physics of the L-H transition, as seen in Table 3-20. Perhaps the most important issue is to better measure the interaction between self-generated or equilibrium flows and turbulent eddies, which should to help understand the dynamics of the L-H trigger. Measurements should be wavenumber resolved and have high spatiotemporal resolution, which is possible with the optional poloidally spaced DBS array. A number of poloidally spaced measurements of intermediate-k density fluctuations using DBS would allow a determination of the poloidal turbulence correlation length, which is crucial to understanding the H-mode trigger dynamics; radial and poloidal correlation lengths for low-k turbulence can be measured with BES. Together with a BES measurement of low-k density fluctuations, the DBS measurements provide crucial data on the spatiotemporal evolution and interaction of zonal flows and turbulence. The high radial resolution of the DBS array will also allow dynamically tracking/mapping the formation of the shear layer during the L-H transition. Another area of fluctuation measurement that little is known about is electromagnetic effects, which could originate from edge resistive ballooning modes as modeled by BOUT++. Implementing cross polarization scattering or increasing the sensitivity of Faraday rotation polarimetry and adding a dedicated channel that only passes through the plasma edge should allow measurements of magnetic field fluctuations.

Table 3-20
Hardware and Diagnostic Improvements for L-H Transition Physics

Scientific Objective	Physics Variable	Hardware/Diagnostic
Interaction between zonal flows and edge turbulence	Turbulence correlation lengths with good *k*/radial/time resolution	2nd DBS option, HNBP option, UF-CHERS upgrade option
Electromagnetic contributions to edge turbulence	Fluctuations in B	Higher sensitivity and more chords for Faraday rotation polarimeter, CPS
Edge profile measurements	n_e, n_i, T_e, T_i, V_ϕ, J_ϕ, E_r	High spatial resolution for edge TS and ECE, upgraded density reflectometer, main ion CER upgrade, lithium beam upgrade, edge MSE, edge carbon CER option, HNBP option
Effect of edge neutrals	Poloidal dependence of n_0	TBD

In addition to fluctuation measurements, upgrades to edge profile measurements will also benefit L-H transition studies, especially in regard to developing theory-based models of the H-mode power threshold. Improved edge profile measurements will help develop validated models of L-mode transport, which in turn will give a better predictive capability of edge parameters that govern the L-H transition. On DIII-D, the high spatial resolution edge TS, ECE and density reflectometer measurements will provide better electron density and temperature profiles. Adding CER channels in the region R=2.20–2.32 m to measure the D_α spectrum will give new measurements of the deuterium density, temperature and rotation in the plasma edge. The option for doubling the spatial range of the high spatial resolution region for the carbon CER measurement will provide accurate E_r determination for a greater range of plasma shapes. A new HNBP can also give high-resolution spatiotemporal measurements of the E_r well inside the pedestal. New analysis techniques for the lithium beam polarimetry and edge MSE will allow us to a better determination of the radial electric field in the transition zone. The neutral density can act as a hidden variable in the physics of the L-H transition, and several ideas to measure the poloidal distribution of edge neutrals are in the works.

3.3.3. Impact

The H-mode edge transport barrier is crucial for achieving the confinement and fusion power goals of ITER and FNSF. Understanding, predicting and controlling both the L-H and H-L transitions are crucial components of successful scenario operation in both devices, and experiments planned on DIII-D for the 2014–2018 period will address this by

- Connecting the L-H transition to the edge gradients and pedestal physics of L-mode plasmas to develop a physics based model of the H-mode power threshold.

- Determining the mechanism(s) that trigger the L-H transition, thus improving the ability to predict the timing of the L-H transition in discharge simulations.
- Building a predictive knowledge of the H-L transition to control its timing for safe current ramp down in ITER.
- Lowering the H-mode power threshold to improve access in large devices with marginal external heating power.

Experiments on DIII-D will use our extensive edge diagnostic set (especially turbulence diagnostics) and plasma flexibility to determine the physics behind the H-mode transition and to develop a physics-based model over a range of burning plasma relevant conditions. This will give confidence in predictions for future burning plasma experiments.

3.4. PLASMA ROTATION

The physics of plasma rotation has strong connections to the physics of turbulence and transport. The plasma rotation is the consequence of the balance between sources and sinks of torque and momentum transport, and many of the techniques used to study particle and heat transport can be applied to momentum transport as well.

3.4.1. Challenges

The goal of rotation research on DIII-D is to develop a first principles understanding of the various sources and sinks of torque in the plasma, including that which gives rise to “intrinsic” rotation, as well as a validated theory-based model of momentum transport. The main research goals for DIII-D on the topic of plasma rotation during the period 2014–2018 are summarized in Table 3-21.

Table 3-21
Rotation Physics Development

<table>
<tr><th>Challenge</th><th>Approach</th><th>Capability Improvements</th></tr>
<tr><td>Manipulate and control the rotation profile to maximize confinement and stability using means applicable to future burning plasmas</td><td>Utilize advanced 3D coil set and high power ECH, joint experiments with rf-heated devices like C-Mod and EAST</td><td rowspan="7">Actuators:
• ECH power upgrade
• Second off-axis beam
• Advanced 3D coil set

Measurements:
• 3D magnetics
• Main ion CER upgrade
• Edge CER (carbon) upgrade option
• XCS option

Codes:
• TGLF/GYRO
• IPEC-NTV</td></tr>
<tr><td colspan="2">Sources:</td></tr>
<tr><td>Determine key properties of intrinsic torque:
• Size scaling for extrapolation to ITER and burning plasmas
• Role of edge rotation layer in establishing rotation profile</td><td>ρ^* scaling experiments with JET, investigate (β, ν^*, q, …) dependences using new edge rotation measurements of carbon and deuterium, study torque-free heating with ECH</td></tr>
<tr><td>Quantitatively understand and benchmark NTV torque via targeted comparisons between data and existing models and codes</td><td>Utilize advanced 3D coil set and 3D magnetics, study torque-free heating with ECH</td></tr>
<tr><td colspan="2">Transport:</td></tr>
<tr><td>Determine whether turbulence can explain difference between measured and neoclassical poloidal rotation</td><td>Use multiple CER systems to accurately measure carbon and deuterium poloidal rotation, multi-field turbulence measurements, dimensionless parameter dependences</td></tr>
<tr><td>Test and optimize integrated models of momentum and energy/particle transport</td><td>Multi-channel transport experiments making extensive use of modulation techniques, validation studies of gyrokinetic codes</td></tr>
</table>

An important goal of this research is to confidently predict the plasma rotation profile on ITER and FNSF through validated models of momentum transport and quantitative assessment of the various torques (i.e., intrinsic, NTV and other magnetic sources). Such projections for ITER are important for determining whether the rotation will be sufficient, for example, to stabilize resistive wall modes (RWMs). Similarly, understanding the NTV torque is one of the most important aspects needed to assess the viability of the QH-mode scenario is future burning plasma devices. In addition, strongly self-heated plasmas such as DEMO will have little external momentum injection, and will therefore need to rely on self-generated or intrinsic torques for rotation. Regarding confinement projections for ITER and FNSF, the poloidal rotation has an increasingly important role in determining the *ExB* shear stabilization of turbulence since the toroidal rotation is low. Presently theory-based transport models often assume that the poloidal rotation is neoclassical, but there is ample experimental evidence that this is not the case [Grierson 2012, Solomon 2006, deGrassie 2007, Bell 1998, Crombé 2005] and a first principles understanding of poloidal rotation is needed.

Many of the hardware upgrades planned for DIII-D in 2014–2018 will strengthen the rotation physics program. The 8.5 MW ECH system will allow DIII-D to study high-beta plasmas with torque-free heating, and a second off-axis neutral beamline will allow DIII-D to vary the torque deposition profile for momentum transport experiments. An advanced 3D coil set will let us study and optimize magnetic torques as a function of the spectrum. Besides improving our ability to diagnose 3D magnetic fields, the diagnostic upgrades will allow much improved measurements of the deuterium, and optionally edge carbon, rotation, which is the key physics region for many of our studies. Momentum transport is currently being implemented in many of our important transport codes, such as TGLF and GYRO. Additionally, the study of NTV and other magnetic torques need improved calculations of the plasma response to externally applied 3D fields.

3.4.2. Research

Overview. Rotation physics research on DIII-D is a natural extension of transport research with greater emphasis on understanding the sources and sinks compared to particle and heat transport. A summary of the research plan in rotation physics for the period 2014–2018 is found in Fig. 3-21. The experimental plan on rotation physics combines two areas of strength on DIII-D — flexible sources of torque injection (including NTV torque) and an outstanding diagnostic set for transport and turbulence measurements — and has the overarching goal of controlling the rotation profile in ITER and FNSF.

Detailed Research Plan. There are four main research elements: intrinsic rotation, NTV and magnetic torques, poloidal rotation and momentum transport. All elements have a strong emphasis on comparison with theory-based models, such as NCLASS and NEO for neoclassical momentum transport, GYRO, TGLF and GS2 for turbulent momentum transport, XGC0 and other edge codes to predict edge boundary conditions for rotation, and IPEC-NTV, M3D-C1 and MARS-Q for torques from 3D fields.

3.4.2.1. Intrinsic Rotation. One of the most important discoveries in rotation physics is that plasmas can have strong toroidal rotation without external torque injection. This was first definitively demonstrated with ion cyclotron radio frequency (ICRF) heating on ALCATOR C-Mod [Rice 1998, Hutchinson 2000], and has been studied in DIII-D using both ECH [deGrassie 2007, deGrassie 2004] and balanced-NBI [Solomon 2009]. Intrinsic rotation [Ida 1998], or as Bruno Coppi called it, spontaneous rotation [Coppi 2002], is in some sense a manifestation of self organization in the confined toroidal plasma, and as such we expect that turbulence will play a key role in the final state. In L-mode plasmas a variety of intrinsic rotation profiles are realized, with the striking property of sudden reversals of the sign of rotation as parameters such as the plasma density or the magnitude of the plasma current are varied [Rice 2011, Duval 2008]. In H-mode it is generally observed that a more universal intrinsic rotation profile develops, having a co-rotation profile that may be hollow, or peaked on axis [deGrassie 2009], a phenomenon that may be associated with a transition in the dominant turbulence mode, for example from ion temperature gradient (ITG) modes to trapped electron modes (TEMs) [Angioni 2011].

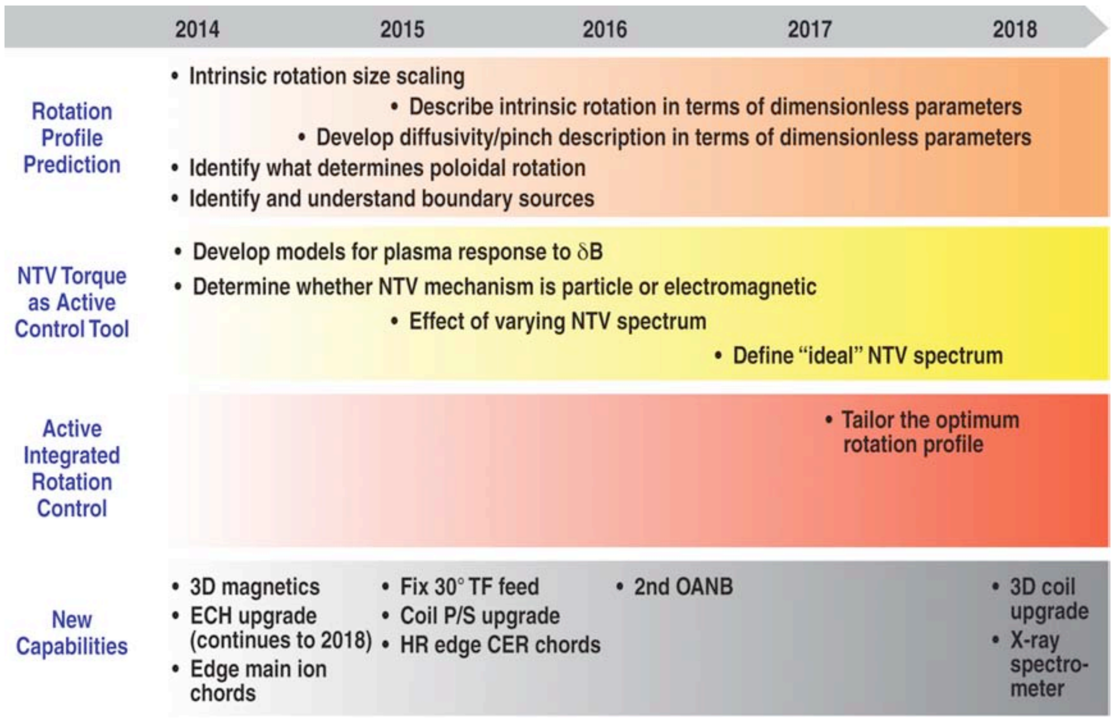

Fig. 3-21. Rotation program elements, hardware, diagnostics.

A critical question for predicting rotation on ITER and FNSF is how does the intrinsic drive and intrinsic rotation velocity scale with plasma size? This can be couched in terms of dimensionless parameters by asking what is the ρ^* scaling of the Mach number from intrinsic rotation? One possible approach to investigating this on DIII-D is to make a reduced minor-radius plasma and then vary the major radius to observe the effect on the intrinsic rotation. Additionally, there is an ITPA joint experiment in the Transport and Confinement Topic Group to address the ρ^* scaling of intrinsic torque. DIII-D will play a key role in this joint experiment by making a similarity match with JET (i.e., matching all of the important dimensionless parameters) followed by a ρ^* scan in an H-mode edge plasmas. The size difference between DIII-D and JET means that the ρ^* scan can cover twice the range as either machine by itself. It would be advantageous to study intrinsic rotation without torque injection at the same collisionality and beta ($\beta_N \gtrsim 1.8$) as ITER using the increased ECH power (along with optional FW heating). Comparisons can be made with other rf-heated tokamaks such as ALCATOR C-Mod and China's Experimental Advanced Superconducting Tokamak (EAST). To avoid the large perturbations to the plasma from using high-power heating beams for CER measurements, the studies of intrinsic rotation with dominant rf heating would benefit from the use an optional x-ray crystal spectrometer to make a passive measurement of the spectrum from high-Z impurities (such as argon) to allow T_i and V_ϕ measurements without NBs.

Another aspect of intrinsic torque research is to clarify the role of thermal ion orbit losses [Chang 2008, deGrassie 2012, Müller 2011], turbulent Reynolds stress [Müller 2011] and neutrals [Versloot 2011] in producing the observed intrinsic flows. Figure 3-22 shows that a simple orbit loss model can correctly predict the existence, direction, position and width of the co-rotating layer measured by probes in the edge of H-mode plasmas on DIII-D. In principle, all of these processes can be contributing, so to understand their relative importance we will benchmark the experiments against models of edge rotation generation beginning with simple tests of the dependences on the directions of plasma current and toroidal magnetic field. An important diagnostic enhancement for this research is an edge measurement of the main ion (deuteron) rotation, which can be accomplished by adding new CER channels to measure the D_α spectrum between R=2.20 and 2.32 m. Towards our goal of controlling the intrinsic rotation profile, we will try to develop methods to manipulate the edge rotation layer. Another possible method of control is to manipulate the pressure profile (thermal and fast ions).

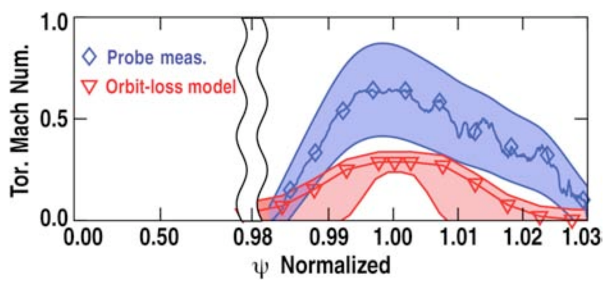

Fig. 3-22. Measured co-rotation layer at the edge of an H-mode plasma on DIII-D (blue) and predicted co-rotation from a simple orbit loss model (red).

Finally, experiments on DIII-D will study the difference between intrinsic rotation in the impurity ions and main ions. Usually intrinsic rotation measurements use impurity ions such as carbon or argon, but as displayed in Fig. 3-23 DIII-D has the new capability of measuring the main ion (deuteron) rotation in the plasma core (with plans to extend this measurement to the edge/pedestal region). This is an important distinction since there is some question as to which rotation "matters" in various physics phenomenon, e.g., mode locking, RWM and neoclassical tearing mode (NTM) stability, island formation, etc. Is the important rotation the main ion rotation, *ExB* rotation, $V_{\perp e}$, or shear in those quantities that affect a given process? Differences between impurity and main ion intrinsic rotation may yield important insights as to the underlying physical processes.

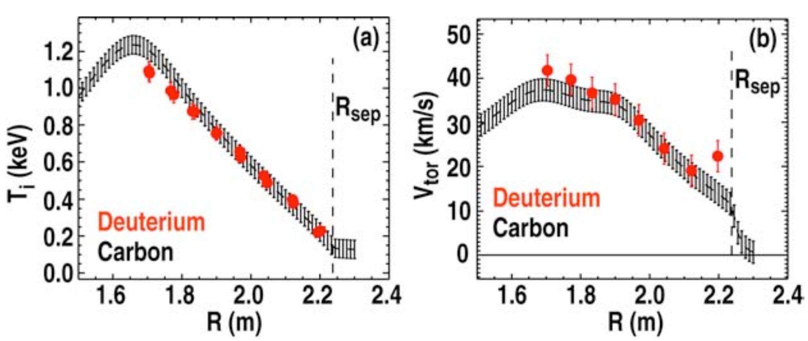

Fig. 3-23. Spectroscopic measurements of main-ion deuterium (red circles) and impurity carbon (black dash line) (a) ion temperature and (b) toroidal rotation velocity.

3.4.2.2. NTV and Other Magnetic Torques. The physics of the interaction of non-axisymmetric, static magnetic fields with a rotating plasma has been the subject of extensive theoretical and experimental studies. It is useful to divide the non-axisymmetric fields into two categories, depending on whether the structure is resonant or non-resonant with respect to the field lines of the plasma. For resonant magnetic fields, plasma rotation at a rate larger than the rate at which magnetic reconnection occurs leads to eddy currents on the resonant surface that shield the plasma from the resonant error field. However, because of plasma resistivity, the shielding is not perfect, and a braking torque inversely proportional to the plasma toroidal rotation results from the eddy currents crossed with the error magnetic field. Non-resonant magnetic fields also can apply a torque on a rotating plasma owing to untrapped-particle ripple drag, trapped-particle ripple drag and trapped-particle radial banana-drift effects. As highlighted by recent work on the neoclassical theory of toroidal flows ([Cole 2007] and references therein), the torque from non-resonant magnetic fields has an offset linear relationship with the plasma rotation. The offset rotation in this relationship is comparable in magnitude to the ion diamagnetic rotation, but it is in the counter-I_p direction. Therefore, non-resonant magnetic fields applied to co-rotating plasmas apply a braking torque that can render the plasma less resilient to penetration of resonant error fields by reducing the threshold of the resonant error field above which a bifurcation occurs. However, non-resonant magnetic fields applied to a plasma with near zero initial toroidal rotation lead to an acceleration toward the offset rotation value. In this case, the non-resonant torque acts in such a way to increase the resilience of the plasma to penetration of resonant error fields.

Enhancements to the auxiliary heating and 3D coil systems on DIII-D will give us great flexibility in varying the torques in the plasmas, as seen in Table 3-22, making it possible to study momentum transport more systematically. Torque-free heating experiments are possible with ECH and FW, the combination of co- and counter-NBI allows the total torque to be varied from positive to negative (including balanced injection with zero global torque), the torque profile can be switched from peaked to hollow using on-axis and off-axis NBI, and the 3D coil set can be used to apply an NTV torque. The combined set of internal and external 3D coils on DIII-D can also be used to study the interplay between resonant and nonresonant torques on the plasma rotation profile. A hardware upgrade to an advanced 3D coil set with twice the number of toroidal coils would greatly expand on our ability to separate resonant and non-resonant effects.

Table 3-22
Sources and Sinks of Momentum on DIII-D

Auxiliary System	Primarily Heats	Torque Injection
ECH	Electrons	Essentially zero
FW option	Electrons	Essentially zero
Co/Ctr NBI	Ions	Peaked profile that can be varied from positive to negative
On-axis/off-axis NBI	Ions	Vary from peaked to hollow profile
Coils (internal or external)	N/A	NTV, resonant/nonresonant braking

The accelerating torque arising from NTV is an exciting new experimental tool as it is a method of driving (counter) plasma rotation using externally applied 3D fields [Garofalo 2008]. The NTV torque has already found important applications for fusion plasmas, such as sustaining the QH-mode with low/positive torque from NBI and improving the confinement with edge *ExB* shear flow [Garofalo 2011]. DIII-D has done initial studies that compared experimental measurements of the NTV torque to theory with qualitative and semi-quantitative success [Cole 2011], as seen in Fig. 3-24; during the 2014–2018 period we plan to continue this validation and benchmarking of NTV physics at a greater level of detail. An important component is the comparison of the measured NTV torque and rotation with the physics encapsulated in codes such as IPEC-NTV, M3D-C1 and MARS-Q. For example, we will investigate the role of fast ion and 3D fields vs. pure NTV torque, since non-ambipolar radial fast ion current produces a torque, whether the fast ion transport is caused by internal magnetic modes [Okabayashi 2011], or externally applied perturbations. Also we will look at the magnitude of the NTV torque in NBI-heated vs. rf-heated plasmas for comparison with code predictions.

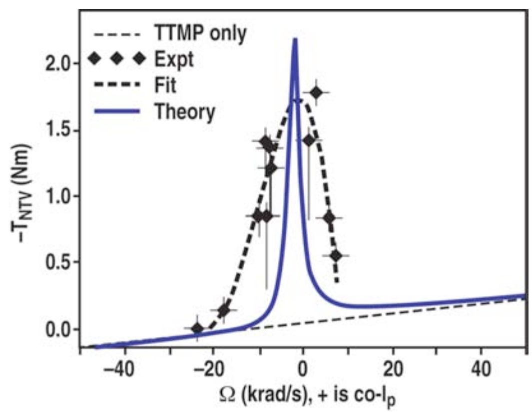

Fig. 3-24. Measured NTV torque from non-axisymmetric fields in DIII-D (black diamonds). The dash blue line is a theoretical calculation of the torque from transit time magnetic pumping (TTMP), while the solid blue line adds the theoretical NTV torque.

Greater flexibility in applying different toroidal/poloidal spectra with the 3D coil set is very important for studying NTV torques. This would also aid our study of the braking torque from resonant and non-resonant fields. Magnetic error fields can cause significant drag on the plasma rotation and act as a momentum sink in transport experiments. Therefore, it will be difficult to do quantitative tests of torques in the plasma without first detecting and characterizing the error fields. The planned addition of many new sensors for “3D” magnetics will greatly improve our study of error fields, and the installation of an advanced 3D coil set will make it easier to correct the error fields so that they do not play such a significant role in rotation studies.

3.4.2.3. Poloidal Rotation. In the poloidal direction, neoclassical theory has been shown to be inadequate to describe the poloidal rotation for both deuterium and carbon ions [Grierson 2012, Solomon 2006]. Indeed, as demonstrated in Fig. 3-25, recent main ion measurements have confirmed that the main ion poloidal rotation velocity is much larger than predicted by neoclassical theory at low collisionality. This has serious consequences in terms of the ability to connect the usual measurements of the impurity (carbon) rotation to the main ion (deuterium) rotation, which is usually done through radial force balance, using the neoclassically calculated poloidal rotation. Additionally, for the expected low toroidal rotation rates on ITER and FNSF, the poloidal rotation has an important contribution towards the radial electric field; therefore, having an accurate prediction of the poloidal rotation is important to predicting the magnitude of *ExB* shear stabilization in ITER and FNSF. Note also that the neoclassical theory of poloidal rotation also has a very close connection to NTV physics.

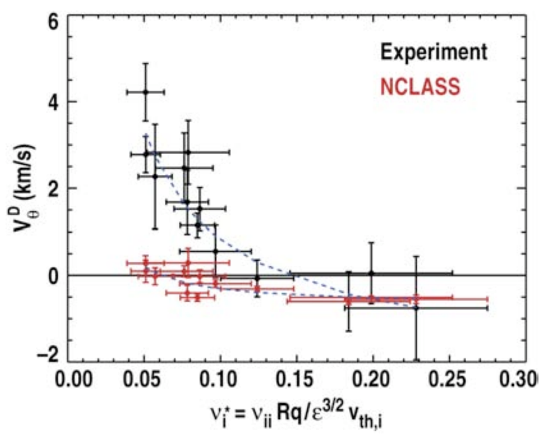

Fig. 3-25. Measured poloidal rotation velocity for main-ion deuterium (black) as a function of ion collisionality. NCLASS predictions (red) are shown for comparison.

Future experiments on DIII-D will make a more thorough benchmarking of poloidal rotation measurements vs. neoclassical codes (e.g., NCLASS, NEO). Using the newly expanded diagnostic suite on DIII-D, this comparison will be multi-faceted. The bulk of the measurements will be with the CER system tuned to carbon impurities; from this, a database will be built that overviews the discrepancy between neoclassical theory and measurement as a function of plasma condition (e.g., dimensionless parameters). This will be complemented by more detailed studies that make use of the CER channels that measure the carbon rotation both the high-field-side and low-field-side of the plasma axis [Chrystal 2012]. This diagnostic ability not only allows for improved accuracy in the poloidal rotation measurement, but it also allows us to study in/out toroidal asymmetries, and has also recently been implemented on Tokamak à Configuration Variable (TCV) [Bortolon 2013]. Finally, the difference between the toroidal rotation of the main ions and impurity ions will be studied. This difference is linked to poloidal rotation via the radial force balance equation and allows a further test of neoclassical theory.

Utilizing the excellent turbulence diagnostic set on DIII-D, experiments during 2014–2018 will examine the contribution to poloidal rotation from turbulent transport mechanisms. Based on previous work, the expectation is that neoclassical theory will fall far short of being an adequate explanation for the observed poloidal rotation rates on DIII-D. Therefore, it is expected that the poloidal rotation data will need to be compared to predictions from transport models such as GYRO that include the effects of plasma turbulence, especially in regimes where turbulent effects are predicted to be significant. Edge codes like XGC0 also will be used to predict the edge boundary conditions for rotation for comparison with experiments.

One of the long term goals of transport research on DIII-D is to develop methods of controlling transport. As the poloidal rotation makes an important contribution to the radial electric field in low toroidal rotation discharges, experiments on DIII-D will begin to investigate poloidal rotation control techniques. This can be an alternate method of controlling the *ExB* shear flow in ITER-relevant plasmas with low toroidal torque injection.

3.4.2.4. Momentum Transport. Neoclassical predictions for toroidal rotation in tokamaks have not been successful to date. Experimentally, the local toroidal momentum diffusivity χ_ϕ is found to be several orders of magnitude greater than the neoclassical prediction. Theory has suggested how the momentum diffusivity can be tied to the ion thermal diffusivity χ_i due to micro-turbulence, but even in cases where the low-*k* turbulence is seemingly suppressed and the ion thermal transport behaves neoclassically, the momentum transport remains anomalous [Greenfield 1999]. Experiments have typically revealed a nonlinear response of the angular momentum to the applied torque, indicating a torque dependence of the momentum transport [Solomon 2007]. It is speculated that the interaction of *ExB* shear with the applied torque may account for this observation.

Using the understanding of the momentum sources and sinks gained in Section 3.4.2.2, momentum transport will be characterized by studying the diffusivity, pinch and residual stress terms (the last of which is tied to intrinsic rotation generation); momentum perturbation experiments are a key way of making such assessments [Solomon 2009, Yoshida 2009, Tala 2011]. New experiments will investigate the beta dependence of the momentum pinch with joint experiments with JET and ASDEX-U. Since the main (deuteron) ions have a different rotation rate than the impurity (carbon) ions, especially for low torque injection, all ion species need to be studied. There should be continued investigation as to whether there is any fundamental relationship between χ_ϕ and χ_i, particularly under varying rotation conditions. Ultimately, the existing theories need to be tested more extensively against our experimental data. Additionally, comparisons should be pursued with gyrokinetic codes like GYRO and GS2, and theory-based transport models like TGLF, to see whether the momentum fluxes are consistent with experimental observations and can be characterized by comparable local transport quantities. It is preferable to self-consistently simulate the particle, heat and momentum transport for comparison with experiment. Edge codes like XGC0 can be used to predict the edge boundary conditions for rotation. A complete verification of the rotation model should be the ultimate goal of the momentum transport research program, and following from that one should gain an understanding of how to manipulate the rotation to maximize fusion performance.

The study of momentum transport will benefit from greater ability to vary the torque profile and the expansion of main ion measurements of toroidal and poloidal rotation in to the plasma edge/pedestal region where differences between the impurity and main ions are expected to be greater. Higher power ECH will allow DIII-D to produce higher beta plasmas that are free of torque injection, and a second off-axis beamline will allow DIII-D to study rotation in plasmas with a broader torque density profile. For plasmas with dominant rf heating, it will be beneficial to have an (optional) x-ray crystal spectrometer make the rotation measurements to avoid large perturbations to the injected torque that would otherwise occur from the high-power heating beams. The edge measurement of main ion rotation will not only enhance the ability to test theoretical models of toroidal/poloidal rotation, but it may also yield insights as the underlying nature of edge rotation that could be used to control the plasma rotation profile in the future.

Capabilities and Improvements. Studies of plasma rotation on DIII-D will benefit from greater ability to control torques separate from heating (and separate from fast ion effects). The proposed hardware upgrades in this area are listed in Table 3-23, with the first two items considered essential requirements and the last item highly desirable. Higher power ECH is crucial to allowing the study of plasma rotation in torque-free plasmas at higher β_N, and has the additional benefit of not generating fast ions. A second off-axis beamline will also be useful, not because it is torque-free heating but because it allows DIII-D to change from a peaked to hollow torque density profile. Similarly, torque experiments on DIII-D will benefit from a more flexible 3D coil set as a means of testing NTV and resonant torques as a function of the applied toroidal/poloidal spectra.

Table 3-23
New Control Tools for Rotation Studies on DIII-D

Hardware Capability	New Physics
Increase ECH to 8.5 MW	Dependence of rotation on torque density profile (and without fast ions)
Advanced 3D-coils	Test NTV/resonant torques with different applied spectra
Second off-axis beamline	Dependence of rotation on torque density profile

The new plasma diagnostics for rotation experiments during the 2014–2018 period are listed in Table 3-24. Magnetic error fields can be a significant source of drag on the plasma rotation; this "hidden" sink of momentum can complicate momentum transport studies. The 3D magnetics planned on DIII-D will greatly enhanced our ability to detect and characterize the error fields, and the flexibility of an advanced 3D coil set with up to 12 toroidal coils will improve our ability to correct the error fields. The plasma edge/pedestal region is of interest to rotation physics experiments as it sets the boundary condition for intrinsic rotation cases, and because the difference between impurity ion and main ion rotation is predicted to be greater. Based on the success of the core main ion diagnostic on DIII-D [Grierson 2012], it is proposed to add new edge CER channels in the region R=2.20–2.32 m to measure the D_α spectrum. Improved impurity ion measurements in the plasma edge will be possible with the optional addition of high spatial resolution CER chords. These upgrades supports intrinsic rotation and (indirectly) poloidal rotation studies. Continued study of intrinsic rotation can be greatly improved by the addition of an alternate method of measuring rotation without using high-power NBI. One option worth considering would be an x-ray crystal spectrometer similar to that used on C-Mod to look at high-Z impurity ions such as argon.

Table 3-24
Diagnostic Improvements for Rotation Physics

Scientific Objective	Physics Measurement	Hardware/Diagnostic
Characterize/detect/correct error fields	Radial/poloidal magnetic fields	3D magnetics
Test NTV/resonant torques with different applied spectra	Impurity/main ion rotation	Main ion CER upgrade, high-res edge CER chords (carbon) option
Edge rotation boundary condition for intrinsic and momentum transport studies	Main ion (deuteron) rotation measurements in edge/pedestal region	Main ion CER upgrade (R = 2.2 to 2.32 m)
Core rotation measurement in torque-free plasmas	Passive spectroscopy of high-Z impurities with high time resolution	XCS option

All elements of plasma rotation research on DIII-D have an emphasis on comparison with theory-based models. A list of the codes that will be used in the 2014–2018 period are their purpose is shown in Table 3-25.

Table 3-25
Codes Used for Plasma Rotation Research

Code	Purpose
XGC0	Edge boundary modeling
GYRO, TGLF, GS2	Turbulent transport modeling
NCLASS, NEO	Neoclassical modeling
IPEC-NTV, M3D-C1, MARS-Q	Plasma response to 3D fields; calculate NTV and other magnetic torques

3.4.3. Impact

Meeting the challenges given in Table 3-21 will have an important influence on burning plasma physics:

- Ability to use intrinsic rotation and other non-traditional sources of torque to control the plasma rotation profile in ITER and FNSF to avoid mode locking, RWM, etc.
- More accurate prediction of intrinsic torque and NTV torque, thus determining whether future burning plasma experiments need other external sources of plasma rotation.
- Determination if poloidal rotation, possibly driven by turbulence, is able to improve confinement in ITER and FNSF by increasing the core *ExB* shear.
- Validation of theoretical models of momentum transport in ITER-relevant regimes with significant β_N but low net injected torque using balanced NBI or strong rf heating.

Enhancements to diagnostics, 3D coil systems, torque-free ECH and a second off-axis beamline will give DIII-D great flexibility in pursuing these plasma rotation experiments.

3.5. REFERENCES FOR SECTION 3

[Angioni 2005] C. Angioni et al., Phys. Plasmas **12**, 040701 (2005).
[Angioni 2011] C. Angioni et al., Phys. Rev. Lett. 1**07**, 215033 (2011).
[Baker 2000] D.R. Baker et al., Nucl. Fusion **40**, 799 (2000).
[Bell 1998] R.E. Bell et al., Phys. Rev. Lett. **81**, 1429 (1998).
[Bortolon 2013] A. Bortolon et al., Nucl. Fusion, **53** 023002 (2013).
[Callen 2007] J.D. Callen et al., Nucl. Fusion **47**, 1449 (2007).
[Casper 2011] T.A. Casper et al., Nucl. Fusion **51** 013001 (2011).
[Chang 2008] C.S. Chang and S. Ku, Phys. Plasmas **15**, 062510 (2008).
[Chrystal 2012] C. Chrystal et al., Rev. Sci. Instrum. **83**, 10D501 (2012).
[Cole 2007] A. Cole, C. Hegna, and J. Callen, PRL **99**, 065001 (2007).
[Cole 2011] A.J. Cole et al., Phys. Plasmas **18**, 055711 (2011).
[Coppi 2002] B. Coppi, Nucl. Fusion **42**, 1 (2002).
[Crombé 2005] K. Crombé et al., Phys. Rev. Lett. **95**, 155003 (2005).
[deGrassie 2004] J.S. deGrassie et al., Phys. Plasmas **11**, 4323 (2004).
[deGrassie 2007] J.S. deGrassie et al., Phys. Plasmas **14**, 056117 (2007).
[deGrassie 2009] J.S. deGrassie, Plasma Phys. Control. Fusion **51**, 124047 (2009).
[deGrassie 2012] J.S. deGrassie et al., Nucl. Fusion **52**, 013010 (2012).
[Diamond 2005] P.H. Diamond et al., Plasma Phys. Control. Fusion **47**, R35 (2005).
[Dudson 2009] B.D. Dudson et al., Comput. Phys. Commun. **180**, 1467 (2009).
[Duval 2008] B.P. Duval et al., Phys. Plasmas **15**, 056113 (2008).
[Evans 2004] T.E. Evans et al., Phys. Rev. Lett. **92**, 235003 (2004).
[Evans 2008] T.E. Evans et al., Nucl. Fusion **48**, 024002 (2008).
[Fenzi 2005] C. Fenzi et al., Phys. Plasmas **12**, 062307 (2005).
[Garofalo 2008] A.M. Garofalo et al., Phys. Rev. Lett. **101**, 195005 (2008).
[Garofalo 2011] A.M. Garofalo et al., Nucl. Fusion **51**, 083018 (2011).
[Gohil 2010] P. Gohil et al., Nucl. Fusion **50**, 064011 (2010).
[Gohil 2011] P. Gohil et al., Nucl. Fusion **51,** 103020 (2011).
[Greenfield 1999] C.M. Greenfield et al., Nucl. Fusion. **39**, 1723 (1999).
[Grierson 2012] B.A. Grierson et al., Phys. Plasmas **19**, 056107 (2012).
[Heidbrink 2007] W.W. Heidbrink et al., Phys. Rev. Lett. **99**, 245002 (2007).
[Heidbrink 2011] W.W. Heidbrink et al., Plasma Phys. Control. Fusion **53**, 085007 (2011).
[Holland 2009] C. Holland et al., Phys. Plasmas **16**, 052301 (2009).
[Holland 2011] C. Holland et al., Phys. Plasmas **18**, 056113 (2011).
[Hubbard 2011] A.E. Hubbard et al., Phys. Plasmas **18**, 056115 (2011).
[Hutchinson 2000] I.H. Hutchinson et al., Phys. Rev. Lett. **84**, 3330 (2000).
[Ida 1998] K. Ida et al., Plasma Phys. Control. Fusion **40**, 1429 (1998).
[Ince-Cushman 2008] A. Ince-Cushman et al., Rev. Sci. Instrum. **79**, 10E302 (2008).
[ITER 1999] ITER Physics Basis, Nucl. Fusion **39**, 2391 (1999).
[Kim 2003] E.J. Kim and P.H. Diamond, Phys. Rev. Lett. **90**, 185006 (2003).

[Kramer 2012] G.J. Kramer et al., "Observation of Localized Fast-Ion Induced Heat Loads in Test Blanket Module Simulation Experiments on DIII-D," Proc. 24th IAEA Fusion Energy Conf., San Diego, California 2012, Paper ITR/P1-32.

[Martin 2008] Y.R. Martin et al., J. Phys.: Conf. Ser. **123,** 012033 (2008).

[Maslovsky 2003] D. Maslovsky, B. Levitt and M.E. Mauel, Phys. Plasmas **10**, 1549 (2003).

[McKee 2000] G. McKee et al., Phys. Rev. Lett. **84**, 1922 (2000).

[McKee 2009] G.R. McKee et al., Nucl. Fusion **49**, 115016 (2009).

[McKee 2012] G.R. McKee et al., "Turbulence and Transport Response to Resonant Magnetic Perturbations in ELM-Suppressed Plasmas on DIII-D," Proc. 24th IAEA Fusion Energy Conf., San Diego, California 2012, Paper EX/P7-06.

[Messiaen 1996] A.M. Messiaen et al., Phys. Rev. Lett. **77**, 2487 (1996).

[Miki 2010] K. Miki and P.H. Diamond, Phys. Plasmas **17**, 032309 (2010).

[Miki 2012] K. Miki et al., Phys. Plasmas **19**, 092306 (2012).

[Müller 2011] S.H. Müller et al., Phys. Rev. Lett. **106**, 115001 (2011).

[Okabayashi 2011] M. Okabayashi et al., Phys. Plasmas **18**, 056112 (2011).

[Pace 2011] D.C. Pace et al., Plasma Phys. Control. Fusion **53**, 062001 (2011).

[Petty 1995] C.C. Petty et al., Phys. Rev. Lett. **74**, 1763 (1995).

[Petty 2000] C.C. Petty et al., Plasma Phys. Control. Fusion **42**, B75 (2000).

[Petty 2008] C.C. Petty, Phys. Plasmas **15**, 080501 (2008).

[Rice 1998] J.E. Rice et al., Nucl. Fusion **38**, 75 (1998).

[Rice 2011] J.E. Rice et al., Nucl. Fusion **51**, 083005 (2011).

[Ryter 1996] F. Ryter et al., Nucl. Fusion **36,** 1217 (1996).

[Salewski 2012] M. Salewski et al., Nucl. Fusion **52,** 103008 (2012).

[Schmitz 2012] L. Schmitz et al., Phys. Rev. Lett. **108**, 155002 (2012).

[Shafer 2012] M.W. Shafer et al., Phys. Plasmas **19**, 032504 (2012).

[Shinohara 2011] K. Shinohara et al., Nucl. Fusion **51**, 063028 (2011).

[Solomon 2006] W.M. Solomon et al., Phys. Plasmas **13**, 056116 (2006).

[Solomon 2007] W.M. Solomon et al., Plasma Phys. Control. Fusion **49**, B313 (2007).

[Solomon 2009] W.M. Solomon et al., Nucl. Fusion **49**, 085005 (2009).

[Spong 2011] D.A. Spong, Phys. Plasmas, **18** 056109 (2011).

[Spong 2012] D.A. Spong et al., Phys. Plasmas **19**, 082511 (2012).

[Tala 2011] T. Tala et al., Nucl Fusion **51**, 123002 (2011).

[Tynan 2009] G.R. Tynan et al., Plasma Phys. Control. Fusion **51**, 113001 (2009).

[Uzun-Kaymak 2012] I.U. Uzun-Kaymak et al., Rev. Sci. Instrum. **83**, 10D526 (2012).

[VanZeeland 2006] M.A. Van Zeeland et al., Phys. Rev. Lett. **97** 135001 (2006).

[VanZeeland 2008] M.A. Van Zeeland et al., Plasma Phys. Control. Fusion **50**, 035009 (2008).

[VanZeeland 2011] M.A. Van Zeeland et al., Phys. Plasmas **18**, 056114 (2011).

[Vermare 2008] L. Vermare et al., J. Phys.: Conf. Ser. **123**, 012040 (2008).

[Versloot 2011] T.W. Versloot et al., Plasma Phys. Control. Fusion **53**, 065017 (2011).

[White 2008] A.E. White et al., Rev. Sci. Instrum. **79**, 103505 (2008).

[White 2010] A.E. White, Phys. Plasmas **17**, 056103 (2010).

[White 2011] R.B. White et al., Phys. Plasmas **17**, 056107 (2010).

[Wong 2005] K.L. Wong et al., Nucl. Fusion **45**, 30 (2005).

4. BOUNDARY AND PEDESTAL

OVERVIEW

The goal of Boundary and Pedestal research on DIII-D is to develop solutions for the edge plasma that are simultaneously consistent with high performance core plasmas while limiting heat and particle fluxes to material surfaces to a tolerable level. These goals result in a number of requirements for the boundary and pedestal plasma solution: (1) a high pedestal pressure for high core plasma confinement; (2) low-pedestal plasma collisionality for efficient core current drive; (3) steady-state heat flux at or below tolerable levels for material surfaces, ≤10 MWm^{-2}; (4) minimal heat flux transients, primarily due to edge localized modes (ELMs), to all surfaces; and (5) minimal particle flux and/or incident particle energy to surfaces to minimize erosion while maintaining particle pumping for density control and helium ash removal. The significant challenge for ITER and future tokamaks is to develop a comprehensive boundary solution that meets all of the above requirements simultaneously.

However, the conditions and plasma dimensionless parameters expected in ITER, Fusion Nuclear Science Facility (FNSF) and a DEMOnstration power plant (DEMO) cannot be simultaneously achieved in the diverter, scrape-off layer (SOL) and pedestal in today's tokamaks. For example it is not possible in existing tokamaks to produce a high density, low temperature radiating divertor at high input power while maintaining a low pedestal collisionality. Since a simple demonstration of a solution meeting all of the requirements cannot be made in current tokamaks, a physical model for each aspect of the divertor and pedestal operation must be developed. With a physical model for the pedestal, ELM control, the SOL and divertor plasma, and plasma-material interactions their integrated performance can be projected and optimized for ITER and beyond (Table 4-1).

The DIII-D research program for optimizing the integration of the above requirements with a high performance core plasma is described in Section 4.1. The DIII-D effort will focus on two aspects of this integration: (1) optimization of divertor geometry, and (2) maximizing radiative power dissipation inside the core plasma while maintaining high performance in advanced operational regimes. The development and testing of models of pedestal and divertor operation that this integration will rely on are described in the following sections.

The requirements for the pedestal plasma is to maintain a high pressure for high core plasma confinement and fusion performance, but also at low collisionality for efficient current drive in future steady-state tokamaks. A comprehensive model of pedestal stability and transport is needed to predict and optimize the pedestal profile for density and temperature for high fusion performance. While the EPED model, combining local and global magnetohydrodynamic (MHD) pressure limits has proved successful for describing the maximum pressure at the top of the pedestal achievable in a given configuration, the DIII-D proposed research program on the pedestal will examine the underlying local transport governing the individual profiles of density and temperature. Prediction and control of the pedestal density will be a particular focus.

The second requirement for the pedestal is to limit transients, primarily from ELMs, to a level tolerable for plasma facing components. DIII-D is pursuing three alternatives for limiting transients from the pedestal due to ELMs to a very low level: (1) limit the pedestal pressure to below the ELM instability limit through increased transport with the application of 3D resonant magnetic perturbations (RMPs); (2) increase the ELM frequency with a concomitant decrease in ELM size, primarily by the high frequency injection of deuterium pellets; and (3) expand the operational space of natural ELM-free regimes, particularly quiescent H-mode (QH-mode). In addition DIII-D will examine other promising ELM mitigation techniques as they are developed at other facilities. For each of these the goal is to develop the scientific basis for the technique so that results obtained in DIII-D can be projected to future tokamaks with confidence.

Table 4-1
High-Level Challenges for the Achievement of Burning Plasma Regimes for Fusion Energy

<table>
<tr><th>Challenge</th><th>Approach</th><th>Key Capability Improvements</th></tr>
<tr><td>Design heat flux dissipation adequate for PFCs and compatible with high overall fusion performance in next-step devices
Section 4.1</td><td>• Explore divertor configurations that promote heat flux dissipation compatible with high fusion performance
• Determine the maximum radiative dissipation that can be obtained in the core plasma without degrading performance</td><td rowspan="5">Hardware upgrades:
• Power supplies for independent bipolar operation of 12 I-coils and 6 C-coils
• Advanced 3D coil set
• Higher frequency pellet injection
• Increased neutral beam and ECH power
• Hot tile surface station
Diagnostics:
• Main ion CER
• Divertor bolometers
• Pedestal current [Edge J(r)]
• Edge CER
• Divertor Thomson
• 3D magnetics
• In-situ erosion (AGNOSTIC)
Code improvements (see List of Computer Codes and Applications, page xxiii):
• Pedestal gyrokinetic transport (GYRO, GEM, GS2, TGLF, BOUT++,XGC0)
• 3D MHD (3DEFIT, VMEC, M3D-C, MARS-F, IPEC)
• Divertor and SOL transport (SOLPS, UEDGE, OEDGE, BOUT++)
• Plasma material interaction (REDEP/WBC, HEIGHTS, ITMC-DYN, DIVIMP)</td></tr>
<tr><td>Determine the operational requirements to achieve dissipation of divertor heat flux in next-step devices
Section 4.2</td><td>• Test boundary plasma models used for predicting and designing next-step divertor
• Determined compatibility of heat flux control with 3D fields</td></tr>
<tr><td>Optimize the pedestal for core plasma high fusion performance
Section 4.3</td><td>• Develop models of pedestal transport
• Optimize pedestal performance guided by validated models</td></tr>
<tr><td>Develop ELM control techniques applicable for ITER and future tokamaks
Section 4.4</td><td>• Validate the basis of promising ELM control techniques: RMPs, pellet ELM-pacing and QH-mode</td></tr>
<tr><td>Develop materials to withstand harsh reactor conditions and for compatibility with high core fusion performance
Section 4.5</td><td>• Test models of plasma-material interactions in realistic tokamak plasmas
• Explore real-time treatment of high-Z surfaces for fusion applications</td></tr>
</table>

In addition to limiting transients to material surfaces, the steady-state heat flux to surfaces must be limited to foreseeable engineering limits, ≤10 MWm^{-2}. This can be achieved by operating the divertor at high density where atomic radiation can disperse the power over a large area. The challenge is to carry out radiative dispersal of divertor heat flux in a manner compatible with high fusion performance in the core plasma. For ITER, whose divertor design is established, the DIII-D research program will focus on validating boundary plasma modeling codes that are used for predicting the conditions required to achieve divertor heat flux control, and the implications for core plasma operation. For FNSF and DEMO with much higher power density, divertor heat flux control is an even greater challenge. To meet this challenge DIII-D will explore innovative divertor configurations that offer the potential for greater heat flux dispersal while remaining compatible with high performance core plasma operation.

Finally, plasma-facing components (PFCs) must also be compatible long-term tokamak operation. New materials and models of plasma-material interactions must be developed to meet this challenge. While the materials and models of plasma-material interaction will be primarily developed elsewhere, DIII-D will contribute to this effort by testing these materials and validating models in realistic tokamak plasmas under a variety of conditions and operational regimes expected to be found in the next-generation tokamaks. For ITER, DIII-D will continue to examine the implications of carbon as a possible divertor material in case the proposed tungsten divertor develops issues that make it unfeasible. For FNSF and DEMO, DIII-D will also explore low-*Z* surface treatment of high-*Z* components to mitigate compatibility issues with high performance core plasma operation.

4.1. OPTIMIZATION OF PEDESTAL AND DIVERTOR OPERATION FOR COMPATIBILITY WITH ADVANCED STEADY-STATE OPERATING SCENARIOS

4.1.1. Challenges

The economics of power plants motivate development of fusion scenarios with high plasma pressure for both high fusion power density and the possibility of true steady-state operation. Approaches realized in experiments to date optimize at higher temperature and lower density, due to the increase in non-inductive current drive efficiencies at low collision frequency. Unfortunately, conventional divertor solutions for handling steady-state heat flux optimize in the opposite direction at low temperature and high density. The research proposed here focuses on compatibility of high performance core scenarios with two potential approaches for effective exhaust of power and particle flux — a radiating mantle to dissipate power before it reaches the divertor and advanced divertor geometries that may both reduce the heat flux to the material surface of the divertor and modify the relation between the core and divertor operating densities to allow optimization of core and divertor operating point independently. Upgrades to the DIII-D heating systems will allow tests at relevant power levels of P/R = 30 MW/m. The research will be carried out largely in the context of the existing divertor hardware and shaping capability with a goal of informing more complete tests of FNSF and DEMO solutions.

An overview of the high-level objectives, the approach to addressing them, and the necessary hardware upgrades is given in Table 4-2.

Table 4-2
Overview of the Strategic Plan

<table>
<tr><th>Challenges</th><th>Approaches</th><th>Hardware Requirements</th></tr>
<tr><td>What geometry optimizes simultaneously the core and divertor operation?</td><td>Single-null vs. double-null divertor
Snowflake configuration
Super-X configuration</td><td rowspan="2">ECH and NBI system upgrades for core scenario flexibility and divertor tests at relevant power levels
Power supplies for independent control of all PF coils
Enhanced pedestal diagnostics for understanding scenario response
Upgraded divertor diagnostics for double-null</td></tr>
<tr><td>Can substantial energy be radiated before it flows to the divertor while maintaining high performance operation?</td><td>Introduce impurities with radiating states matched to the temperature and density conditions at the top or bottom of the pedestal</td></tr>
</table>

4.1.2. Research Plan

4.1.2.1. Overview. The principal goal of the research plan described here is to combine the emerging understanding from research on optimization of core operating scenarios and steady-state heat and particle exhaust to formulate integrated core-edge operating scenarios that can be projected to next-step fusion energy systems. Until now, the focus has been on separate development of core operating scenarios and solutions to handle steady-state heat and particle flux. Continued development and validation of models for the core operating scenario are described in Section 2 while research on models of divertor heat flux dissipation are described in the following Section 4.2. The research proposed here combines these two independent lines of research, to project an optimized unified scenario that simultaneously addresses the constraints of each to reach the fusion energy goal.

Two areas of research are being proposed. The first is a detailed investigation of the optimization of the physical geometry of the core plasma and divertor for the overall fusion performance of the tokamak. This includes the question of how to optimize the space within the toroidal field coils and blankets for maximum fusion performance. The lowest-order issue is whether to have one divertor in a single-null configuration or two divertors in a double-null configuration. A highly-shaped double-null plasma has higher normalized pressure limits theoretically, but it is absolute pressure and volume that are essential. In addition, the highly-shaped plasmas move the divertor to smaller major radius, where the total heat flux will be higher, making the divertor solution more challenging. This research also will test two proposed enhancements to the classic divertor geometry — the Snowflake [Ryutov 2007], which uses a higher-order null to enhance the flux expansion, and the Super-X [Kotschenreuther 2010], which uses additional coils to move the point where the open field lines contact a material surface to larger major radius and thus reduce the heat and particle to the target to a tolerable level. The proposed geometries will examine the potential for poloidal flux expansion, connection length, total magnetic field expansion, neutral density isolation and their combination to optimize the overall solution. The potential for geometry optimization to radiatively dissipate heat flux at lower core plasma densities compatible steady-state advanced operating scenarios will be evaluated within the context of the existing DIII-D divertor hardware and shaping capability. The plasma heating system upgrades to 35 MW will allow for testing at relevant power levels, P/R = 30 MW/m. A more complete test of optimized solutions for FNSF and DEMO will require additional divertor baffling and internal coils which could be the focus of a proposal for the next contract period.

The second area of research is development of a radiating mantle to diffuse the heat over much larger area than is possible in the divertor. Reactor studies have shown that a large fraction of exhaust power from a high power density fusion core must be radiatively dissipated over the main chamber to keep heat fluxes to divertor surfaces to a tolerable level, even if the divertor heat flux is dissipated over the entire divertor chamber [Wong 1997]. The key issue to investigate is the compatibility of high mantle radiation with advanced steady-state core-operating scenarios. Key features of this compatibility include: (1) the minimum power flowing through the separatrix to maintain a robust pedestal, (2) the effect of increased pedestal collisionality due to impurities on the current profile and MHD stability of the operating scenario, and (c) impurity transport and the potential for core plasma dilution and energy confinement.

While discussed independently, these two areas of research are not incompatible, and the ultimate solution may combine elements of both. Indeed, the ultimate goal of this research is to provide the physics basis for an optimized divertor solution, viable in future steady-state devices, such as an FNSF. This improved solution could potentially be tested on DIII-D in a later five-year plan, with the current plan exploring the approach to this. However, at this stage of research, the work needed to advance the state of the art can proceed independently.

The DIII-D team has developed a number of advanced inductive and steady-state operating scenarios as described in Section 2, on which the research can proceed immediately. Both advanced inductive and steady-state operating scenarios must have suitable steady-state solutions to handle the heat and particle fluxes. In fact, the existence of the physics basis of such solutions may be the key factor in choosing between these approaches for the next-step burning plasma experiment. In the near-term DIII-D research plan, the focus will be on inductive scenarios, because the capability of stationary operation for long pulses in DIII-D under a variety of conditions already exists. However, exploratory work on the more highly constrained steady-state scenario will begin. As the electron cyclotron heating (ECH) and neutral beam injection (NBI) system upgrades become available, the focus will shift to integrated core-edge solutions for true steady-state operation, as this is conceptually the most attractive for fusion energy production. Similarly, the near-term focus of the geometric optimization will be on optimum shaping including single-null versus double-null divertor operation. As the controls and the requisite power supplies become available, the focus will shift to testing the effects of these geometries on the high performance operating scenarios.

DIII-D does not propose to replace the carbon first wall on the timescale of this research proposal. While carbon is not considered to be a relevant first-wall material for future fusion energy devices, it does provide the flexibility to explore advanced core operational scenarios and divertor configurations. DIII-D has the demonstrated capacity to control the inventory of hydrogenic species through high temperature baking and high-speed cryogenic pumps, so outgassing in the main chamber is not a key player in the particle balance, similar to the behavior expected in metallic-wall devices. The carbon wall facilitates exploration of performance boundaries, both in the core and the divertor scenario, including finding the disruptive limits without damage to the wall. It also allows high heat fluxes and energy input in a wide variety of geometries without the need for developing mitigation strategies for each geometry. Finally, radiation from various charge states of carbon plays the same role in the divertor power balance that is expected from low-*Z* impurity injection for divertor heat flux control in metal wall tokamaks. Therefore, the use of carbon as a first-wall material appears to be neutral or even advantageous to this line of research in its present stage.

A timeline overview of the proposed research program is shown in Fig. 4-1.

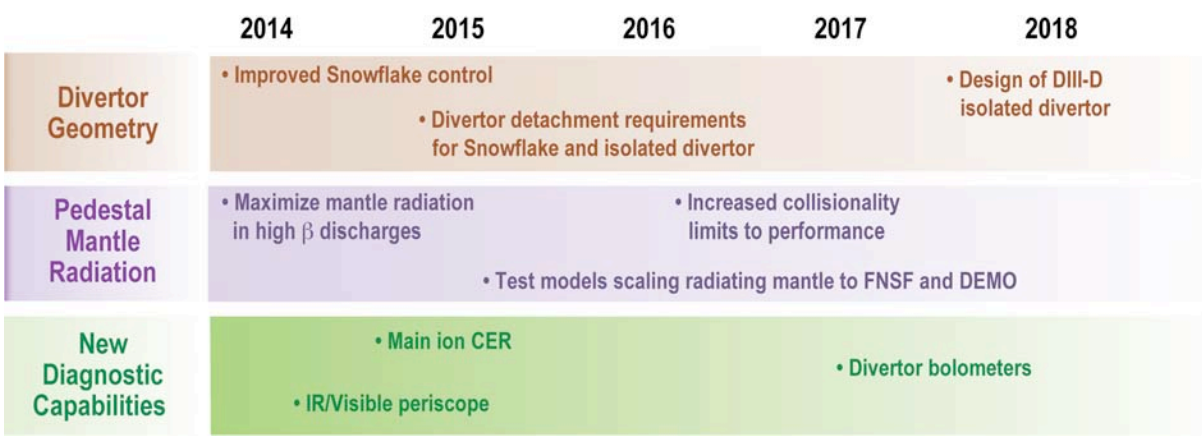

Fig. 4-1. FY14–FY18 program elements, hardware upgrades, diagnostics.

4.1.2.2. Research Plan. As discussed in the overview, two areas of research are being proposed—investigation of the role of geometry and development of a radiating mantle. The research plan in each area is discussed in the following subsections.

Influence of plasma geometry. This area has three proposed objectives:

- Comparison of single-null versus double-null divertor operation and the effects of plasma geometry parameters.
- Test of Super-X configuration physics (divertor leg geometry and toroidal flux expansion).
- Test of the Snowflake configuration — the roles of connection length and poloidal flux expansion.

Single-null vs. Double-null. Significant work on the optimization of the geometry of operating scenarios has already been carried out, highlighting the importance of both upper and lower triangularity. However, the focus of that activity was optimization of normalized pressure and, to a lesser extent, energy confinement. The focus of the research proposed here is to examine the parameters related to absolute fusion performance and absolute divertor performance. For example, if a plasma with higher triangularity has higher energy confinement, the improved confinement leads to less power for the divertor to handle, which may compensate for the smaller wetted area. Similarly, the higher plasma volume of a single-null plasma may compensate for higher heat flux and need to handle power on the inner divertor leg. Geometric effects may also change the core density at which divertor detachment is obtained. These types of simultaneous optimizations have not been carried out to date. DIII-D has the shaping flexibility to carry out wide ranging scans of geometry, particularly in variations between single-null and double-null at different triangularities. The planned upgrades to the poloidal field power supplies will further increase DIII-D's shaping capability.

Key aspects of the research plan include:

- Definition of parameters to define the optimization.
- Experiments that vary elongation, triangularity, and squareness in single-null and double-null plasmas.
- Experiments comparing directly single-null and double-null plasmas, guided by the optimization above.
- Measurement of core density at which detachment of the divertor is obtained.

Super-X divertor. The Super-X divertor has been proposed as a configuration to improve the heat flux handling capability of the divertor [Kotschenreuther 2010]. As shown conceptually in Fig. 4-2, the divertor strike point is moved out to large major radius to large major radius to spread the target plate heat flux over a larger area. In addition at larger major radius, and resulting lower toroidal field, the parallel heat flux at the target is reduced enabling a detached radiative divertor state at lower core plasma density. In principle the midplane separatrix density is inversely proportional to the strike-point major radius if all other factors, such as exhaust power are kept constant. This configuration also allows baffling and control of neutrals to promote stable radiative dissipation of divertor exhaust power. The Super-X configuration offers the potential to isolate a high density radiating divertor plasma from a high performance, low collisionality core plasma.

While the complete realization of the configuration shown in Fig. 4-2 cannot be implemented in DIII-D without installing internal coils and extensive baffling, many of the basic principles of the basic concept can be tested utilizing DIII-D's current capabilities. Shown in Fig. 4-3 are two divertor configurations that have been run in DIII-D where the major radius of the strike-point is varied by ~40% with only small changes to the geometry of the core plasma. These configurations will be utilized to test underlying advantages of the Super-X configuration and compatibility with advanced scenarios. Successful tests of the concept within the limitations of DIII-D's planned capabilities will be expected to lead to a design and proposal for internal coils and baffling to fully realize and test the concept in the next DIII-D contract period.

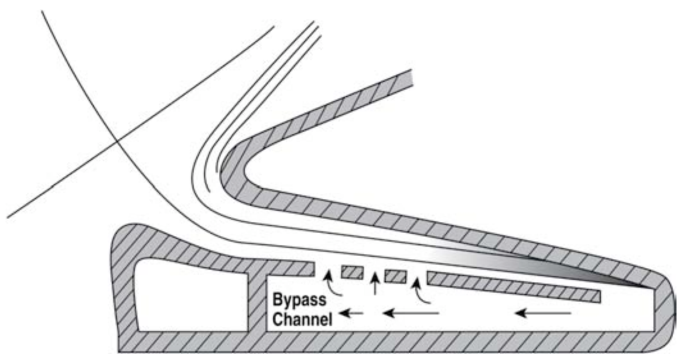

Fig. 4-2. Conceptual divertor design featuring Super-X configuration and baffling of neutrals.

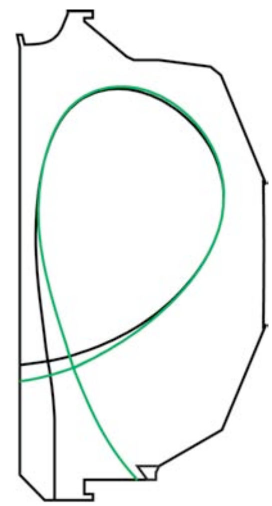

Fig. 4-3. Two divertor configurations achieved in DIII-D to test effect of strike-point position.

Key research activities include:

- Measurement of pedestal and global performance variations in advanced scenarios in the configurations shown in Fig. 4-3.
- Measurement of core performance variations in advanced scenarios, including comparison of performance with different triangularity, but fixed major radius of the outboard midplane and outer divertor strike point.
- Exploration of the influence of divertor leg geometry on detachment and SOL properties.
- Testing the role of divertor closure at large major radius.
- Measurement of midplane and divertor parameters as detachment is approached with deuterium injection.
- Test double-null divertor solutions and compare with single-null divertor results.

Snowflake configuration. The Snowflake divertor configuration utilizes multiple poloidal field nulls to increase the poloidal flux expansion in the divertor and increase the area of divertor heat flux. The Snowflake also incorporates greater divertor volume in a compact configuration. The Snowflake divertor was first produced in TCV [Piras 2010a] and later shown in the National Spherical Torus Experiment (NSTX) [Soukhanovskii 2011] to reduce the divertor peak heat flux and enable detached divertor operation at lower core plasma density. The Snowflake divertor has also been realized in DIII-D with its flexible poloidal coils as part of a collaboration with NSTX, as shown in Fig. 4-4, and similarly shown to reduce peak divertor heat flux. Upgrades to the poloidal field coil power supplies will enable greater control of the Snowflake configuration. The research program on the Snowflake configuration will focus on the effect on detached divertor operation and the compatibility with advanced operational scenarios.

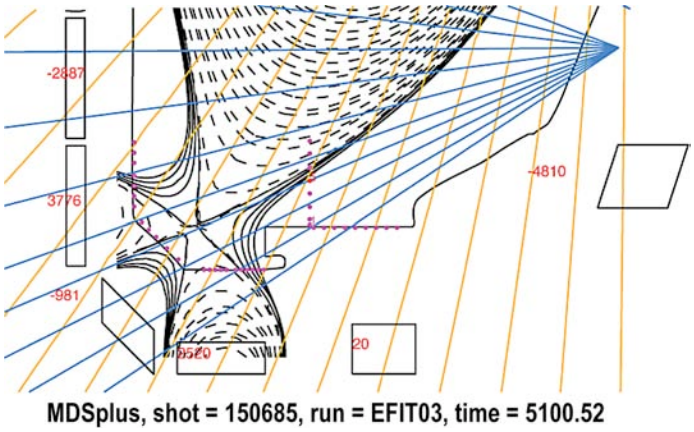

Fig. 4-4. The Snowflake divertor configuration in DIII-D.

Key research activities include:

- Measurement of pedestal and global parameters for advanced scenarios in standard and Snowflake divertor configuration with same geometry of the separatrix.
- Measurement of midplane and divertor parameters as detachment is approached with deuterium injection.
- Test isolation of the core from impurity injection.
- Test double-null divertor solutions and compare with single-null divertor results.

Development of a Radiating Mantle. Because of the limited volume, and surface area, available for the divertor in a fusion power plant it will be necessary to radiatively dissipate a large fraction of the exhaust power over the greater surface area of the main chamber [Wong 1997]. Pioneering work on radiative mantle operation in DIII-D has shown significant power dissipation and compatibility with H-mode confinement [Jackson 2002]. In this research plan the previous work will be extended by applying the radiative mantle to advanced scenarios. In addition the increased understanding of the pedestal structure and future pedestal research as described in Section 4.3 will allow exploration of the ultimate potential and limitations of this technique. The research plan will focus on (1) the maximum mantle radiation achievable without pedestal degradation, (2) the effect of increased radiating impurity density and collisionality on the pedestal current profile and operational scenarios, and (3) the transport of impurities and effect on core plasma dilution and energy confinement.

Key research activities include:

- Selection and testing of operating points for advanced scenarios compatible with dominant temperature ranges of high radiation for various impurities. Radiation at both the top and bottom of the pedestal will be attempted.
- Test of impurity penetration and accumulation in various operating scenarios.

- Optimization of radiation with respect to plasma performance by variation of impurity types and levels.
- Comparison of single-null and double-null solutions, including issues with drifts.

4.1.2.3. Capability Improvements. The DIII-D facility has unique capabilities to carry out research on the compatibility of core operating scenarios with solutions for steady-state heat and particle flux. Foremost among these are the 18 independent poloidal field coils, pulse lengths longer than the resistive equilibration time (>10 s), and capacity to exhaust substantial energy (up to 150 MJ).

To take full advantage of these unique capabilities, several enhancements to the DIII-D facility are proposed that would further the research plan for simultaneous optimization of the core and divertor steady-state solutions.

- To make maximum use of the poloidal field set of DIII-D, two new power supplies are proposed. These supplies are configurable such that all 18 poloidal field coils could be controlled independently. At present, only 14 combinations of coils can be controlled independently, which limits the range of plasma shapes that can be made for a given coil configuration and prevents some shapes from being made. This flexibility will be critical for making and evaluating the advanced divertor configurations discussed above. It will also enable evaluation of extreme shape configurations at higher plasma currents to better explore performance issues.
- Enhancements to the ECH and NBI power and pulse length are also critical to the research proposed here. The higher heat power, up to 35 MW, will allow tests of at relevant power levels of P/R = 30 MW/m for divertor configurations with the divertor at R=1.2 m. The upgrades will also allow the performance of the core scenarios under a variety of conditions, including the approach to divertor detachment, to be evaluated. This means that the power requirements will be higher than those needed for an existence proof of a core scenario solution alone. In addition, testing of the core-edge solution compatibility needs to be carried out on timescales approaching the resistive equilibration time, especially with the introduction of impurities for the radiating mantle. Control of the current rise phase can initiate the plasma with the current profile close to the equilibrium and the combination of baking and cryopumping reduces the equilibration time of the particle inventory, but the simultaneous solutions still need to be tested for timescales approaching the resistive equilibration timescale, which ranges from 1–7 s, depending on the exact plasma parameters.

These proposed hardware enhancements are summarized in Table 4-3.

In addition to the above noted hardware improvement to the facility, diagnostic capability will be improved to carry out the proposed research. The key diagnostic improvements needed are those that can yield accurate comparative measurements of the pedestal and divertor region in a variety of configurations and scenarios. These are the same diagnostic improvements that are described in greater detail in the sections describing Divertor and SOL physics (Section 4.2), Pedestal physics (Section 4.3) and ELM control (Section 4.4). The diagnostic upgrades of particular importance to this research are summarized in Table 4-4.

Table 4-3
Hardware Enhancements to the DIII-D Facility

Hardware Capability	New Physics Enabled
Additional poloidal field coil power supplies	• Increased flexibility and larger variation of shaping, enhanced capability to make and control advanced divertor configurations
Higher ECH and NBI power	• Access to scenario limits under a larger range of parameters, especially steady-state scenarios at higher density
Longer pulse length for NBI and ECH	• Access to resistive relaxation time scale to evaluate performance of radiating mantle and advanced divertors in stationary conditions

Table 4-4
Present Diagnostic Proposals

Desired Measurement Capability	New Physics Possible	Diagnostic Upgrade
Greater coverage of heat flux to both divertors and main chamber	Accurate assessment power flows from the core to the vessel	Periscope view in IR and visible
Improved accuracy and resolution of pedestal electron density and temperature	Assess impact of radiating mantle and advanced divertor configurations on core	Improved Thomson scattering, reflectometry
2D map of temperature and density in the divertor over a wider range of configurations	More detailed validation of models	Upgraded divertor Thomson
Neutral density in the divertor	More detailed validation of models	More Langmuir probe cover-age and neutral pressure gauges

4.1.3. Impact

The research proposed provides a physics basis for simultaneous optimization of the core and divertor operating scenarios. This includes understanding the trade-offs between the optimal core and divertor solution. It will also supply a basis for practical design solutions, including the number and location of poloidal coils needed for next step devices. While this research will have a substantial impact on ITER, especially in the technology phase, the focus is directed toward the design of next-step devices that must achieve high fluence such as FNSF and DEMO. In particular the research will provide a basis for an improved divertor design approach, likely to be needed for the quasi-continuous operation of an FNSF. The heating power upgrades proposed in this plan will provide high power densities to enable development of an improved solution for FNSF which could be thoroughly tested in the next five-year plan. The solutions explored here should also inform the design of fusion energy solutions other than the standard aspect ratio tokamak, such as the spherical tokamak and the stellarator. These exploratory tests of divertor configurations will be carried out within the existing DIII-D infrastructure. However the proposed solutions may be the subject of a future proposal for exploiting the DIII-D facility, to test out improved solutions in full, arising from the physics basis developed in this five year period.

4.2. DIVERTOR AND SOL PHYSICS

4.2.1. Challenge and Opportunity

A major challenge for future large-scale tokamaks is limiting the heat flux to PFCs to a tolerable level, ≤10 MWm^{-2}. A number of tokamaks have demonstrated divertor heat flux control by operating in the so-called "detached" divertor regime where cold dense plasma radiates the majority of the exhaust power for dispersal over a large area [Petrie 1979, Rapp 2004, Kallenbach 2005, Goetz 1996]. ITER will require operation in this detached divertor regime divertor regime to keep divertor target heat fluxes to a tolerable level. FNSF and DEMO will be even more dependent on this regime where power densities are expected to be a factor of 5–10 greater than for ITER. Though the detached divertor regime has been adequately demonstrated in existing tokamaks, computer models of divertor operation fail to reproduce a number of key features found in experiments. In particular the models fail to predict the midplane separatrix density required to achieve the detached divertor state. These models are particularly important for prediction and design of the overall operational scenarios of the future generation of tokamaks. The DIII-D divertor and SOL physics research program will focus on experimentally identifying the physical processes and boundary conditions responsible for transport and dissipation of power and particles flowing into the divertor for the purpose of their inclusion in the 2D models used for design and operation of future divertor tokamaks. While a number of tokamaks in the world fusion program are currently investigating and demonstrating heat flux control with detached divertor operation, DIII-D is particularly well suited to address the theoretical modeling of this process with its comprehensive boundary plasma diagnostic set, flexible divertor configuration and wide operational space. These challenges and the proposed approaches to addressing them are summarized in Table 4-5.

Table 4-5
Divertor and SOL Physics Challenges, Approach and Upgrades

<table>
<tr><th>Challenge</th><th>Approach</th><th>Capability Upgrades</th></tr>
<tr><td>Determine the physical processes responsible for the width of the heat flux channel flowing into the divertor</td><td>Test MHD stability as model for SOL heat flux width with detailed measurements over a range of divertor heat flux widths and conditions</td><td rowspan="4">Measurements:
• Main ion CER
• Divertor T_i
• Expanded spatial range of Divertor Thomson Scattering
• Divertor Bolometers
• IR and visible with periscope imaging
Code improvements (see List of Computer Codes and Applications, page xxiii):
• Collaboration with 2D boundary plasma models (SOLPS, UEDGE, OEDGE, BOUT++)
• 3D boundary plasma models (Trip3D, SURFMN, MAFOT)</td></tr>
<tr><td>Identify physical processes and boundary conditions required for 2D divertor models to accurately predict divertor performance</td><td>Detailed 2D measurements of divertor plasma in dissipative regime for testing models</td></tr>
<tr><td>Develop active control of divertor heat flux dissipation for application to ITER and beyond</td><td>Determine timescale and stability of divertor dissipation diagnostics and actuators</td></tr>
<tr><td>Implement steady-state heat flux control compatible with 3D fields applied for ELM control.</td><td>Toroidally rotate applied 3D fields to average toroidally asymmetric divertor heat flux</td></tr>
</table>

4.2.2. Research Plan Overview

The overarching goal of the divertor and SOL physics research program is to establish the physical basis for prediction of divertor heat flux control in future devices. This predictive capability requires advances in understanding several aspects of divertor plasma physics and its control.

1. **Identify the processes controlling width of power flux into divertor.** The most basic parameter for predicting divertor heat flux is the width of the channel conducting this flux into the divertor. This parameter will determine the fraction of power exhaust that must be radiated and the plasma conditions that will be required to achieve this radiation. While recent multi-machine studies have identified an empirical scaling of this width, a physical basis for the observed scaling is needed for predicting this parameter with confidence. The DIII-D divertor physics research program will focus on MHD stability as a potential mechanism for controlling the heat flux width in the SOL with the scaling of high resolution measurements of midplane SOL profiles and divertor plasma conditions and comparison with SOL MHD stability and transport models.
2. **Identify processes and boundary conditions required for accurate modeling of dissipative divertors.** Current 2D models of dissipative divertor operation fail to reproduce key aspects of the divertor and SOL, including in/out divertor asymmetry and the midplane density required for divertor dissipation. The DIII-D divertor physics research program will address this issue by identifying physical processes and boundary conditions that are not being adequately described in the models. This will be accomplished largely through detailed 2D measurements of well-designed parameter scans, focusing on the local transport of energy and particles.
3. **Develop techniques for active control of divertor heat flux with application to ITER, FNSF and DEMO.** Active control of divertor heat flux dissipation will be critical in the next generation of tokamaks. Too little heat flux dissipation could lead to extensive damage to the divertor structure in as little as 1 s. Too much dissipation could result in degradation of core plasma performance and possible disruption. The state of the divertor plasma, measured in real time with radiative emission and surface heat flux, will be controlled by gas puffing of deuterium and/or impurities and the divertor geometry. While a demonstration in DIII-D will show that heat flux control is possible, designing control schemes for application to future devices will require more detailed understanding of the timescales of divertor evolution and response to control actuators.
4. **Implement steady-state heat flux control compatible with 3D fields applied for ELM control.** The application of 3D fields, RMPs, for ELM control has been shown to split the divertor strike-point into a spiral pattern. This observation offers the promise of spreading the divertor heat flux footprint over a larger area if the perturbation can be rotated toroidally at a sufficient frequency. However additional heat flux dispersal through divertor radiation during applied RMPs must also be shown to be compatible with a robust pedestal. The DIII-D research program will address this compatibility by measuring the pedestal and divertor plasma response to rotating RMP fields and raising of the divertor density to detachment.

The proposed DIII-D divertor and SOL physics research plan is summarized in Fig. 4-5. This figure describes the timing of elements of the research plan as well as diagnostic upgrades that will be implemented to execute the plan.

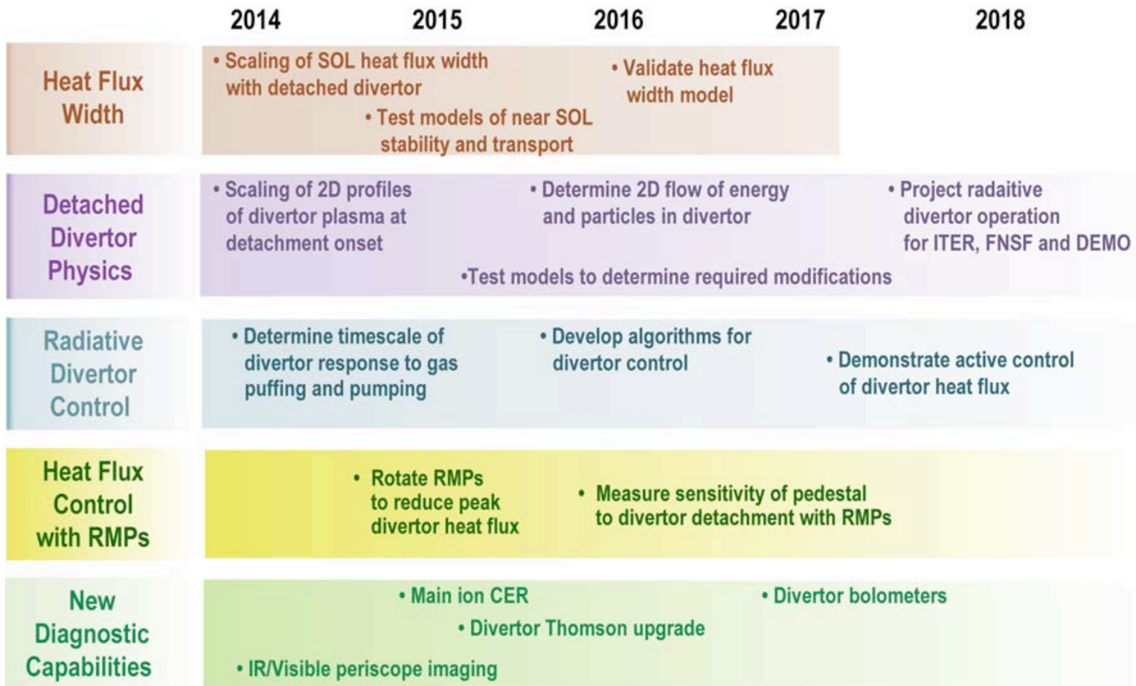

Fig. 4-5. Timeline of the divertor and SOL physics research plan elements and diagnostic upgrades.

4.2.3. Detailed Research Plan

The goal of the divertor and SOL physics research program is to establish the physical basis for prediction of divertor heat flux control in future devices. This goal will be addressed with the four issues of (1) the heat flux width, (2) physics of divertor detachment and energy dissipation, (3) active control of the radiative divertor state, and (4) compatibility of heat flux control with applied 3D fields. The research program to address these issues are described below.

Heat Flux Width. The most fundamental parameter for assessing the fraction of power that is required to be dissipated to meet material limits, ≤10 MWm^2, is the width of the channel carrying the heat flux exhausted from the core plasma. Recent international work comparing a number of tokamaks has led to an empirical scaling that predicts a very narrow heat flux width, ~1–2 mm, for ITER. This scaling implies need for further divertor radiative dissipation and a possibly constrained operational space. However, this multi-machine scaling was carried out under attached divertor conditions with little power dissipation. It is uncertain if the width of the power channel scales similarly when a large fraction of the exhaust power is dissipated through radiation in the divertor. In addition, a physical basis of the empirical scaling of the heat flux width must be developed in order to develop confidence in extrapolating these results to ITER and other future tokamaks. The DIII-D program will address this issue with the following elements.

- **Measure scaling of midplane SOL profiles.** It is important to first characterize the scaling of midplane SOL profiles under attached divertor conditions where the target heat flux represents the profile of power flowing into the divertor. This will not only test models of parallel heat transport, but will also validate use of measured midplane profiles for characterizing the heat flux width under dissipative divertor conditions where the resulting target plate heat flux no longer reflects the profile of power flowing into the divertor. A significant challenge in meeting this goal is determination of the separatrix location on the profile. Parallel transport models with the measured profiles will be applied to determine the most accurate location of the separatrix.

Once the link between midplane SOL profiles and the heat flux channel flowing into the divertor has been established the scaling of the width of the heat flux channel will be extended to dissipative divertor conditions. The scaling of the DIII-D SOL heat flux width at high density and detached divertor conditions will be part of an ITPA effort to develop an empirical scaling of heat flux width under conditions expected in ITER. These experiments are expected to collect detailed midplane profile data as well as divertor data. The divertor data should include heat flux profiles as well as radiation profiles to document transport of power within the divertor.

- **Test models of radial transport in the near SOL.** Confidence in scaling of heat flux width to ITER and beyond will be greatly enhanced by validation of a model describing that scaling. A leading candidate for the regulating the profiles near the separatrix is MHD stability, as represented by the kinetic ballooning mode (KBM) that is also thought to regulate the local pressure gradient in the pedestal just inside the separatrix. Tests of this model will require accurate measurements of the midplane profiles, and particularly their values and gradients at the separatrix. The effort to consistently determine the separatrix location, as described earlier, will greatly aid this goal. The main ion temperature and density is an important component of the pressure profile, but is currently not being adequately measured. The plans for developing this measurement are described in Section 4.2.4.

  Several models will be employed to test critical gradient, or MHD stability of the SOL. The simplest tests include BALOO for the ideal limits in a simplified geometry. More definitive tests will be made with BOUT++ and JOREK which include real geometry, plasma outside the separatrix and other realistic effects such as resistive corrections. Other models, such as radial drift transport, developed by the broader fusion community, will also be tested.

- **Diagnostic requirements.** The research plan outlined above will rely on detailed midplane profile measurements with high spatial resolution. This will be provided by the existing high resolution edge Thomson scattering system. However, the research plan also requires measurement of the ion temperature profile, not only for its contribution to the pressure profile, but also for determining the power flowing into the divertor through the ion channel. The plans for developing this measurement are presented in Section 4.2.4. The divertor measurements will include an infrared (IR) camera for surface heat flux, Langmuir probes for the surface ion flux, bolometry for radiated power, and the divertor Thomson system for density and temperature profiles within the divertor. Plans for upgrading these existing systems are also detailed in Section 4.2.4.

Establish the Physics Basis for Prediction of Radiative Divertor Operation. Radial heat transport, however, is only one of the physical processes needed to describe the boundary plasma and the requirements for limiting the divertor heat flux to tolerable levels. Other processes include parallel heat and particle transport, and cross-field drifts, as well as numerous atomic physics processes. These processes are embodied in fluid models, such as UEDGE and SOLPS, and are used to design and predict divertor operation in future tokamaks. However, these models have been found to inadequately reproduce a number of features of radiative divertor operation in existing tokamaks, including; the midplane separatrix density at which divertor radiation and detachment onsets, the asymmetry in conditions between the inner and outer divertor and the flow of SOL plasma into the divertor. The deficiencies and limitations within the models must be identified and addressed if they are going to be used with confidence to design the configuration and operation of divertors in the next generation of tokamaks.

DIII-D is well equipped to carry out these studies with an extensive diagnostic set and a flexible configuration and operational space for a wide range of scans. While ITER, FNSF and DEMO are likely to operate with metal surfaces and require low-*Z* impurity injection, DIII-D will generate the bulk of its divertor radiation from the intrinsic carbon impurities. However the radiation rates and other relevant atomic physics processes are similar for carbon compared to low-*Z* impurities such as nitrogen and neon. Therefore the physics that will be tested by comparing DIII-D experiments to models will be the same that is required for accurately modeling ITER divertor operation.

- **Scaling of divertor and SOL conditions near detachment.** An important method for testing models is to compare trends in scaling over appropriate control parameters to examine the controlling physical processes. In addition, experimental parameter scans can be compared with results from other tokamaks for construction of multi-machine databases with the goal of projection to future tokamaks. The experimental effort will result in a database of both inboard and outboard divertor detachment onset as a function of control parameters, including input power, density through gas puffing, impurity puffing, divertor shape and q_{95}. An important result of this effort will be the midplane separatrix density at divertor detachment onset across the range of input parameters. The scaling of divertor detachment onset will then be compared between experiment and modeling, and other tokamaks, as a function of these input parameters.

  The divertor scaling outlined above will require measurements of both the inboard and outboard divertor plasmas including target plate density, temperature and heat flux as well as detailed profile measurements of the midplane SOL. DIII-D's existing diagnostic capability and plans for additional measurements to meet these needs are described in Section 4.2.4.

- **2D profiles of divertor energy and particle transport.** Testing boundary models will require detailed measurements across carefully controlled parameter scans. However identifying the limitations and/or deficiencies within the codes will be a challenging task due to multiple linked processes. The approach of the DIII-D research program will be to isolate and examine each of the transport channels within the experiment and compare to the models.

  This onset of detachment is essentially one of power balance when the divertor electron temperature becomes low enough that neutral-plasma interactions become significant throughout the divertor plasma, ≤10 eV. The divertor density at which this occurs is given by $q_{\parallel} \propto \mathrm{n} v_s\,(T_e{+}T_i)$ where $q_{\parallel}$ is parallel heat flux, v_s is the ion sound speed, n is the plasma density and T_e and T_i are the ion and electron temperatures. To test the energy and particle transport that leads to this condition the following pathways will be examined:

  — Parallel transport from the midplane SOL into the divertor. The parallel transport analysis will be developed as described in the previous section on heat flux width studies, and then extended to detached conditions. This should provide a radial profile of energy and particles flowing parallel to the field into the divertor. This will require measurement of the upstream and downstream profiles of plasma density and temperature.

— Radiative losses in the divertor. Radiation represents a significant energy sink in the divertor near detachment. The radiation losses as described in the models must be shown to match the divertor radiation for similar experimental conditions. This is a test that the models contain the relevant atomic physics responsible for radiation. The measurement of the 2D profile of radiation in the DIII-D divertor will be enhanced with a new bolometer system as described in Section 4.2.4.

— *ExB* drifts of plasma. Radial electric fields in the SOL, set up by the sheath condition are responsible for carrying particles from the outboard divertor to the inboard divertor for the typical toroidal field direction favorable for the H-mode transition. This important transport mechanism in the models will be checked in an experiment with existing insertable probes to measure the SOL and divertor plasma potential and electric fields.

- **Diagnostic requirements.** Tests of the transport described above will require multiple high resolution diagnostics. One of the most important of the measurements is the 2D profile of divertor plasma density and temperature. An example of such measurements are shown in Fig. 4-6, where a 2D profile of electron density and temperature has been reconstructed from divertor Thomson measurements of a detached divertor plasma. This 2D profile is reconstructed by sweeping the divertor plasma across the vertical Thomson view locations and shows the spatial resolution down to several cm. An important plasma parameter not currently measured is main ion temperature in the SOL and divertor. The main ions are an important channel for energy transport and plans for its temperature measurement are described in Section 4.2.4.

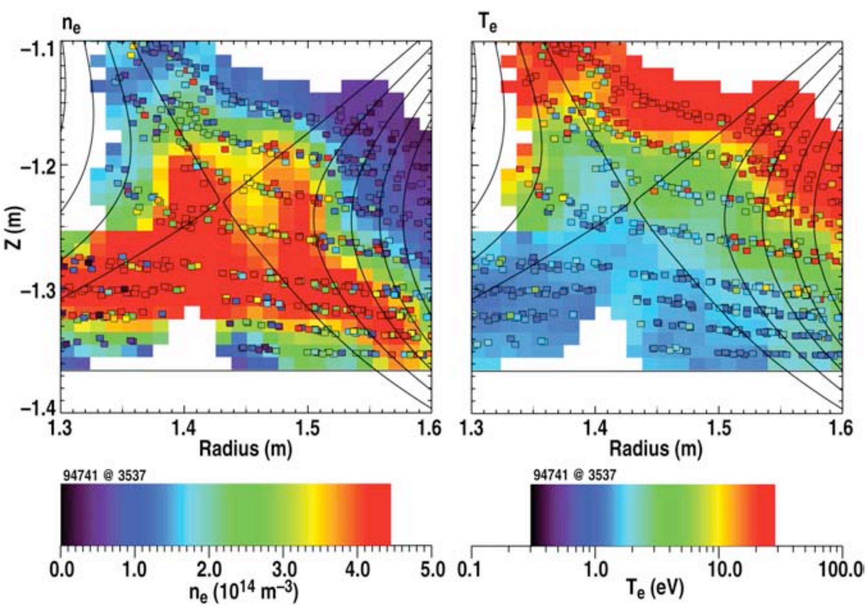

Fig. 4-6. The fitted 2D profile of electron density and temperature as measured by Thomson scattering.

Power balance measurements are also needed to determine the parallel and radial transport of energy, and they include 2D tomography of the divertor radiated power from bolometry and heat flux to the target from IR camera measurements. Visible spectroscopic imaging will provide information on the specific contributions of different radiated species including; deuterium, intrinsic carbon impurity and injected impurities such as neon.

- **Modeling requirements.** Achieving the goals of this task will require a close coupling of modeling with experimental analysis. This effort will consist of a careful comparison of power flow as measured in the experiment and as predicted in the models. The particular channels of energy transport that will be examined include; parallel transport into the divertor, *ExB* flows and radiative losses. The modeling will be provided primarily by collaborators with the boundary codes including UEDGE, SOLPS and BOUT++.

Develop Techniques for Control of Divertor Heat Flux. Active control of divertor target plate heat flux through divertor radiative dissipation will be critical in the next generation of tokamaks. Too little heat flux dissipation could lead to extensive damage to the divertor structure in as little as 1 s in ITER, while too much dissipation could result in degradation of core plasma performance and possible disruption. The actuators for heat flux control, both in current and future tokamaks, are gas puffing of deuterium and impurities, such as neon or nitrogen. Also divertor pumping can be utilized to control divertor density, typically by adjusting the configuration to control the coupling of target plate ion flux to the pumps.

- **Time-dependent divertor response to actuators.** Design of a heat flux control system for future tokamaks will require development of a model of the interaction of processes active in the divertor. Of particular importance is the time dependence of the divertor to a change in the available actuators including: (1) deuterium injection, (2) impurity injection, (3) divertor pumping with strike-point location. A time-dependent model of the response will be constructed by measuring the 2D divertor state with step changes, both up and down, to each of these actuators.

  The divertor response should also be reproduced by time-dependent divertor models, such as UEDGE or SOLPS, in order to insure they can be extrapolated to future tokamaks. A few of the processes to accurately model include:

  — Residence time of impurities in the SOL and divertor.

  — Divertor pumping efficiency dependence on strike-point location.

  — Divertor recycling rate dependence on surface temperature.

  — Configurations where divertor conditions rapidly bifurcate with small changes to the control request.

  — Impurity generation dependence on divertor plasma conditions and surface temperature.

- **Demonstrate divertor heat flux control system.** A goal of the above work on divertor plasma response is to build a control scheme based on the insight gained above. This control scheme should be based on physical models of the divertor response to the actuators in order to extrapolate the scheme to future tokamaks. An important aspect to include is the time response of the control scheme in order to design a stable control system. An example of where this is important [Ghendrih 1995] is the observation of a rapid bifurcation of the divertor between an attached strike-point with low radiation and a detached state with high radiation, with very little change to the input request. The control scheme should be capable of extrapolation to the future tokamaks to test the stability of the control scheme.

- **Diagnostic requirements.** The diagnostic requirement for divertor heat flux control is similar to that for the other divertor studies described above, but the signals must be acquired in real time for the plasma control system. These are currently available for individual bolometer channels for radiated power and signals of divertor recycling D_α. Additional real-time diagnostic signals that will be made available include spectroscopy, divertor target Langmuir probes, divertor plate thermocouples, divertor neutral pressure and divertor plasma temperature from Thomson scattering.

Implement steady-state heat flux control compatible with 3D fields applied for ELM control. ELM control with 3D fields, RMPs, is a promising technique for limiting heat flux transients to the divertor target. However the implications for steady-state, or time-averaged, heat flux control have not been adequately addressed. RMP application for ELM control has been shown to split the divertor heat flux footprint into a spiral pattern, similar to the vacuum calculation of the connection length profile shown in Fig. 4-7. If the RMP fields are rotated the spiral heat flux pattern should also rotate resulting in time-averaged heat flux profile that is broader than the toroidally symmetric case without RMP fields. However, compatibility with divertor dissipation and detachment must also be established.

- **Rotation of RMP heat flux pattern.** To demonstrate a broader time-averaged heat flux profile with RMP application, the RMP fields will be rotated toroidally at a higher frequency that the characteristic thermal equilibration time of the divertor tiles. A rotation frequency greater than a few tens of hertz should be adequate for DIII-D. This requirement is similar to the field rotation studies in Section 4.4 to study the plasma response to applied fields. The divertor target plate temperature and heat flux profiles with be measured with an IR camera from the periscope view. This view will provide the toroidal, as well as poloidal, variation of the heat flux.

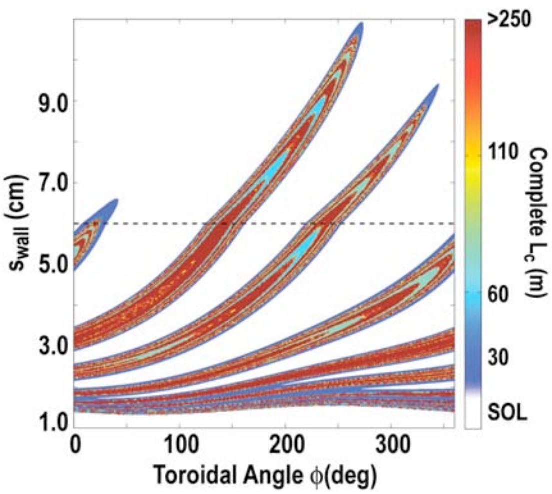

Fig. 4-7. Connection length to target plate with application of RMP fields.

- **Detached divertor operation with applied RMP fields.** Though the spiral pattern of Fig. 4-7 may reduce the peak divertor heat flux, there will still be a need to operate the divertor in a dissipative detached state in order to further reduce the target heat flux and to limit erosion with a low divertor plasma temperature. This detached divertor state must be attained without degrading the pedestal plasma parameters. This operation will be tested in DIII-D by increasing the density during RMP application until the plasma in the high heat flux lobes attains low temperature and becomes detached. The important plasma parameters to monitor are the separatrix density at detachment and whether the pedestal can maintain high pressure during detachment. It is as yet unknown what effect the 3D structure of the separatrix, divertor and SOL will have on these parameters.

- **Hardware and diagnostic upgrades.** Toroidal rotation of the RMP fields will require upgrades to the I-coil power supplies. These are the same requirements as for the ELM control studies and are described in more detail in Section 4.4. 3D divertor measurements will be particularly important for these studies. These measurements will be provided by an IR and visible camera view through the periscope facility. Other diagnostic requirements are similar to those for the pedestal studies, Section 4.3, and other divertor and SOL studies described above in this section.

4.2.4. Diagnostic Upgrades

The primary hardware upgrades for the divertor and SOL physics research program are for diagnostic capability. The measurement requirements for this research program have been described above. The plans for obtaining these measurements are summarized below.

1. **Main ion temperature.** The ion temperature is a basic plasma parameter that affects many aspects of the edge plasma, including pressure balance and energy and particle transport along the magnetic field. Currently the only ion temperature measurement is of the carbon impurity ion, CVI, through charge exchange recombination (CER) measurements of the pedestal to the separatrix. It may be possible for the deuterium ion temperature to be significantly different than that of CVI at the separatrix and SOL due to several factors including finite impurity charge state lifetimes and particle transport. While the higher collisionality in the divertor may lead to closer equilibration between the electron and ion temperatures there is still the potential for significant difference, particularly at lower densities. The plans for measuring main ion temperature in the divertor and SOL include:

   a. Retarding field analyzers (RFA). These probes will be built into the divertor target and/or inserted with the Divertor Materials Evaluation System (DiMES) facility as part of the Sandia National Laboratory (SNL) collaboration for ion temperature measurements at the divertor strike-point. Similar probes will also be mounted on the University of California San Diego (UCSD) midplane reciprocating probe for the SOL. Such midplane probes can withstand only limited heat flux so such measurements will be limited to the far SOL. Ion sensitive probes may also be mounted to the midplane reciprocating probe and can withstand higher heat flux. However interpretation of their data may be more complicated.

   b. Main ion CER. Detection of main ion charge-exchange with the heating beams has been developed for core measurements as part of the Princeton Plasma Physics Laboratory (PPPL) collaboration. These measurements will be extended into the pedestal to the separatrix. Scanning of the separatrix location will provide measurement across the separatrix.

2. **Divertor Thomson.** The divertor Thomson scattering (DTS) diagnostic is a critical tool for diagnosing the 2D structure of the divertor plasma, as shown in Fig. 4-6. However the laser and measurement geometry require the divertor to be run on top of the lower baffle and be swept across the measurement locations. Modifications to allow scanning of the major radius of the vertical laser will provide diagnosis of a much larger variety of divertor plasmas. In particular, divertor plasmas in a pumping geometry with the strike point located at the entrance to the lower

pumping baffle can be diagnosed. This will also allow measurements in alternative divertor configurations such as the Snowflake and Super-X divertors, that are otherwise constrained outside of the current DTS viewing geometry. Finally, a scannable vertical chord will also allow 2D characterization while keeping the divertor geometry fixed and eliminate divertor plasma evolution that would otherwise occur due to sweeping the divertor geometry.

3. **Radiated power from bolometry.** The existing bolometer arrays have a spatial resolution of 5–10 cm in the SOL and divertor. While this is sufficient resolution for the radiation profile parallel to the magnetic field, it is inadequate for the radial profile. Installation of absolute extreme ultraviolet (AXUV) diode arrays will provide for higher spatial and temporal resolution of this important power balance measurement for detailed comparisons to models.
4. **Visible imaging with high spatial and temporal resolution.** New visible camera technology also offers the potential for higher resolution. Fast cameras with 10 or 12-bit resolution, coupled with the new periscope system that has recently been installed by Lawrence Livermore National Laboratory (LLNL) will allow detailed mapping of visible emission profiles. This will provide 2D profiles of emission characteristic of density and temperature contours.

In addition to the important diagnostic additions listed above, other diagnostic upgrades will include increases in coverage and performance of existing diagnostics, including visible spectroscopy, flow imaging, fixed Langmuir probes, and gas pressure measurements. An option also exists for new diagnostics such as midplane gas puff imaging for SOL turbulence and He line ratios for fast measurements of T_e and n_e. A summary of the planned diagnostic upgrades are summarized in Table 4-6.

4.2.5. Impact

Success of the DIII-D divertor and SOL physics research program outlined above would greatly enhance the basis for control of heat flux to material surfaces for ITER and fusion energy development. First improvements in divertor physics models will allow the development of ITER operational scenarios. In particular this will address the constraints heat flux control will place on ITER core plasma density requirements. Beyond ITER the physics basis for heat flux control is needed for optimization of divertor configurations and operational scenarios. Divertor heat flux control is one of the major challenges facing fusion energy development. This work will provide the basic tools for meeting that challenge.

Table 4-6
Diagnostic Upgrades to Address Divertor and SOL Physics Research

Desired Measurement	New Physics Enabled	Diagnostic Approach
Main ion temperature at divertor target and midplane SOL profile to separatrix	• Separatrix pressure gradient for stability comparison • Parallel heat flux through ion channel • Pressure balance along magnetic field	• Main Ion CER for pedestal to separatrix T_i • Divertor T_i with RFA and ion sensitive probes at midplane for SOL T_i
2D profile of divertor density and temperature in several divertor configurations	• Tests of divertor transport models • Test detachment physics • Test radiation rates in boundary models	• Divertor Thomson upgrade with scannable major radius of vertical Thomson laser • Inner wall insertable probe for inboard divertor plasma
Divertor radiated power2D profile	• 2D energy balance and energy transport within the divertor	• Divertor Bolometers with multiple arrays of AUXV diodes viewing lower divertor
2D profile of visible and IR emission	• 2D divertor plasma profiles during detached conditions • Divertor heat flux in pumping configurations • Toroidal asymmetry of plasma-wall interactions • Main chamber plasma-wall interactions	• Toroidally viewing periscope with high speed and high resolution visible and IR cameras
SOL and divertor 2D flow profile	• Test and constrain boundary plasma models	• 2D flows by coherence imaging of carbon flow
SOL turbulence in H-mode near separatrix	• Test models of SOL radial heat transport	• Line ratio measurements with gas puff for turbulence imaging
Neutral density 2D profile	• Tests and constraints of 2D boundary plasma models	• Additional neutral pressure gauges • Additional surface Langmuir probes

4.3. PEDESTAL

4.3.1. Challenges

The international fusion community has made major advances in understanding pedestal structure in the last decade. For example, a large body of evidence shows that the theory of peeling-ballooning (PB) stability successfully predicts the ultimate operational limits on pedestal size that have been observed in tokamaks. The EPED model, which combines constraints from PB modes and from kinetic ballooning modes, successfully predicts pedestal pressure height over a range of parameters in several machines. DIII-D has made early and important tests of these models but tests on other devices have been crucial to show the generality of these models. The numerous tests provide confidence that EPED can be used to perform useful studies for ITER predictions and optimization.

The community is beginning to focus more on the physics of individual profiles and a qualitative picture of profile evolution during pedestal buildup has emerged from studies on several devices with DIII-D being a leader in these studies. These studies are leading to an increasing emphasis on identifying the physics processes that control individual pedestal profiles of temperature and density. These processes must be understood so that a fully predictive model of the pedestal can be developed. Such a model is needed because the pedestal in an H-mode reactor must simultaneously satisfy a number of important criteria, as discussed below. Obtaining a satisfactory pedestal solution in a reactor requires a much deeper understanding of pedestal physics than now exists and this understanding must be available when reactors are designed. The combined efforts of the international theoretical, modeling and experimental communities are needed to develop this understanding and DIII-D is eager to play a major role in this research activity. Thus, these considerations form the background to DIII-D plans for pedestal research in the next five years.

The long-term goals for DIII-D pedestal physics are to work with the international fusion community to develop a validated, predictive model for pedestal structure and to develop techniques to optimize the pedestal for ITER and future machines. These pedestals must meet several criteria, including:

1. The pedestal pressure must be sufficiently high to ensure good core performance.
2. The pedestal must release energy and particles in a benign way to the SOL and divertor; in other words, ELMs must be eliminated or mitigated.
3. The pedestal must not overly shield fueling neutrals and ions for adequate fueling of the core.
4. The pedestal must prevent the influx of impurities, particularly high-Z impurities, so that radiated power and dilution of the core fuel ions by impurities are kept to acceptable levels.

In the coming five years, the DIII-D pedestal program will address the first three of these criteria. The required research includes improving our existing understanding of physics limits to the pressure pedestal profile (Fig. 4-8), gaining understanding of physics limits to individual profiles, particularly the density profile (Fig. 4-9), harnessing this understanding to predict and achieve high performance operational scenarios (Fig. 4-10) and ultimately to predict and produce pedestals that simultaneously meet the criteria of having high pressure and tolerable or no ELMs. The fourth goal will be addressed within the core-edge integration research activity (Section 4.1) where pedestal research will contribute to the goal of reducing impurity generation by minimizing heat flux to the divertor.

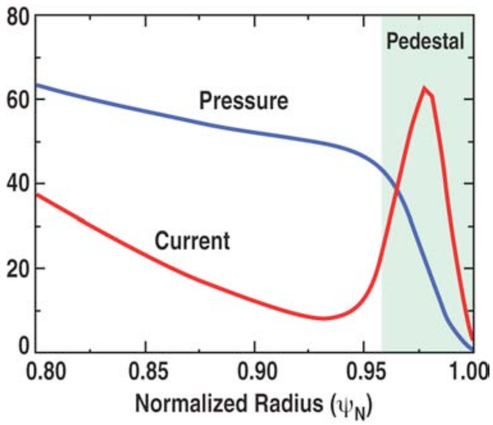

Fig. 4-8. H-mode pedestal is characterized large pressure gradients and large current densities, with the pressure-driven bootstrap current being a significant component. The physics of peeling-ballooning and kinetic-ballooning modes, predicted to limit the pressure gradient, is controlled by interplay between these two profiles.

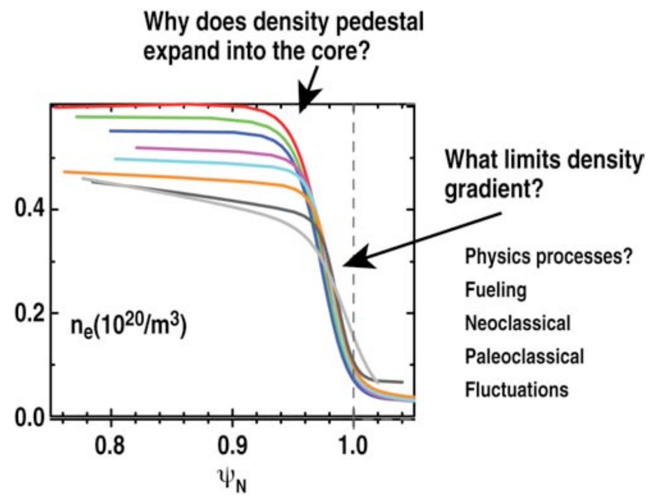

Fig. 4-9. Evolution of density pedestal during ELM cycle exhibits barrier expansion with roughly constant pedestal gradient. The physics controlling this process is not understood. The relative importance of fueling vs. transport is not understood.

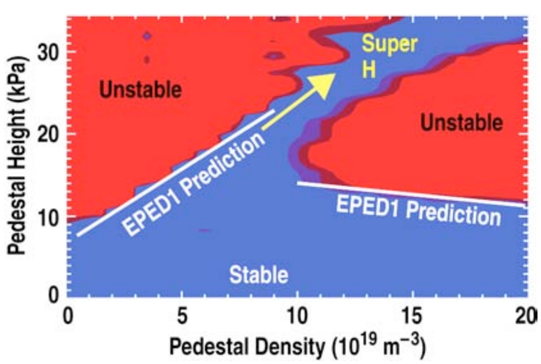

Fig. 4-10. Studies with the EPED model predict that there is stable access to very high pedestal pressures in some pedestals. Achieving these pressures imposes strong requirements on how pedestal pressure and density must simultaneously evolve [Snyder 2012a].

These challenges (or goals), the approach to addressing them, and the necessary hardware upgrades are summarized in Table 4-7.

Table 4-7
Challenges to be Addressed by Pedestal Physics

Challenge	Approach	Hardware Upgrades
Identify processes that regulate pedestal pressure profile	• Measure pedestal current and compare with bootstrap models • Measure total pressure profile, including main ions • Test models for limiting pedestal pressure gradient and height	**Measurements:** • Edge J(r) upgrade for edge current density • Main ion CER for density and temperature **Codes (see List of Computer Codes and Applications, page xxiii):** • ELITE, EPED, GYRO, GEM, GS2, TGLF, BOUT++
Determine fueling requirements to achieve optimal pedestal density	• Improve data-constrained modeling of fueling • Test models for density profile, including neoclassical, paleo, gyrofluid and gyrokinetic • Measure fluctuation-driven particle flux in pedestal with Langmuir probe	**Measurements:** • Increased Langmuir probe coverage for particle fluxes to walls • Edge J(r) upgrade for edge current density • Main ion CER for density and temperature • CER upgrade for increased E_r spatial coverage at high spatial resolution • TALIF for pedestal neutral density **Codes:** • TGLF, XGC0, TGYRO, GYRO, GEM, GS2, OEDGE, UEDGE, SOLPS, BOUT++
Demonstrate pedestals optimized for pressure to improve prospects for fusion performance in ITER and beyond	• Use EPED model to identify pathways to high pedestal pressure in high performance scenarios • Demonstrate that these pedestals can be achieved in experiment	**Codes:** • EPED
Resolve compatibility between ELM mitigation methods and high performance pedestals	• Use EPED model to identify pathways to high pedestal pressure in ELM suppression/mitigation scenarios • Demonstrate that these pedestals can be achieved in experiment	**Codes:** • EPED

4.3.2. Research Plan

4.3.2.1. Overview. The DIII-D facility is very well suited for advancing the study of the pedestal along the lines described above. Key features of the program are an excellent diagnostic set for pedestal studies, the flexibility of the machine which allows tests of models over a wide range of parameters and a good coupling with theory and simulation efforts both at General Atomics and in the broader theory community. Additional diagnostic upgrades and anticipated advances in modeling capability will be used to make new and powerful tests of pedestal models. As shown in Fig. 4-11, the research will be performed in a staged way to accommodate the implementation of diagnostic and modeling advances. The work on pedestal optimization will start with modest goals, with plans to optimize the pedestal pressure in a robust scenario and ultimately advancing to simultaneously optimize the pedestal for high pressure and mitigated or suppressed ELMs.

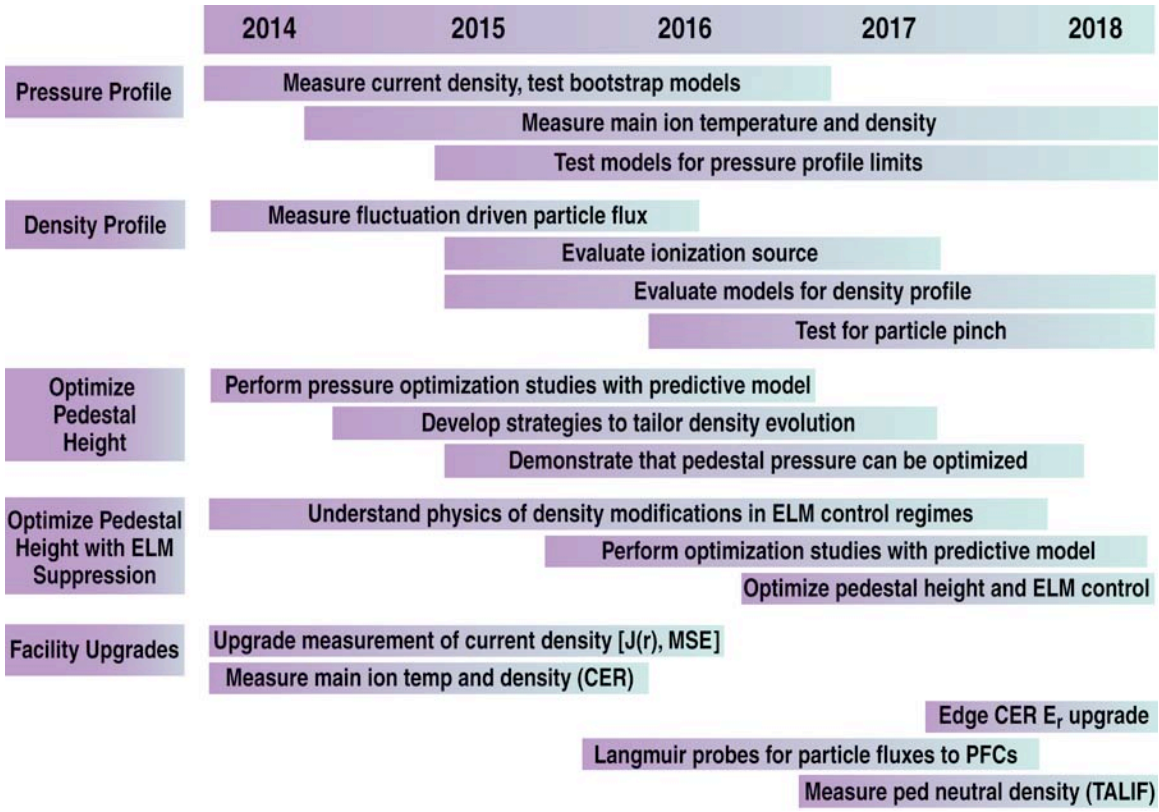

Fig. 4-11. GANTT chart for implementing program elements and diagnostic improvements.

4.3.2.2. Detailed Research Plan. The physics elements of the pedestal program follow from the main research goals.

- Identify processes that regulate pedestal pressure profile:
  - — A successful paradigm has been developed for understanding and predicting the limits to the pedestal pressure profile. In this paradigm, two constraints set by peeling-ballooning stability and kinetic-ballooning modes limit the achievable pedestal pressure. The EPED model [Snyder 2009], built on these constraints, has successfully predicted pedestal widths and heights in DIII-D and other machines [Snyder 2012a] and is being used to predict pedestal performance in ITER [Snyder 2012a]. Due to the importance of making accurate predictions, the research plan will provide new data to test physics in the EPED model and in other models that make predictions for pedestal structure. Models of interest include TGLF [Staebler 2007], TGYRO [Candy 2009], XGC0 [Chang 2004], XGC1 [Ku 2009], GEM [Chen 2007], GS2 [Kotschenreuther 1995], BOUT++ [Xu 2000] and the paleoclassical pedestal model [Callen 2012a].
  - — The pedestal current density is an important element of this model. The research plan will provide data to benchmark models of the pedestal current density, including the contribution due to the bootstrap current. For this purpose, existing diagnostics used to measure the edge current

will be upgraded. These measurements need to achieve accuracy in measuring the magnetic field pitch angle of 0.1 deg and obtain a spatial resolution of about 3 mm at the outboard midplane. Models of interest include XGC0 [Chang 2004], NEO [Belli 2008], the Massachusetts Institute of Technology (MIT) global kinetic code [Landreman 2012], NCLASS [Houlberg 1997], the Sauter model [Sauter 1999] and the Callen bootstrap model [Callen 2011].

— The total plasma pressure is also an important ingredient in this model. Due to uncertainties of existing techniques in obtaining the contribution to pressure from the main ions, a goal of the research plan is to directly measure the main ion temperature and density in the pedestal with diagnostic upgrades.

— In addition, the research plan will study the physics of pressure-gradient limiting phenomena in the pedestal and determine if these limits are due to kinetic-ballooning modes. For these purposes, advances in theoretical modeling capability will be used to make first principles predictions of limits to the pressure profile and of fluctuation characteristics for comparison with existing diagnostics. This model development work is outside the purview of the DIII-D group, but the plan calls for using advances from the General Atomics theory group and external collaborators who are developing pedestal models.

- Quantify fueling requirements to achieve optimal pedestal density:

  — The physics determining the structure of the density pedestal is not well understood. At this time, it is not clear if the width of this region is determined by atomic physics, transport or some combination of the two. Of particular interest is the physics that causes the often-observed expansion of the density barrier during pedestal buildup in DIII-D [Groebner 2009] and in other machines [Dickinson 2011, Diallo 2011]. This issue will be studied by using experimental measurements to evaluate several models of particle transport coupled with an improved determination of the wall particle source, which fuels the pedestal density.

  — Knowledge of the wall particle source is obtained with data-constrained edge/2D modeling with codes such as OEDGE [Lisgo 2005], SOLPS [Schneider 2006] and UEDGE [Rognlien 2002]. Previous work shows that this analysis can be significantly improved with more complete measurements of the ion fluxes to the walls. For this purpose, additional Langmuir probes will be added to strategic locations, including the inner wall, the upper baffle and the outer wall.

  — Models for particle transport will be tested with experimental data to identify those models that can explain the density pedestal characteristics over a wide range of parameters. Improved measurements of sources, discussed above, will be used to constrain these models. Models of interest include: TGLF, XGC0 and the paleoclassical pedestal model. Measurements of the turbulent-driven particle flux from a Langmuir probe will be used in these studies.

  — Given that expansion of the density pedestal is very commonly observed in DIII-D and other devices, the physics by which the inner edge of the profile penetrates into the core is a very important issue. ExB shear suppression will be studied to determine if it plays a role in allowing the profile to penetrate into the core. For this purpose, the CER system will be upgraded to increase the region over which the E_r profile is measured with high spatial resolution.

- Demonstrate pedestals optimized for pressure to improve prospects for fusion performance in ITER and beyond
  - — From existing scoping studies, it is anticipated that high shaping (particularly triangularity) will be an important tool for optimizing the pedestal pressure. For this purpose, the EPED model will be upgraded to use real geometry in order to properly handle discharges with high shaping.
  - — With the EPED model, predictions will be developed for optimizing the pedestal pressure height in one or more high performance DIII-D scenarios, such as the ELM-free QH-mode regime or an ELMing advanced tokamak (AT) regime.
  - — Initial studies show that the route to very high pedestal pressure requires that the pedestal evolve along a narrow trajectory of pedestal pressure versus pedestal density in order that the pedestal remain stable to ELMs. Thus, techniques will be developed to properly tailor the density evolution. Techniques of interest include pumping to reduce recycling, core fueling (such as core pellet injection), feedback control of gas puffing and changes of plasma shape and position to modify recycling.
  - — Based on model predictions, experiments will be performed to demonstrate that the pedestal pressure can be increased to new values in one or more high performance DIII-D scenarios.
- Resolve compatibility between ELM mitigation methods and high performance pedestals
  - — The first step of this plan element will be to identify an ELM control scenario for optimization. This will be a scenario that normally exhibits degradation of pedestal height when ELMs are suppressed or mitigated. One such scenario is the use of 3D RMP fields to suppress ELMs.
  - — The next step will be to characterize the relation between pedestal pressure height and the control for ELM suppression. In the case of the RMP scenario, a primary control would be the I-coil current.
  - — Scoping studies will be done to predict a path to optimize the pedestal height while maintaining ELM suppression/mitigation in the chosen ELM control scenario. Important elements for optimization will include the plasma shape and strategies to control the density profile. The importance of the density profile is one of the motivations for identifying it as an important element in the research plan.
  - — The final step of this plan element is to demonstrate that ELM mitigation and a high pedestal pressure can be simultaneously obtained in the chosen ELM control regime.

4.3.2.3. Capability Improvements. This research plan requires several diagnostic developments, discussed here and summarized in Table 4-8.

- Because magnetic shear is a key ingredient in some critical gradient processes, such as KBM and electron temperature gradient (ETG) physics, a critical need is local measurements of the safety factor profile. Thus, it is important to make the best possible measurements of pedestal current density or q profile in order to provide the best constraints on reconstructions of the shear profile. This work is also necessary to provide good measurements of the pedestal current density to benchmark models of bootstrap current.

Table 4-8
Diagnostic Upgrades for Pedestal Physics

Hardware Capability	New Physics Enabled
Edge J(r) upgrade for high accuracy and high spatial resolution by upgraded LiBeam and edge motional Stark effect (MSE) systems	• Allow benchmarking and discrimination between different bootstrap current models. Provide important tests of several transport mechanisms, including kinetic ballooning modes
Main ion CER for ion temperature and density with new tangential system	• Greatly improve ability to construct total edge pressure profile and gradient, required for numerous studies, such as studies of peeling-ballooning and kinetic-ballooning.
Additional Langmuir probes for ion flux to strategic parts of vessel	• Improve ability to perform data-constrained edge modeling. Will reduce errors of ionization source in the plasma and is necessary to unravel physics of density pedestal
Edge CER upgrade for increased spatial coverage of high resolution E_r	• Much improved ability to evaluate ExB shear for study of shear suppression models and barrier expansion
TALIF for neutral density in pedestal	• A breakthrough measurement which would provide a new and stringent test of edge/2D modeling to obtain ionization source

- It is also necessary to measure main ion parameters, including the temperature, density and rotation velocity in order to test several of these physics processes. Main ion measurements will be made to test theories of ion thermal and particle transport as well as to provide complete measurements of the pedestal pressure profile.
- This work will require good values for the flux-surface averaged profile of ionization of deuterium in the pedestal. This information will be produced with edge/2D models that are highly constrained by measurements. Improved constraints will be obtained with more complete measurements of ion fluxes to the surfaces of the DIII-D PFCs. In addition, direct measurements of the neutral deuterium profile within the pedestal would be extremely valuable to constrain and test models. Since the deuterium profile has a strong poloidal variation, measurements at two or more well-chosen poloidal locations are highly desirable.
- Another highly desirable diagnostic is an upgraded measurement of pedestal radial electric field that includes increased spatial resolution and spatial coverage. This advance is needed to provide improved measurements of E_r and ExB shear in the pedestal for comparison with theories and for use in the interpretation of fluctuation diagnostics.

A successful research campaign also requires the development and use of suitable models for making predictions that can be tested. For instance, predictions of gradients for different physics processes are needed to help identify the most important process. For fluctuation-driven processes, we need qualitative and quantitative predictions of the characteristics of fluctuations are needed for comparison with measurements. These requirements for models are at or beyond the state of the art at this time. However, there is active work on development of suitable models within the General Atomics theory program and within external collaborations. DIII-D pedestal research has been engaged with these efforts and will continue to be engaged so that these models can be used to interpret DIII-D observations and so that DIII-D data can be used to benchmark the models. An important issue is that individuals must be identified and trained to test these models. A list of codes and the new physics that they will be able to provide for pedestal studies is provided in Table 4-9.

Table 4-9
Codes Which Will Enable New Physics in Pedestal Studies

Code Development	New Capability or Physics
GYRO/TGYRO/TGLF	• Develop ability to use these in edge; test KBM, physics of temperature and density profiles
EPED	• Implement real geometry, gyrokinetic KBM model; predict optimization scenarios; predict improved limits to pressure profiles
BOUT++	• Being upgraded to gyrofluid status; test KBM, physics of temperature and density profiles
EPSI codes (XGC0/XGC1,…)	• A SciDAC project; test KBM, physics of temperature and density profiles
NEO	• Test bootstrap current models, other neoclassical physics

4.3.3. Impact

The research program outlined here will provide major advances towards developing a predictive model of pedestal structure and optimizing the pedestal in ITER and future machines. It is well appreciated that a high pedestal is required for these machines to achieve their performance goals. In addition, it is necessary that these pedestals simultaneously meet other criteria in order that these machines succeed. These criteria include the absence of damaging ELMs, compatibility with fueling technology and shielding or expulsion of impurities. These machines will not have the flexibility to perform research to achieve all of these goals. The capability for optimization must be built into the devices. Therefore, it is necessary that the international fusion community learn how to predict and optimize the pedestal based on research in existing devices. DIII-D is well suited for this research and the research program described here will provide major advances towards understanding how to optimize the pedestal height in ITER and other future machines. In addition, this work recognizes the great importance of having a high performance pedestal while also not having large ELMs. This research will provide very significant advances in understanding how this can be done. In summary, this research will provide crucially important guidance for the design and operation of burning plasma machines, operating in the H-mode regime.

4.4. ELM CONTROL

4.4.1. Challenges

The highest level goal of the ELM Control topical area is to develop techniques to control the effects of ELMs and the physics understanding needed to confidently extrapolate those techniques to future devices. To achieve this the research will focus on understanding and comparing three techniques that can have high impact on the ELM control requirements that are essential for the success of ITER and future tokamak reactors: RMP ELM suppression, QH-mode operation, and pellet ELM pacing. An essential aspect of this research is developing physics understanding of the mechanisms that affect the ELM behavior and the scaling of those effects with actuators available in ITER and future device operation.

We summarize these challenges, our approach to addressing them, and the necessary hardware upgrades in Table 4-10.

Table 4-10
Challenges, Approach and Hardware Upgrade Plans for ELM Control

<table>
<tr><th>Challenge</th><th>Approach(es)</th><th>Capability Improvements</th></tr>
<tr><td>Understand magnetic response to RMP and identify key processes that connect plasma response to pedestal transport and ELM stability</td><td>Determine connection of ELM suppression q_{95} window with RMP spectrum (n=1, 2, 3)
Understand RMP induced edge particle transport
• Vary applied spectrum
• Rotate perturbation past diagnostics</td><td rowspan="4">Actuators:
• DC supplies (2)/SPAs (12) for up to 16 independent bipolar circuits of I-coils and C-coils
• Increased neutral beam power
• Increased ECH power
• 24-element advanced 3D coil
• Injector upgrades for higher frequency, smaller pellets
• 120 Hz D_2 pellets, Li-pellet pacing, improved delivery hardware
Measurements:
• 3D magnetics (Phases 1 and 2)
• Main ion CER upgrade
• 2nd ECE, 2nd DBS
• Edge J(r) upgrade
• Edge CER E_r upgrade
• Microwave imaging reflectometer (MIR)
• 2nd ECEI
• 2nd SXR camera
Codes (see List of Computer Codes and Applications, page xxiii):
• Trip3D, SURFMN, MAFOT
• 3DEFIT, VMEC
• M3D-C^1, MARS-F, IPEC
• JOREK</td></tr>
<tr><td>Understand role of edge rotational shear in generation of EHO and develop control techniques</td><td>Establish QH-mode with balanced NBI and ECH
Vary NRMF spectrum for control of edge rotation shear</td></tr>
<tr><td>Determine mechanism and its scaling responsible for pellet-triggered ELMs</td><td>Increase frequency of pellet injectors
Vary pellet size and speed to determine minima for ELM triggering
Validate non-linear modeling of pellet ELM triggering physics</td></tr>
<tr><td>Show compatibility of viable techniques with operational constraints of ITER and beyond
• Low input torque
• High density radiative divertor
• Pellet fueling
• Low impurity accumulation</td><td></td></tr>
</table>

4.4.2. Research Plan

4.4.2.1. Overview. DIII-D is in an excellent position to investigate and compare multiple high impact ELM control techniques and make leading contributions to the physics understanding needed to extrapolate those techniques to future devices. DIII-D is the only facility capable of state-of-the-art RMP ELM suppression, QH-mode at low input torque, and high frequency pellet ELM pacing in a single device. Upgrades to hardware systems and diagnostics, combined with existing world-class pedestal, SOL and divertor diagnostics, will provide the experimental and measurement flexibility needed to compare and understand the physics mechanisms of these ELM control techniques. The sequential plan for the research and upgrades is summarized in Fig. 4-12 and described in detail in Section 4.4.2.2.

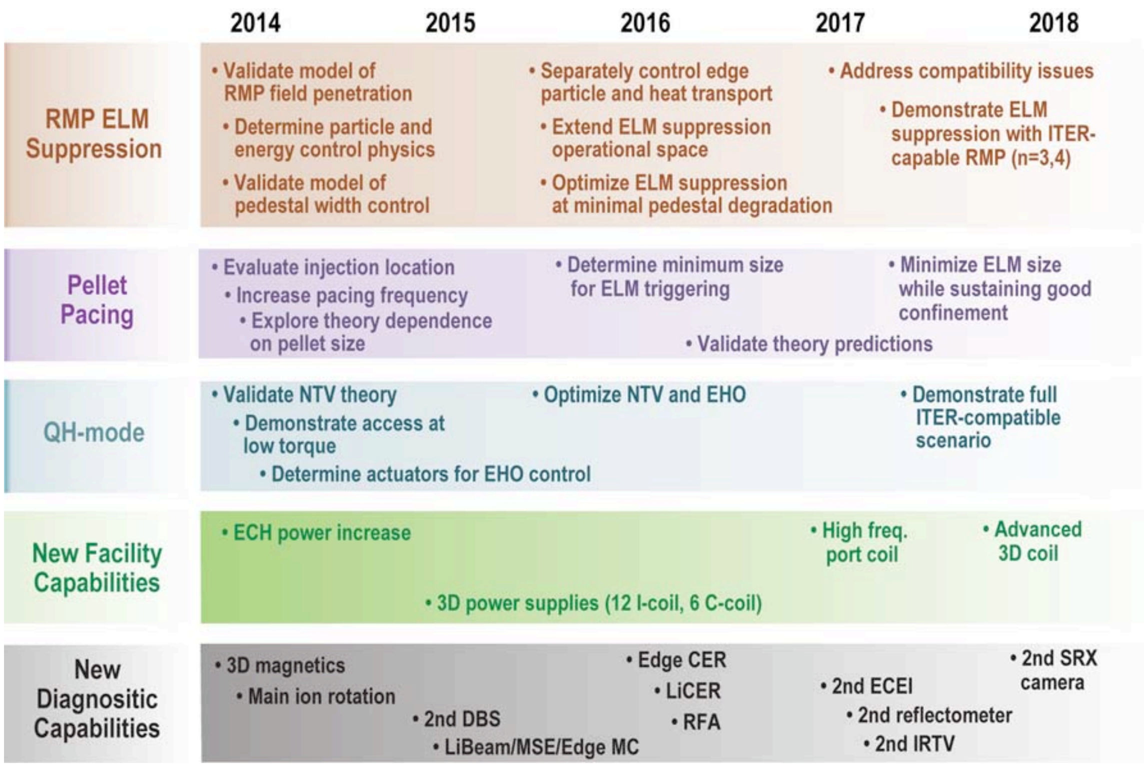

Fig. 4-12. Elements and upgrades for ELM control research.

4.4.2.2. Detailed Research Plan. The primary goals of the ELM control effort are to:

1. Understand the physics mechanisms for established ELM control techniques.
2. Optimize the leading ELM control techniques toward solutions compatible with constraints of ITER operation, and anticipated constraints of operation in future devices, FNSF, DEMO and reactors.

The optimization of all future tokamak devices operating with high confinement (H-mode) edge plasma requires control of the transient heat and particle fluxes from ELMs. In present tokamaks the fluxes from ELMs are sufficiently low that they do not significantly erode or damage the PFCs. Extrapolations for ITER and other future high power devices show that the erosion due to unmitigated Type-I ELMs will be so severe that the PFCs would need to be replaced at an unacceptable frequency [Loarte

2010]. The extrapolations also show that any ELM control techniques must be compatible with multiple operational constraints (Table 4-11) to optimize future tokamak operation.

Table 4-11
Constraints or Compatibility Requirements for Application of ELM Control Techniques in Future Tokamaks (e.g., ITER, FNSF, DEMO or Reactors)

Device(s)	Constraint or Compatibility Requirement
ITER, FNSF, DEMO	Low collisionality H-mode
ITER	Moderate $\beta_N \sim 1.8$, low $q_{95} \sim 3.1$, $P_{in} \sim P_{L\text{-}H}$
ITER	Lower single-null ITER-similar shape (ISS)
ITER, FNSF, DEMO	Low input torque
ITER, FNSF, DEMO	Control of 1st ELM and during I_p ramp
ITER	Compatibility with high core and separatrix densities, HFS pellet fueling
ITER, FNSF, DEMO	Low heat flux to FW and compatible with radiative detached divertor
ITER	Compatibility with high p_{ped} and low collisionality
ITER	Small effect on $P_{L\text{-}H}$, toroidal rotation, core MHD, and locked mode thresholds
ITER, FNSF, DEMO	If heat flux asymmetries are introduced pattern will need to be rotated
ITER	Minimal change to between ELM heat flux level or structure by ELM control structure
ITER, FNSF, DEMO	Achieve $f_{ELM}^{pellet} / f_{ELM}^{natural} > 25$x for pacing schemes with predictable scaling of ELM energy loss with f_{ELM}^{pellet}
ITER, FNSF, DEMO	Compatible with metal wall operation and acceptably low high-Z metallic impurities in the core
FNSF, DEMO	High elongation double-null shape
FNSF, DEMO	High beta, steady-state operation

The research will concentrate on three primary techniques (described in detail below), vis.:

1. RMP ELM Suppression
2. Quiescent H-mode (QH-mode)
3. Pellet ELM Pacing

The Five-Year Plan strategy includes the option to explore other promising techniques [e.g., I-mode, Snowflake divertor operation, other ELM pacing methods including vertical kicks, small ELM regimes including supersonic molecular beam injection (SMBI) etc.], with the goal of specifying the optimum techniques for ITER, FNSF and DEMO operation (see detailed descriptions in the section on "Other ELM Control Techniques" at the end of Section 4.4.2.2).

- In the RMP area the program will focus on understanding and exploiting the RMP mode spectrum to optimize ELM control.
- In the QH-mode area the program will work to understand, control and exploit the edge harmonic oscillation (EHO) produced in the pedestal to extend stationary QH-mode operation without ELMs to future device conditions.

- In the pellet ELM pacing program the focus will be to understand and exploit the ELM triggering physics to optimize the control of the ELM particle and energy losses.

A common theme of this research area is that understanding and controlling local transport in the edge may be the key to many of the techniques for ELM control. In particular the research will focus on the effect of several techniques (e.g., QH-mode and RMP) on the evolution of the pedestal width and gradient, including techniques to independently control the density and temperature pedestals. In the RMP case for example, the research will determine whether local modification of the particle and heat transport near the top of the pedestal can be an effective mechanism to restrict the expansion of the edge barrier width, which may prevent the ELM by restricting the total free energy in the edge barrier (when the pressure gradient is restricted by kinetic ballooning modes or related micro-instabilities). Other techniques mitigate ELM size by making temporal perturbations to the edge density (e.g., pellet ELM pacing), which can lead to local pressure perturbations, in order to trigger small, high frequency ELMs. Key to each of these is understanding of edge particle and heat transport and its connection with edge MHD stability.

Another common aspect to the research in the ELM control program is that there are significant 3D effects that are important for understanding and optimizing the ELM control. In the RMP case the external coils apply a 3D magnetic perturbation to the edge. In QH-mode one of the keys to the optimization is to exploit the EHO, which is an inherently 3D plasma mode. Likewise in pellet ELM pacing, the 3D localized perturbation of the edge due to the pellet must be fully understood to optimize the triggering physics. Also, the 3D intrinsic error fields in DIII-D can couple to the ELM control techniques in ways that must be understood. The ELM control program will be a strong driver of the need for advanced 3D magnetic coils and additional pellet injectors (Table 4-12), upgraded 3D equilibrium reconstruction capability and expanded 3D diagnostic capabilities (Table 4-13) in the next five years of DIII-D operation.

Table 4-12
Hardware Upgrades

Name	Priority	Plan or Optional	Section Ref.	Research Area
DC supplies (2)/SPAs (12) for up to 16 independent bipolar circuits of I-coils and C-coils	1	Proposed	5.7.1, Fig. 5-1 Table 5-1	RMP, QH-mode
Twenty-four element advanced 3D coil set with 12 toroidal coils per row each with an independent power supply	1	Proposed	5.6.2, Fig. 5-1 Table 5-1	RMP, QH-mode
120 Hz D_2 pellets, improved delivery hardware	2	Proposed	5.9.2, Fig. 5-1 Table 5-1	Pellet ELM pacing
Increased ECH power sufficient for $\beta_N = 2$ with electron heating	3	Proposed	5.3, Fig. 5-1 Table 5.1-1	QH-mode
Li-pellet pacing with high frequency solid pellet (e.g., Li) injectors	4	Program Option	5.9.2, Fig. 5-1 Table 5-1	Pellet pacing
3 MW FW power plus 1 MW helicon drive	5	Program Option	5.5, Fig. 5-1 Table 5-1	I-mode

Table 4-13
Diagnostic Upgrades

Name	Plan or Optional	Section Ref.	Physics
3D magnetics Phase 1	Planned	6, Fig. 6-2, Table 6-4	Improved magnetics measurements to allow generation of 3D kinetic EFITs
3D magnetics Phases 2	Proposed	6, Fig. 6-2, Table 6-4	Complete magnetics measurements to allow generation of 3D kinetic EFITs
Second ECE radiometer	Proposed	6, Fig. 6-2, Table 6-11	Determine 3D nature of electron temperature perturbation during RMP and QH-mode
Second profile reflectometer, microwave imaging reflectometer	Proposed	6, Fig. 6-2, Table 6-11	Determine 3D nature of pedestal and near SOL electron density profile under RMP and QH-mode operation
Edge j(r) upgrades (LiBeam and MSE)	Proposed	6, Fig. 6-2, Table 6-10	Measure edge bootstrap current profile, a critical quantity for pedestal stability analysis
3D kinetic EFIT	Proposed	6	Calculate 3D equilibrium surfaces needed for interpretation of multiple measurements during RMP and QH-mode
Second DBS system	Program Option	6, Fig. 6-2, Table 6-7	Measure 3D structure of edge fluctuations leading to particle transport during RMP and QH-mode
Edge heavy neutral beam probe	Program Option	6, Fig. 6-2, Table 6-10	Directly measure effect of RMP and QH-mode on pedestal E_r and ion fluctuations to validate enhanced edge particle transport models
Pellet ablation monitors	Program Option	6	Directly measure pellet penetration needed for ELM triggering
Divertor IRTV at multiple toroidal locations	Program Option	6, Fig. 6-2, Table 6-11	Determine effect of RMP and pellet ELM pacing on 3D heat flux topology
Second tangential SXR camera	Program Option	6, Fig. 6-2, Table 6-11	Verify both poloidal and toroidal structure of plasma response to RMP perturbations
Second ECE imaging system	Program Option	6, Fig. 6-2, Table 6-4	Verify both poloidal and toroidal structure of T_e response to RMP perturbations and EHO
Reciprocating probe with fast magnetic field sensors	Program Option	6, Fig. 6-2, Table 6-10	Measure magnetic field fluctuations in the edge plasma to validate enhanced edge particle transport models
Fast edge MSE or LiBeam	Program Option	6, Fig. 6-2, Table 6-10	Determine effect of pellet on edge current peak

Present theoretical understanding of PB modes and the evolution of the pedestal to the ELM instability boundary (Section 4.3 Pedestal Structure and [Snyder 2012b]) suggests that an effective method to reduce the magnitude of ELM fluxes or eliminate ELMs entirely is to either limit the expansion of the pedestal pressure width or limit the pedestal pressure to values just below that needed to trigger the PB mode that produces Type-I ELMs (Fig. 4-13). The ELM control research program will combine with the DIII-D theory group to try to understand if the key to the success of various ELM control techniques is that they prevent the expansion of the pedestal width to the instability boundary. With this understanding it will be the goal to hold either the expansion of the pedestal width to a value just below the instability boundary in order to maximize the pedestal height (at fixed maximum gradient), or to limit the pedestal pressure at large pedestal width, for optimum core plasma performance without ELMs.

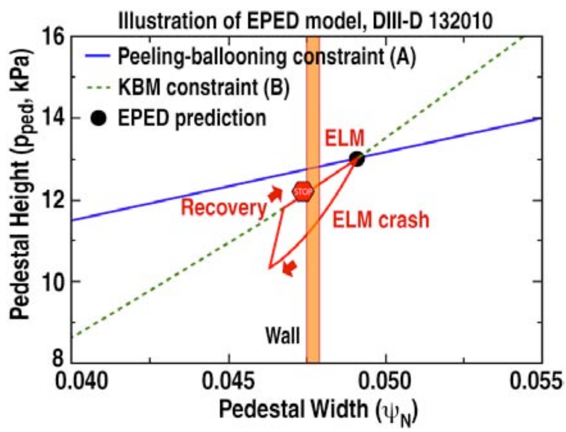

Fig. 4-13. EPED model of ELM triggering at the intersection of peeling- and kinetic-ballooning mode constraints, and the key to ELM control being to restrict the expansion of the pedestal width and height below the intersection point.

DIII-D is in a unique position to play a key role over the next five years in developing viable ELM control techniques and predictive capability for extrapolations to future tokamaks. Multiple tokamak experimental programs, including DIII-D, are currently exploring various ELM control techniques. However, in most cases, other devices can explore one or at most two different techniques, frequently with restrictions on the core plasma operating conditions. In the next five years DIII-D will be capable of exploring and comparing essentially all of the leading ELM control techniques in a single device with significant flexibility of operating conditions. Multiple heating systems, flexible input torque control, state-of-the-art shaping control (including ITER Similar Shapes), extensive pedestal, SOL and divertor diagnostics, and forgiving carbon PFCs, all contribute to a capability for exhaustive and thorough study of the physics of ELM control. DIII-D has demonstrated a unique capability to simultaneously match the pedestal collisionality and pedestal beta of ITER with ELM suppression at very high pedestal temperature. Also DIII-D has unique capability, through use of balanced neutral beam injection and wave heating, to compare various ELM control techniques at high power density and low input torque, a key operational constraint of ITER and future power reactors.

This multi-technique program will complement the worldwide effort in two ways. First, it will allow unique comparisons of techniques, in a single device under common conditions and with common diagnostics. Second, it will allow scaling relations to be developed using similarity experiments with other devices by taking advantage of the unique flexibility of DIII-D heating, shaping and input torque capabilities. The details and sequential research program elements of the proposed ELM control research plan are given below.

RMP ELM mitigation and suppression. Following on present understanding, this research area will focus on the key physics for exploiting and extrapolating RMP ELM mitigation and suppression in future devices. It will explore the connection between the applied RMP mode spectrum, the plasma response to it, and the resulting perturbation fields within the plasma, and near-edge transport of particles, heat and momentum, with particular focus on preventing the expansion of the pedestal width to the ELM instability boundary. This research will use the proposed power supplies upgrade (2-dc supplies and 12-SPAs, Section 5.7.1) to independently configure the 12 internal I-coils in a much greater variety of n=1, 2, or 3 poloidal mode spectra to determine the dependence of ELM suppression on the resonant vs. non-resonant applied fields. In the later years of this plan it will also use the proposed 24-element advanced 3D magnetic coil set (Section 5.6.2) to test ITER-relevant RMPs using the capability of up to n=4 toroidal modes which can be rotated toroidally past fixed diagnostics for comprehensive measurements of the resulting fields and other effects on the edge plasma.

The RMP research in this plan will complement research ongoing or planned at many other tokamak facilities, including at ASDEX-Upgrade (AUG) [Suttrop 2011], UK's Joint European Torus (JET) [Liang 2011], Korean Superconducting Tokamak Advanced Research (KSTAR) [Kim 2012], Culham's Mega-Ampere Spherical Tokamak (MAST) [Kirk 2013], China's Experimental Advanced Superconducting Tokamak (EAST) [Wan 2012], National Spherical Torus Experiment Upgrade (NSTX-U) [Kaye 2012] and Japan's Tokamak-60 Super Advanced (JT-60SA) [Kamada 2012]. RMP ELM suppression has been achieved using coils internal to the vacuum vessel in AUG (n=2 fields) and KSTAR (n=1 fields). ELM mitigation has been achieved in these devices, also with internal coils at MAST, and also using coils external to the vacuum vessel at JET. The combined research in these devices is focused on the goal of optimizing the use of the internal coil set (three rows of nine independently powered coils) for ELM control in ITER and providing sufficient physics understanding to design optimized ELM control coils for future devices.

The sequential research steps to investigate the hypothesis that preventing expansion of the pedestal width is key to RMP ELM suppression are:

- Fully understand the plasma response to the applied RMP fields and the resulting perturbation fields within the plasma (Fig. 4-14). This includes:
  - — Determining if the perturbation structure is kink-like or contains reconnected magnetic islands
  - — Evaluating the role of rotation in the RMP field penetration and plasma response
  - — Determining the dependence of the plasma response to the ratio of pedestal beta (β_{ped}) normalized to the MHD critical beta.

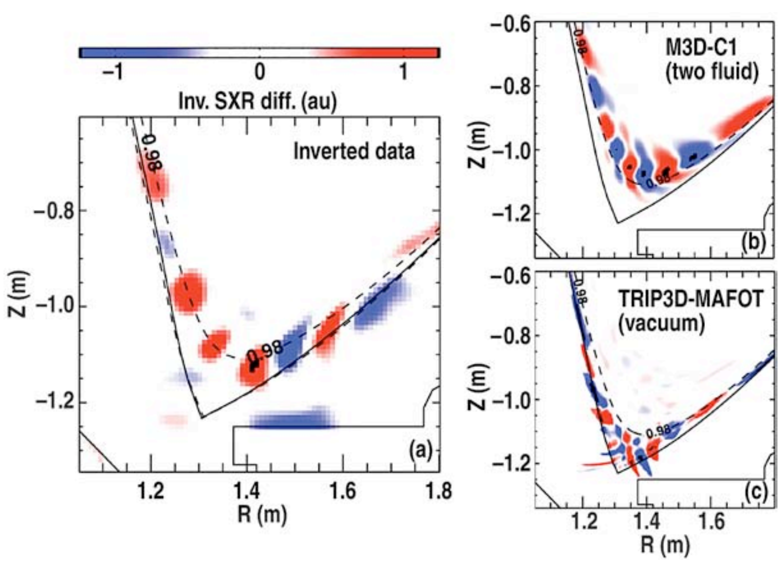

Fig. 4-14. Reconstruction (a) of the perturbation of soft x-ray emission due to applied n=3 RMP fields from difference of emission with 0 and 60 deg toroidal RMP phase during ELM suppression, and simulation of the soft x-ray emission using synthetic diagnostic processing of the (b) M3D-C[1] solutions including the plasma response to the applied fields, and (c) vacuum field from MAFOT [Wingen 2009].

This research will fully exploit 2-fluid resistive MHD theory and simulation codes (e.g., M3D-C[1] [Ferraro 2010] and others) to both guide experiments and interpret experimental results.

- Determine if the self-consistent penetrated fields in the plasma modify local particle and thermal transport in the pedestal.
  - Develop theories or models of the mechanisms for particle or thermal transport modification (e.g., magnetic flutter [Callen 2012b, Callen 2012c, Callen 2012d], $\langle JxB \rangle$ flutter [Waelbroeck 2012], zonal flow damping by islands [Leconte 2012], *ExB* convection from islands, magnetic stochasticity, neoclassical transport, turbulence induced transport etc.)
  - Determine if the modification can be made local to the top of the pedestal or is more global in character.

  A key part of this step will be to understand why the achievement of ELM suppression by RMP techniques seems to be a phenomenon resonant with the equilibrium field structure under some conditions (low collisionality ELM suppression by n=2 or n=3 fields in DIII-D [Evans 2008, Lanctot 2013]) but not in other experiments (high collisionality ELM suppression in both DIII-D [Evans 2005] and Germany's Axisymmetric Divertor Experiment Upgrade (ASDEX-Upgrade) [Suttrop 2011] experiments).
- Understand how locally enhanced transport at the top of the pedestal produces a viable mechanism to stop the expansion of the pedestal pressure width.
  - Design perturbation fields that can affect the plasma transport at an optimum radial position in the pedestal.
  - Hold the pedestal pressure width at a value just below the instability boundary.
  - Maximize the height of the pressure pedestal without ELMs.

  A key component of this step is the use of a feedback system, e.g., by employing a real-time microwave density reflectometer that is tuned to monitor the pedestal density, to provide a control signal for adjusting the current in the ELM coil in order to maintain the highest possible pedestal density and pressure without triggering an ELM. Through a series of upgrades to the existing reflectometer systems the plan is to develop the physics and technology basis for this type of feedback control system over the next few years. In DIII-D this feedback control system will be implemented by installing a crossover network between the high current dc power supplies, which set the base current level in the 3D coils, and a set of fast, lower current audio amplifiers that are used to adjust the ac component of the 3D coil current on a 1 ms timescale. The real-time microwave density reflectometer that will supply the control signal for the high frequency component of the system, will be tested under various DIII-D plasma conditions before integrating it into the ELM coils feedback algorithm in the DIII-D Plasma Control System.
- Long-range plan must consider the optimized operating conditions of ITER, FNSF, DEMO and future tokamak reactors.
  - Understand how to produce ELM control with minimum pedestal pressure and density reduction for optimized core performance.
  - Understand the depth of penetration of the resonant field components for optimum ELM control.

— Determine the effect on plasma performance of the non-resonant spectral components that arise from any finite RMP coils set.

— Determine the scaling of the ELM control mechanism with input torque, density vs. collisionality, β_N, and other dimensionless parameters for extrapolation to future devices.

— Demonstrate RMP ELM control for ITER in scenarios with low input torque to the plasma.

— Show RMP ELM control compatibility with the various constraints on operation of ITER and other future devices (Table 4-11), including:

- o Partially detached radiative divertor operation for steady-state heat flux control.
- o Pellet fueling for core density control.
- o Suppression of the first ELM after the L-H transition.
- o Operation near the L-H power threshold.
- o Show either RMP ELM control is possible during the current ramp-up when q_{95} is evolving, or demonstrate scenarios combining RMP ELM control at I_p flattop with another ELM control technique during I_p rampup/rampdown, to satisfy ITER requirements.
- o Suppression without accumulation of high-Z impurities.

QH-mode stationary operation without ELMs. This research area will focus on expanding the operating regime of stationary QH-mode without ELMs, by determining the precise characteristics of the EHO that forms in the pedestal, and developing actuators that can control those characteristics for QH-mode access and sustainment over a wide range of operating conditions. It will build on not only the QH-mode experience at DIII-D, but also on previous observations of QH-mode operation at JET [Suttrop 2005], AUG [Suttrop 2003], and JT-60U [Oyama 2005]. This research will leverage ongoing theoretical analysis with the EPED code [Snyder 2011] and collaborations with PPPL using IPEC [Park 2007]. The sequential research steps to obtain EHO control are:

- Verify the theoretical prediction that the EHO is a saturated edge kink-peeling mode.

  — Test theory suggesting [Snyder 2012b] that a key to this verification is to determine whether a threshold edge rotation shear is critical to sustain the EHO as predicted.

  — Determine whether it is shear of the main ion rotation or the ExB rotation that is the critical quantity. At present, theory cannot predict which rotation is more important, but experiments suggest that while QH-mode can be sustained for a range of ion rotation profiles, it can only be sustained for ExB rotation shear above a threshold value (Fig. 4-15 [Garofalo 2011]).

  The proposed upgrade to the main ion rotation diagnostic for the pedestal will provide the direct measurements needed to answer this physics question and validate the EHO theory. Theory developments are needed to develop understanding and extrapolate to future devices. Once the critical rotation shear requirement is identified the research will need to determine the scaling of the required conditions with machine/plasma parameters.

- Determine how the EHO can affect edge particle transport.

  — Validate models of the EHO and its effect on particle transport for extrapolation to future devices

— Assess the role of neoclassical toroidal viscosity (NTV) on particle loss and on the overall edge particle transport.

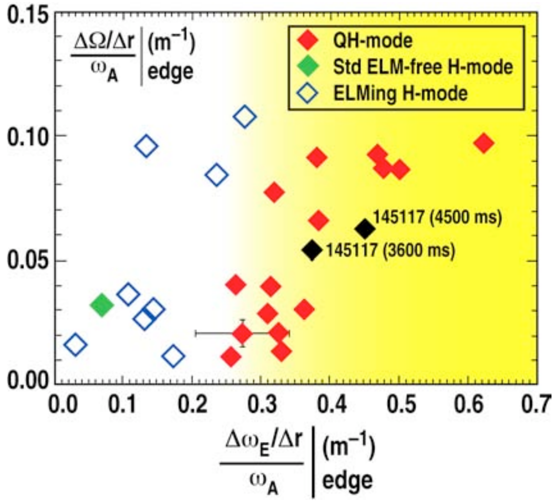

Fig. 4-15. QH-mode operation in carbon poloidal vs. *ExB* rotation shear space suggesting that a threshold shear in the *ExB* rotation is needed to sustain QH-mode [Burrell 2012a].

- Evaluate how the EHO produces the required edge transport to hold the pedestal pressure or its gradient below the ELM instability boundary for the conditions of ITER and future devices.

  — Determine if actuators for control of the EHO mode spectrum are required. Present experiments show that n=1 dominated EHOs are effective for generating the required edge particle transport to sustain QH-mode, but plasmas with n=1 EHOs tend to lock at low input torque [Burrell 2012b]. Plasmas with higher n (n=2, n=3 or broadband) EHOs can be sustained in QH-mode down to essentially zero input torque using non-resonant magnetic perturbations (NRMFs).

- Extend the edge rotation shear and EHO mode control to the conditions of low input torque predicted for ITER and future devices.

  — Determine if NTV torque can produce the edge rotation shear and EHO spectrum needed for ITER.

  — Validate the theory of NTV torque produced from applied NRMFs.

  — Investigate whether the theory correctly predicts the resulting edge rotation shear for particular edge plasma conditions and applied NTV torque.

  This research step will use the proposed 24-element advanced 3D magnetic coil set (Section 5.6.2) to produce much stronger non-resonant fields than the present I-coils or C-coils, to generate significantly larger NTV torque than the present I-coils and allow extension of QH-mode to higher fusion performance parameters.

Long range plan. Use DIII-D unique capabilities to control and expand QH-mode operating space toward ITER, FNSF, DEMO and reactor requirements.

- Establish QH-mode with electron heating only, using a combination of the ECH, fast wave (FW) and torque balanced NBI systems.

- Investigate access to QH-mode during low torque plasma startup scenarios, thereby preventing the first Type-I ELM even for L-H transitions during I_p ramp-up, or at low temperature or plasma beta.
- Study the compatibility of the QH-mode with other requirements of ITER and devices beyond ITER, including compatibility with:
  — Partially detached radiative divertor operation.
  — High field side (HFS) pellet fueling.
  — Low accumulation of high-Z impurities.

Pellet ELM pacing. The pellet ELM pacing research program will focus on understanding and exploiting physics mechanisms of ELM triggering by pellets to optimize and control pellet induced ELM energy loss. This research will compliment ongoing pellet ELM triggering and ELM pacing research on JET [Lang 2011] and AUG [Lang 2008], for example by extending to higher ratios of pellet ELM pacing frequency normalized to natural ELM frequency than achieved so far. It will make use of the proposed upgrades to 120 Hz D_2 pellets and Li pacing pellet capability (Section 5.9.2) to increase the ratio of injected pellet frequency to natural ELM frequency. The sequential steps in the Pellet ELM Pacing research plan are:

- Validate theoretical model dependencies of ELM triggering on pellet size, injection speed and injection geometry [Baylor 2012a, Futatani 2012]. This will include parameter scans to test critical aspects of the theory, e.g.:
  — Whether the triggering is more sensitive to density or collisionality variations.
  — How the flux expansion of the SOL affects the penetration of the pellet into the pedestal.
  — Whether the triggering depends more strongly on the absolute real space penetration depth or on the deepest flux surface reached by the pellet within the core plasma.

  The latter scan will take advantage of the DIII-D capability to inject pacing size pellets from multiple poloidal locations including two locations on the HFS, the low field side (LFS) midplane and the LFS lower X-point region [Baylor 2012b].
- Determine the optimum pellet size for reliable triggering with minimum particle throughput and core fueling.
  — Determine the minimum pellet size needed for high efficiency ELM triggering through a series of pellet injector upgrades already in progress [Baylor 2012] and continued in this five-year plan (Fig. 4-16).
  — Evaluate the optimum combination of pellet size, velocity and injection geometry for DIII-D.
  — Determine the parametric dependencies of this optimization so that predictions can be made of optimal parameters for ITER and FNSF applications.

  Previous experiments have shown that ELMs are effectively triggered with pellets launched from the LFS (either the midplane or X-point locations) at approximately 100 m/s having diameters of 2.0, 1.8, 1.3 and 0.9 mm [Baylor 2012]. Other experiments have shown that 1.0 mm pellets dropped vertically at approximately 10 m/s from a V+3 port location did not trigger ELMs, and in fact these pellets did not penetrate through the SOL to the separatrix.

- Determine the maximum pellet paced ELM frequency possible in DIII-D while maintaining good H-mode core plasma confinement. This performance goal will make use of the optimizations of pellet size, velocity and injection geometry obtained earlier in the plan.

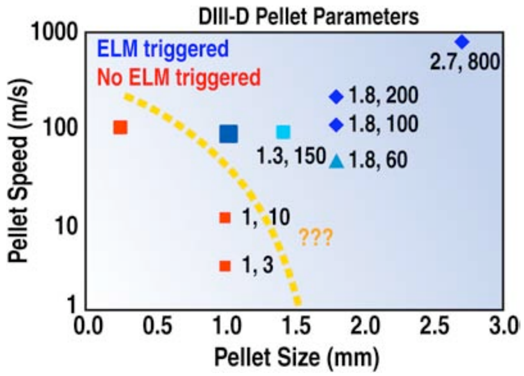

Fig. 4-16. Operating space of pellet ELM pacing from previous DIII-D experiments suggesting the range of combinations of minimum pellet velocity and size needed for ELM triggering [Baylor 2012].

Other ELM control techniques. The five-year plan strategy includes options to explore other promising ELM control techniques, especially if they can help to directly expose the underlying physics mechanisms common to several of well-established techniques. Candidate techniques that have shown promise in limited experiments on other devices include:

- I-mode operation [Whyte 2010, Hubbard 2012, Ryter 2012] pioneered at MIT Tokamak Modification (ALCATOR C-Mod) and also observed in AUG.
- Use of the Snowflake divertor configuration [Ryutov 2008, Soukhanovskii 2011, Piras 2010b] to modify pedestal stability, pioneered theoretically by LLNL and tested at NSTX and TCV.
- ELM pacing by various techniques such as:
  — Modulated RMP fields [Solomon 2012, Canik 2012] as tested by both DIII-D and NSTX.
  — Modulated loop voltage or by vertical plasma position kicks [Saibene 2011] as tested on JET.
  — Modulated SOL currents induced by applied voltage on divertor target plates.
  — Pulsed un-magnetized plasma jets.
- There are also several "small ELM" plasma operating regimes that could be tested such as:
  — The "grassy ELM" regime [Oyama 2010] pioneered at JT-60U.
  — The Type-III ELM regime induced by seeding the SOL with impurities such as nitrogen [Rapp 2009, Rapp 2012] as tested at both JET and AUG.
  — The Type-II ELM regime seen in strongly shaped double-null plasmas [Ozeki 1990, von Thun 2008] in DIII-D and AUG.
  — SMBI [Kim 2012] as tested on KSTAR and EAST.

As an example, a promising candidate for investigating the connection between ELM control and edge particle transport/density pedestal control is I-mode. Extensive work on I-mode has been done in ALCATOR C-Mod and joint experiments were recently performed in AUG. The research plan for I-mode would focus on partnering with the C-Mod team to investigate physics processes necessary to achieve simultaneous H-mode-like edge temperature pedestals with L-mode-like edge density profiles. The first step in this research plan would be to exploit the unique DIII-D capabilities that complement those at C-Mod and AUG in initial scoping studies to expand the operating space for I-mode to DIII-D parameters. The optimum second step would be to perform joint experiments with C-Mod as a continuation of work started for the 2013 Joint Facilities Research Target on alternated ELM control techniques. Further steps would include:

- Optimizing I-mode performance via shaping variation and optimized plasma density control through pumping.
- Extending I-mode edge operation to high core performance.
- Extending I-mode operation to plasmas with zero input torque, i.e. wave heating or balanced neutral beams.
- Optimizing upstream SOL profiles and divertor target heat loads in I-mode.
- Controlling core helium and impurity content under stationary I-mode conditions without ELMs.
- Using the knowledge obtained to develop robust I-mode scenarios with ion grad-B drift toward the dominant X-point.

4.4.2.3. Capability Improvements. The primary new hardware actuators proposed for the ELM control program are:

- Upgrades of the I-coil and C-coil power supplies (2-dc supplies and 12-SPAs, Section 5.7.1) to allow fully bipolar control of up 16 circuits independent of I-coils and C-coils.
- Additional high frequency pellet injectors (Section 5.9.2) with:
  - — Capability to reach the ITER required $f_{ELM}^{pacing}/f_{ELM}^{natural}$ for robust Type-I ELMing H-mode operation in DIII-D.
  - — Both reduced pellet size capability and simultaneously the capability to inject both large fueling pellets addressing compatibility of all ELM control techniques with HFS pellet fueling of the core plasma.
  - — Restored capability to inject Ar pellets for the generation and physics studies of runaway electrons.
- A new 24-element advanced 3D coil (A-coil) system (Section 5.6.2) with:
  - — Capability to produce up to n=4 (ITER-like) perturbations which can be rotated toroidally for diagnostic sampling and physics understanding.
  - — Increased strength and spectral flexibility for NRMFs to produce NTV torque.

Additional hardware upgrades are proposed that would be beneficial to the ELM control program including:

- Increased ECH power (Section 5.3) sufficient for β_N = 2 with electron heating to allow the QH-mode and RMP programs the capability to explore electron heated, zero input torque plasmas.

- High frequency solid pellet (e.g., Li) injectors (Section 5.9.2) to provide the pellet ELM pacing program the capability for very high frequency demonstration of pacing with reactor-relevant pellets.

Diagnostic sensor upgrades are also proposed to extract the measurements needed to understand the physics mechanisms of the various ELM control techniques. All of the proposed diagnostics needed by the Pedestal Structure Program (Section 4.3) will be extremely valuable to the ELM control program as well, e.g., the main ion rotation measurements in the pedestal to validate the theory of EHOs. In addition, the physics of essentially all ELM control techniques has an inherent 3D component, vis. the application of RMP fields results in an externally controlled 3D magnetic perturbation, the EHO that forms in QH-mode is a 3D structure, and the localized perturbation from a pellet that triggers an ELM is a localized 3D structure. As a consequence, the ELM control program motivates the proposal to duplicate plasma parameter measurements for different toroidal locations to properly evaluate 3D dynamics (Section 6, Fig. 6-2, Table 6-4 and 6-11). Examples include a second electron cyclotron emission (ECE) radiometer for T_e measurements (Table 6-11), and second Doppler backscattering system (DBS) for density fluctuation measurements (Table 6-7), a second profile reflectometer for density profile measurements (Table 6-11), a second infrared television (IRTV) to measure target heat flux asymmetries (Table 6-11), a second ECE imaging system (ECEI) (Table 6-4) and a second soft-x-ray (SXR) camera (Table 6-11), both for 3D electron temperature perturbations. The 3D magnetic sensors, including a second set of upgrades during this plan (Table 6-4), will be combined with proposed 3D kinetic EFIT equilibrium reconstruction capability to calculated magnetic perturbations.

4.4.3. Impact of ELM Control Research Program

The Five-Year ELM Control Research Plan above represents an essential step to the success of ITER's Q=10 mission, and high performance operation of future tokamaks, all of which require H-mode thermal energy confinement without the excessive plasma facing components erosion due to unmitigated Type-I ELMs. Detailed physics understanding of the mechanisms controlling the effect of each technique on ELMs will allow confident prediction of the effectiveness of each technique to the unique operating conditions and constraints of future devices such as ITER, FNSF and DEMO. This research program will lead to identification of the most promising technique for each future device application. The predictive capability generated from this research will increase confidence in predictions of optimized stationary high power H-mode scenarios without large Type-I ELMs for future devices.

4.5. PLASMA-SURFACE INTERACTIONS

4.5.1. Challenge and Opportunity

For plasma-surface interactions (PSIs), the material surfaces directly in contact with the fusion plasma suffer extreme perturbations due to the continual energetic bombardment of plasma particles that both exhaust heat and “recycle” the hydrogen fuel. The surfaces are rapidly reconstituted and altered by this PSI with the potential for significant material migration and tritium fuel retention and permeation; for example a surface atom may be removed and re-deposited over a million times in a single year. For fusion power plants this PSI will take place at elevated temperatures ~500°C–1300°C, where the processes will be very different from the experience gained in the lower temperatures, ≤300°C, of present day experiments. A central challenge for fusion energy development, as summarized in recent community reports chaired by Hazeltine [Hazeltine 2009] and Zinkle [Zinkle 2012], is the development of PFCs that can survive the harsh conditions of a fusion reactor yet remain compatible with a high performance burning plasma. DIII-D will play an important role in this development by utilizing realistic tokamak divertor and chamber conditions for testing the models of PSI that will be used for designing PFCs for FNSF and DEMO.

The staging of divertor PFC materials to be deployed in ITER is still under discussion. There are known risks to the use of W in the ITER divertor, particularly in the early phases when operating scenarios are being developed. Thus while much research is needed on high-*Z* PFCs, it is still prudent to explore alternates, e.g., low-*Z* materials. As the only remaining large tokamak with carbon divertor targets, DIII-D can provide essential data and experience for making an informed choice.

The challenges that PFC material choices represent and DIII-D’s role in solving them are summarized in Table 4-14.

Table 4-14
PFC Material Choice Challenges and DIII-D’s Approach for Solutions

<table>
<tr><th>Challenge</th><th>Approach</th><th>Capability Upgrades</th></tr>
<tr><td>Develop materials and component designs to withstand harsh reactor conditions and for compatibility with high core plasma performance</td><td>Test models of PSI and their dependence on material temperature in realistic tokamak plasma conditions</td><td rowspan="3">• Hot tile surface station for measurement of PSI versus temperature
• AGNOSTIC for in-situ measurement of erosion and re-deposition
• Smart tiles for multiple measurements
• Quartz microbalance
Modeling capabilities:
• REDEP/WBC, HEIGHTS, ITMC-DYN, DIVIMP, OEDGE, UEDGE, SOLPS
• PSI model development via SciDAC projects</td></tr>
<tr><td>Mitigate high-Z surface material migration and contamination of core plasma</td><td>Apply consumable, flow-through, low-Z “coatings” to high-Z surfaces</td></tr>
<tr><td>Establish compatibility of carbon targets with ITER operational constraints</td><td>Determine erosion and fuel retention rates in DIII-D divertor under ITER relevant conditions</td></tr>
</table>

4.5.2. Research Plan Overview

The primary role for the DIII-D research program on PSI is to provide realistic tokamak conditions for detailed tests of the models now under development that will be used for the PFC design. This is a complementary, but critical role, in the U.S. materials development program. In addition the DIII-D program will pursue two specific solutions for ITER and future tokamaks that take advantage of unique capabilities and plasma facing materials.

1. **Test material temperature dependence of PSI models.** A renewed emphasis on PFC material solutions for FNSF and DEMO has resulted in a U.S. Scientific Discovery through Advanced Computing (SciDAC) program to develop fundamental models of PSI appropriate for the design of future PFCs. Several DIII-D scientists are already active members of this SciDAC project. Furthermore DIII-D has strong collaborative ties to the PSI science center led by D. Whyte, R. Doerner, and B. Wirth, an element of which is PSI model development and benchmarking. DIII-D will develop the capability to carry out detailed tests of the models developed via SciDAC and the PSI Science Center in a variety of realistic tokamak conditions that that extend tests in linear devices. This will include detailed measurements of the basic plasma-material processes included in the models. A key component of this work will be the dependence on material temperature, as the high temperatures, ≥500°C–1300°C, needed for maintaining W-material ductility and efficient fusion power generation is expected to lead to significantly different behavior. While high-*Z* materials are the leading candidates for future PFCs, other materials can also be tested as new material solutions are developed.
2. **Develop basis for in-situ, low-*Z* material coating of high-*Z* PFCs.** While high-*Z* materials are also the leading candidates for PFCs in FNSF and DEMO, they carry distinct issues that must be overcome, e.g., tungsten blisters or fuzz formation and control and disposal of eroded material that is re-deposited in locations incompatible with operation, and compatibility of main chamber surfaces with high performance core plasmas. A nascent mitigation scheme is the deposition of low-*Z* material injection, to serve as a consumable flow-through surface treatment. Both real-time, continuous and between discharge deposition techniques will be evaluated. Even though the PSI will create a dynamically evolving surface film, we will refer to this as a “coating” for brevity in this document. The basis for this approach will be explored and developed in DIII-D.
3. **Establish compatibility of carbon divertor targets with low fuel retention in ITER.** The choice of tungsten as the ITER’s divertor PFC material is nearly finalized, but tungsten has known risks. It is recognized that the greatest risk with regard to using W is melting, and the 11/2013 ITER divertor decision will be made on the basis of limited information about W melting under ITER-relevant conditions; such information will only become available over the next five years. If that analysis shows that ITER is at high risk of mission failure if it attempts to start with the W divertor, a switch to carbon-fiber-composites (CFC) targets to get through the initial learning period might provide the best risk mitigation strategy. As the only large-scale divertor tokamak with carbon PFCs, DIII-D is uniquely situated to provide data for this choice. The DIII-D program will specifically address: (1) the erosion rates from the divertor target under ITER expected conditions, (2) the migration distribution of material eroded from the divertor target, (3) the co-deposition of fuel with material eroded from the divertor, and (4) the retention of tritium under high carbon surface temperature.

The DIII-D research program on PSI and PFC material choices is summarized in the timeline of Fig. 4-17. This figure includes the timing of the major research topics in this area as well as the installation of new capabilities.

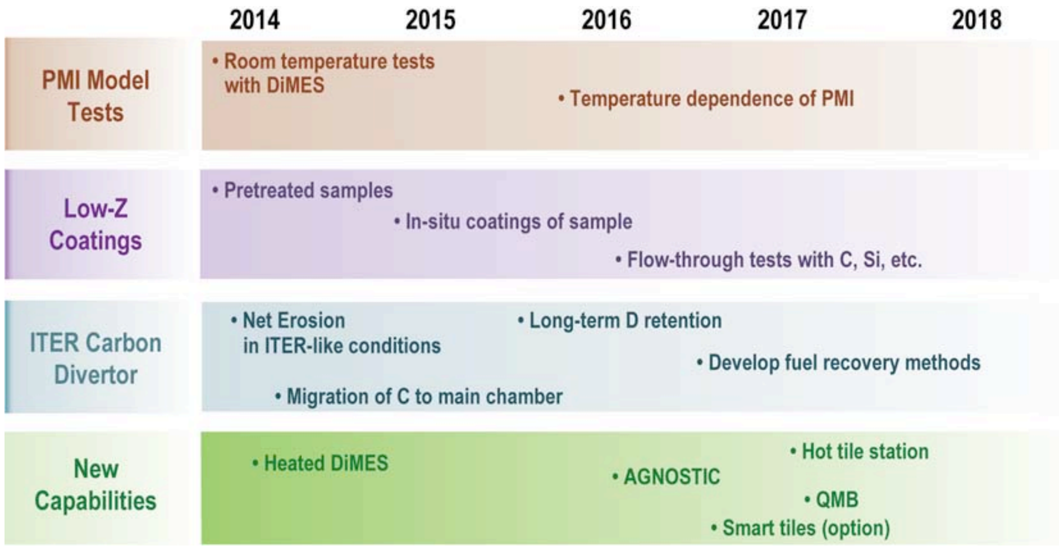

Fig. 4-17. Timeline of major thrust activities and new capabilities.

4.5.3. Detailed Research Plan

The DIII-D program has a critical role to play in the development of plasma-facing material solutions for ITER, FNSF and DEMO. This role is a result of several unique DIII-D characteristics: realistic divertor, chamber wall and SOL plasmas in a variety of operational regimes that may be unachievable in linear devices and other tokamaks, carbon PFCs, and comprehensive diagnostics to measure PSI. To address this role the DIII-D program will pursue three areas of materials related research:

- Test the temperature dependence of PSI models.
- Develop in-situ low-*Z* coatings to mitigate issues with high-*Z* PFCs.
- Establish viability of carbon divertor targets for ITER.

4.5.3.1. Temperature Dependence of PSI Models. There are a number of models of varying sophistication used to describe near-surface PSI processes. On a first principles level, atomistic simulations are employed, with resolution of the very fine temporal (ps) and spatial scales (nm). The state-of-the-art models for large scale erosion and re-deposition processes are the 3D Monte Carlo codes, e.g., REDEP/WBC erosion/redeposition code package coupled to the HEIGHTS package ITMC-DYN mixed-material evolution/response code, and ERO. Substantial insight has also been obtained with the 3D DIVIMP model, also used in a 2D mode. The background plasma for these codes is provided by fluid codes, such as UEDGE, and B2, or by empirical “plasma reconstruction” using the OEDGE code; good progress has been obtained with coupling of plasma and neutrals codes, e.g., B2/EIRENE, also known as SOLPS.

While the models described above are used for basic processes, they do not capture the physics of larger scale processes, e.g., bubble nucleation, blistering, nano-tendril or “fuzz” growth, formation of mixed material compounds and the diffusion and permeation of tritium into the bulk material. An important aspect of these processes is the very strong temperature dependence that must be extended to the high operating temperatures expected in FNSF and DEMO. A new SciDAC project on PSI (funded in 2012) aims to bridge the gap from the nanometer to micron scales through development of models that leverage advanced computing capabilities. The goal is to use models such as the above and others to help evaluate and even design materials for PFCs. The time scale of model development in this activity is 3–5 years, coinciding with the timing of this five-year plan. It is important that there be as strong as possible a linkage between this SciDAC project and experiment, particularly tokamak experiments. While this SciDAC project focuses on development of models for tungsten, model development and benchmarking is an integral part of the PSI Science Center (PIs: D. Whyte, R. Doerner, B. Wirth), with which DIII-D has strong collaborative ties.

DIII-D research plans. The PSI program in DIII-D will perform detailed scientific investigations with specifically designed, well-characterized samples and tiles, including heated surfaces, inserted directly into DIII-D. The conditions to be investigated include: (1) quasi-steady plasmas with standard attached and radiative detached divertors; (2) plasmas with transient events, e.g., ELMs and disruptions; and (3) runaway electron effects.

The primary sample materials to be tested will be tungsten and carbon, in a variety of manufactured compositions. Other materials will also be tested as they are proposed and developed. As the temperature dependence of PSI processes is a key issue for predicting behavior in future devices, that capability will be developed within the DIII-D program. A staged approach will bring the following progression of capability.

- Small sample exposure at room temperature with the existing DiMES facility.
- Small high-temperature samples with additional heating capability for DiMES.
- Tile-size heated samples in the divertor that can be inserted and/or retrieved during periods of DIII-D maintenance or other extended periods of non-operation: the hot tile surface station (HTSS) (Section 4.6.4).
- Tile-size heated samples that can be inserted and/or retrieved overnight as an upgrade to the HTSS.
- Deployment of the in-situ ion beam analysis (“AGNOSTIC” diagnostic) for between shot measurements of sample erosion and deposition will greatly aid characterization of samples that cannot be quickly or easily retrieved (details in Section 4.6.4).

With the capability described above, material samples will be installed and exposed to DIII-D divertor plasmas. A variety of properties of the material surface will be measured and utilized to test models of PSI now under development. The material properties that will be measured include:

- Temporal evolution of the near-surface morphology, composition or film.
- Fuel retention, bubble formation and film or tendril growth.
- Impurities in the evolving surface composition.
- Thermal and heat removal capability of the evolving surface composition.
- The effect of surface temperature on tritium migration and retention.

In-situ measurements will utilize DIII-D's extensive diagnostic capability to characterize the plasma conditions that are needed for benchmarking PSI models including heat flux, particle flux, plasma temperature, impurity concentration, recycling, PFC surface temperature, and gross erosion of the sample. After successful exposure the samples will be removed and then characterized for to address the issues described above. These post-mortem measurements will be made in collaboration with institutions with specialized capability including SNL and MIT. Both the in-situ measurements and post-mortem material analysis will be used to test and benchmark models under development in the SciDAC PSI project and also the PSI Science Center mentioned above, as well as through other ongoing collaborations in this area.

DIII-D contribution to worldwide PSI research. The research at DIII-D described above will complement the much larger effort of PSI research on linear devices and high-*Z* divertor tokamaks in the world's fusion facilities. The Zinkle report reflects both the need for a large effort on tungsten, complemented with a modest parallel effort in carbon:

> "4.2.2 The leading FNSF/DEMO candidate solid material to meet the variety of PFC material requirements is tungsten due to its projected erosion resistance, high melting temperature and high thermal conductivity. Initiatives with the following objectives are required: (1) Identify and characterize suitable tungsten based materials in appropriate plasma, thermal and radiation damage environments; and (2) Develop engineering solutions for tungsten PFCs with high pressure helium gas coolant. The majority of PFC material research should be oriented towards tungsten, however due to open questions on tungsten melting and microstructural evolution; a parallel effort should be maintained in carbon based solid materials with similar objectives."

DIII-D's effort will supplement and corroborate the data from dedicated linear devices. Linear device tests of PSI models face several limitations in reproducing tokamak divertor conditions, including grazing incidence magnetic fields simultaneously with high heat fluxes, and non-Maxwellian thermal populations. DIII-D will test what effects these parameters may have on the data produced by linear devices.

DIII-D's efforts will also supplement the data from high-*Z* PFC tokamaks and long-pulse tokamaks. DIII-D's carbon PFCs may allow for easier interpretation of tile-size, high-*Z* sample erosion and migration, where the analysis is not complicated by other background high-*Z* materials.

4.5.3.2. Develop Basis for In-Situ, Real-Time, Low-*Z* Coating of High-*Z* PFCs. While high-*Z* materials, in particular tungsten, remain the leading candidate for PFCs in FNSF and DEMO, serious limitations and uncertainties remain. The high duty cycle and energy throughput of these devices is expected to result in the migration of significant mass as PFC material is eroded from one location and deposited in another. The deposition of a large mass of high-*Z* material in inconvenient locations such as divertor targets and pumping ducts would be very difficult to remove without extended device shutdowns. In addition main chamber high-*Z* surfaces are vulnerable to charge-exchange erosion, leading to core plasma contamination and degradation of overall fusion performance. Also high-*Z* surfaces are vulnerable to melting by thermal transients, e.g., ELMs and disruptions, that could leave the device inoperable. Finally high-*Z* materials like W have demonstrated the formation of W blisters and fuzz under background He bombardment at high surface temperature.

Low-*Z* coatings, such as carbon, boron or silicon, over high-*Z* material surfaces are candidates to mitigate some of the issues described above. In the main chamber with the presence of low-*Z* impurities will be much less restrictive for high core plasma performance than high-*Z* impurities. The removal of low-*Z* material deposited in the divertor — "slag" — may be much easier to remove by chemical means, or by using the plasma to sweep deposits into removal ducts. Low-*Z* surfaces are less vulnerable to thermal transients, as the material ablates in lieu of forming dangerous leading edges. Tritium retention will be much less of an issue in low-*Z* deposits at the high surface temperatures of FNSF and DEMO. Finally boronization, between discharge coatings with boron, has efficiently increased plasma performance and operational flexibility in the all-metal devices C-Mod and ASDEX-Upgrade.

The application of real-time, low-*Z* injection for high duty cycle devices has a number of issues that must be resolved before its use can be projected with confidence. However the potential benefits warrant a dedicated investigation to determine if such an approach is feasible. The benefits of low-*Z* coatings applied before plasma operation in current devices typically endure for a few hundreds of seconds at best. To be applicable in FNSF and DEMO, the techniques must be advanced towards continuous application during plasma operation with a clear metallic surface. This would represent a consumable, or flow-through, surface mixed material film or treatment. The DIII-D program will investigate this concept to establish the basis for its application to longer pulse devices; tests would be done both on specific high-*Z* samples, as well as the existing carbon PFCs.

DIII-D research plans. A number of issues have to be addressed with this approach, including:

- **Optimal introduction of low-*Z* material**. The optimal thickness of a high-*Z* surface treatment will be examined in relation to the following issues: (1) heat transfer to the substrate, (2) minimization of mixed-film thickness to avoid surface flaking or spalling, (3) protection of the metallic substrate against thermal transients, e.g., from ELMs and disruptions. Metallic small samples will be inserted with the existing DiMES facility and the proposed Hot Tile Surface Station. With DIII-D's flexible configuration and operation, the optimal low-*Z* injection rate for a variety of conditions will be determined, including attached and detached divertor operation, and main chamber conditions at low and high density.
- **Application techniques.** Several options for the application of a low-*Z* layer will be tested. A gas injection inlet near the DiMES facility will be utilized for testing local application under a number of conditions. Other options to be tested include real-time introduction of a selected low-*Z* material via gas, powder or shell pellets containing low-*Z* powder.
- **Material choice.** Primary candidates, including B, C, and Si have different surface temperature limits and form different compounds at high temperature, which will be especially important for FNSF and DEMO. Each material is therefore expected to have both advantages and disadvantages from the point of view of performance and delivery techniques. Optimization may entail a combination of delivery techniques and/or materials.
- **Removal of excess material.** This investigation will also include techniques to remove excess material that has migrated due to plasma processes. This will include divertor strike-point sweeping to move deposited material into collection facilities, and chemical removal techniques.

4.5.3.3. Establish Compatibility of Carbon Divertor Targets with Low Fuel Retention in ITER. The divertor PFC materials to be used in ITER are still under discussion, with a final decision to be made November 2013. Melting, blister and fuzz generation are three main problems with tungsten, as well as startup issues, H-mode pedestal performance, and even global energy confinement. While PSI with low-Z materials tends to smooth away problematic areas, there is no evidence that high-Z surfaces can "self-correct" after damage from e.g., off-normal events. Recent ALCATOR C-Mod research regarding tungsten melting highlights this problem. In that set of experiments, frequent disruptions were observed when the strike points approached the damaged tile. In addition, no self-healing of the damaged tungsten region was observed after repeated plasma contact. Indeed the solution to avoid disruptions was to avoid running the strike points in the vicinity of the damaged area [Lipschultz 2012]. Thus while much research is needed on high-Z PFCs, it is nonetheless prudent to explore alternates as well, e.g., low-Z materials.

In order to get approval from the ITER licensing authority for use of a graphite divertor in ITER, one has to demonstrate that divertor retention would be an acceptable fraction of the maximum allowed total site hydrogen inventory of 2.5 kg. To satisfy this requirement the rate of carbon net erosion and redeposition, and eroded carbon distribution and corresponding tritium inventory will have to be quantified within the operational envelope of ITER.

Since ITER divertor heat flux is projected at ~10 MW/m^2 with the corresponding CFC surface temperature in the range of 800°C–1000°C, the corresponding net erosion and migration of carbon needs to be investigated at high temperature. At the same time, the corresponding tritium inventory due to carbon co-deposition must be quantified.

Other key necessary technical data is the transport of the eroded carbon from the divertor to the main walls and to remote regions. Various ways of inhibiting or reducing the deposition of carbon, e.g., by the injection of N_2 or NH_3, and of reducing tritium inventory on the graphite tiles and deposited graphite will also have to be demonstrated.

DIII-D research plans. There are several elements in this area:

- Measure net erosion rates from the divertor target under ITER-relevant conditions. These conditions include partially detached plasmas with minimal transients, high divertor surface temperatures and minimal leading edges.
- Measure the distribution of eroded material as it migrates away from the divertor targets; of particular importance is whether eroded material can migrate from the divertor to the main chamber walls.
- Measure the co-deposition of hydrogenic species with material eroded from the divertor, and develop ways to reduce the co-deposition.
- Measure the retention of tritium under high PFC surface temperature as expected in ITER, including the effect of long-term out-gassing, as reported by Tore Supra.
- Develop and demonstrate methods to recover retained fuel.

4.5.4. Capability Upgrades

A heated tile surface station is proposed for PSI studies at controllable bulk temperature. In addition PFC surface evolution will be probed with AGNOSTIC [Whyte 2012]. Finally three modest cost advanced diagnostics that will contribute significantly are the quartz microbalance (QMB), the hydrogen sensor, and densely populated "smart tiles".

4.5.4.1. Heated Tile Station, With Robotic Arm for Manipulation. The heated tile should be capable of operations at high surface temperature of ~700°C to 1000°C, with either carbon or tungsten as the substrate. Such a tile will be inserted and removed with a 2D remote robotic arm.

Heater design. The heater design for the heated tile is shown in Fig. 4-18, which can be used for the three heated tile options. The size and surface area of the resistive heated element is limited by the thermal insulation around the heater, such that the heated tile will be designed to not interfere with the normal operation of DIII-D. In addition the heated tile thermal properties will match the replaced tile from DIII-D. The surface material on top of the heater will be graphite or W as required for specific studies. The heating element is designed to allowed a maximum tile surface temperature of 700°C.

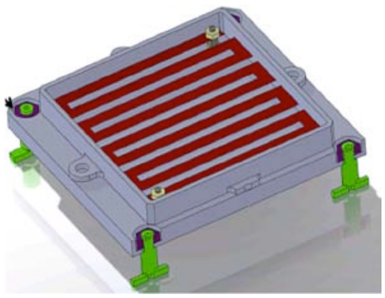

Fig. 4-18. A tile heater design with heating W-elements shown.

In this concept the removable tile is installed from the plasma facing side by a robotic arm, as shown in artist's views on the attached Fig. 4-19, whereas the heating element as shown before is either a permanent installation or is integrated into the tile. The latter case has the advantage that the heating element could be repaired without a vent.

In principle the 2D robotic arm could serve several tiles in one poloidal plane. The robotic arm would consist of four elbows functioning in one plane, and if necessary a simple translation stage in the toroidal direction and rotating trimmer (not shown in the figure). A typical example of the sort of arms available are shown Fig. 4-19 (a modular system available from Trossen Robotics®). This concept would provide a facility that could exchange tiles at various locations including the divertor and chamber wall overnight, in preparation for a day on DIII-D exposing the tiles to desired plasma conditions.

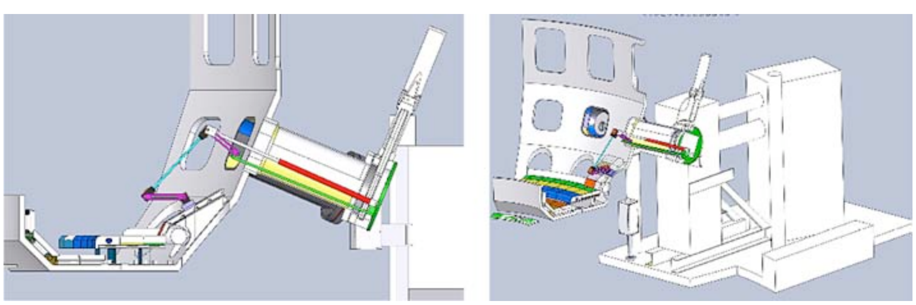

Fig. 4-19. 2D robot arm showing its reach to the DIII-D divertor, its transfer tunnel, the gate valve and the supporting equipment outside of the DIII-D vessel.

4.5.4.2. AGNOSTIC – In-Situ Ion Beam Analysis. Implementation of a recently developed diagnostic method based on mega-electron-volts ion-beam analysis (IBA) that provided in-situ measurements of the isotope and element composition of plasma facing surfaces in ALCATOR C-Mod (shown schematically in Fig. 4-20) is being proposed for DIII-D. IBA is the surface diagnostic technique of choice for ex-situ material analysis. The broad palette of IBA techniques [Esser 2003] provides non-perturbing sensitivity, large dynamic range, depth resolution and element/isotope discrimination. Ex-situ accelerator facilities provide the ~mega-electron-volt ion beams required for IBA.

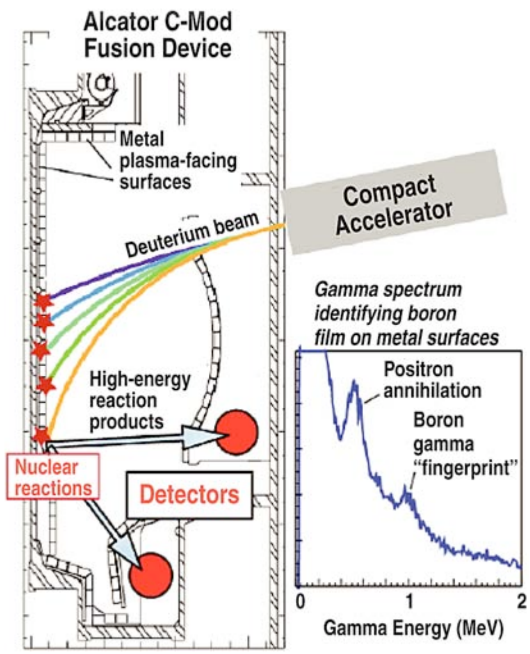

Fig. 4-20. AGNOSTIC diagnostic as implemented in ALCATOR C-Mod.

A deuterium beam triggers nuclear reactions at the PFC surfaces, which produce gamma rays and neutrons. These are detected by appropriately located detectors. By using a novel magnetic steering scheme, the diagnostic covers a large portion of the plasma-facing surfaces, thus diagnosing surface erosion, material mixing and fuel retention spatial patterns.

4.5.4.3. Quartz Microbalance. To promote solutions to key fusion problems like tritium retention and wall erosion, more data on carbon deposition in remote areas of fusion devices are needed. These data are essential to understand and model local and global particle fluxes and to make predictions for future devices like ITER. One diagnostic that has been used successfully by JET [Esser 2003] to measure material/dust deposition is the quartz microbalance (QMB). The QMB measurement is based on the high mass sensitivity of quartz resonator frequencies and on the accuracy of frequency readings of resonator circuits. They are excited into mechanical vibrations by an alternating electric field applied between their electrodes by means of the piezoelectric effect. The amplitude of vibration is negligibly small except when the frequency of the driving field is in the vicinity of a resonance mode. At that time the amplitude of vibration increases and the otherwise stable resonance frequency does only depend on mass and temperature of the quartz. Adsorbed layers on the quartz will increase its weight and lower the frequency [Esser 2003] which is monitored. The resonators consist of piezoelectric SiO_2, precisely dimensioned and oriented with respect to the crystallographic axes optimized for temperature stability and/or layer growth measurement. When implemented as part of the DiMES diagnostic in DIII-D, operation of the QMB will have to be maintained within the temperature limit of the selected quartz.

4.5.4.4. Hydrogen Sensor. Quantifying the flux and energy of charge exchange neutrals to the walls of fusion experiments is important for understanding wall erosion and energy balance in a tokamak. Measurements made using time-of-flight spectrometers and electrostatic analyzers (using stripping cells) are limited due to their size and complexity. For divertor measurements, the use of a palladium metal oxide semiconductor (Pd-MOS) detector overcomes these size limitations, and offers the ability for broader spatial coverage. These devices do not offer rapid time resolution, however, and can only be used to evaluate differences between discharges. The detectors can be fabricated as either capacitance or diode devices. Experimental evidence from fielding of devices on TFTR and NSTX has indicated that the Shottky diode devices are more resistant to long-term damage. This is due to the thinner oxide layer used in the diode-type device, as fewer ultraviolet (UV) and x-ray generated charges are created and trapped there. Additional resistance to oxide and semiconductor damage from high-energy particles can be achieved by increasing their trapping with a thicker Pd layer. The thicker layer does not degrade detector response due to the rapid transport of hydrogen in Pd (<1 s). Preliminary fabrication of thicker Pd detectors has been accomplished using an array of titanium posts to reduce the film stress. Such a hydrogen sensor with a Pd-MOS detector was previously designed and operated as part of a DiMES experiment.

4.5.4.5. "Smart" Tiles. The third type of diagnostic is a cluster of diagnostics installed on one tile. For most tokamaks, including DIII-D, key diagnostics are distributed around the chamber surfaces at different locations, and not necessarily close to the DiMES location. One possible solution is to have several of the key diagnostics implemented on a single tile, which is the basic idea of a "smart" tile. Figure 4-21 shows examples of different samples that have been developed with the use of DiMES modules that includes the exposure of different PFC materials, development of advanced Langmuir probe, and a DiMES module with a heater and the exposure of Li at the lower divertor of DIII-D. One important feature of the DiMES system is the possibility of making electrical connections to the DiMES sample.

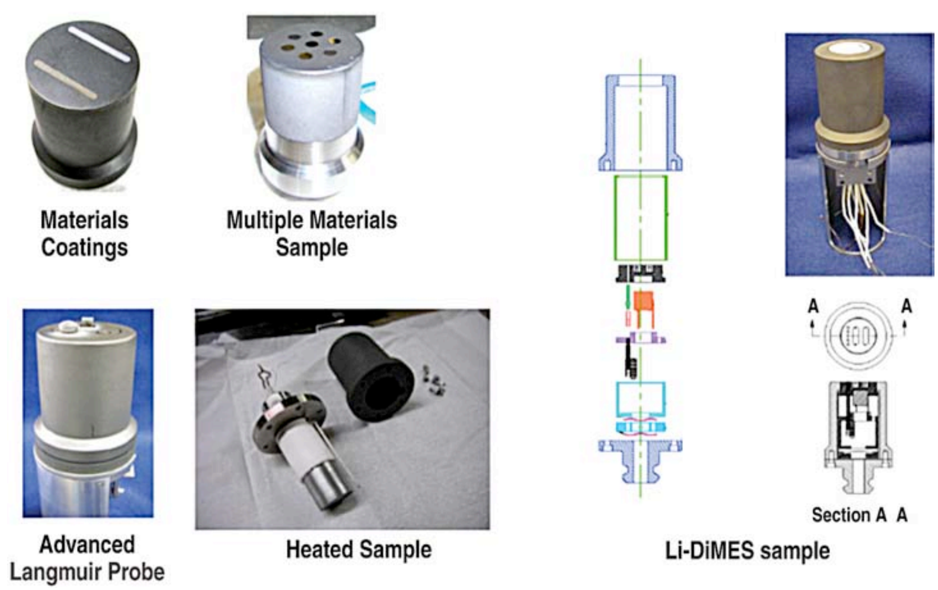

Fig. 4-21. Illustrations of some of the experiments performed with the use of DiMES module.

4.5.5. Impact

The hot tile surface station will provide technical data on the behavior of material erosion and re-deposition, material migration and tritium inventory and permeation at high surface temperature relevant to ITER, FNSF and DEMO. Coupled with data from the other diagnostics and model comparison, validation of the temperature dependence of PSI processes will improve confidence in projections for future reactors that operate with higher temperature PFCs than present day devices. The low-Z coating program will begin to assess the feasibility of this technique, as a first step to assessing the technique for FNSF and DEMO. Finally excessively high fuel retention and material migration at low PFC temperature is a primary reason why ITER is moving away from graphite PFCs; our assessment will provide a technical evaluation at elevated ITER-like temperatures, toward determination of the viability of graphite PFCs in the ITER pre deuterium and tritium (DT) phase.

4.6. REFERENCES FOR SECTION 4

[Baylor 2012a] L.R. Baylor et al., "Experimental Demonstration of High Frequency ELM Pacing by Pellet Injection on DIII-D and Extrapolation to ITER," Proc. 24th IAEA Fusion Energy Conf., San Diego, California, 2012, Paper EX/6-02.

[Baylor 2012b] L.R. Baylor et al., "Reduction of ELM Intensity on DIII-D by On-demand Triggering With High Frequency Pellet Injection and Implications for ITER," submitted to Phys. Plasmas 2012.

[Belli 2008] E.A. Belli and J. Candy, Plasma Phys. Control. Fusion **50**, 095010 (2008).

[Burrell 2012a] K.H. Burrell et al., Phys. Plasmas **19**, 056117 (2012).

[Burrell 2012b] K.H. Burrell et al., "Quiescent H-mode Operation Using Torque from Non-axisymmetric, Non-resonant Magnetic Fields," submitted to Nucl. Fusion 2012.

[Callen 2011] J.D. Callen, "Parallel neoclassical resistivity evaluation," U. Wisconsin Reports UW-CPTC 11-05 (2011).

[Callen 2012a] J.D. Callen et al., Phys. Rev. Lett. **108**, 245003 (2012).

[Callen 2012b] J.D. Callen et al., Nucl. Fusion **52**, 114005 (2012).

[Callen 2012c] J.D. Callen et al., Phys. Plasmas **19**, 112505 (2012).

[Callen 2012d] J.D. Callen et al., "RMP-Flutter-Induced Pedestal Plasma Transport," submitted to Nucl. Fusion 2012.

[Candy 2009] J. Candy et al., Phys. Plasmas **16**, 060704 (2009).

[Canik 2012] J.M. Canik et al., Nucl. Fusion **52** 054004 (2012).

[Chang 2004] C.S. Chang et al., Phys. Plasmas **11**, 2649 (2004).

[Chen 2007] Y. Chen and S.E. Parker, J. Comput. Phys. **220**, 839 (2007).

[Diallo 2011] A. Diallo et al., Nucl. Fusion **51**, 103031 (2011).

[Dickinson 2011] D. Dickinson et al., Plasma Phys. Control. Fusion **53**, 115010 (2011),

[Esser 2003] H.G Esser et al., Fusion Engin. Design **66–68**, 855 (2003).

[Evans 2005] T.E. Evans et al., Nucl. Fusion **45**, 595 (2005).

[Evans 2008] T.E. Evans et al., Nucl. Fusion **48**, 024002 (2008).

[Ferraro 2010] N.M. Ferraro et al., Phys. Plasmas **17**, 102508 (2010).

[Futatani 2012] S. Futatani et al., "Non-linear MHD Modelling of ELM Triggering by Pellet Injection in DIII-D and implications for ITER," submitted to Nucl. Fusion 2012.

[Garofalo 2011] A.M. Garofalo et al., Nucl. Fusion **51**, 083018 (2011).

[Ghendrih 1995] P. Ghendrih J. Nucl. Mater. **220-222**, 305 (1995).

[Goetz 1996] J.A. Goetz, Phys. Plasmas **3**, 1908 (1996).

[Groebner 2009] R.J. Groebner et al., Nucl. Fusion **49**, 045013 (2009).

[Hazeltine 2009] R. Hazeltine, "Research Needs for Magnetic Fusion Energy Sciences," ed. Patti Wieser, Report of the Research Needs Workshop (ReNeW), Bethesda, Maryland, 2009, US DOE/OFES Report (2009); http://burningplasma.org/renew.html

[Houlberg 1997] W.A. Houlberg et al., Phys. Plasmas **4**, 3230 (1997).

[Hubbard 2012] A.E. Hubbard et al., Nucl. Fusion **52**, 114009 (2012).

[Jackson 2002] G.L. Jackson, Nucl. Fusion **42**, 28 (2002).

[Kallenbach 2005] A. Kallenbach, J. Nucl. Mater. **337-339**, 732 (2005).

[Kamada 2012] Y. Kamada et al., "Progress of the JT-60SA Project," submitted to Nucl. Fusion 2012.

[Kaye 2012] S.M. Kaye et al., "The Dependence of H-mode Energy Confinement and Transport on Collisionality in NSTX," submitted to Nucl. Fusion (2012)

[Kim 2012] Jayhyun Kim et al., Nucl. Fusion **52**, 114011 (2012).

[Kirk 2013] A. Kirk et al., Plasma Phys. Control. Fusion **55**, 015006 (2013).

[Kotschenreuther 1995] M. Kotschenreuther et al., Comp. Phys. Comm. **88**, 128 (1995).

[Kotschenreuther 2010] M. Kotschenreuther, Nucl. Fusion **50**, 035003 (2010).

[Ku 2009] S. Ku et al., Nucl. Fusion **49**, 115021 (2009).

[Lanctot 2013] M. Lanctot et al., "Complete Suppression of Large Type-I Edge Localized Modes Using Multi-harmonic Magnetic Perturbations in DIII-D," submitted to Nucl. Fusion 2013.

[Landreman 2012] Matt Landreman and Darin R Ernst, Plasma Phys. Control. Fusion **54**, 115006 (2012).

[Lang 2008] P.T. Lang et al., Nucl. Fusion **48**, 095007 (2008).

[Lang 2011] P.T. Lang et al., Nucl. Fusion **51**, 033010 (2011).

[Leconte 2012] M. Leconte and P. Diamond, Phys. Plasmas **19**, 055903 (2012).

[Liang 2011] Y. Liang et al., Nucl. Fusion **51**, 073001 (2011).

[Lipschultz 2012] B. Lipschultz et al., "The Effect of Divertor Tungsten Tile Melting on Core Plasma Performance and Material Properties," submitted to J. Nucl. Mater. 2012.

[Lisgo 2005] S. Lisgo et al., J. Nucl. Mater. **337-339**, 139 (2005).

[Loarte 2010] A. Loarte et al., "ITER ELM Control Requirements, ELM Control Schemes and Required R&D," Proc. 23rd IAEA Fusion Energy Conf., Daejeon, Republic of Korea, 2010 (IAEA, Vienna, 2010) Paper ITR/1-4.

[Oyama 2005] N. Oyama et al., Nucl. Fusion **45**, 871 (2005).

[Oyama 2010] N. Oyama et al., Nucl. Fusion **50**, 064014 (2010).

[Ozeki 1990] T. Ozeki et al., Nucl. Fusion **30**, 1425 (1990).

[Park 2007] J.K. Park et al., Phys. Plasmas **14**, 052110 (2007).

[Petrie 1979] T.W. Petrie et al., Nucl. Fusion **37**, 321 (1997).

[Piras 2010a] F. Piras, Plasma Phys. Control. Fusion **51**, 155003 (2010).

[Piras 2010b] F. Piras et al., Plasma Phys. Control. Fusion **52**, 124010 (2010).

[Rapp 2004] J. Rapp, Nucl. Fusion **44**, 312 (2004).

[Rapp 2009] J. Rapp et al., Nucl. Fusion **49**, 095012 (2009).

[Rapp 2012] J. Rapp et al., Nucl. Fusion **52**, 122002 (2012).

[Rognlien 2002] T.D. Rognlien and M.E. Rensink, Fusion Engin. Design **60**, 497 (2002).

[Ryter 2012] F. Ryter et al., "L-H Transition, Pedestal Development and I-mode Studies in the ASDEX Upgrade Tokamak," submitted to Nucl. Fusion 2012.

[Ryutov 2007] D. Ryutov, Phys. Plasmas **14**, 064502 (2007).

[Ryutov 2008] D. Ryutov et al., Phys. Plasmas **15**, 092501 (2008).

[Saibene 2011] G. Saibene, E. de la Luna, A. Loarte, private communication, 2011.

[Sauter 1999] O. Sauter et al., Phys. Plasmas **6**, 2834 (1999).

[Schneider 2006] R. Schneider et al., Contrib. Plasma Phys. **46**, 3 (2006).

[Snyder 2009] P.B. Snyder et al., Phys. Plasmas **16**, 056118 (2009).

[Snyder 2011] P.B. Snyder et al., Nucl. Fusion **51**, 103016 (2011).

[Snyder 2012a] P.B. Snyder et al., 39th EPS Conf. on Plasma Physics and 16th Int. Congress on Plasma Physics 2012 (Stockholm, Sweden) vol. 36F (European Physical Society, 2012) P4.029; http://ocs.ciemat.es/epsicpp2012pap/html/

[Snyder 2012b] P.B. Snyder et al., Phys. Plasmas **19**, 056115 (2012).

[Solomon 2012] W.M. Solomon et al., Nucl. Fusion **52**, 033007 (2012).

[Soukhanovskii 2011] V. Soukhanovskii et al., Nucl. Fusion **51**, 012001 (2011).

[Staebler 2007] G.M. Staebler et al., Phys. Plasmas **14**, 055909 (2007).

[Suttrop 2003] W. Suttrop et al., Plasma Phys. Control. Fusion **45**, 1399 (2003).

[Suttrop 2005] W. Suttrop et al., Nucl. Fusion **45**, 721 (2005).

[Suttrop 2011] W. Suttrop et al., Plasma Phys. Control. Fusion **53**, 124014 (2011).

[von Thun 2008] Perez von Thun et al., Plasma Phys. Control. Fusion **50**, 065018 (2008).

[Waelbroeck 2012] F. Waelbroeck et al., Nucl. Fusion **52**, 074004 (2012).

[Wan 2012] B. Wan et al., "Progress of Long Pulse and H-mode Experiments on EAST," submitted to Nucl. Fusion 2012.

[Whyte 2010] D.G. Whyte et al., Nucl. Fusion **50**, 105005 (2010); A. White et al., Nucl. Fusion **51**, 113005 (2011).

[Whyte 2012] D.G. Whyte, private communication (2012).

[Wingen 2009] A. Wingen et al., Nucl. Fusion **49**, 055027 (2009).

[Wong 1997] C.P.C. Wong, Fusion Engin. Design **38**, 115 (1997).

[Xu 2000] X.Q. Xu et al., Phys. Plasmas **7**, 1951 (2000); D. Dudson et al., Comp. Phys. Commun. **180**, 1467 (2009).

[Zinkle 2012] S.J. Zinkle et al., "Opportunities for Fusion Materials Science and Technology Research Now and During the ITER Era," US DOE Fusion Energy Sciences Advisory Committee Report DOE/SC-0149 (February 2012).

5. THE DIII-D NATIONAL FUSION FACILITY – OPERATION AND ENHANCEMENTS

5.1. INTRODUCTION TO FACILITY UPGRADES AND OPERATING SCHEDULE

The DIII-D National Fusion Facility is a world-class facility capable of carrying out a wide range of experiments to explore high performance tokamak discharges as well as fundamental fusion science. This section describes improvements to the device hardware and infrastructure that will enable steady research advances while maintaining high system availability. Table 5-1 summarizes the improvements proposed in the next five years and the research elements that are driving the changes. Major upgrades will include significant increases in the heating and current drive (H&CD) power and pulse length, more flexible coil systems for edge localized mode (ELM) and resistive wall mode (RWM) control, upgraded vessel armor compatible with higher input energy, and upgrades to the disruption avoidance and mitigation systems.

Table 5-1
Major Hardware Upgrades

New Capability	Hardware Upgrades	Research Elements	Section
Electron cyclotron (EC): increase injected power from 3.5 to 8.5 MW	4–1.5 MW gyrotrons; high voltage PS#5; 2 transmission lines, electronics, launcher	$J(\rho)$, NTM, $T_e \sim T_i$	5.3
Neutral beam (NB): increase off-axis power from 5 to 12 MW Increase total power from 19 to 24 MW Increase injected energy from 60 to 130 MJ	Tilt second beamline Increase beam voltages up to 105 kV Improve power handling of internal beam collimators	$J(\rho)$, energetic particles, toroidal/poloidal rotation; long-pulse advanced tokamak (AT)	5.4
Radio frequency (rf): Add 0.8 MW of helicon power (source) 30 MHz operation (option)	500 MHz, 0.8 MW klystron, antenna, waveguide, switches Transmission line changes	$J(\rho)$, long-pulse AT	5.5
Reduced error field	30 deg TF feed modification	Low rotation physics	5.6.1
More flexible control of 3D fields	24-element (2x12) outer wall coil (3D coil)	ELM control, heat and particle control	5.6.2
Improved operation of resonant magnetic perturbation (RMP) and multi-mode error correction	2 dc supplies (16 kA, 500 V) and 12 switching amplifiers (±2.7 kA, ±450 V)	Integrated scenario operation, 3D physics	5.7.1
Improved RWM stabilization with dynamic error correction	24 additional amplifiers; cross-over network	AT and 3D physics	5.7.2
150 MJ heat removal (75 MJ present)	Vessel armor upgrade – carbon-fiber-composite (CFC) tiles	Longer pulse AT	5.8
Improved disruption mitigation	Rupture disk, multi-port massive gas and shattered pellet injectors	Disruption mitigation	5.9.1
Improved pellet-pacing systems	120 Hz D_2 pellets; Li pellet-pacing	ELM control	5.9.2

Section 5.2 summarizes the present system capabilities and Sections 5.3 through 5.11 provide details on each of the proposed major system upgrades and discussions of enhancements and refurbishments to existing systems.

The record of the DIII-D program provides good confidence that the proposed upgrades can be completed. In the past 10 years, numerous upgrades to the DIII-D facility were proposed and completed successfully, including the internal coil project (2003), the conversion of the 210 beamline from co- to counter-injection (2006), the lower divertor upgrade (2006), the restoration of the eighth ion source and high voltage (HV) supply (2010), the conversion of the 150 neutral beam (NB) to an adjustable off-axis beamline (2011), and the recent 3D magnetic probe array (2013). The electron cyclotron (EC) system has been continually expanding since the commissioning of the first megawatt-class gyrotron and has successfully brought 10 gyrotrons and 4 HV power supplies on-line.

The five-year plan provides 14 weeks of research operations annually to the experimental program for the years 2014–2018 (an operating week is 5 days of single shift, 8 hours/day). The remainder of the time is used for facility upgrades and improvements outlined in this proposal, system testing and commissioning, and equipment maintenance and repair (Fig. 5-1).

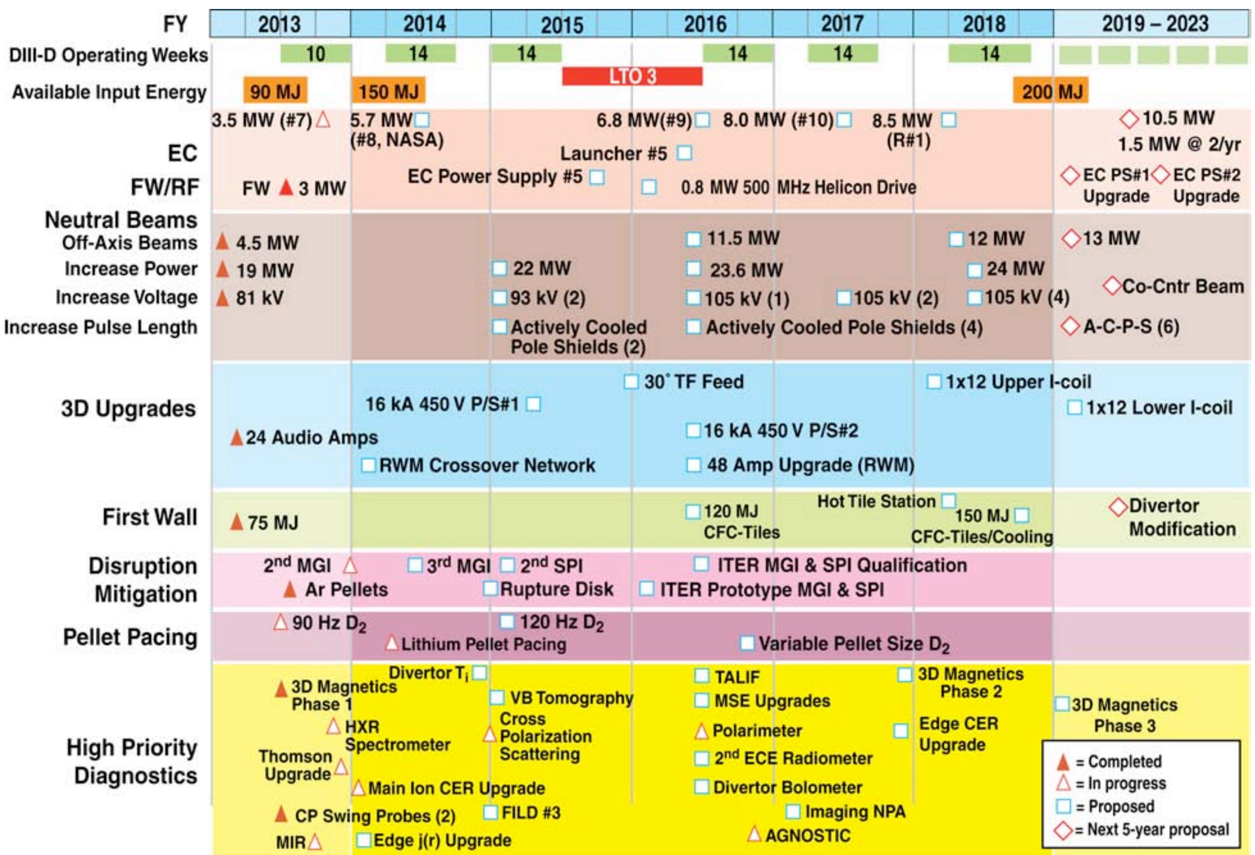

Fig. 5-1. Proposed operations and improvement schedule.

In a typical operating year, the 14 weeks of operation are performed during 22 calendar weeks with alternating periods of 2–3 weeks of experimental operations followed by 2 weeks of maintenance. These short maintenance periods are extremely important since they allow us to perform on-going maintenance and repair to maintain high availability (75%–80% over the past five years), provide opportunities for installation and testing of new system throughout the year, and allow modification of existing systems to respond to changing experimental needs. This operating schedule is a cornerstone of the flexibility of the DIII-D program in that it enables new systems to be installed and/or modified throughout the year to accommodate schedules from collaborators or evolving research results. Following the completion of the experimental program each year, there is typically an extended maintenance period of four to five months to enable the performance of longer maintenance tasks, permit modest upgrades and new system installation and commissioning, both in-vessel and ex-vessel. The annual vessel openings are also used to perform routine diagnostic calibrations and alignments. There is typically a one-month "cooldown" period prior to the start of any extended in-vessel work in order to allow radiation levels to decay to levels that will permit useful work periods within the constraints of our radiation guidelines. At the end of an extended maintenance period involving significant in-vessel work or facility modifications/upgrades, there is a six-week startup period. This includes a three-week period that includes leak checking, high temperature baking, system testing and checkout, and new system commissioning. This is followed by two weeks of plasma cleaning operation and one week for diagnostic calibrations that require plasma operation. Excluding experimental operating weeks and the extended in-vessel work period, the device is typically operated with magnetic fields and/or plasma for an additional 60 days per year for system testing, diagnostic calibration, baking, boronization, plasma conditioning, and new system commissioning. Conditioning of the EC and fast wave (FW) systems are performed on an as needed basis throughout the year.

The modification of the second beamline for off-axis injection will require a non-operating period longer than the periods described above. Figure 5-1 shows the proposed operation and upgrade schedule with a one-year long upgrade period bridging FY15 and FY16. This will be modeled after the 2010/2011 schedule during which the full experimental schedule was executed in early FY10, a long maintenance period was held crossing 2010/2011, and experiments were again executed during the latter half of 2011.

The proposed upgrade schedule is driven by a variety of factors. The off-axis beamline project and new 3D coil array require significant engineering, fabrication and procurement time and the severely constrained FY13 budget prevents those projects from being initiated prior to FY14 with the earliest installation in mid-FY15. In addition, resource limitations will prevent both projects from being performed simultaneously without a much longer shutdown period since both are highly labor intensive. The early installation of the new power supplies for the poloidal field (PF) and existing 3D coil systems will enable full utilization of the existing systems and operation of integrated scenarios that fully utilize multiple coil systems. The exploitation of these new capabilities suggested that the new 3D coil array installation be moved to the second half of the five-year period. To maximize operating time in the two years following the FY15/FY16 shutdown, the installation of the new 3D coil array project is being split into two shorter vessel openings with half the array being fabricated and installed in each period. This results in 42 weeks of operation in the final 2.5 years of the five-year plan. The EC and NB power increases continually throughout the five-year period and are paced by demonstrated technical success of the new high power gyrotrons, source, NB source operation at higher voltage, and the higher heat handling components in the neutral beamlines.

5.2. OVERVIEW OF CURRENT CAPABILITIES

At the heart of the facility is the DIII-D tokamak, which is capable of operating at plasma currents up to 2.5 MA with a toroidal field (TF) of 2.2 T. The DIII-D tokamak is renowned for its operational flexibility, which enables a wide range of research in highly shaped limiter and divertor plasma configurations. Substantial plasma heating and current drive capability is available from 19 MW of neutral beam heating, 4 MW (source) of FW heating and current drive, and 4.4 MW (injected) of EC power. The DIII-D diagnostics set provides over 50 diagnostics systems capable of providing definitive measurements of plasma parameters in the core, edge, and boundary regions of the plasma. A summary of all major non-heating systems is shown in Table 5-2.

Table 5-2
Summary of All Major Non-Heating Systems

System	Description
Poloidal field	7.5 V-s OH transformer Eighteen independently controllable field shaping coils Fourteen phase controlled dc supplies 36 switching current regulators (2.5 kA)
Toroidal field	2.2 T on axis (1.695 m) for 5 s
Non-axisymmetric field	
• **C-coil**	Six external coils on midplane, $B_{2,1}$ ~ 5 G on q=2 surface Five phase controlled dc supplies (7 kA); Four switching current regulators (4.5 kA)
• **I-coil**	Twelve internal coils above and below midplane, $B_{2,1}$ ~ 5 G on q=2 24 amplifiers (190 A, 0–20 kHz)
Vessel/first wall	Water-cooled Inconel vessel, 90% graphite coverage
Vessel conditioning	350°C induction bake system for vessel walls Boronization, He glow cleaning
Fueling/disruption mitigation	Gas puffing/pellets — Eleven valves, 19 inlet locations, at 1–200 Torr-l/s each valve — Two fast valve arrays for massive puff — each at 2000 Torr-l/s in 1–2 ms — Pneumatic pellet injector — three barrels at 30 Hz each — Shattered D_2 pellet 3000 Torr-l — Ar pellet 20 Torr-l
Pumping	Two turbopumps at 5000 l/s each, two turbopumps at 1500 l/s each Three in-vessel cryopumps — one at 40,000 l/s, two at 20,000 ls
Prime power	Motor generators — 2.25 GJ at 525 MVA 138 kV transformer — 20 MVA (CW), 110 MVA (10 s)
Computers	Primarily Linux® based, 20 GB raw data/shot, 212 TB data storage
Cryogenics	150 l/h He liquifier, 11,000 gal LN_2 tank, 3000 gal LN_2 tank, 1000 gal He Dewar

The DIII-D tokamak uses conventional water-cooled copper coils to provide the magnetic field configuration. The coil systems are designed to operate in a pulsed mode with the joule heat stored in the coil mass during the discharge and removed in the 10-minute interval between discharges. DIII-D routinely operates at 2.2 T toroidal field and at 1.6 MA plasma current with a discharge flattop duration of 5 s (Fig. 5-2). Operation for longer duration at lower field and plasma current is also possible. Eighteen independently controllable poloidal field shaping coils provide a wide range of highly shaped, noncircular plasma cross sections. A set of six external picture frame coils mounted around the midplane (C-coils) corrects small magnetic imperfections arising from non-axisymmetries in the coil systems and provides the capability to stabilize magnetohydrodynamic (MHD) instabilities. A set of 12 water-cooled internal picture frame coils (I-coils) mounted on the interior vessel surface (six above and six below the midplane) provides improved error field correction, and improved instability control, allowing control of the RWM and ELMs.

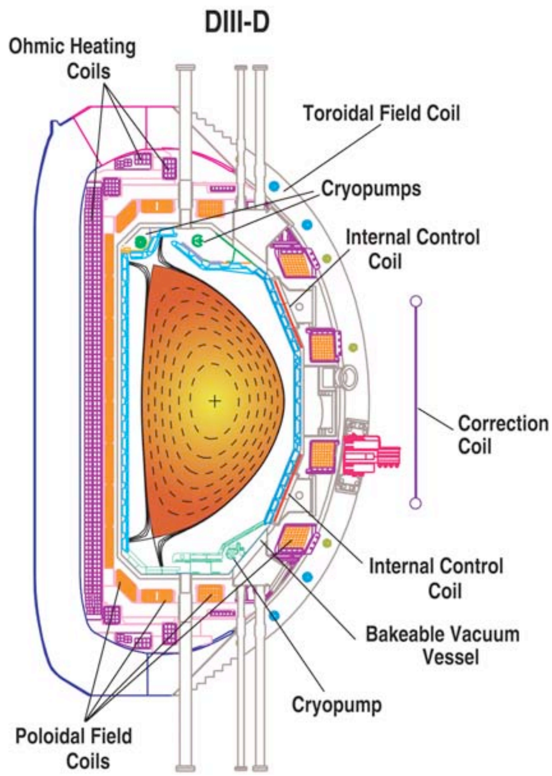

Fig. 5-2. DIII-D capabilities allow a wide range of research and technology issues to be addressed.

Graphite tiles cover more than 90% of the interior plasma-facing surface. The tiles absorb heat during the discharge and are cooled by water channels in the vessel wall in the period between discharges. In the high heat flux areas of the upper and lower divertor regions and centerpost, the edge-to-edge tile misalignment and tile gaps are less than 0.25 mm to reduce erosion and provide axisymmetry. Wall conditioning techniques include baking to an average wall temperature of 350°C, boronization (deposition of a thin boron layer during high temperature bake) prior to each operating period, and helium glow cleaning between discharges. These techniques enable rapid recovery of good plasma discharges following vents with personnel activity in the vessel and robust operation following plasma disruptions.

An extensive gas puff system and pellet injector provide the tools for plasma fueling. The gas puff system permits independent edge fueling with up to 5 different gases from 19 locations around the plasma including the inner wall and the upper and lower divertor regions. Three independent 30 Hz pneumatic pellet injectors provide ITER-relevant edge fueling as well ELM mitigation via pellet pacing technique.

Injection locations are either on the high field side, low field side near the midplane or the X-point. A massive gas puff system used for disruption mitigation experiments is provided by a multi-valve injector in which each of six high speed valves are independently controllable and are designed to deliver fast rise time gas puffs. A second similar system at a different toroidal/poloidal location will be operational in FY13. Four separate pellet systems are available for disruption studies: two fast valve arrays for massive gas injection (2000 Torr-l/s), a shattered pellet injector provides deeper penetration, a pneumatic system is capable of injecting custom-designed shell pellets filled with chosen impurities, and an Argon pellet injector for triggering runaway electrons will be installed in FY13.

Three in-vessel baffled, cryopumps provide pumping of neutral gas in both the upper and lower divertor regions. The two pumps in the upper divertor regions separately pump both the inner and outer strike-points (S ~ 20,000 l/s and 37,000 l/s respectively for D_2) of high triangularity upper single-null or double-null discharges. The geometry of the lower divertor was modified in 2005–2006 to pump the edge of high triangularity, single or double null divertor discharges (pumping speed ~20,000 l/s for D_2), thus improving the density control in high triangularity advanced tokamak (AT) discharges. The new geometry consists of a water-cooled shelf extending from the pump aperture to the outer baffle plate and permits the operation of lower triangularity divertor discharges at high power with the strikepoint(s) located on the top of the shelf. The pumps operate at liquid helium temperatures and actively pump both the D_2 fuel and all volatile impurities during the discharge. An argon frosting technique has been used to provide effective pumping of He.

The present and proposed capabilities of the three heating and current drive systems are summarized in Table 5-3. The eight neutral beams are capable of delivering 15 MW for 4 s or 19 MW for 3.0 s and are routinely used in most experiments for the primary source of heating and as a critical part of key diagnostic systems: charge exchange recombination (CER) for ion temperature, rotation speed, and impurity concentrations; beam emission spectroscopy (BES) for fluctuation measurements; and motional Stark effect (MSE) for current profile and radial electric field measurements. Six of the sources are injected in the normal direction of the plasma current ("co-" sources) and two sources are injected in the counter direction. By pulse-modulating the sources and adjusting the mix between the co- and counter-sources, the injected power and momentum can be continuously and independently controlled. This capability permits independent control of the plasma energy and toroidal rotation. By reversing the direction of the plasma current, experiments can be performed with a full range of co and counter injection. Two of the sources are capable of being tilted so that they can be aimed nearly 40 cm below the plasma axis to provide off-axis current drive. The tilt angle is variable from 0 to 16.5 deg and can be moved in 1 hour.

Table 5-3
Auxiliary Heating System Power

System	Power (MW) Mid-FY13	Pulse (s)	Proposed Power (MW)	Pulse (s)
Neutral beam	19	3	24	3–6
Fast wave (source)				
— ABB (90 MHz)	4.0	10	4.0	10
EC (injected)	3.5	5	8.5	10

The electron cyclotron system presently consists of five long pulse (10 s) 1 MW class gyrotrons and a sixth gyrotron, a 1.2 MW, 10 s depressed collector tube, should be operational by early 2013. A second 1.2 MW tube will be installed in mid-2013 and should be available in early FY14 bringing the injected power to 4.4 MW. Approximately 60% of the nominal power is delivered to the tokamak via low-loss corrugated waveguide into seven launchers. All launchers are independently steerable in the poloidal direction in real time and in the toroidal direction between discharges.

The FW system consists of three transmitters: two manufactured by Asea Brown Boveri (ABB) [Asea Brown Boveri transmitter #1 (ABB1) and Asea Brown Boveri transmitter #2 (ABB2)] are operated at 90 MHz and the third system, obtained from the Fusion Materials Irradiation Test (FMIT) facility is operated at 60 MHz. All are capable of delivering 2 MW into a matched load. The ABB systems are connected to DIII-D via a coaxial transmission line into two four-strap, water-cooled antennas with Faraday shields. The FMIT system is similarly connected to an inertially cooled, four-strap antenna whose energy handling is limited to 4 MJ or a 2 s pulse at full power. At the end of FY12, it was decided to permanently cease use of the FMIT antenna and to mothball the remaining two systems for FY13. All systems were fully functional at the end of FY12.

The plasma control system (PCS) provides state-of-the-art high-speed digital control of the magnetic configuration and other key plasma parameters. The system is capable of fully integrated control of plasma shape, density, pressure, current profile, energy, and toroidal rotation as well as performing feedback stabilization on the neoclassical tearing mode (NTM) and RWM.

A substantial number of other support systems are necessary to operate the facility. Prime power for the heating systems is taken directly off the utility grid while a 525 MVA motor generator (MG2) supplies the power for the coil system. A second, smaller 260 MVA MG1 is presently mothballed. The coils are powered by a set of fourteen phase controlled power supplies. In the case of the shaping coils, there are high speed switching current regulators (choppers) in series with each; the non-axisymmetric coils utilize a combination of switching current regulators (0–4 kHz) and higher bandwidth amplifiers (0–20 kHz).

The computer systems for the facility are generally Linux® based systems. The internal network at the DIII-D site is 100 MB and 1 GbE (gigabit Ethernet) at the main computer center, with a 10 Gb dual link between DIII-D and the computing center. The Fusion site is a node on the Energy Sciences Network (ESnet) operating at 10 GbE. The data acquisition system routinely acquires approximately 20 GB per shot and a 212 TB on-line storage array permits all present and historical DIII-D data to be available for rapid access.

A closed loop, cryogenic system comprised of a 150 l/h helium liquefier and two compressors provides liquid helium needed to support operation of the neutral beamlines and in-vessel cryopumps. The liquid helium (LHe) used for the EC superconducting magnets and the D_2 pellet injector is produced by our helium liquefier, but is used in a once-through system and is not recovered. The liquid nitrogen (LN_2) used for the beamlines and in-vessel cryopumps is purchased and is stored in an 11,000 gallon tank and an 3,000 gallon tank. A set of water conditioning systems provides high purity, low conductivity, de-oxygenated water to cool the DIII-D vessel, coils, neutral beams, gyrotrons, power supplies, diagnostics, and other systems.

Operation of the tokamak with deuterium fuel results in significant neutron production. The radiation shield forming the wall and roof of the machine hall reduces the radiation levels to acceptable levels for the public and the staff. Radiation levels at the site boundary are limited to 100 mrem/yr by the state of California regulations and internally to 60 mrem/yr by DIII-D procedures. Radiation levels for staff are limited to 5000 mrem/yr by the state of California regulations and internally to 2400 mrem/yr (600 mrem/qtr) by DIII-D procedures. An active ALARA program keeps radiation doses from facility operation “As Low As Reasonably Achievable”.

Presently, the radiation dose at the site boundary for a typical week of operation is 1.0 mrem, based on the 2012 experimental campaign. If the balance in the experimental program between high performance discharges producing high radiation dose and lower dose discharges remains the same, an extension of the typical pulse length by a factor of two would increase the typical weekly dose to 2.0 mrem. Further discussion of expected dose rates based on the higher power and pulse length discharges expected in the next five years is included in Section 5.8.2.

5.3. ELECTRON CYCLOTRON HEATING AND CURRENT DRIVE SYSTEM

5.3.1. EC System Power Upgrade

The research program for the next five-year period requires continued growth in gyrotron power and pulse length. The proposed hardware plan takes advantage of the worldwide progress in higher power gyrotrons and will increase the injected power from 3.5 MW to almost 9 MW, well along the path to our long-term target of 12 MW. Pursuing the higher power gyrotron is a more cost-effective path to higher system power than increasing the number of existing 1 MW gyrotron systems because it minimizes the need for additional HV power supplies, gyrotron sockets, transmission lines, launchers, and DIII-D ports. Using 1.5 MW higher efficiency gyrotrons, only one additional HV supply, two gyrotron sockets, two transmission lines, and one dual launcher are required.

Figure 5-3 shows the detailed plan for this five-year period to expand the EC system from the current seven-gyrotron EC system, which includes a 1.2 MW gyrotron being made available to the DIII-D program by the National Aeronautics and Space Administration (NASA). One of the existing 1 MW gyrotrons recently suffered a vacuum failure, and the gyrotron from NASA replaces this failed gyrotron. The first of the 1.5 MW tubes will be available in mid-FY14 and two additional 1.5 MW gyrotrons will be procured in FY16 and FY17. One additional 1.5 MW unit will be procured as a replacement, as the 1 MW units are phased out. The failed 1 MW gyrotron will be repaired early in the five-year period to have a spare gyrotron should another 1 MW gyrotron fail before a replacement 1.5 MW gyrotron can be made available. At the end of the five-year period, the system will consist of four 1 MW tubes, two 1.2 MW tubes, and four 1.5 MW tubes.

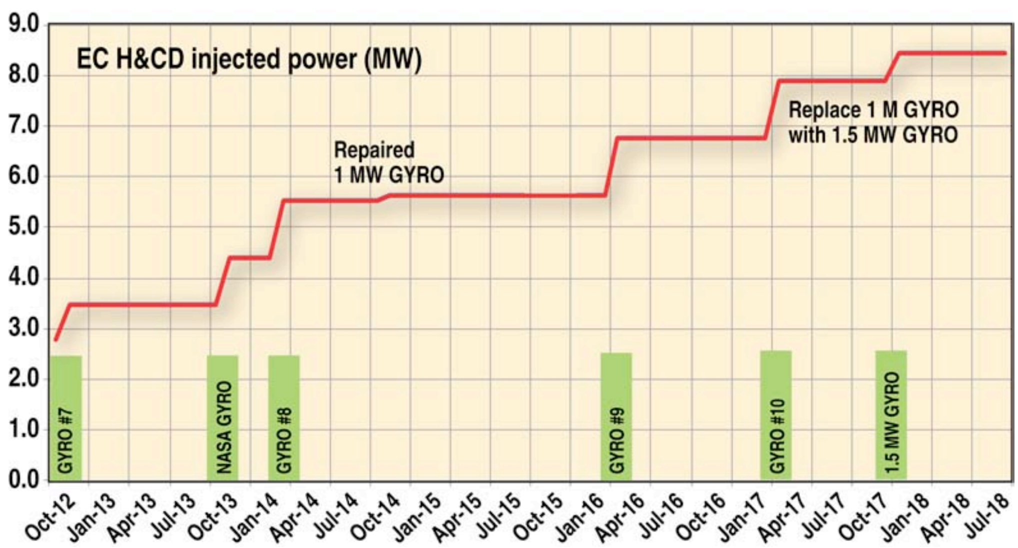

Fig. 5-3. Plan to increase the EC system power to almost 9 MW as part of the path toward 12 MW.

The final and future step of the EC upgrade would be to replace the four remaining 1 MW gyrotrons with new 1.5 MW higher efficiency gyrotrons. Each existing 1 MW socket will need to be adapted for the depressed collector gyrotron and EC power supply (ECPS) #1 and #2 also need to be modified to incorporate two modulators as in ECPS #4.

5.3.1.1. Gyrotrons. General Atomics (GA) is leading the development of a higher power (1.5 MW), higher efficiency depressed collector gyrotron that is focused on the reliable support of physics. This development leverages the continuing progress worldwide in gyrotron performance with a goal of attaining the highest reliable output power available. A gyrotron capable of generating a robust 1.5 MW long pulse has been designed and is consistent with the capability of our existing power supplies. The first article, gyrotron 8, is being built and will then be tested at GA (Fig. 5-4). Upon satisfactory demonstration of the gyrotron performance, two additional new gyrotrons (9,10) will be procured. A cryogen-free superconducting magnet and its associated power supplies will be procured with each new gyrotron.

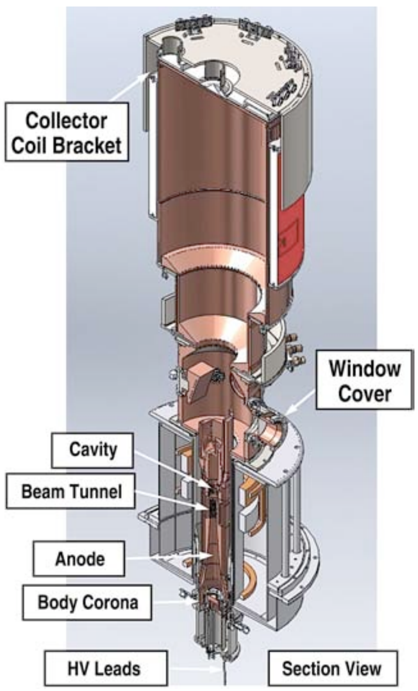

Fig. 5-4. The first 1.5 MW gyrotron design is complete and delivery is expected in fall 2013.

An additional 1.5 MW gyrotron will also be procured late in this five-year period to replace one of the existing 1 MW gyrotrons, some of which will be over 15 years old by 2018. Because the existing superconducting magnets are compatible with the 1.5 MW gyrotron, a new magnet need not be procured. The 1 MW gyrotron socket will be adapted for this depressed collector gyrotron. A test socket will be built to condition this gyrotron and further replacement gyrotrons to ready them to support physics without interrupting the physics support being provided by the operating 1 MW gyrotrons.

5.3.1.2. Gyrotron Vault, Sockets, and I&C. An extension to the North end of the building will be added to house the two new gyrotrons as well as a gyrotron test socket as shown in Fig. 5-5. Each socket has a HV tank, water-cooling manifold, and a gyrotron instrumentation and control subsystem, all of which will be essentially copied from the existing DIII-D EC system. The instrumentation and controls for the test socket and two new gyrotron sockets will be located in the new building extension.

5.3.1.3. Power Supplies. The current EC H&CD system has four EC power supplies, one of which has three tetrode-based 80 kV, 50 A modulator-regulators in it. A fifth EC power supply, which will have two modulator-regulators as in ECPS 4, will be built and installed in the location shown in Fig. 5-5. It will use one of the onsite neutral beam power supplies obtained from the Lawrence Livermore National Laboratory (LLNL) Mirror Fusion Test Facility (MFTF) program for the HV dc input to the modulator-regulators.

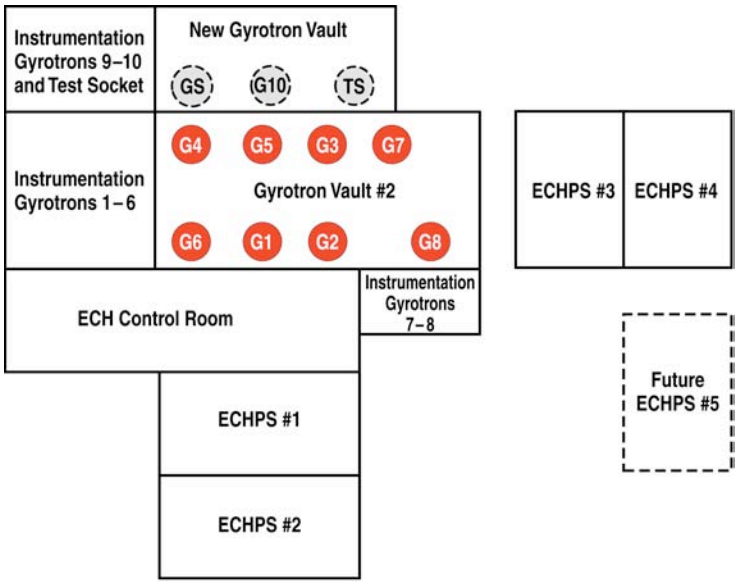

Fig. 5-5. Upgrading EC system towards 12 MW with only 10 gyrotrons. Only one additional power supply, ECPS 5 is required.

5.3.1.4. Transmission Lines. Two new transmission lines will be fabricated and installed to route the radio frequency (rf) power from the new gyrotrons to the fifth dual launcher to be installed on DIII-D. These lines will use the same components as the existing lines that are capable of safely transporting 1.5 MW. The test socket will only have the transmission line for the rf dummy loads and will not have the components that route the rf power to the torus.

5.3.1.5. Launchers. A fast-steering dual launcher will be fabricated and installed in a port already reserved for it, expanding the current capability to inject rf power from ten gyrotrons.

5.3.2. Refurbishments and Enhancements to Existing System

5.3.2.1. Replacement Waveguide Loads and Tank Loads. As the generated power and pulse length is increased, some components in our transmission systems will be operating near their limits. During the five-year operational period, it is expected that a number of replacement loads will be required, with possible upgrade in the power handling capability. A commercial dummy load, designed to handle 2 MW, is being used at other laboratories and will be evaluated.

5.3.2.2. Gyrotron Filament Power Supplies. The stability of the filament current is critical for operating gyrotrons at peak performance, since the cathodes are temperature limited emitting devices. The chopper regulated filament power supplies currently in use have exhibited limitations especially when being commanded to boost the filament current on long pulses. New ac amplifiers have been integrated into the newest systems and will be installed on all gyrotrons in stages.

5.3.2.3. Power Monitor Miters. The EC system is being equipped with power/mode monitors on four lines and these will be added for all systems. These power dividers provide real-time rf power at the tokamak, polarization measurements, and diagnostic mode analysis of the injected beam and will replace the uncalibrated monitors which have to have calibration coefficients checked and applied after the plasma shot by the electron cyclotron heating (ECH) operators.

5.3.2.4. Low Loss Miter Bends. The easiest way to improve transmission line efficiency to increase delivered power at low cost per Watt is to reduce losses, which are primarily due to mode conversion in the miter bends. An initial attempt at this was unsuccessful due to non-optimum transmitted rf in the lines. New concepts involving better mode control should be successful and, as these are tested, some fraction of the present miters will be replaced with low loss designs.

5.4. NEUTRAL BEAM SYSTEM

5.4.1. Second Off-Axis Beam

Off-axis current drive is essential to generating current profiles needed for stable high beta, steady-state discharges with high bootstrap driven current. In 2010/2011, the 150 deg neutral beamline was modified to enable it to be tilted hydraulically from 0 to 16.5 deg and thus provide injection of beam power significantly off-axis. This was successful and up to 5 MW of power has been injected at the maximum angle into DIII-D discharges (Fig. 5-6).

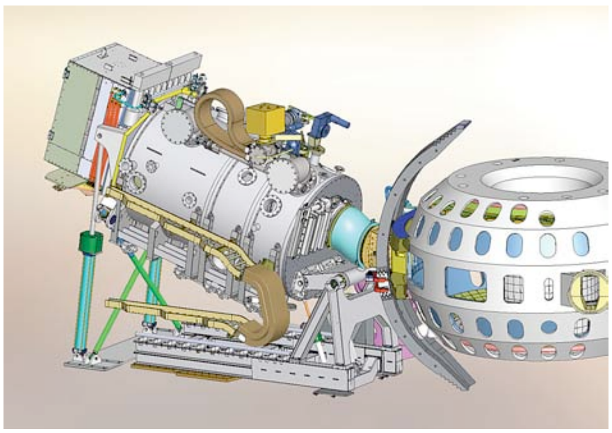

Fig. 5-6. OANB 150 layout.

To obtain the 12 MW of off-axis beam injection required for the target AT discharges, a second beamline will be modified. The 30 and 330 deg beamlines were compared and the 30 deg beamline was chosen since it has similar geometry relative to the vessel and the anti-torque structure as the 150 deg beamline and this significantly reduces the engineering effort. The hydraulic system hardware and motion control system have worked flawlessly and will not require any redesign. Two additional hydraulic brakes will be installed in the rear of the beamline to replace hand-turned clamping nuts to enable the beamline motion to be fully automated and reduce the time for a full tilt to less than 30 minutes. The design of the flexible cryogenic lines, cable tray, gas lines, and the entire vacuum system can be reused without modification. A study was performed to identify and do a preliminary evaluation of all the new engineering issues. The most significant issues include:

- Modification of the beamline support stand. The PF coil cables from the supplies to the coils are routed under the beamline and this will require the stand to be modified.
- Modification of the front beamline support columns, floor plates, concrete foundation for the support column, and horizontal seismic supports. While the anti-torque structure has three-fold symmetry, the concrete foundation and machine hall is square and thus the support of the front of the beamline and its interface with the main walls of the machine hall will need to be modified. Additionally, these modifications will require new seismic analysis.
- Modification of the HV transmission line. The routing of the 30 deg beamline and the 150 deg beamline transmission lines are different relative to the ion sources and the wall of the machine hall and this will require the flexible part of the transmission line entering the source housing to be redesigned. Fortunately, there is considerably more room available behind the 30 deg beamline and

this should enable the design to be simplified without the need for the extensive modification to the source housing that was required for the 150 deg beamline.

- Diagnostic impact. The 30 deg left source is used heavily for CER, MSE and Survey, Poor Resolution, Extended Domain (SPRED) impurity measurements. When the beamline is fully tilted (~16 deg), these systems will be unable to provide measurements in the plasma core (r/a < ~0.6). A simple strategy has been developed to recover the key features of these systems:
  - The radial MSE system (presently located at 15R0) will be moved to 255R0 with a blue-shifted view of the 330 deg beamline. Note that this new system will also improve core radial resolution of MSE when both 30 (on axis) and 330 are used.
  - As an option, the CER system would be augmented by adding a view of the 330 deg beamline from the now vacated 15R0 port.
  - SPRED diagnostic will remain the same, losing active measurements during these experiments in the core.

To reach the full target 12 MW of off-axis injection, the 30 deg beamline will be operated at 105 kV, delivering 3.5 MW per source. A similar increase in power cannot be readily achieved for the 150 deg beamline because the tight geometry of the transmission line into the source housing limits the maximum voltage standoff to ~95 kV (discussion below).

5.4.2. Power/Energy Upgrade

In order to address the needs for higher power and longer pulses from the NB systems, a series of increases in beam voltages and pulse lengths are planned over the next five years. The goal is to significantly increase the energy delivered for both off-axis and co-injection neutral beam heating. The increases in power and pulse length will require upgrades of various systems, including ion sources, high voltage equipment, and internal beamline components. A summary of planned power and pulse length capabilities by the end of each fiscal year is presented in Table 5-4 below. The following subsections briefly describe each of the major system upgrades required to achieve the increased parameters.

Table 5-4
Planned Power and Pulse Length Parameters for All Beamlines

	FY13	FY14	FY15	FY16	FY17	FY18
30 deg beamline power (MW)	5.00	5.00	5.00	6.50	6.75	7.0
150 deg beamline power (MW)	4.50	5.00	5.00	5.00	5.00	5.0
210 deg beamline power (MW)	5.00	5.00	5.00	5.00	5.00	5.0
330 deg beamline power (MW)	4.80	6.40	6.40	6.75	6.75	7.0
Total off-axis power (MW)	4.50	5.00	5.00	11.75	11.75	12.0
Total co-injected power (MW)	14.30	16.40	16.40	18.45	18.50	19.0
Total beam power (MW)	19.30	21.40	21.40	23.25	23.50	24.0
30 deg BL pulse length at 80 kV (s)	3.0	3.0	3.0	6.0	6.0	6.0
150 deg BL pulse length at 80 kV (s)	3.0	3.0	3.0	3.0	3.0	3.0
210 deg BL pulse length at 80 kV (s)	3.0	6.0	6.0	6.0	6.0	6.0
330 deg BL pulse length at 80 kV (s)	3.0	6.0	6.0	6.0	6.0	6.0

5.4.2.1. Ion Sources. Five of the currently operating ion sources have been fitted with reduced aperture masking plates between the arc chamber and the accelerator to reduce the heating of the bending magnet pole shields and allow longer pulse length. However, the reduced aperture causes a reduction of approximately 15% in power, so it is proposed to replace the aperture with full-size versions in three of the sources to increase the power, while addressing the pole shield heating as described in Section 5.4.2.3. The masking plate replacements are planned in FY14 and lead to some of the power increases shown for the 30 deg, 150 deg, and 330 deg systems. Increased power is not required from the counter-injected 210 deg beamline. As such, the reduced aperture masking plate will be installed in those sources allowing extended pulse operation at 2.5 MW. In addition, the current ion sources can only be operated up to 93 kV. Above 93 kV, the spacing between the accelerator grids must be increased to provide adequate voltage standoff. We plan to re-gap the 330 deg right source in FY16 and then test source performance. Larger gaps in the accelerator are expected to decrease the perveance of the source, but if the overall increase in power from higher voltage operation is large enough, three additional sources will be re-gapped in the next two years to allow operation of four ion sources at voltages up to 105 kV (this tetrode-based voltage limit is discussed below). Because of voltage standoff limitations between the 150 deg beam and the ion source housing, the 150 sources will not be modified for 105 kV operation.

5.4.2.2. Voltage Upgrades. Along with source modifications, a series of upgrades are planned for various high voltage equipment to enable operation at higher voltage. The planned voltages available at the end of each year are listed in Table 5-5. New tetrodes will be purchased for increased reliability at higher voltages, but the basic tetrode design of the modulator/regulator limits the maximum operating voltage of the 30 and 330 sources to 105 kV. The 150 sources will remain at 81 kV, 2.5 MW operation because the geometry of that beamline design requires a one year shutdown and extensive labor resources to remove and replace the power limiting component (pole shield discussion below) and this is not in our current plans. If the pole shields for the 150 deg beamline are upgraded at a later date, those sources can be operated up to 93 kV, generating an additional 0.5 MW per source. The 210 beamline will operate at 88 kV providing 2.5 MW and doubled pulse length to 6 s with the reduced aperture masking plate. If requested, it is likely the 210 sources could be operated up to 93 kV, delivering 2.8 MW at the expense of somewhat shorter pulse length. The timing and sequence of the upgrades to 105 kV is determined by the voltage capability of the step-up transformer and the long procurement time for the new transformers required. Details of the component upgrades required for each voltage level are discussed in Section 5.8.3.

Table 5-5
Planned Operating Voltages for Each Ion Source

	FY13	FY14	FY15	FY16	FY17	FY18
30 deg left, right voltage (kV)	85, 81	85, 81	85, 91	93, 93	105, 93	105, 105
150 deg left, right voltage (kV)	81, 81	81, 81	81, 81	81, 81	81, 81	81, 81
210 deg left, right voltage (kV)	81, 81	88, 88	88, 88	88, 88	88, 88	88, 88
330 deg left, right voltage (kV)	85, 85	90, 93	90, 93	90, 105	90, 105	105, 105

5.4.2.3. Beamline Internal Components. The heating of the bending magnet pole shields is currently the limiting factor that sets the pulse length (and thus the maximum deliverable energy) for all ion sources with full aperture masking plates. A new pole shield design with an actively cooled micro-channel cooling module inserted in the region of the "hot spot" area of the copper has been proposed, and prototype modules have already been fabricated (Fig. 5-7).

Fig. 5-7. Prototype micro-channel cooling module utilizes parallel water flow through multiple molybdenum flow channels to provide active cooling of the pole shield.

The pole shield design, incorporating the actively cooled plate, will be completed and the new assembly will be installed into two beamlines over the next five years. The first shields to be replaced will be in the 330 deg beamline in FY14, followed by the 30 deg systems in FY16 when the 30 deg beamline is modified for off-axis injection. Concomitant increases in both pulse length and power are reflected in Table 5-4. It is expected that the pulse length and energy throughput of beam could then be doubled, limited by the magnet exit collimator heating instead of the pole shields. These collimators could also be upgraded at the same time as the pole shields are being replaced, providing an even higher pulse length capability. Note that the capacity of the ion source cooling water system must be expanded because the actively cooled pole shields require de-ionized, de-oxygenated water for the micro-channel cooling module.

5.4.3. Refurbishments

5.4.3.1. Ion Sources. Most of the ion sources currently in use at DIII-D have been operated continuously since 1986. The aging accelerator grid modules eventually develop water leaks due to slow corrosion of the thin-walled molybdenum grid rails and must be repaired. Over the last few years, the technology has been developed in-house to fabricate new grid modules and new Langmuir probes for the ion sources using high temperature brazing techniques. Grid modules and probes have been successfully built and this work will continue with a proactive effort to build spare grid modules, with the goal of building 16-grid modules a year, enough to completely replace the accelerator section of one ion source each year.

Successful operation of an ion source requires good control of the gas flowing into the arc chamber of the ion source and the neutralizer inside the beamline. The existing gas delivery systems exhibit sensitivity to electromagnetic noise caused by beam modulation. This causes failure of the gas regulation from flow controllers and results in poor source performance. To address, the old mass flow controller system will be replaced with a new system based on piezo-valves that have shown more robust performance in the noisy machine hall environment.

5.4.3.2. Data Acquisition and Control. Within the last few years, the task of acquisition of neutral beam waveform data has been removed from the computer automated measurement and control (CAMAC) system and transferred to an Ethernet-based system, with a vast improvement in the reliability of the data. In addition, the local control station (LCS) for the HV tetrode power supplies on NB system 7 (30R) was replaced with a PLC-based system that does not use CAMAC. We propose to continue phasing out the old, CAMAC hardware and replace it with modern equipment. Modern commercially available programmable logic controllers (PLCs) and new timing sequencer electronics will be installed at every LCS, eventually eliminating all LCS CAMAC hardware. In addition, the “mode-control” hardware controlling the beam modulation system will be replaced with a modern PLC, eliminating the last of the system CAMAC.

The present thermocouple acquisition system has proven to be failure-prone and frequently develops offsets, making automatic acquisition of heating data difficult and error-prone. With over 150 thermocouples in each beamline, it is critical that this data is reliable as the energy output is increased over the next five years. To achieve this, the present system will be replaced with an alternative system that is currently being tested and showing good performance.

5.4.3.3. Local Control Stations. Prompted by the success of the NB 7 system upgrade, the upgrade of the LCS electronics on the other beam systems will continue (Section 5.8). In addition, a major improvement to the telemetry of the NB 5 and 6 systems will be achieved by separating the 480 Vac cables from the instrumentation and control wiring to the LCS. These two systems are difficult to diagnose during operations due to the excessive electromagnetic noise coupled onto the telemetry, especially during beam modulation.

All LCS systems would also be improved significantly by replacing the ion source power transmission cable “core bias” power supply electronics. The current system has no remote control, no remote readout, and high voltage must be shut down to make adjustments. It is planned to replace the old system with a modern supply that can be monitored and adjusted remotely, thus significantly reducing down time caused by the core bias power supply.

5.5. RF SYSTEMS

The present DIII-D rf system comprises two ABB 2 MW transmitters and long pulse antennas and one FMIT 2 MW transmitter and short pulse (2 s) antenna. The ABB systems are presently operated at 90 MHz, although the transmitters are rated for operation from 30–120 MHz. The FMIT system (32–60 MHz rating) has been operated in recent years at 60 MHz. The system excites the fast wave and can be used for either current drive or direct electron heating depending on the phasing of the antenna straps. Recent operation of the system has been plagued with metallic impurity generation and low coupling efficiency in AT discharges. An assessment of the system in FY12 concluded that the operational availability of the systems had improved considerably and was acceptable, but budget constraints have led to the two ABB systems being mothballed in a state of “ready-to-resume” operations. A programmatic decision was made to permanently stop use of the short pulse antenna on the FMIT system. Since the systems provide valuable electron heating, it is proposed to restart the two ABB systems in FY14 with the goal of resolving the impurity issue. No major upgrades are proposed for operation of these two fast wave systems. Refurbishment and modernizations of these systems is described below in Section 5.5.2. If the impurity and coupling issues cannot be resolved satisfactorily, then operation of the ABB systems for FW heating and current drive will be terminated. The possible conversion and operation of the systems at 30 MHz may be pursued as an option (Section 5.5.1.2). Additionally, development and testing of a new 500 MHz, 0.8 MW Helicon wave system as a higher efficiency solution to driving off-axis current in future devices is planned (Section 5.5.1.1).

5.5.1. RF System Upgrades

5.5.1.1. Helicon Current Drive. The use of Helicons (also known as “whistlers” or very high harmonic fast waves) has been proposed as a high efficiency method of driving off-axis current drive in future devices such as the Fusion Nuclear Science Facility (FNSF) or DEMOnstration power plant (DEMO). The high electron beta in DIII-D AT discharges provides an excellent platform to test this proposal. The proposed system, shown in Fig. 5-8 will utilize commercially available hardware including a 0.8 MW, 500 MHz klystron, waveguides, a waveguide switch, and loads. One of the existing EC gyrotron power supplies will be used to power the klystron with instrumentation and controls based on the existing gyrotron system. The antenna and feedthroughs will be based on the proven design of the traveling wave antenna designed and built by GA for the Japanese tokamak JFT-2M. Additional switches would be needed in the torus hall to facilitate testing in both co-and counter current drive configurations.

5.5.1.2. 30 MHz Operation (Option). Operation at 30 MHz would deposit rf power into ions at either at the fundamental ion cyclotron resonance of the H minority or the second harmonic of the main D species. Depending on the plasma density, H concentration, and rf power the slowing-down of the energetic tail on the bulk plasma species can provide significant electron heating and/or thermal ion heating. Assuming that code calculations and low power loading tests at 30 MHz with the existing antennas show promise, two ABB systems would be converted to high power operation at 30 MHz. This involves a test of the transmitters at 30 MHz and modification of the transmission lines, which may require the addition of fixed lengths of line to enable the proper tuning. In addition, a load resilient transmission line system using hybrid junctions is proposed, similar to that used on German tokamak, ASDEX-Upgrade. This conversion is proposed in the FY16/FY17 period.

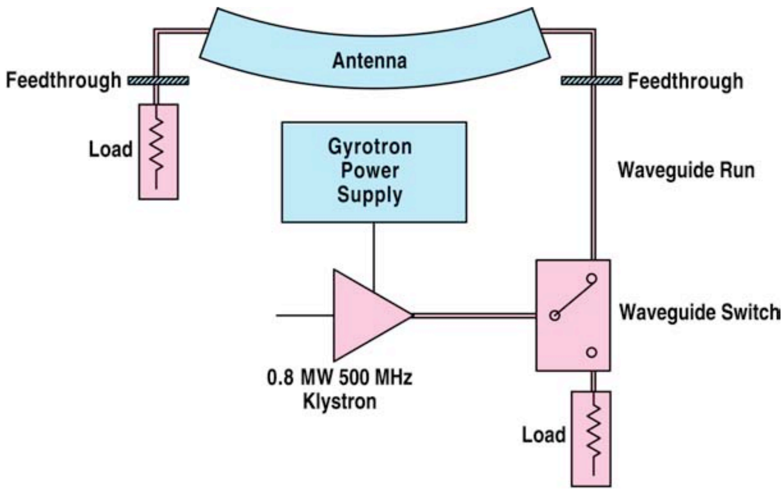

Fig. 5-8. Proposed helicon system hardware. The items in red are commercially available and an existing gyrotron power supply will be used. The antenna will be based on an previous antenna built for JFT-2M.

5.5.2. RF System Refurbishments

The following refurbishments and modernizations are proposed for the two ABB systems to improve the system reliability:

- Phase-amplitude rf diagnostic system. This system is used to tune and operate the fast wave systems and major components are now obsolete. A new system is proposed based on a successful prototype that was developed in collaboration with National Instruments. Initial tests on DIII-D in FY12 were successful.
- The ABB control system. Similar to the phase-amplitude system, the control system is obsolete, difficult to troubleshoot, and replacement parts are difficult to obtain. It is proposed to replace the HV power supply feedback controller initially and then update the remainder of the control system with newer hardware.
- Tuner controls. A prototype drop-in replacement for the tuner control boxes has been designed. Testing and fabrication of the 25 required modules is planned.

5.6. COIL SYSTEMS

The DIII-D coil system consists of the axisymmetric main coils [toroidal field (TF), ohmic heating coil, 18 field shaping coils (F-coil)] and non-axisymmetric coils (6 external C-coils and 12 internal I-coils). The scope of this task is to reduce the error field associated with the 30 deg TF current feed point (Section 5.6.1) and to upgrade the existing 3D coil system (Section 5.6.2).

5.6.1. Reduced Error Field from Toroidal Field Feedpoint

Magnetic error fields are well known to negatively impact plasma performance by reducing confinement, slowing plasma rotation, destabilizing the plasma, and restricting low-density operation. On DIII-D the primary sources of error fields are due to non-axisymmetries in F7A and F6A field shaping coils and the 30 deg TF current feed point. This task covers the correction of a significant fraction of the error field arising from the 30 deg TF current feed point, one of the two TF feed points on DIII-D.

The TF feed point at 210 deg was redesigned during 2005–2006 and reduced the error field by a factor of ten (Fig. 5-9). This has brought significant benefits to the research program: the region of stable low density operation without locked modes was extended from n_L = 1.2 to 0.85x10^{19} m^{-3}, a 30% reduction, and a reduction of external torque has enabled steady plasma rotation at low torque input and thus low velocity. A similar amplitude field error remains at the 30 deg TF feed point. Unlike other sources of error fields from the F and TF coils, the feed point is spatially localized, and so it has a slowly decaying spectrum of higher-*n* Fourier harmonics. If the TF-coil 30 deg feed error were reduced several-fold, then the remaining DIII-D intrinsic error would be predominantly *n*=1 and *n*=2 from coil alignment and spacing errors. Such an intrinsic error is amenable to good correction by the C-coil alone.

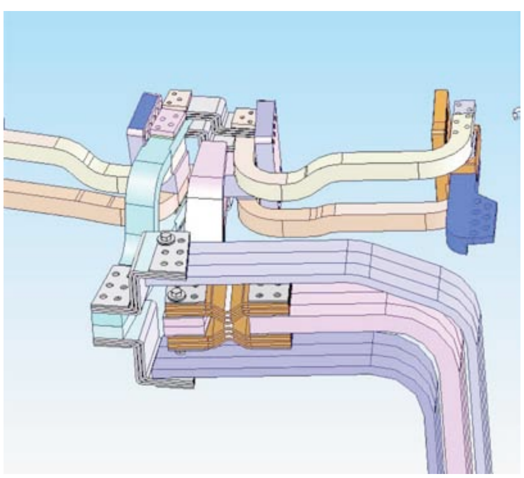

Fig. 5-9. Modified TF feedpoint at 210 deg reduced magnetic error field by a factor of 10.

Two proposed improvements should provide significant error field reduction. The conductors in the vertical section of the buswork are spaced widely apart in a dipole configuration that contributes approximately half of the error field from the feed. This section is amenable to correction by redesigning the buswork with reduced spacing between conductors and changing from a dipole to a quadrupole configuration. The lower section of the feed consists of elaborate buswork that extends from the vertical conductor to the output of the TF-supply coax, and this contributes the other half of the error field. This section is not amenable to any simple realignment of conductors, but may be correctable using a bucking coil. The close proximity of the 30 deg beamline to the feedpoint makes this region inaccessible for removal and reinstallation of large buswork. However, the planned modification of the 30 deg beamline during the FY15/FY16 shutdown period requires its removal from the machine hall and this presents an opportunity to modify the feed point conductors.

5.6.2. 3D COILS

The twelve internal I-coils, located above and below the midplane are used in conjunction with six external coils (C-coils) for correction or enhancement of magnetic error fields, feedback stabilization of the RWM, and for the creation of a resonant magnetic perturbation (RMP) for ELM stabilization. The coils can produce 3D field structures with toroidal mode numbers of n=1, 2 or 3 and a poloidal mode number that depends on the relative phasing of the upper and lower arrays. The n=1 and 2 configurations can be rotated and the phase of the n=3 perturbation can be flipped 180 deg. A number of new configurations have been proposed to improve the effectiveness of the coil array in stabilizing ELMs and correcting error fields, while maintaining our ability to perform RWM stabilization. This translated in the following key design goals:

- Field configurations of n=1, 2, 3, 4 and 6 and independent phasing of upper/lower arrays.
- Rotation capability for n=1–4 structures.
- Field strength at the plasma surface comparable to or larger than that produced by the I-coil.
- Bring all conductor leads out of the vessel to provide maximum experimental flexibility.
- Maintain effective RWM stabilization capability.

There are three different concepts that are under consideration for the purpose of providing an improved RMP for ELM stabilization and more flexible error field correction: (1) an internal 36-element (3x12) array on the centerpost, (2) an internal 24-element (2x12) array on the outer wall, and (3) an external 24-element array. The favored concept, Option 2, is an internal 24-element array arranged in 2 poloidal rows of 12 coils each above or below the midplane on the outer wall that would replace the existing I-coil. The general arrangement is shown in Fig. 5-10.

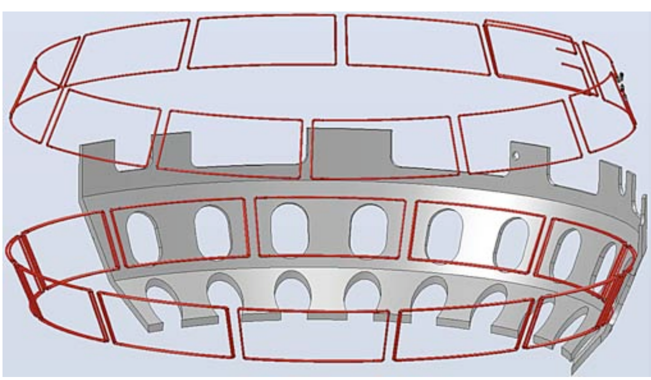

Fig. 5-10. Proposed layout of 24 outer wall coils arranged in two rows of 12 coils above and below the midplane. The entire array will be protected by armor tiles.

The proposed coil will be a two-turn coil with basic construction similar to the I-coils. The conductors are coaxial with a water-cooled copper center conductor inside an Inconel outer conductor that also serves as the vacuum boundary. Insulation is provided by a combination of Vespel® and Kapton®. The entire assembly is bakeable to 350°C with the ability to evacuate and backfill the water and insulating regions with nitrogen gas during baking or for leak checking. The conductor cross section will be the same as for the I-coils, so the two-turn design will require taller protective tiles to provide additional room under the tiles. The choice of two turns for the coils was based on an optimization of the size and cost of the power supplies, maximizing the RMP field, and maintaining the low inductance of the coils for effective RWM stabilization.

All 24 leads will exit the vessel and be routed externally via low inductance and low resistance quadrupole cables to a patch panel for complete flexibility to enable independent control of all coils. This will enable production of toroidal mode numbers n=1,2,3,4 and 6 and independent control of poloidal phasing of the upper and lower array. Patch panels, interlocks, and data acquisition and control will be based on the I-coil system.

5.7. AUXILIARY HEATING AND COIL POWER SYSTEMS

This section addresses the proposed power system upgrades to support improved utilization of the existing and future 3D coils, improved shaping coil capabilities, enhanced RWM stabilization using audio amplifiers, increased neutral beam power and various smaller system refurbishments needed to maintain operational reliability.

5.7.1. Power Supplies for 3D Coils and PF Shaping Coils

On DIII-D, the existing 3D coils (2x6 I-coil and 1x6 C-coil) are used for a variety of different applications including error field correction, stabilization of resistive wall modes, ELM stabilization using n=2 and n=3 RMPs, and magnetic braking experiments. The proposed upgrade of the internal I-coil array to a 2x12 array would significantly enhance the ability to create different mode structures, and in particular it would enable studying configurations up to n=6 with the ability to rotate both n=2 and n=3 structures. This extensive set of applications for our 3D coils requires a highly flexible set of power supplies and patch panels since practical budgets do not permit a dedicated full current, bi-polar power supply on each of the 18 existing coils (+12 additional proposed). However, both the existing 3D coil arrays and the proposed 24-element 3D coil array would benefit from expanded set of power supplies with similar operational characteristics to the existing dc-supply and invertor combination but with higher operating voltage and current. In addition, similar supplies would enhance the capability of our PF-coil shaping system by providing sufficient power to control all 18 coils rather than the 14 coils typically controlled for a double null configuration. We propose to add two new dc power supplies each capable of driving six four-quadrant switching amplifiers (SAs) as described below. Table 5-6 summarizes the specifications of both the existing and proposed supplies.

Table 5-6
Specifications of Both the Existing and Proposed Supplies

Name	Status	Quantity	Type	Current, Voltage
C Supply	Existing	5	dc	7 kA, 350 V
SPA	Existing	4	Four-quadrant switching amplifier	±4.5 kA, ±300 V
I Supply	Proposed	2	dc	16 kA, 500 V
I Invertor	Proposed	12	Four-quadrant switching amplifier	±2.67 kA, ±450 V

In order to drive the calculated 3D coil inductance, the supplies will need to have an operating voltage of ±450 Vdc and up to 8 kA, while operation with the shaping coils will require currents up to 16 kA. In order to maximize flexibility, each of the power supplies will be comprised of a slow response dc power supply supplying 16 kA with a buss voltage of ~ ±500 Vdc. This buss will then feed six insulated gate bipolar transistor (IGBT)-based SAs each capable of operating at ±450 Vdc at 2.67 kA. Any number of switching amplifies can be connected in parallel in any combination supplying output currents of up to the system rated 16 kA (1) or independently at 2.67 kA (6) or any other combination of the six SAs. The first of these dc supplies and six switching amplifiers are projected to be installed during FY14 and be operational for the FY15 campaign. The second supply and switching amplifiers are planned to be operational for the FY16 campaign. Based on this schedule, the number of independently controllable coils at the 2.6 kA level will increase from 4 in FY14 to 16 in FY16 and beyond (Fig. 5-11).

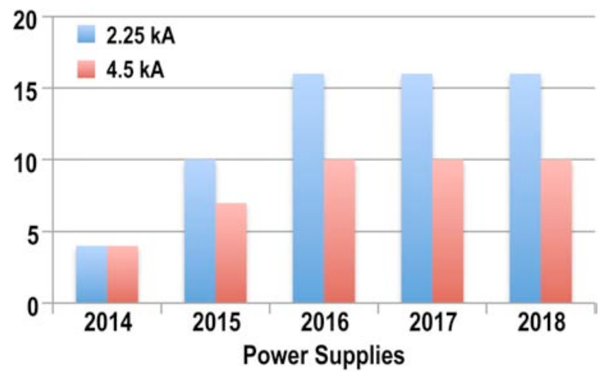

Fig. 5-11. The number of independently controllable coils will increase significantly.

The new supplies will get their ac power from a dedicated feed off of the motor generator #2 (MG2) distribution bus after being stepped down from the 13.8 kV (nominal MG2 output voltage) to the supply's 4160 Vac or 480 Vac (manufacturer specified). The step-down transformer will be an oil-filled outdoor unit requiring both power switchgear and cabling support as well as a new concrete pad to mount it on. The feed to the transformer will incorporate a line reactor and fused disconnects for system protection and personnel safety. The existing MG2 distribution bussing will need to be extended in order to provide space for the above mentioned support equipment. In addition, two lab offices will be cleared and converted to space for the switchgear and line reactors. The first of the two supplies will be located in an existing building space and will be available in early FY15, but the second power supply will require a building modification and expansion and will be available in FY16, after the shutdown.

5.7.2. Audio Amplifier Upgrade for RWM Stabilization

As described above, the two sets of 3D coils on DIII-D are used for a variety of applications, and in particular, fully integrated AT discharge scenarios will need to simultaneously apply high current (4–8 kA), low frequency (0–60 Hz) currents for RMPs and error field correction on the I-coil and C-coil and low current (1 kA), higher frequency (>1 kHz) for RWM stabilization on the I-coil. In addition, independent operation of each of the 12 I-coils is required for control of RWM modes above n=1. The present set of power supplies for RWM stabilization consists of 24 high bandwidth, low current amplifiers (20 kHz, 190 A). When grouped into 12 sets of 2 amplifiers, the current is insufficient for robust RWM stabilization and these cannot be operated simultaneously on the same coil set with the higher current, lower bandwidth amplifiers.

Two upgrades are proposed that will satisfy both the need for higher current and for simultaneous operation of both types of amplifiers. In Phase 1, a crossover network will be developed that enables operation of the higher current, switching amplifiers with the higher bandwidth, low current audio amplifiers. In Phase 2, the number of audio amplifiers will be doubled from 24 to 48. This will enable currents up to 750 A into each of the 12 coils (4 amplifiers/coil) or 1500 A into helical pairs. The crossover network will also be modified to accommodate the higher current audio amplifier set.

5.7.3. NB HV System Upgrade

This set of upgrades provides the necessary enhancements to support the proposed increases in beam voltage to either the 93 kV or 105 kV level discussed in Section 5.4.2. Table 5-7 outlines the various component upgrades necessary for each of the beamline voltage increases and in which year they will take place. A summary of the main elements of the upgrade include:

- New tetrodes are required for many of the systems for improved reliability at the higher voltage.
- Several tap changers will need to be rebuilt in order to provide the increased voltages and to improve reliability at the higher beam currents. Most of the existing units have been in service for many years and are already having difficulty meeting higher current demands.

Table 5-7
Various Component Upgrades Necessary for Each of the Beamline Voltage Increases

System Name		150L&R	150L&R	210R	210R	210L	210L	330R	330R	330L	330L	30R	30R	30L	30L
Voltage		93	105	93	105	93	105	93	105	93	105	93	105	93	105
Transformer/Rect Voltage		116	128	116	128	116	128	116	128	116	128	116	128	116	128
Source current		82	92	82	92	82	92	82	92	82	92	82	92	82	92
Mod/Reg Tetrodes		X	X	X	X			XX	XX			X	X	X	X
Mod/Reg grid drivers		X	X	X	X	X	X								
Switchgear cabling															
Tap changerrewire/rebuild			X		X		X			X		X			
Xfmr/rect & step up trans											X		X		
Duct rework															
HV cable cap bank to P.S.			X		X		X		X		X		X		X
Cap bank			X		X		X		X		X		X		X
HV breakers															
Arc, Fil & Cont. Iso. Xfmr								X	X	X	X	X	X	X	X
Bidecks, ion source trans line															
Suppressor power supply															
Voltage/current sensors															
Crowbar system		X	X			X	X	X	X	X	X	X	X	X	X
Core bias															
Analog logic system (LCS)															
Grad-grid Volt dvdr cooling		X	X	X	X	X	X	X	X	X	X	X	X	X	X
Ion source housing			X		X		X		X		X		X		X
Fiscal Year															
210 L&R 88kV	2014			X		X		X		X					
	2015														
	2016								X			X		X	
	2017														X
	2018										X		X		

- New arc, filament, and control isolation transformers will be required for increasing the voltage on the four 30 and 330 sources. [These transformers on the Universal Voltronics Corp. (UVC)-based power supplies have lower capability than the similar units on the Transrex-based systems (150 and 210 systems).]

- An additional stage must be added to the crowbar for all systems except the 210 systems prior to increasing the voltage to 93 kV. The crowbar on the 210 system has already been upgraded.
- Two of the outdoor transformer/rectifier units will need to be rewound to provide higher voltages for 105 kV source operation.
- The HV cable from the capacitor bank to the power supplies and an additional set of capacitors are required on all systems going above 93 kV.

5.7.4. Refurbishments/Modifications

The following is a proposed list of refurbishments/modernizations that have been identified as necessary to maintain system reliability and safety or offer enhancements to existing equipment by reducing workload requirements or increasing system performance.

- Continue NB LCS modernization program.
- Rebuild NB high voltage power supply transformers and tap-changers.
- Replacement high power tetrodes.
- Upgrade toroidal field supply and ohmic coil supply silicon-controlled rectifiers (SCRs).
- Replace baking power supply capacitor bank.
- Convert PF-coil power supply SCR firing controls to Enerpro® control boards.
- Replace FPS 01,02,03 CAMAC based control/interface with modern technology (PLCs).

5.8. POWER AND PULSE EXTENSION

The present divertor and first wall structures are engineered with the purpose of providing particle control and pumping of plasma particles, dissipation of the high heat loads exhausted from the plasma, and protecting the vessel wall during injection of high power auxiliary heating. To this end, there are three in-vessel cryopumps located under protective divertor baffles, and nearly all plasma-facing surfaces including the divertor structures are covered with GrafTech ATJ™ isostatic-molded graphite armor tiles. The major goals of the hardware upgrades proposed in this section are to address the following research needs: increased peak injected power as well as total injected energy and reduced erosion of plasma-facing components. The hardware changes proposed to meet these needs include: an improved tile design (Section 5.8.1.1), modified heat flow to upper divertor structures (Section 5.8.1.2), and upgrading other in-vessel components, such as diagnostic windows (Section 5.8.1.3).

5.8.1. Vessel Thermal Upgrade

The goal for the next five years is to increase total injected power and extend injection duration, resulting in an increase in the total injected energy from the existing level of 60 MJ (20 MW, 3 s) to 200 MJ (35 MW, 3–6 s). This will be for double null divertor as well as upper and lower single-null divertor plasma shots. Cool down time between shots will be extended from the existing 10 to 15 minutes. The engineering requirements assume an energy deposition pattern based on 30% radiation of the input power, with the remaining 70% conducted to the first wall, typically the divertor region. The conducted power is assumed to be distributed 60%/40% to the outer/inner strike points for single null plasmas and 90%/10% to the outer/inner strike points for double-null plasmas, with a 20% up/down asymmetry assumed for the double null configurations. The power deposited on the tiles is assumed to be a triangular deposition over the full height of the tile. Since the injected power and total energy will be increasing continually throughout the next five years, phased upgrades of the vessel armor are planned. Upgrades required to operate at or above each of these levels are described in the following sections.

- 75 MJ (3 s at 25 MW)
- 100 MJ (4 s at 25 MW)
- 120 MJ (4 s at 30 MW)
- 150 MJ (5 s at 30 MW).

To provide maximum flexibility for the research program, the high heat fluxes at the divertor strikepoints must be able to be positioned over a wide spatial range. This capability requires modifications to the plasma-facing tiles, tile-to-baffle plate gasket material, and specific diagnostics and other specialized in-vessel components.

5.8.1.1. Vessel Plasma-facing Tiles. The DIII-D first wall and divertor surfaces are covered with plasma-facing tiles made from GrafTech ATJ™ graphite. These tiles are inertially cooled during the plasma shot and are cooled down between shots by water flowing in the tile support structure. GrafTech ATJ™ is a low cost graphite with traditionally acceptable, but not high, thermal conductivity. The material has performed well for shot energies up to 60 MJ with a 10 minute cool down period between shots. The majority of the approximately 3000 tiles on the inner and outer walls will still be acceptable at injected energy target levels through 150 MJ and will remain ATJ™.

At the strike point areas, thermal analysis shows that at higher energy loadings, the existing ATJ™ tiles have limitations based on peak surface temperatures and thermally induced stresses. To avoid these limits, improvements will be required in plasma-facing tile thermal conductivity and material tensile strength. It is expected that carbon-carbon (C-C) composite materials will be required in the high heat flux areas shown in Fig. 5-12 at the target energy levels listed below.

- 75 MJ (3 s at 25 MW)
  — Replace lower divertor nose tile and inner floor tile with C-C tiles (120 tiles).
- 100 MJ (4 s at 25 MW)
  — Replace ceiling tile and upper and lower centerpost tiles with C-C tiles (240 tiles).
- 120 MJ (4 s at 30 MW)
  — Replace upper inner and outer divertor nose tiles with C-C tiles (120 tiles).
- 150 MJ (5 s at 30 MW)
  — Replace outer floor tile with C-C tiles (48 tiles).

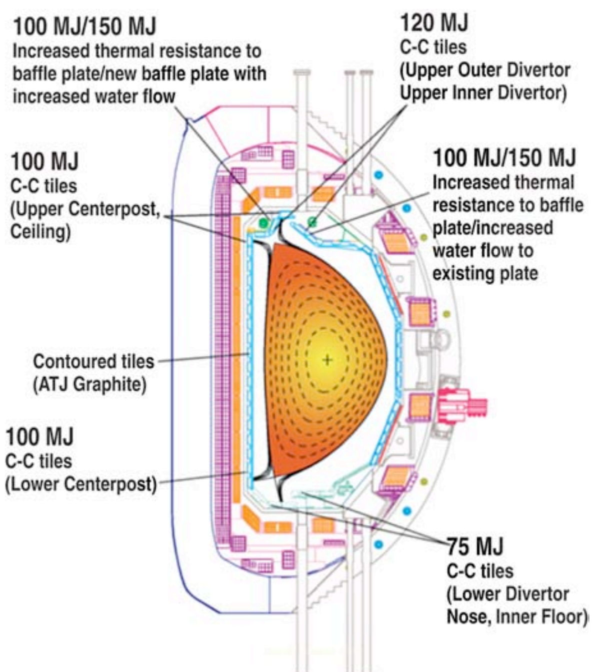

Fig. 5-12. Locations of armor tile and water system upgrades required to increase vessel thermal capability from present 75 MJ to levels above 150 MJ.

Progress in developing integrated scenarios with high power injection and either increased radiation or increased flux expansion at the strikepoint regions (e.g., Snowflake configuration) will raise the target energy levels for each specified set of tile upgrades. For example, increasing the radiated power fraction from 30% to 65% would effectively reduce the heat flux by 50% and would allow for 120 MJ of injected energy on existing ATJ™ tiles.

It is also planned to replace the flat tiles on the centerpost with existing ATJ™ material contoured to the radius of the wall with smaller tile-to-tile spacing and improved alignment. These will reduce edge heating and thus reduce both tile erosion and toroidal non-axisymmetries that make it difficult to interpret diagnostic signals.

5.8.1.2. Modified Heat Flow to Upper Divertor Baffles. The basic water-cooling system for the DIII-D vessel is adequate to remove 300 MJ between shots. However, the upper divertor cooling water flow is significantly lower than the flow in the lower divertor or vessel walls. With our present armor tile system and water flow rates, the heat flowing to the upper divertor baffles will boil the cooling water for upper single null and double null divertor configurations with input energies above 100 MJ. Increasing the thickness of the GRAFFOIL® gasket between the tiles and the baffle plate can reduce the thermal conductivity sufficiently to prevent this boiling while still allowing the tiles to cool adequately within the 15 minute shot cycle. Above 150 MJ, the water flow rate must be increased in the baffle plates and this is not proposed under the present plan.

5.8.1.3. Other Vessel Components. Other than heat directly conducted to tile surfaces, all other in-vessel components are exposed to heat primarily via plasma radiation. Based on existing measurements, peak radiation levels of 50 W/cm^2 are expected to occur in plasmas with highly radiating mantles. While this level is relatively benign for even our existing graphite armor tiles, the thermal impact on diagnostic systems may be significant. Some of the large diagnostic windows that are located close to the plasma surface for enhanced viewing angle will need to be evaluated and may require modification to handle these high heat fluxes. The neutral beam drift ducts may also require additional protection due to interaction with re-ionized beam particles that focus in this region. A molybdenum plate installed in one of the beam drift ducts looks like a promising solution to handling this heat flux for all the beamlines.

5.8.2. Radiation Dose for Long-Pulse, High-Power Discharges

Operation of the tokamak with deuterium fuel in high performance discharges results in significant neutron production. The radiation shield forming the wall and roof of the machine hall reduces the radiation levels to acceptable levels for the public and the staff. Radiation levels at the site boundary are limited to 100 mrem/yr and 2 mrem/h by the state of California regulations and internally to 60 mrem/yr by DIII-D procedures. Radiation levels for staff are limited to 5000 mrem/yr by the state of California regulations and internally to 2400 mrem/yr (600 mrem/qtr) by DIII-D procedures. An active ALARA program strives to keep radiation dose low.

Presently, the radiation dose at the site boundary for a typical week of operation is 1.0 mrem. If the balance in the experimental program between high performance discharges producing high radiation dose and lower dose discharges remains the same, an extension of the typical heating pulse length by a factor of two would increase the typical weekly dose to 2.0 mrem. More detailed calculations of expected dose rates were performed for the high performance discharge (Table 5-8). For the highest performance, steady-state advanced tokamak discharge with β_N~5, stored energy of 2.2 MJ at 1.75 T, the neutron rate is 1.02x10^{16} neutron/s. This limits the number of 5-s discharges to approximately 470 discharges per year. Although this permits the research program to proceed, these high dose rates will require prudent operation of these high-performance, long-pulse discharges.

Table 5-8
Number of High Performance Discharges Based on Radiation Dose Limits

Discharge Type	Neutron Rate	Number of 10 s Shots/yr (60 millirem/yr limit)	Number of 5 s Shots/yr (60 millirem/yr limit)
Steady-state AT	1.02x10^{16} n/s	235	470

5.9. FUELING FOR DISRUPTION MITIGATION AND PELLET PACING

This section addresses upgrades to the fueling systems used for disruption mitigation (Section 5.9.1) and for controlling ELMs (Section 5.9.2).

5.9.1. Disruption Mitigation

For disruption mitigation studies, DIII-D has conducted experiments using two different systems. The first uses the DIII-D pellet injector to produce killer impurity pellets; to date, both argon and neon have been used. The second system is the massive gas injection system and this is presently configured as a six-valve injector, each of which is an independent fast acting valve capable of injecting large amounts of gas with a short rise time.

While the killer pellets have been successful at significantly reducing disruptive heat loads and halo current forces, they generated runaway electrons. The massive gas injection valve has had good success with both heat loads and halo currents, but to date the technique has not been successful at getting enough gas into the plasma to assure collisional suppressions of the runaway avalanche.

In the next five years, the DIII-D program will develop and characterize techniques to achieve sufficiently high core density to prevent runaway electron avalanching: an inverse jet using a rupture disk, customized solid and shell pellets, large shattered cryogenic pellets, and multi-port massive gas injection. Detailed plans and scientific goals can be found in Section 2.4.

5.9.1.1. Inverse Jet Injection with Rupture Disk. In the inverse jet technique, a long cylindrical tube prefilled with gas at high pressure is sealed at the plasma-facing end with a rupture disk and placed close to the plasma edge. A fast-acting valve is attached to the other end with a higher pressure gas reservoir behind it so that when the valve is activated, the rupture disk breaks and the gas rapidly reaches the plasma. This technique attempts to avoid the long time delay associated with gas moving through a long guide tube that is inherent in the present massive gas injection system. By reducing the time delay and increasing the fueling rate, the goal is to fuel the plasma more effectively during the thermal collapse phase. A laser could also be used to more rapidly open the rupture disk, but it is likely to increase the complexity of the system. The possibility of metal shards from the rupture disk entering the vessel must be examined. Work will be done in collaboration with France’s Commissariat à l'Énergie Atomique (CEA) Tore Supra.

5.9.1.2. Customized Solid/Shell Pellets. This technique refers to using prefabricated solid pellets at room temperature consisting of various layers of materials chosen to optimize core impurity deposition and the fueling deposition profile. Alternately, shell pellets filled with chosen impurities (e.g., boron) will be tested. The thickness and material of the shell is chosen to provide deeper penetration before emptying its contents. These pellets are fabricated at the GA Inertial Confinement Fusion facility. Pellet injection is being done using a dedicated injector (shot-gun injector). Different injection geometries and locations will be studied.

5.9.1.3. Shattered Cryogenic Pellets. This technique utilizes large cryogenic pellets with a diameter of up to 1 cm, and containing the necessary 10^{23} particles. To avoid penetration through the plasma and damage to the opposite wall, the pellet is shattered and appropriately aimed prior to vessel entry by firing it into a shaped tube located at the port opening. A modified shatter-plate is being installed in FY13 Oak Ridge National Laboratory (ORNL) and a second complete injector (back-end pellet system and front-end shatter plate) to be located at a different poloidal and/or toroidal position will be installed in FY15 in order to increase the plasma density and reduce localized radiated power loads on the first wall, which could lead to melting in ITER. ITER prototypes will be fielded and qualifying tests are scheduled in the latter part of the five-year plan.

5.9.1.4. Massive Gas Injection. Work will continue in further developing the technique and qualifying it for ITER. As with the shattered pellet, the main focus of the effort is on investigating the effect of multiple injection ports, at different poloidal and/or toroidal angles in order to increase the plasma density and reduce localized radiated power loads on the first wall. A second massive gas injection system (consisting of three valves) is being fielded in FY13 (Fig. 5-13). The valve design has been optimized to minimize the rise time and the system has been used with D_2, He, Ar, and Ne. ITER prototypes will be fielded and qualifying tests are scheduled in the latter part of the five-year plan.

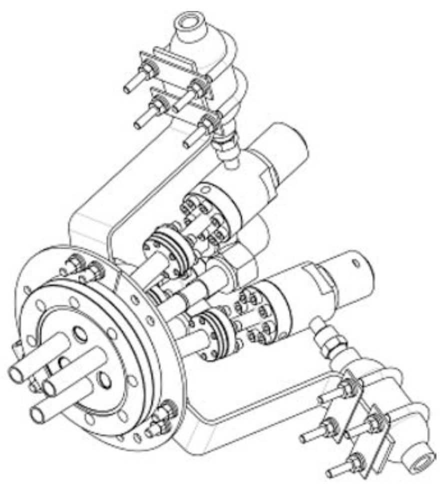

Fig. 5-13. Second massive gas injector being installed in FY13.

5.9.2. Pellet Pacing

The present DIII-D pellet-pacing system (ORNL) consists of three guns each producing a stream of 30 Hz deuterium pellets for a net injection rate of 90 Hz. This has been successful at significantly increasing the ELM frequency (details in Section 4.4) and decreasing ELM size. The frequency will be further increased to 40 Hz for a net rate of 120 Hz in FY15. The capability of injecting variable size pellets will be added in FY16.

Separately, a lithium injection system is being installed on DIII-D in FY13 that is capable of injecting small dust-size particles of lithium (40 microns) for the purpose of studying the effect of lithium on wall conditioning. This system will be modified in FY14 by Princeton Plasma Physics Laboratory (PPPL) to provide fast and controllable bursts of lithium to enable studies of pellet-pacing with a non-recyclable element instead of deuterium.

5.10. MECHANICAL SYSTEMS

This section discusses the major changes to the mechanical systems required to support the operations systems.

5.10.1. Water and Air Systems Upgrade

Three water-cooling systems will need to be upgraded. These include:

- The cooling water to the ECH systems will require expansion to support the planned 11 gyrotron sockets. Three additional main pumps and five booster pumps will be required (Section 5.3).
- The Neutral Beam Ion Source Cooling Water System will need to be upgraded to supply the new pole shield micro-channel cooling panels (Section 5.4.2.3).
- The capacity of the DIII-D vessel and coil cooling water system will be increased to provide water to the new PF power supplies and 3D coil array.

The Clean Dry Air system will be expanded to have a dedicated diagnostic cooling system as the cooling needs of the diagnostics in the DIII-D machine hall have been steadily increasing.

5.10.2. Refurbishments

The MG2 lower ring header is approximately 30 years old and is in need of refurbishment. This system will be refurbished in early FY14 with new piping and heat exchanger cleaning. Replacement of much of the above grade piping for the MG2 will be performed in CY13.

5.11. COMPUTER SYSTEMS, DATA ACQUISITION AND CONTROL

The DIII-D experiment requires a computing infrastructure that is capable of quickly adapting to the expanding fast paced needs of the fusion research program while providing a dependable and secure environment. Fusion computing includes the data acquisition, instrumentation and control systems unique to DIII-D which are directly involved in the operation of the tokamak along with all of the underlying Information Technology (IT) infrastructure encompassing user support services, networking and data storage.

5.11.1. Fusion Computer Systems Organizational Overview

The DIII-D computer systems (Fig. 5-14) dedicated to experimental plasma operations supply the real-time control, data acquisition and plant operation functions at the tokamak site. These systems rely heavily upon custom in-house developed computing solutions in order to fulfill the many unique requirements of the research program.

Those computer systems and services not specifically dedicated to the DIII-D operational environment are grouped under the moniker User Service Center (USC). Included in this grouping are the general purpose computational systems, the mass storage disk arrays, the DIII-D backup systems (computers, tape robots, tapes, software), the DIII-D Control Room user computers, operational services, the complete DIII-D network infrastructure and an overarching cyber security program.

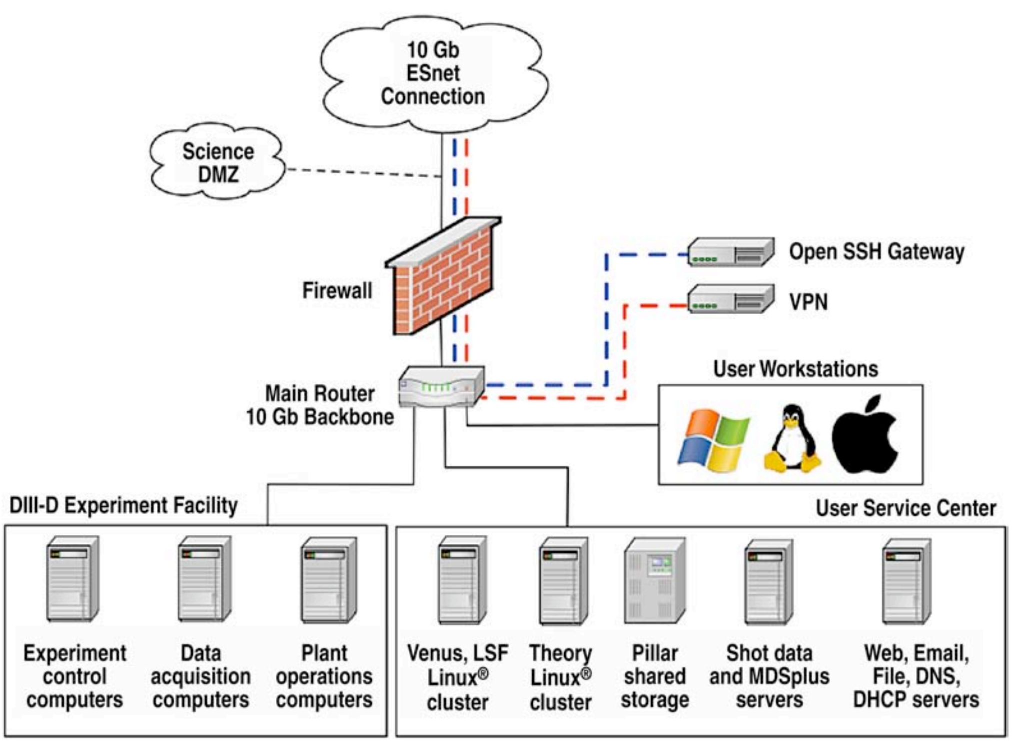

Fig. 5-14. DIII-D fusion computer systems overview.

5.11.2. DIII-D Experiment Support

Steady growth in the amounts of data generated by DIII-D (Fig. 5-15) along with further expansion of the overall control capabilities are expected to continue to drive up the fusion computing requirements. The total amount of raw diagnostic data collected from DIII-D data acquisition systems in FY12 alone was 33 Terabytes. With raw data from digitizers projected to exceed 160 Terabytes annually during the course of the next five years, upgrades to both immediate and long-term data storage capacities will be made on a regular basis. In addition to the raw digitized data, provisions have been made for the long-term storage of even higher volumes of data from new camera (or video) diagnostic systems.

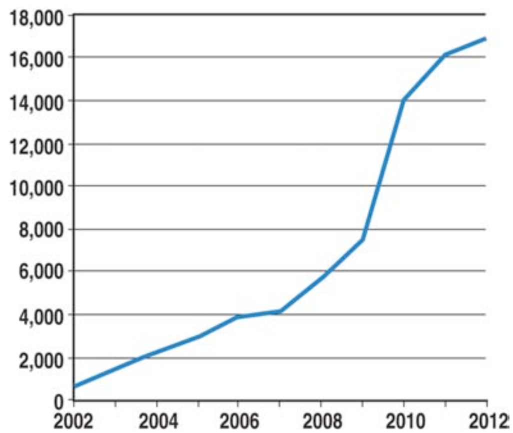

Fig. 5-15. Growth of DIII-D raw data size. Largest shot (megabit) per fiscal year.

Important hardware and software updates are planned to the PCS to support advanced control scenarios and to keep it current with the latest hardware technology. An upgrade of all PCS equipment that is dependent upon older and slower Peripheral Component Interface (PCI) bus technology is scheduled to begin in FY14. This will improve PCS maintainability and allow for the steady incorporation of faster more modern computing hardware utilizing the latest PCI express bus standard. A complete replacement of all outdated 2.1 GB Myrinet networking hardware used in the PCS for the past decade will be an important objective of the next five-year period. The present plan involves migrating to 10 GbE Myrinet real-time networking equipment to increase throughput and broaden interoperability with other DIII-D systems. An expansion of the real-time data acquisition capabilities of the PCS is planned through upgrades and additions of new streaming cPCI digitizers with higher sampling frequencies. This will provide further detailed information on characteristics of the plasma to the real-time control system and greatly improve experimental capabilities.

Expanded use of the DIII-D developed PCS by a number of collaborating fusion institutions worldwide will further increase the levels of required hardware and software support. Upgrades to the PCS hardware test system will be made in order to satisfy important testing requirements for the different versions of the PCS used at DIII-D, China's Experimental Advanced Superconducting Tokamak (EAST), Korean Superconducting Tokamak Advanced Research (KSTAR), and PPPL in addition to possible work in support of ITER. Significant upgrades will be made to provide and support new capability for generating C-code from control algorithms using modeling and simulation development tools, and for easily incorporating the code into the PCS. This capability will enable a large advance in development and deployment of off-normal and fault response algorithms, in support of a major new control research initiative during this five-year plan. It will also enable planned large-scale upgrades and revisions to existing complex algorithms in the areas of profile control and neoclassical tearing mode (NTM) control.

A further move away from legacy CAMAC hardware is planned to decrease dependence on unsupported equipment that has become increasingly difficult to replace and maintain. While good progress has been made in the upgrades of a number of CAMAC based acquisition systems using modern cPCI digitizers, a few key systems still remain that will need to be updated within the next five years. This includes a major upgrade of all of the DIII-D CAMAC based timing control hardware, which is expected to occur before FY17. In addition to this work will be an ongoing effort to replace the remaining set of diagnostic channels still dependent upon CAMAC clocks and digitizers by the end of the next five-year period.

5.11.3. User Service Center Support

Upgrades are planned to the mass storage capacities of the USC based computing resources to meet the projected growth in data generated by the DIII-D experiment (as described in the previous section). The existing Pillar mass storage array will be expanded from 212 TB to 1000 TB (1 Petabyte). Improvements to the Linux® computational cluster (introduced in FY11) will be needed throughout the course of the next five-year period to increase the processing power required for codes used to analyze DIII-D shot data, in addition to providing more storage for accompanying analyzed results. Included in this are plans to steadily build upon the cluster concept by adding and replacing computational nodes as needed and a move from basic Network File System protocol to fiber channel to enhance data accessibility and overall performance within the cluster.

An upgrade is planned for the Tape Robotic storage equipment in order to keep pace with the increasing amounts of raw experimental and analyzed data, and help ensure a full disaster recovery capability is maintained. This will also serve as an important security measure to safeguard against compromise or loss of critical DIII-D data. The feasibility of incorporating cloud services will also be investigated. Due to the breadth of the DIII-D collaboration, the USC operates on a 24x7 basis. To ensure services remain at a level of maximum availability, the establishment of a mirroring site will be actively pursued.

Ongoing support and maintenance activities are also planned. One such task is modernizing the DIII-D Control Room user terminals by incorporating a net bootable configuration to improve flexibility and user interaction. Maintaining the workable computer environment remains an important goal for the next contract period. Regular software updates to compilers (which include licensed Fortran and C optimized versions), scientific and numerical libraries and analysis and visualization applications will be required to provide the DIII-D research staff with the latest tools to assist in their work. Upgrades to operating systems and continual installations of software patches will be necessary ongoing efforts throughout the upcoming five-year period that will also be helpful to maintaining system security.

5.11.4. Networking

The DIII-D project is currently enjoying a 10 GbE Internet connection to the Energy Sciences Network (ESnet). Within the fusion firewall protected network are two distinct segments comprised of the USC computers presently operating at 1 GbE and the computer systems located at the DIII-D experiment facility running primarily at 100 MB speeds. A number of important upgrades have been planned for the next five-year period to improve the overall fusion networking capabilities and address critical cyber security concerns.

Upgrades to increase to 10 GbE performance are planned for all major USC servers during the next five-year period. An upgrade is also planned to migrate the DIII-D experimental facility network to 10 GbE. This will greatly improve performance at the site where all of the experimental data is generated. To further enhance communications during Tokamak operations, an expansion of the existing wireless network deployed in a central portion of the DIII-D experimental building will be performed to provide coverage to all outlying areas. Additional plans are being made for extending and enhancing wireless networking capabilities to other buildings involved in fusion research. Deployment of Internet Protocol version 6 (IPv6) will be required to allow for expansion of the number of devices on the network.

Another goal for this next period is to deploy a Science DMZ. The Science DMZ is a portion of the network built outside the firewall-protected network and optimized for high-performance scientific applications and data exchange. This sort of isolation allows for performance and security to be tailored for the data transfer systems while reducing the risk for the production network. To enhance cyber security at the DIII-D facility, a plan will be developed and implemented to isolate the portion of the network directly related to the operation of the Tokamak such as control computers, PLCs, monitors, etc., from the general fusion network.

Participation on the ESnet Site Coordinators Committee will continue, as well as maintenance, monitoring and performance tuning when needed of the DIII-D local area network (LAN).

5.11.5. Cyber Security

Continued efforts to uphold and advance the existing DIII-D Cyber Security Program Plan (CSPP) will be an important emphasis of the upcoming five-year period. Training for both end users and technical staff will continue to be provided and expanded to promote cyber security awareness and provide the necessary skills and certification to keep up to date with the latest threats. Included with this are regular distributions of security bulletins to all registered users, allocation of security training to support staff and annual participation in security conferences. Virtual Private Network (VPN) access to the DIII-D environment has been an important conduit for remote researchers. Continued VPN support will be required to provide access to a growing number of off-site users. The present Juniper VPN service that has reached its end-of-life will need to be replaced with a like service. Continued support of and cooperation with the DOE Joint Cyber Security Coordination Center (JC3) will be important to obtaining valuable tools and resources to assist DIII-D security personnel. An additional external resource that will be investigated is the use of third party security auditors that may include DOE Red Team visits to aid in the evaluation and testing of DIII-D security. Continual risk evaluation of both new and existing computing equipment will require increased support from technical staff.

Further improvements to security are planned to enhance existing tools and practices. An upgrade of the patch management system is required to address limits that have been reached in the amounts of software that can be tracked and disk space required for updates and patches, in addition to increasing the number of supported operating system (OS) and software packages. Improvements to wireless security are planned to provide stricter control and authentication over all connections made to the network. To provide increased protection over critical computer controlled equipment located at the DIII-D facility, deployment of a secondary firewall system will be made a priority in order to further restrict access from within the fusion network to only those individuals and processes that are directly involved in the operation of the tokamak.

Additional enhancements to DIII-D security are planned through the deployment of a number of important new systems. Included in these plans is the purchase of a professional log management system to extend upon the current DIII-D developed central logging tools and increase capabilities for storing information from more systems over a longer period of time. This will also assist in the task of parsing logs for specific information that would be useful during forensic investigations. Improvements to the management of administrative privileges are planned through the installation of a Lightweight Directory Access Protocol (LDAP) server that will help provide tighter access controls. Additional training to those requiring elevated privileges, and regular audits of the use and impact of administrative privileges on the IT environment are also planned. Deployment of an intrusion detection and continuous monitoring system will provide an important preemptive capability that is highly desired for the next five-year period. This would be used to help monitor and prevent network compromise and to analyze patterns in network traffic, in addition to protecting access to ports and services that are presently allowed through the DIII-D firewall. Installation of http and https bidirectional traffic monitoring and malware protection hardware and software (such as websense®) will be investigated to safeguard web users from redirection to nefarious sites that could present potential security risks to the DIII-D network.

6. DIAGNOSTICS – PLASMA MEASUREMENTS

Diagnostic measurements are the key enabler of progress in scientific understanding and plasma control as recognized in the Plasma 2010 report for the National Research Council (NRC):

> ***"The required progress in […] key areas will not be possible without significant expansion of our plasma diagnostic capabilities. Quite simply, we cannot understand what we cannot measure."***

The Plasma 2010 panel recommends in their report that a new initiative in diagnostic development be formulated at the Department of Energy, Fusion Energy Sciences (DOE FES) level. That recommendation was echoed in the Research Needs Workshop (ReNeW) report (2009), which assigned Thrust 1 to the development of new diagnostic techniques, which are still very much needed in many areas. Although DIII-D presently has the most comprehensive diagnostic set of any magnetic fusion facility, diagnostic improvements planned over the next five years will greatly enhance our understanding of and our capability to control fusion plasmas.

The ability to accurately measure the relevant parameters in fusion plasmas is an essential component in bringing about predictive understanding and validating theories and models. To adequately test theories, a comprehensive set of diagnostics is required which not only measures all relevant equilibrium parameters [i.e., $T_i(\rho)$, $T_e(\rho)$, $n_e(\rho)$, $V(\rho)$, $J(\rho)$, …] with appropriate spatial and temporal resolution, but also measures the turbulence fields. Measurements are needed in the plasma core, the scrape-off layer, the divertor region, and on the first wall material interface. Comprehensive measurements are also required for control of the plasma shape, equilibrium profiles, and magnetohydrodynamic (MHD) stability, and such control enables the optimization of the tokamak concept.

The diagnostic set assembled on DIII-D is the result of many fruitful collaborations with national and international partners. Developing and fielding a diagnostic on DIII-D remains a key involvement for many groups, especially from universities, and offers the capability to participate directly in experiments and scientific discoveries, and opens a particularly engaging and formative path for students. This large involvement and integration are particularly evident in Table 6-1, which summarizes the diagnostics presently found on DIII-D. In addition, the operation, development and maintenance of these diagnostics largely extend across institutional boundaries, through integrated teams.

Table 6-1 also shows (in bold, blue letters) the systems, which were added or significantly upgraded in the last five years. Separately, shown in Fig. 6-1, is a view of the interior of the tokamak (outer wall) showing some of the diagnostics and their very good port access. Presently, more than 180 access ports are available, with the majority dedicated to diagnostic use. Of that large number of ports, a sufficient fraction remains available to cover the proposed systems described in the following sections.

The previous success encountered in fusion research at DIII-D required the pursuit of three important aspects related to diagnostics:

- QUALITY measurements, accurate, precisely calibrated.
- RELIABILITY of the measurement to support experiments.
- COMPLETENESS of the set (in coverage, resolution, and/or parameters).

Table 6-1
Summary of Current DIII-D Diagnostics

		Lead Institution
Electron Temperature and Density		
Thomson scattering	10 lasers, 54 points	General Atomics (GA)
ECE Michelson interferometer	Horizontal midplane	U Texas
ECE radiometer	Horizontal midplane, 40 channels	U Texas
CO_2 interferometer	3 vertical chords, 1 radial chord	GA
Microwave reflectometer	Midplane profiles, 5 systems	UCLA(4), ORNL(1)
ECE imaging (ECEI)	2D ECE emission, 2 areas, 320 channels	UC Davis
Correlation ECE (CECE)	4 radial channels	UCLA
Li beam injector (edge current profile)	Radial beam with 32 vertical viewing channels	GA
Ion Temperature and Velocity		
Charge exchange recombination (CER) spectrometer	24 vertical, 39 tangential, 1 radial chords	GA
Main ion CER	16 tangential chords	PPPL
Fast ion density profile (FIDA)	2 vertical, 12 oblique views, imaging	UCI
Core Impurity Concentration		
VUV survey spectrometer (SPRED)	Radial midplane view	GA
Visible bremsstrahlung array	Radial profile at midplane, 16 channels	GA
Radiated Power		
Bolometer arrays	2 poloidal arrays, 48 channels each	GA
Fast bolometers	3 poloidal arrays, 90 channels	UCSD
Divertor Diagnostics		
Visible spectrometer	12 channels, upper and lower divertor	ORNL
Tangential TV (visible)	2D image and plasma flow of lower divertor	LLNL
Tangential TV (visible)	2D image and plasma flow of upper divertor	LLNL
Infrared (IR) cameras	3 camera views	LLNL
Main chamber periscope	IR and visible	LLNL
Fast neutral pressure gauges	6 locations, 5 in divertors, 1 main chamber	GA
Penning gauges	Under divertor baffle (upper and lower)	GA
Baratron gauge	Under divertor baffle	GA
Langmuir probes	32 in lower divertor, 28 in upper divertor and centerpost	SNL
Moveable scanning probe	Scannable through lower divertor outer leg (X-point)	UCSD
Tile current monitors	10 lower divertor, 6 upper	GA
Fast Thermocouple array	20 in lower divertor	GA/SNL
Magnetic Properties		
Rogowski loops	3 toroidal locations	GA
Flux/voltage loops	44 poloidal locations	GA
B_θ probes	135 probes	GA
Diamagnetic loops	2 toroidal locations	GA
External B_r loops	4 arrays, 36 loops	GA
Internal B_r loops	64 loops	GA
Internal B_T loops	4 toroidal locations	GA

Table 6-1 (Cont.)

		Lead Institution
Plasma Edge/Wall		
Plasma TV	4 cameras, radial view, rf antennae, main chamber	GA, LLNL
Fast framing camera	Tangential views (2)	UCSD
IR camera	Inner wall and ceiling views, floor	LLNL
Visible filterscopes	24 locations	ORNL
Moveable scanning probe	Scannable across outer midplane	UCSD
Swing Langmuir probes	Poloidal swing centerpost, 2 poloidal locations	UT/GA
Fluctuations/Wave Activities		
Beam emission spectroscopy (BES)	2D, 64 channels	U Wisc.
Microwave reflect meters	2 radial systems	UCLA
Far IR scattering	Radial view	UCLA
High-*k* backscattering	3 radial positions	UCLA
Phase contrast imaging (PCI)	Vertical view, 32 channels	MIT
CECE	2 radial channels	UCLA
UF-CHERS	Ion temperature fluctuations, 2 correlated channels	U Wisc.
Doppler backscattering (DBS)	2 toroidal locations, 13 radial channels	UCLA
Mirnov coils	Toroidal, poloidal, and radial arrays, 60 coils	GA
Polarimeter	1 radial chord	UCLA
Li beam injector	Radial beam with 32 vertical viewing channels	GA
X-ray imaging system	100 channels, 5 arrays	UCSD
SXR X-point imaging	Tangential view, lower X-point	ORNL
RF probes	5 plasma-facing antennae, 6 recessed loops	GA
Scanning probes (midplane, Xpt)	Temperature, plasma potential	UCSD
Particle Diagnostics		
Fast neutron scintillation counters	2 radial channels	UCI
Lost beam ion detector	2 toroidal locations	UCI
Fast ion loss detectors (FILD)	2 locations	GA
Neutron detectors	4 toroidal locations	UCI
Deuterium and tritium (DT) neutron counters	2 locations	UCI
Neutral Particle Analyzers	3 channels	UCI
Plasma Current Profiles		
Motional Stark polarimeter	5 views, 65 channels, full radial coverage	LLNL
Li beam injector (edge current profile)	Radial beam with 32 vertical viewing channels	GA
Miscellaneous		
DiMES, MiMES	Lower divertor, outer midplane	GA
Hard x-ray monitors	4 toroidal locations	GA
Hard x-ray monitors/spectrometers	20 locations	UCSD
Torus pressure gauges		GA
Residual gas analyzer		GA

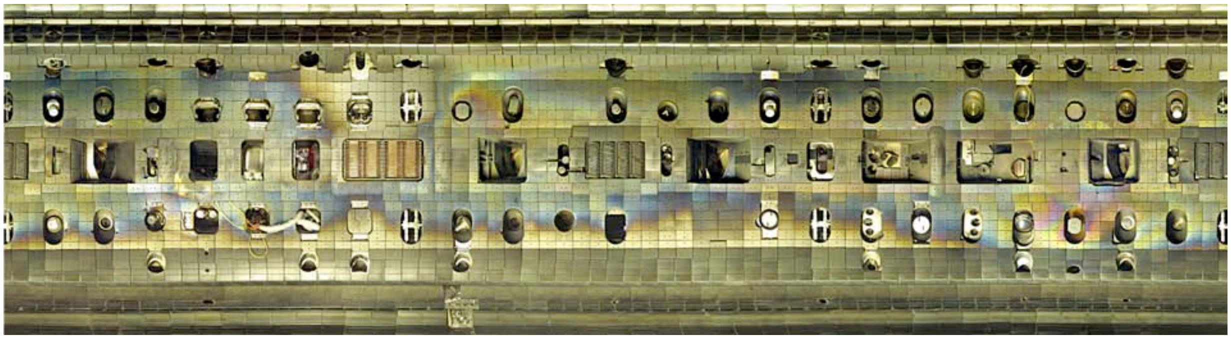

Fig. 6-1. View of the tokamak interior (outer wall) showing some of the internal diagnostics and large port access.

The scientific goals are also coupled with a renewed challenge in the required coverage (spatial, temporal and spectral). New and upgraded diagnostics are thus required to address the new challenges. When it comes to reliability, there is an even bigger question than the simple availability for physics analysis. We are moving toward a fully controlled system, where sensors (i.e., diagnostic) are called upon to control actuators (power, fields, fueling, etc.) in an increasingly complex way in order to control and sustain performance. Reliability will become a major issue in a successful reactor, where systems have to be available and reliable high duty factors. Finally, the need for completeness is crucial when one contemplates the interconnections between particles and fields, in a multi-dimensional system (space, velocity, and time).

Significant progress in our scientific understanding of fusion plasmas will require the development of new diagnostic techniques. For the DIII-D program, this includes:

- A concerted and collaborative effort between facilities, at the national and international levels.
  - Small lab development and testing (e.g., universities, small business).
  - Sharing of experience, engineering design capability and proof of validity.
  - Testing and exploitation on larger device such as DIII-D.
- A continuous thrust into the introduction of new technologies.
  - Small scale, increased sensitivity and ultra-fast detectors.
  - Upgrading data acquisition systems for speed and reliability.

The plan includes new, improved measurement capabilities which are derived directly from the mission and objectives of the experiment. These objectives lead to a set of measurement requirements, which are then turned into techniques (i.e., diagnostics) that can be fielded. A series of objectives were identified in the various scientific areas as described in Sections 2 through 4. These scientific objectives will require a certain number of tools, many being new or upgraded diagnostics. For each objective, physics measurements have been identified and a series of proposed diagnostic techniques elaborated. In some cases well-known techniques can be applied. In others, the development of a new technique will be required. The overall plans for the implementation of these new or upgraded measurements are shown in Fig. 6-2. In each subsection, the items are arranged by priority (top: high priority). Detailed design and available resources will affect the details of the timeline. These needs are further detailed in the next sections arranged by topical areas.

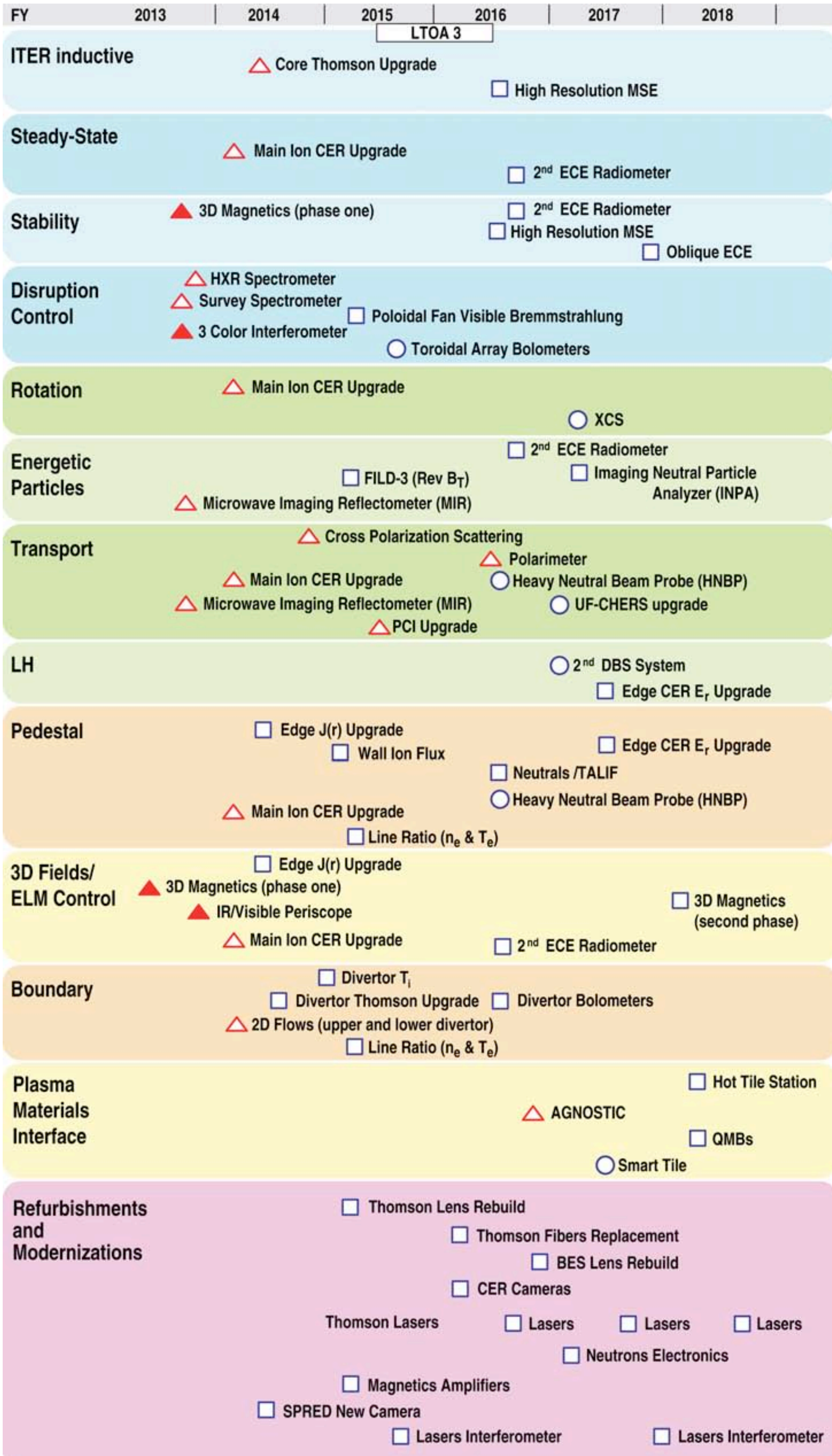

Fig. 6-2. Timeline for the implementation of new or upgraded diagnostic systems. Within each subsection, the priority runs from high (top) to lower (bottom). Triangles indicate completed (filled), in progress or planned (open) while squares are proposed and circles are optional diagnostic systems beyond the basic proposal.

The plan for the DIII-D diagnostic set shown in Fig. 6-2 illustrates several categories as denoted by the symbols. The open triangles are systems that are in progress, i.e., work has been started or there is an award in place to build and install this diagnostic on DIII-D in the future. The squares show the additional diagnostics proposed in this Plan for the next five-year period. Further, there are additional program diagnostic options to this Plan that would make valuable contributions which are indicated by open circles. Lastly, the solid triangles are systems that are in the completion stage now and will be exploited in 2013. These are listed to show the continuity within the research areas and relation to the future diagnostics additions.

6.1. DYNAMICS AND CONTROL RESEARCH

6.1.1. Optimize ITER Inductive Scenarios

The development of the best inductive scenario for ITER requires detailed analysis of the underlying physical mechanisms, and also the physics basis for extrapolating conditions from existing tokamaks to ITER. Of particular interest is a careful characterization of the performance and physical mechanisms in the core of the plasma (Section 2.1) with sufficient resolution and accuracy. To support these studies, additional measurements are required and are summarized in Table 6-2.

Table 6-2
ITER Inductive Scenarios Measurement Needs

Scientific Objective	Physics Measurement	Proposed Diagnostic Technique
Characterize scenario performance and stability	Improved electron density and temperature profiles	Redesigned tangential Thomson scattering system
	High precision core current profile measurement	Additional MSE chords (core)

- **Redesigned tangential Thomson scattering.** This consists in reversing the laser beam direction (thus enhancing the scattering angle sensitivity at higher electron temperature and to enlarge the collection optics for these chords.
- **MSE.** The addition of a new system at the equatorial port at 255 deg, viewing the 330 NB, will serve two purposes. The first one will supply the core motional Stark effect (MSE) measurements when the 30 NB is tilted. It will add chords near the core where additional resolution is needed (e.g., near q~2) (LLNL).

6.1.2. Develop a Steady-State Solution

The long term goals for the development of steady-state operation (see also Section 2.2) include a variety of sensors/diagnostics, and their full integration into the control system. While the standard feedback diagnostics, magnetics, density and others have been routine for quite some time, others are being integrated for the optimization of the tokamak approach. These include measurements of the electron temperature (Thomson) and electron cyclotron emission (ECE), ion temperature and rotation [charge exchange recombination (CER)] and current profile (MSE and lithium beam). A clear push for reliable and dedicated measurement will be necessary. Others critical areas include the measurement and control of radiating impurities in the divertors together with a real-time measurement of heat flux. The proposed additional and/or upgraded capability is described in Table 6-3 (options shown in *italics*).

Table 6-3
Integrated Steady-State Operation Measurement Needs

Scientific Objective	Physics Measurement	Proposed Diagnostic Technique
Control current profile evolution	Current profile (core, edge)	Upgraded MSE, upgraded lithium beam
	Current profile during off-axis neutral beam injection (OANBI)	Additional MSE chords (core)
Control heat flux to divertor plates	Heat flux	Divertor bolometers, *additional IR camera views*
Understand role of fast ions	Escaping fast ion flux	Third FILD (Reverse B configuration)

- **Upgraded lithium beam.** Section 6.3.1.
- **MSE.** Section 6.1.1.
- **Divertor Bolometers.** An array of AXUV diodes will be installed in a lower port (R-1 level) to view the lower divertor through a poloidal fan arrangement. The overall design will be similar to the poloidal SXR and DISRAD systems.
- **FILD-3.** The array of fast ion loss detectors will be augmented by adding a third detector, to be located above the equatorial midplane. The detector will use the same scheme where escaping fast ions are dispersed onto a scintillator according to their pitch-angle and energy (gyroradius). The system will be oriented to perform in a reverse B_T and reverse I_p configuration, a configuration not covered by the existing two systems.

6.1.3. Validate Plasma Stability Physics Theories

The establishment of the scientific basis for understanding and predicting limits to macroscopic stability of magnetically confined plasmas has many control implications. While a large part of the research (Section 2.3) is aimed at investigating and validating basic MHD stability physics, making use of DIII-D's extensive set of diagnostics for precise, detailed measurements of the pressure and current density profiles, along with details of the internal structure of MHD modes can increase substantially the operating regimes of the tokamak approach. In fact, stability research includes critical issues for both conventional and advanced tokamak (AT) plasmas. With recent advances in scientific understanding and technical tools, we are beginning to study plasmas compatible with steady-state operation, and to develop active means of controlling stability, which will require appropriate sensors. In addition, the detection and mitigation of disruptions (Section 6.1.4) will require specific diagnostics, which includes the development of sensitive, dedicated and reliable sensor for the feedback control. The proposed additional and/or upgraded capability is described in Table 6-4 (options shown in *italics*).

Table 6-4
Plasma Stability Measurement Needs

Scientific Objective	Physics Measurement	Proposed Diagnostic Technique
Characterize NTM, RWM and TAE radial mode structure	ECE (T_e) measurements	Second ECE radiometer, oblique ECE, second ECEI
Characterize error field, NTM and RWM poloidal and toroidal mode structure	Magnetics (first wall) High precision core current profile measurement	Additional magnetics coverage (3D) Phase 2 Additional MSE chords (core)

- **Second ECE radiometer.** This consists in reversing the laser beam direction (thus enhancing the scattering angle sensitivity at higher electron temperature and to enlarge the collection optics for these chords (U. Texas).
- **Oblique ECE.** A 16-channel radiometer (ECE) will be first installed using one of the ECH waveguide/transmission line. A switch inserted in the transmission line allows the choice between ECE measurements or heating (PPPL).
- **Additional magnetics coverage (3D) Phase 2.** The installation of the new internal 3D coils will require the further addition of internal magnetic probes (both poloidal and radial), which will potentially reach n=6 resolution and high poloidal number m.
- **MSE.** Section 6.1.1.

6.1.4. Understand Disruption Physics and Mitigation Effectiveness

It is well understood that for high performance burning devices, such as ITER and eventually the DEMOnstration power plant (DEMO), disruptions need to be avoided, and in the last resort mitigated. Because of the unique characteristics of disruptions and the associated mitigating technique, their study requires dedicated diagnostics, which encompasses very fast time scales, localized interaction, and difficult environmental conditions. A focus of the DIII-D research plan (Section 2.4) includes the understanding of the electron runaway generation and its mitigation through massive gas injection and pellet injection. The proposed additional and/or upgraded capability is described in Table 6-5 (options shown in *italics*).

Table 6-5
Disruption Measurement Needs

Scientific Objective	Physics Measurement	Proposed Diagnostic Technique
Characterize runaway formation	Current channel width, energy of runaways	HXR spectrometer, survey spectrometer, *additional IR camera* view, *EUV camera*
Characterize magnetic structure	Halo currents	*Increased tile current monitor and halo sensor coverage*
Understand mitigation relationship with plasma	Measure ion temperature during quenches	Low temperature core CER
	Measure electron temperature during quenches	*Dedicated Thomson chord/channel, spectroscopy*
	Neutral and low state emission	Poloidal visible bremsstrahlung array (fan), fast imaging, survey spectrometer, *EUV camera*

- **HXR spectrometer.** The first technique to measure the spectrum of emitted hard x-rays (HXRs) will rely on shielded Bismuth Germanium Oxide (BGO) detectors (UCSD). Additional spectrometers will be fielded around the tokamak to measure the anisotropy in runaway dynamics. Other techniques (Germanium, diodes, etc.) will be tested, and will yield different regions of the x-ray spectrum, up to gamma energies.
- **Survey spectrometer.** A survey spectrometer (visible) (UCSD) is being fielded to quantify the assimilation of impurity during mitigation. The spectrometer will be located with the same field of view than the fast framing tangential camera in order to unfold some of the radiation patterns and impurity state levels.
- **Low temperature core ion and electron measurements.** During disruption mitigation the ion temperature is reaching very low levels, therefore temperatures can be difficult to measure with the standard core CER. Various modifications will be made to the CER system (different slits, additional filters, …) to reach those levels. Similar attempts will be made to the Thomson scattering system, although initial attempts have not been very successful due to high background levels.
- **Poloidal visible bremsstrahlung array (fan).** The assimilation of neutrals (deuterium and impurities) can be best measured with an array of fast detector that can view the emission through a poloidal fan of detectors (ORNL). The front end of the system will be similar to a Thomson scattering collection optics design, whereas the back-end will be based on the filterscope design. Figure 6-3 shows a visible view of these emission with a tangential view together with a pre-conceptual design of the collection optics.

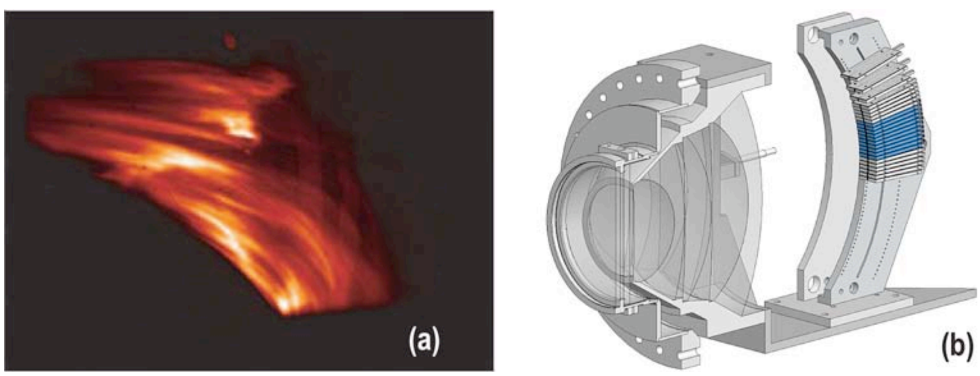

Fig. 6-3. (a) Tangential view of continuum emission during shattered pellet injection. (b) Pre-conceptual design of the collection optics for the proposed poloidally viewing fan.

6.2. BURNING PLASMA SCIENCE RESEARCH

6.2.1. Develop Predictive Turbulent Transport Models

In the last few years, significant progress has been obtained in the study of the different roles of the turbulent mechanisms in heat transport [ion temperature gradient (ITG), trapped electron mode (TEM), electron temperature gradient (ETG), etc.]. This progress is also helping to guide the selection of the next generation of key measurements. These key elements are the basis for scientific understanding and model validation (Section 3.2), which will be required for an optimized utilization and operation of devices such as ITER. In particular, a renewed focus is being developed for the study of particle transport, a natural complement to heat and momentum transport studies already well underway. The proposed additional and/or upgraded capability is described in Table 6-6 (options shown in *italics*).

Table 6-6
Core Transport Measurement Needs

Scientific Objective	Physics Measurement	Proposed Diagnostic Technique
Understand role of turbulence	High-k density turbulence	Upgraded PCI
	Turbulent flux	Polarimeter, *High resolution BES, 2nd ECEI*, MIR
	Magnetic fluctuations	Polarimeter, cross-polarization scattering (CPS)
	Ion temperature and velocity fluctuations	*UF-CHERS upgrade*
Understand evolution and role of rotation	Main ion temperature and velocity (core and edge)	Increased D_α CER coverage

- **Upgraded PCI.** The Phase Contrast Interferometer (MIT) measures density fluctuations near the core of the plasma. Additional views will be implemented to increase the radial coverage and k range to be probed.
- **Polarimeter.** The equilibrium and fluctuating magnetic field structure will be probed using multiple polarimeter chords (UCLA), all within the poloidal plane. A 3-wave FIR laser operating at 694 GHz will be used. First chord will be located at the midplane (radial chord), followed by vertical chords.
- **Cross-polarization scattering.** This internal magnetic field fluctuation diagnostic (UCLA) is based on cross-polarization scattering (CPS) technique, a process where magnetic fluctuations scatter EM radiation into the perpendicular polarization. The proposed system advances the CPS technique by taking advantage of the Doppler backscattering technique for the probe beam sharing the same access port.
- **Increased D_α CER coverage.** Section 6.2.3.

6.2.2. Unravel L-H Transition Mechanism

A renewed effort is being undertaken to fully diagnose and understand the mechanisms leading to a L-mode to H-mode (L-H) transition. This is particularly timely as qualifications of early systems development for ITER is critical (see Section 3.3 for details). These studies encompass also the back transition (L-H) which present additional concerns for ITER. Many edge/pedestal measurements have been commissioned for this purpose in the last five years. The present needs are identified in Table 6-7 (options shown in *italics*).

Table 6-7
L-H Transition Studies Measurement Needs

Scientific Objective	Physics Measurement	Proposed Diagnostic Technique
Understand role of rotation and shear	Measure turbulent rotation Main ion temperature and velocity (core and edge)	Second DBS system (different poloidal location) Upgraded main ion (D_α) CER
Understand role of edge radial electric field	Radial electric field	Upgraded edge CER (carbon)

- **Upgraded main ion CER.** Section 6.2.3.
- **Upgraded edge CER (carbon).** The number of chords in the edge CER system will be roughly doubled, improving the spatial resolution in the pedestal for the radial electric field measurement.

6.2.3. Explain Plasma Rotation Make-Up and Evolution

The study of plasma rotation has long been a hallmark of the DIII-D program (Section 3.4). Recent progress has benefited from the additional measurement capability across the plasma profile. A few key additions are envisioned and are described in Table 6-8 (options shown in *italics*).

Table 6-8
Plasma Rotation Measurement Needs

Scientific Objective	Physics Measurement	Proposed Diagnostic Technique
Understand evolution and role of rotation	Main ion temperature and velocity (core and edge)	Upgraded main ion (D_α) CER
	Impurity ion temperature and velocity without torque injection	*X-ray crystal spectrometers (XCSs)*

- **Upgraded main ion CER.** The CER system has been recently upgraded to measure the deuterium velocity and temperature through the full analysis of the excited D_α line. The system will be expanded from 8 to 16 chords from the core towards the SOL, using existing CER access ports, sharing views with the carbon-based system.

6.2.4. Understand Energetic Particles Physics

It has long been recognized that energetic particles bring new challenges (and opportunities) in reaching the needed conditions for a burning plasma. The confinement of these particles is particularly important and their impact on plasma instabilities, such as Alfvén instabilities is very critical. At DIII-D, a renewed effort (see details in Section 3.1) has been applied to the study of energetic particles in the last recent years. That development has been possible with the capability enabled by new and upgraded diagnostics such as the fast interferometer, scattering, ECE, beam emission spectroscopy (BES), fast-ion D-alpha (FIDA), fast ion loss detectors (FILDs) and more recently by the electron cyclotron emission imaging (ECEI). This comprehensive set of measurements has led to many breakthroughs and a few targeted additions in diagnosis capability are described in Table 6-9 (options shown in *italics*).

Table 6-9
Energetic Particles Measurement Needs

Scientific Objective	Physics Measurement	Proposed Diagnostic Technique
Understand mode structure	Measure toroidal mode number	Second ECE radiometer, upgraded PCI
	Measure radial mode structure	*High resolution BES array*
	Measure mode polarization	*Two-axis magnetic probes (wall)*
Understand interaction of mode with fast ions	Measure confined fast ion population (profile)	Imaging neutral particle analyzer (INPA)
	Measure loss of fast particles	Additional fast ion loss detector (FILD-3)

- **Second ECE radiometer.** A second radiometer (radial profile) will be used to identify the toroidal mode number (n) of the Alfvén modes. This system would take advantage of the direct equatorial access provided for the ECE Michelson interferometer (U. Maryland and U. Texas) which is located nearly 180 deg away toroidally from the primary radiometer (U. Texas).
- **Upgraded PCI.** The phase contrast interferometer (PCI) measures density fluctuations near the core of the plasma using 32 radially displaced chords, in a vertical view. The system will be rotated 90 deg therefore allowing the measurement of the toroidal structure of Alfvén modes.
- **INPA.** The Imaging neutral particle analyzer is a magnetic spectrometer, scintillator-based neutral particle analyzer. Escaping fast neutrals are ionized by a foil then ion gyro motion causes them to strike scintillator which is captured by a viewing camera. Images of scintillator provide energy resolved radial fast ion profiles. The system will be installed at port 105R+1 which has an optimal view of the fast ion phase space, which is intercepted by the 150 NB.
- **FILD-3.** The array of fast ion loss detectors will be augmented by adding a third detector, to be located above the equatorial midplane (Fig. 6-4). The detector will use the same scheme where escaping fast ions are dispersed onto a scintillator according to their pitch-angle and energy (gyroradius). The system will be oriented to perform in a reverse B_T and reverse I_p configuration, a configuration not covered by the existing two systems.

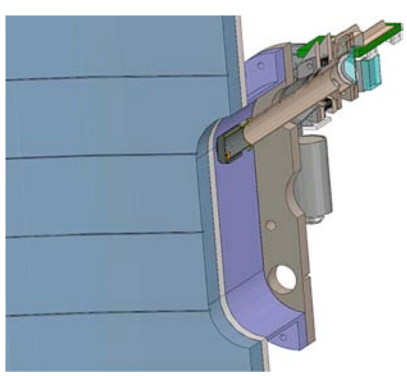

Fig. 6-4. Conceptual design of the third fast ion loss detector, to be located above the midplane with aperture facing upwards. The system will be used in reverse B_T operation.

6.3. BOUNDARY AND PEDESTAL PHYSICS RESEARCH

6.3.1. Uncover Physical Mechanisms of Pedestal Structure

One of the largest levers in expected performance in burning plasma experiments (BPXs) such as ITER is based on the size (height and width) of the edge pedestal. This region of the plasma represents a significant challenge for modeling, theory and measurements, because it is relatively small in scale (a few centimeters), exhibits large gradients and very fast events [e.g., edge localized modes (ELMs)], and is not necessarily poloidally and/or toroidally symmetric. It is clear that core confinement of H-mode discharges is strongly influenced by the boundary conditions set by the pedestal values of pressure or temperature; it is necessary to develop a scientific understanding of how fluxes of heat, particles and momentum control the pedestal structure. Three main themes will require new measurements; the study of fueling (neutrals) and the dynamics and evolution of ELMs, including the dynamics associated with their mitigation through resonant magnetic perturbation (RMP). The proposed additional and/or upgraded capability is described in Table 6-10 (options shown in *italics*).

Table 6-10
Pedestal Measurement Needs

Scientific Objective	Physics Measurement	Proposed Diagnostic Technique
Characterize edge stability	High resolution edge current	Upgraded lithium beam, *upgraded edge MSE, mode conversion reflectometry*
Understand role of fueling	Ion flux to wall 2D neutral population Ion dynamics (T_i)	Increased poloidal coverage (fixed Langmuir probe) LIF, high resolution visible imaging Upgraded main ion CER
Understand role of rotation	Ion dynamics (v_i)	Upgraded main ion CER
Characterize role of edge radial electric field	Radial electric field	Upgraded edge CER (carbon)
Characterize edge turbulence	Measure turbulent flux	*High resolution BES*, probes, gas puff imaging (GPI), *HNBP*

- **Upgraded lithium beam.** The performance of the system will be enhanced by improving the filtering of the polarized lines. In addition, new and more sensitive detectors will be progressively added. Fiber optics will be replaced to improve the radial resolution. Additional background subtraction will be added. The improvements will increase its signal-to-noise ratio (SNR), allowing better time resolution and sensitivity.
- **Increased poloidal coverage (fixed Langmuir probe).** We are planning to add a series of additional fixed probes on both centerpost (near the equatorial midplane) and outer wall. The design will be based on the existing design (SNL).
- **Laser-Induced Fluorescence (LIF).** A two-photon fluorescence scheme is proposed to measure the local neutral deuterium density. The two photon beams will enter the lower divertor through a vertical port, and the emission captured by collection optics sharing the same lower vertical port. The system has shown to perform well in the laboratory (WVU) and is ready to be integrated through the lower divertor.
- **Upgraded edge CER (carbon).** Section 6.2.2.

6.3.2. Validate ELM Control Techniques and Advance 3D Physics Research

The development of ELM control solutions for ITER and next step devices is a critical element of DIII-D research and has spanned many techniques, which require dedicated diagnostics. This line of research line also encompasses the details of 3D structures and their effects on plasma behavior, especially at/near the edge, including at the plasma wall boundary. In addition, stochastic/ergodic edges produced by non-axisymmetric fields introduce explicit 3D geometry and added complexity. These measurements are particularly difficult as deviations from axisymmetric conditions are expected to be small and localized. Dedicated upgrades in measurement capability for these variations are shown in Table 6-11 (options shown in *italics*).

Table 6-11
ELM Control and 3D Physics Measurement Needs

Scientific Objective	Physics Measurement	Proposed Diagnostic Technique
Characterize RMP effects	Field structure at edge (islands?)	Second ECE radiometer, B dot probe, *Hall probe*, polarimeter, *second Xpt soft x-ray (SXR) camera, additional reflectometer*
Characterize ELM structure	Mode structure ELM dynamics	3D magnetics, Phase 2, *second Xpt SXR camera* *Fast reflectometer*

- **Second ECE radiometer.** A second radiometer (radial profile) would readily yield the non-axisymmetric components of the plasma response to internal or external field perturbations. This system would take advantage of the direct equatorial access provided for the ECE Michelson interferometer (U. Maryland and U. Texas) which is located nearly 180 deg away toroidally from the primary radiometer (U. Texas).
- **B dot probe.** A new, simple probe head will be designed, which will incorporate a miniature magnetic pick-up loop. That loop will measure local magnetic field intensity and direction. It will be installed on the midplane scanning probe (UCSD). Other types of magnetic pick-up sensors will also be evaluated and/or tested.

6.3.3. Expand Understanding of Boundary Physics

Arguably, the next frontier in magnetically confined plasmas resides in the development of a scientific and technological solution to the challenges encountered in the boundary of a magnetically confined plasma, and especially in the case of burning plasma devices. The boundary layer encompasses vastly different conditions over a small physical scale. Temperatures of the order of kilo-electron-volts and high densities are found very near inside the last closed flux surface (e.g., pedestal), whereas much lower temperatures are encountered at the plasma-wall interface. This wide contrast and the presence of severe background issues depict the challenge encountered in diagnosing this region of the plasma. Several underlying physical issues complicate our attempt in understanding boundary physics. Transport, MHD stability and atomic physics all play a role in controlling the conditions encountered in that region. The boundary physics has a strong two-dimensional character due to various poloidal asymmetries and the presence of an X-point, and strong variations are encountered in the radial direction from the inner edge of the pedestal out to the limiting surfaces. The interaction of the hot plasma with the first wall material and the impact of any eroded material on the plasma core are important and relevant issues for understanding boundary physics. The proposed additional and/or upgraded capability is described in Table 6-12 (options shown in *italics*).

Table 6-12
Boundary Physics Measurement Needs

Scientific Objective	Physics Measurement	Proposed Diagnostic Technique
Understand particle transport in SOL	Flow velocities Particle deposition and composition SOL electron temperature and density	Spectroscopy (coherence imaging) Quartz micro-balance (QMB) Helium emission line ratio (GPI)
Understand and control heat flux to divertor plates	Ion heat transport	Retarding field analyzer, upgraded main ion CER, coherence imaging, increased fixed Langmuir probe coverage, divertor bolometers, *lithium beam ion CER*
Characterize edge turbulence	Density, electric field fluctuations	GPI, *HNBP*

- **Coherence Imaging.** Spectrographic information of emitted line radiation (e.g., carbon) can be stored through interferogram techniques directly onto a camera (video) image. Line shifts will give the local flow speed, and its width the local ion temperature. This technique is applied to both upper and lower divertor through tangential views. This technique was developed by J. Howard, at the Australian National University (ANU) [Howard 2010] and fielded at DIII-D through ANU/LLNL collaboration.
- **Retarding field analyzer.** A simple technique where the ion distribution function is locally probed using a series of biased grids. The first unit is planned for the lower divertor.
- **QMB.** The quartz micro-balance consists of two thin quartz crystals (one exposed, one reference) which are vibrated at high frequency. The observed frequency is mass dependent and relay in-situ the amount of deposited material onto the exposed crystal. Both operation within DiMES and installed by the lower divertor (behind protective tiles) are planned. Other details can be found in Section 4.5.4.3.
- **Helium emission line ratio (GPI).** The injection of small amount of helium through a set of nozzles will enable the local measurement of electron temperature and density based on the ratio of two (or more) known emission lines. First measurements will be done near the outer midplane. The measurements will be performed using filterscope-type of views (ORNL) and using a camera, which will yield 2D coverage. Local turbulence measurements will also be available with the camera view (UCSD).
- **Upgraded Main Ion CER.** The CER system has been recently upgraded to measure the deuterium velocity and temperature through the full analysis of the excited D_α line. The system will be expanded from 8 to 16 chords from the core towards the SOL, using existing CER access ports, sharing views with the carbon-based system.
- **Increased poloidal coverage (fixed Langmuir probe).** We are planning to add a series of fixed Langmuir probes on both centerpost (near the equatorial midplane) and outer wall. The design will be based on the existing design (SNL).

6.3.4. Strengthen Plasma Material Interface Research

A remaining challenge for burning plasma experiments [e.g., ITER, Fusion Nuclear Science Facility (FNSF), DEMO] is the development of a fully integrated and compatible plasma-material solution. The interaction of plasmas and first wall material requires a set of dedicated diagnostics, both from the point of view of plasma conditions, but also in situ characterization of the wall components (tiles, divertors, etc.). The diagnosis of these conditions also requires additional facility capability for handling, access and modifying local conditions. These needs are summarized in Table 6-13 (options shown in *italics*).

Table 6-13
Plasma Material Interface Measurement Needs

Scientific Objective	Physics Measurement	Proposed Diagnostic Technique
Characterize surface conditions	In situ measurement deposition	AGNOSTIC, hot tile station (including tile remote handling, *smart tile)*, quartz microbalances (QMBs)
	Hydrogen retention	Hydrogen sensor, AGNOSTIC

- **AGNOSTIC.** The implementation of this system, designed at MIT, includes the installation of the mega-electron-volt ion-beam onto a lower port. The system allows an in-situ ion-beam analysis of the first wall material, based on nuclear reactions measured through emission of neutron and gamma radiation. Additional details can be found in Section 4.5.4.2.
- **Hot tile station.** This station includes the remote handling capability (Fig. 6-5) of changing in-situ tile or first wall elements. This would enable hot tile operations and associated instrumentation and control. Additional details can be found in Section 4.5.4.1.
- **QMB.** The quartz micro-balance consists of two thin quartz crystals (one exposed, one reference) which are vibrated at high frequency. The observed frequency is mass dependent and relay in-situ the amount of deposited material onto the exposed crystal. Both operation within DiMES and installed by the lower divertor (behind protective tiles) are planned. Other details can be found in Section 4.5.4.3.
- **Hydrogen sensor.** Following recent successful testing onto DiMES, the sensor would be added to an access point located within the lower divertor. Additional details are found in Section 4.5.4.4.

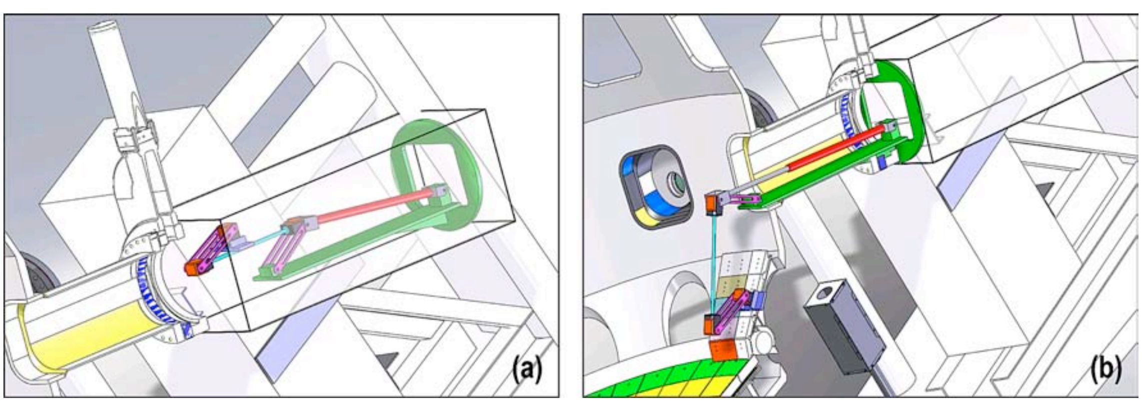

Fig. 6-5. Conceptual design of the remote handling system for hot tile in-isitu operation and diagnosis. The views show retracted (a) and deployed (b) positions.

6.4. INTEGRATE DEVELOPMENT OF DIAGNOSTICS FOR BURNING PLASMA EXPERIMENTS (BPX)

Diagnostic development for a burning plasma experiment (ITER, FNSF, DEMO, etc.) is also sorely needed. In a BPX, the application of standard techniques and the fielding of specialized diagnostics are facing challenges including environmental issues (e.g., radiation), access, long pulse, etc. Additional measurement requirements (e.g., alpha particles) are particularly difficult to meet. The development of these new or alternate techniques presently lack testing capability in an existing tokamak. The development of burning plasma diagnostics and related technology requires a coordinated effort with the U.S. Burning Plasma Organization (USBPO), U.S. ITER Project Office (USIPO), the International Tokamak Physics Activities (ITPA) and the ITER Organization (IO).

Specifically, these activities aim to address the following questions/issues:

- The development of a new technique where needed.
- The test of a new technique in a large tokamak with relevant parameters.
- Development of alternative technique for problematic measurements.
- Complete test of control techniques (reliability, versatility).
- Continue study of erosion and deposition (for eventual input to diagnostic design, e.g., first mirrors).
- Continue evaluation of measurement requirements for a BPX, in regard to profile, divertor and/or control-associated needs.

We anticipate that in the time frame covered by this proposal, a series of prototypes will be fielded on DIII-D to test proposed designs for the U.S.-procured systems to ITER. That list includes the tangential interferometer and polarimeter (TIP), ECE, MSE, viewing systems [infrared (IR) and visible], reflectometer and possibly x-ray crystal spectrometers (XCS).

In addition, we propose to develop alternate techniques that may be required for ITER and/or other BPX, including but not limited to FNSF and DEMO.

They include such techniques as:

- Demonstration of fast-Alfvén reflectometry for isotope mix ratio measurement.
- CER- and microwave-based measurements for q profile reconstruction.
- CER-based measurement of fast ion population.
- New soft x-ray (SXR) concepts.
- New concepts in polarimetry and interferometry.
- Fizeau effect interferometer for electron velocity diagnostic.

6.5. SPECIFIC DIAGNOSTIC REFURBISHMENTS

While periodic maintenance on diagnostic systems aims at ensuring their reliability, the refurbishment and/or modernization of many systems is often a necessary step for the long-term health of DIII-D’s capability. In those cases, maintenance is prohibitive or impossible, due to the availability of parts (detectors, electronics, etc.). In the last five-year period, Thomson scattering, CER, filterscopes, and magnetics systems have undergone significant modernization efforts. The electronics, data acquisition, and laser systems for the Thomson scattering diagnostics have been redesigned, rebuilt and commissioned. Next step includes the replacement of all key optical components (lens assembly and fiber optics) which have degraded over the years due to radiation levels present near the tokamak (browning). Other planned refurbishments include the gradual replacement of the CER cameras (~10), toroidal SXR system (3 cameras), and refurbishment of all neutron diagnostic electronics. In each case mentioned, the refurbishment has been accompanied by significant upgrades of their capability, in large part due to the advancement in technology over the last 20 years. The refurbishment of data acquisition systems is also planned and details can be found in Section 5.11.

6.6 REFERENCE FOR SECTION 6

[Howard 2010] J. Howard, J. Phys B **43**, 144010 (2010).

7. DATA ANALYSIS AND REMOTE PARTICIPATION

Providing an infrastructure that allows for the effective and efficient analysis of data is both critical and fundamental to the DIII-D scientific mission (Fig. 7-1). The term data analysis is used in the broadest sense and includes a body of methods that help to describe facts, detect patterns, develop explanations, and test hypotheses. In today's world, such an infrastructure by necessity consists of a broad range of Information Technology components and includes data management, scientific visualization, high performance computing, analysis algorithms, web technology, monitoring, software regression testing, and advanced collaborative environments. This analysis infrastructure is layered on top of the User Service Center environment described in Section 5. For DIII-D, data analysis needs to be accomplished on two time-scales (real-time computing is considered in Section 5), each having unique challenges. The faster time scale is the ~20 minute pulse cycle where data analysis is critical for informing effective decision making during an experiment [Schissel 2010]. The longer time scale are the periods prior to and after the experiment; this data analysis is critical to developing an effective experimental plan, post-experimental understanding, and subsequent publication of results.

Substantial progress was made in the previous five years to support the ever-expanding data analysis needs of the DIII-D National Team. One measure of this overall expansion is the exponential growth of the analyzed data repository that more than quadrupled during this period compared to a doubling in the previous period. A distributed MDSplus installation is fundamental for analyzed data management and its performance continues to scale with increased size and increased usage; new hardware was put into service as required. Hardware and software updates to the associated metadata repository (used for rapid searching) were also made with the largest relational database now being 7.5 M rows and 5 GBs. Between pulse data analysis was enhanced through faster computation and greater reliability by upgrading numerous analysis codes, obtaining newer analysis clusters, and deploying a dedicated system for all single-processor codes. Data analysis was further supported through the design and production installation of the Venus computational cluster used for both interactive and batch analysis by the scientific staff. Data analysis on graphical processing units (GPUs) was also put into production for the first time resulting in ~55x reduction in computational time [Kalling 2011]. New visualization tools were created and deployed and IDL virtual licensing techniques were utilized allowing increased usage of tools with no increase in software licensing costs. Interactive HTML5-based graphics were deployed on the DIII-D web site allowing the web browser to be used for scientific visualization [Kim 2012]. In general, the usage of web technology greatly expanded this past period including the creation of the DIII-D experimental web portal [Abla 2010], the DIII-D blog, and the usage of a Wiki allowing scientists to directly author content related to the run campaign as well as many of the scientific topical research areas. Given the highly collaborative nature of the DIII-D program, remote participation continued to play a large role in daily activities. Most significantly, a remote control room was built on site that pushed technology associated with remote experimental participation [Schissel 2012].

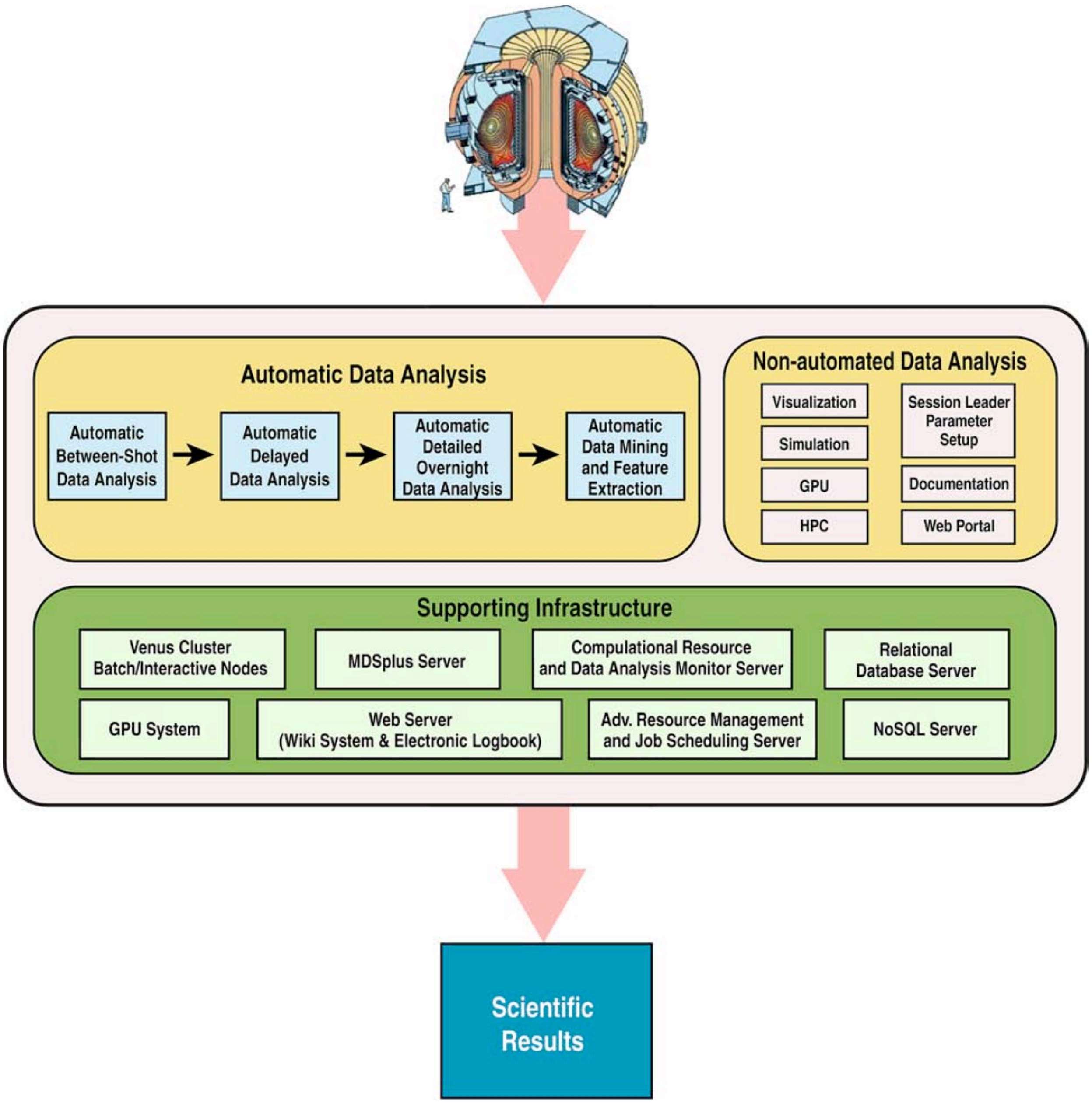

Fig. 7-1. DIII-D's scientific data analysis will be enhanced in the next five years through increasing the amount of automatic and interactive data analysis and by expanding the supporting infrastructure as required.

This section outlines six areas of work in computer science and enabling technologies to facilitate DIII-D's mission over the next five years. Table 7-1 summarizes some recent progress, challenges, and future plans in the areas of analysis software, between shot analysis, data storage, analysis infrastructure, web technology, and control room/remote participation. As always, the overarching goal is to allow faster, more secure, easier access to all analyzed data, data analysis codes, and visualization applications on a 24/7 basis, and the ability for more effective scientific communication amongst the distributed team members. Improvements to the DIII-D analysis infrastructure are aimed at making the DIII-D team more scientifically productive. The desire to more fully understand the plasma's 3D behavior (e.g., advanced 3D coil set) will require modifications to existing visualization applications since the vast majority of existing data visualization on DIII-D is 2D. With the exponential growth of DIII-D's data, new capabilities will be deployed to track data provenance (e.g., data lineage) as well as to perform more advanced data mining. The ability to compare and contrast old data with new data is critical to DIII-D's scientific mission. The concept of between shot processing will be expanded to include same run-day processing. An entirely new infrastructure will be deployed to support this capability thereby greatly enhancing the data that is available in the control room for the scientific staff. Data storage will continue to be expanded as it has in the past but the large addition will be the ability to support the scientific push to understand the plasma's 3D characteristics. Data and metadata associated with the advanced 3D coil set, new diagnostics, and new analysis codes will need to be added and integrated into DIII-D's existing analysis infrastructure. To insure that the exponential growth in data does not slow down our ability to rapidly serve data to the scientific staff, novel memory-based data caching techniques will be investigated for both data (MDSplus) and metadata (relational database). DIII-D's data analysis infrastructure will be enhanced through the addition of automated analysis code regression testing and the expansion of the Venus cluster to support large batch analysis code runs including those requiring multi-processors. Web technology will be further integrated into DIII-D's analysis fabric through the addition of fully interactive graphics and the enhancement of support for mobile devices. As in the past, close attention will be paid to security as web sites continue to be a target for cyber attack. In DIII-D's control room, multi-touch displays will be investigated to enhance co-located data collaboration. For remote participation, a fully deployed science data DMZ will facilitate secure rapid data collaboration for our work with China's Experimental Advanced Superconducting Tokamak (EAST) and the Korean Superconducting Tokamak Advanced Reactor (KSTAR).

Table 7-1
Progress and Plans for Data Analysis

Recent Progress	Challenges	Plans
Analysis Software Improvements		
• Overnight data analysis • Virtual machine IDL tools • TRIP3D GPU code deployed • Analysis codes to 64-bit • Prototype python-based graphics tool	• Harder to mine old data given exponential data growth • Maintain integrated analysis environment • Maintain full data provenance • Support new 3D physics studies	• Improve algorithms for faster temporal transport analysis • Instrument workflows to track data provenance • 3D physics graphics tools • Expand data mining capability
Between Shot Data Analysis		
• Improved queuing system • Expanded MDSplus data analysis cycle duration • Expanded data analysis suite • Auto detection of L-H transition times	• More data and more complicated analysis but same shot cycle time • More analyzed data needed in the control room • More complicated data analysis environment	• Same run-day automated data analysis • Support new between shot analysis as required
Data Storage		
• Distributed MDSplus and expanded storage • Support of long-pulse MDSplus • Expanded SQL database usage	• Scalability-NAS vs. local disks • Exponential growth of data • Rapid data availability in an expanding environment • Support new 3D physics studies	• MDSplus memory caching • Enhance profile storage • Multi Snap-file EFIT storage • Expand MDSplus storage for new 3D physics studies • Faster SQL via NoSQL/SSD
Analysis Infrastructure		
• Expanded STAR to 72 cores • New SQL Server • Venus computational cluster • Nagios® monitoring system	• Increased analysis complexity • Monitoring/maintenance	• Auto code regression testing • Venus allowing MPI/batch • Upgrade STAR/MDSplus clusters as needed
Web Technology		
• Web based electronic log book • Web graphics in log book • Improved security • Experimental web portal • Supported/maintained ~500 users	• Web security • Interactive scientific visualization • Tools for mobile users • Difficult data discovery	• Fully interactive graphics • Expand mobile web site • Improve documentation via tutorials/podcasts • Improve layout and search • Expand auto-security scanning
Control Room and Remote Participation		
• Real-time EFIT on display wall • Upgraded DIII-D display wall • H.323 in control room • Deployed remote control room • Deployed tools to support remote EAST and KSTAR operations	• Expanded international remote collaboration and machine operation • Meeting attendance spread over many time zones • Remote participation robustness	• Support remote participation on laptops/tablets/phones • Deploy Science Data DMZ • Real-time display in remote control room • Multi-touch control room displays

7.1. ANALYSIS SOFTWARE IMPROVEMENTS

The continual improvements in diagnostics at DIII-D combined with advanced data analysis has resulted in a complete time history of kinetic profiles such as n_e, T_e, T_i, V_r, P_{rad}, and Z_{eff} along with a time-independent power balance available between shots. Looking forward the desire is to perform fully time-dependent power balance analysis (ONETWO) on a rapid time scale; faster than the next day as is done today. Key to this progress will be the ability to perform the neutral beam deposition and slowing down calculations on a much faster time scale. Recent advances in parallelizing this calculation will be investigated as well as usage of the GPU for massively parallel problems (Fig. 7-2). A hybrid solution of central processing unit (CPU) and GPU may allow for a dramatic decrease in computational time. The end goal is to put this capability into routine production usage.

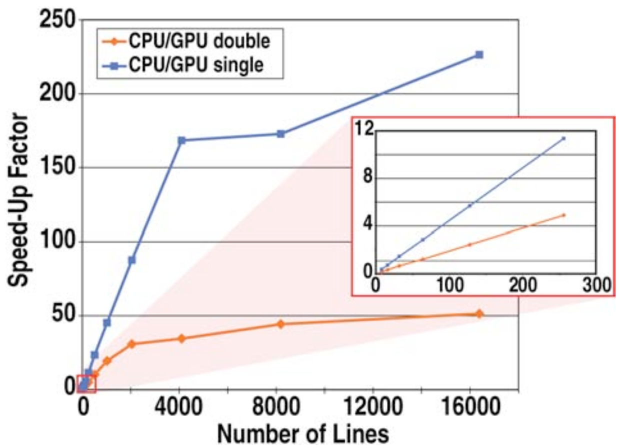

Fig. 7-2. The simulation of DIII-D's magnetic field lines is greatly accelerated by the usage of GPUs. The GPU surpasses the CPU computation ability at around 50 lines for double precision, 25 for single precision and continues getting faster relative to the CPU up through 16,000 lines, when the speedup factor begins to level out.

Visualization is an important component of the data analysis workflow and in the next five years existing core tools (e.g., ReviewPlus, EFITViewer) will be extended and new ones developed. During the previous five years the usage of the Python programming language by the scientific staff has increased substantially. Looking forward, previous work on a Python-based general visualization program will be extended into a production tool. The vision is that this tool will be built using a customized scientific graphics library (pan, zoom, crosshairs, slicing, etc.) similar to the way DIII-D's IDL tools have been built. By creating the tool in this manner not only is the general tool available for the scientific team but an easy to use graphics library is created that individual scientists can utilize to create customized visualization tools for their specific research needs. Completely new visualization capabilities will need to be deployed to support the new advanced 3D coil set, the new 3D magnetic diagnostics, and associated analysis codes [e.g., 3D kinetic EFIT]. The desire to understand the plasma's 3D structure is a central part of this proposal and is new for DIII-D and will thus require novel ways for scientists to visually digest the data. One area where visualization tools will be expanded is in the area of scatter plots derived from data stored in DIII-D's relational database (metadata). As the size of some of these databases has grown the existing tool no longer presents an interactive visualization. To speed up this interactive discovery, intelligent data decimation algorithms along with enhanced visualization techniques will be combined with improved storage (see below). Another area of enhancement is the visualization of time dependent plasma profiles. To meet this need, extensions will be made to the existing Python-based profile visualization tool.

With the quantity of data generated at DIII-D growing exponentially, it is becoming increasingly harder to mine old data to allow the semi-automatic discovery of knowledge in the form of patterns, changes, associations, anomalies, rules, and statistically significant structures and events. Work in the past five years on automatic detection of the L-H transition times has shown the promise of such automated techniques [Farias 2012]. This new capability has the potential to broaden data retrieval beyond shot-based to feature-based extraction. Additionally, anomaly detection can be possible where a scientist looks for a feature that is unique or unexpected. Where beneficial, such advanced mining capabilities will be implemented into production usage.

Fundamentally, data analysis transforms a piece of data into a new piece of data. Data provenance is defined as keeping track of a data's lineage. In concrete terms, any calibrations applied, any algorithms used to transform data, and input control parameters for those algorithms are all metadata needed to track data provenance. During the next five years an infrastructure will be put into place that allows better tracking of data provenance through the instrumentation of our scientific workflows (e.g., a Python script or MDSplus events and dispatching). The goal is to start on simple workflows (e.g., between shot EFIT) and expand to more complex (ONETWO runs). Tracking data provenance has the benefit of understanding a data's reliability and quality (e.g., automated analysis with no human examination) and also allowing for its reproducibility. It also always for rapid understanding of when an analysis change requires dataset recomputation.

However, by implementing such an infrastructure, it affords the DIII-D facility the added benefit of having an historical record of all workflows and therefore an easy methodology to understand what analysis has been done on any particular shot. As the team grows in size and is more geographically dispersed, this will be an excellent way for results to be shared thereby eliminating unnecessary duplication of analysis.

As new analysis capability is deployed, care will be taken to not create a series of new independent systems. A lack of interoperability has the potential to raise the barrier of adoption and can increase the time for a new team member to become productive. Therefore, concurrent with the efforts outlined in this section will be a thrust to consolidate tools and capabilities wherever possible.

7.2. BETWEEN-SHOT ANALYSIS

Between-shot data processing is a critical component of DIII-D's operation since decisions for changes to the next pulse are informed by this data analysis. The dedicated 72-core STAR computational cluster is filled to capacity to satisfy the automated between shot data analysis requirements (Fig. 7-3). If we examine the evolution of such data analysis at DIII-D, what was done previously overnight or the next day is today done between shots. This historical trend is mostly the result of Moore's Law but has also benefited from improved computational algorithms. Thus, looking towards the future, analysis codes that do not run between shots but use as inputs data that is calculated between shots, are prime candidates to try to move into the between shot cycle. There are numerous candidates for consideration that include kinetic EFITs, TGLF, and time dependent ONETWO runs. Those deemed appropriate will be deployed along with the required software infrastructure.

It is possible that some of the desired codes will not fit into the shot cycle time. However, their completion, and thus their data availability several shots later is still of greater value than waiting until the next day. The software infrastructure to support such delayed analysis was previously extended to only support analysis that was one shot behind. This infrastructure including monitoring will be extended to support a more general implementation allowing longer running analysis (e.g., hours) to be run during an experimental day.

Since the existing STAR hardware is filled to capacity, additional computational nodes will need to be purchased to allow greater computation during the run day. Additionally, the present STAR cluster is composed of nodes of varying age. Those that have reached end-of-life, will need to be replaced.

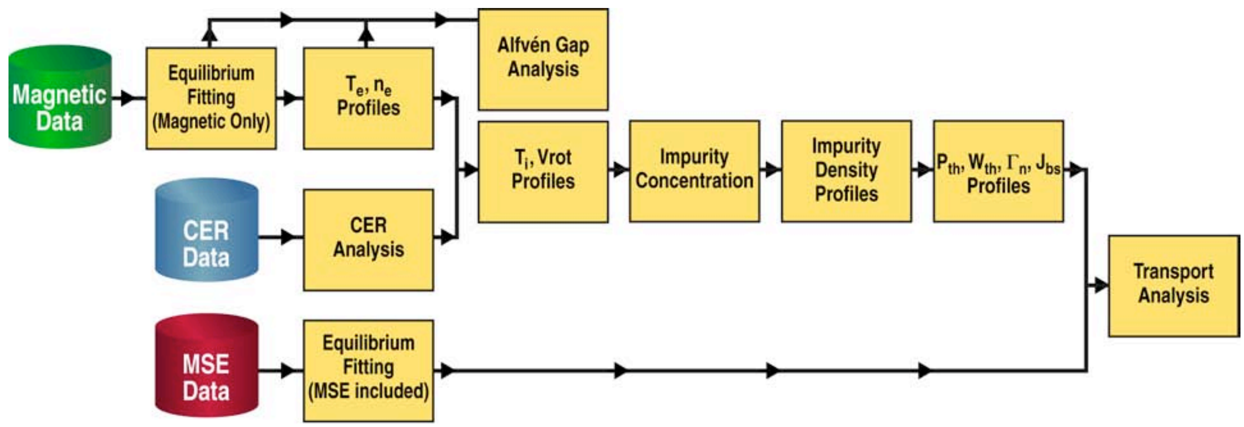

Fig. 7-3. The amount of data analyzed between shots has grown dramatically with the deployment of the 72-core STAR computational cluster. Today at 20 ms intervals, a complete set of profiles and time-independent power balance analysis is performed for each DIII-D plasma. This cluster will be used for additional between-shot processing as well as more detailed overnight processing over the next five years.

7.3. DATA STORAGE

The secure and efficient worldwide distribution of analyzed data is critical to the success of the DIII-D mission. To facilitate data distribution, DIII-D adopted in 1997 the MDSplus data system to organize, under one common client/server interface, the storage of analyzed data. Working in concert with MDSplus is a relational database that stores highlights (metadata) of the MDSplus repository. The metadata catalogue is used by the scientific staff to rapidly search through the data highlights to find the subset of pulses that have special interest. Both systems have proven their ability to meet requirements, to scale with increased storage, and to accommodate a larger user community. Therefore, both of these data systems will continue to be the vehicle for analyzed data distribution.

During the previous five years, DIII-D's MDSplus system was transitioned to a fully distributed installation. The advantage from a computer infrastructure standpoint is that additions to the system are easy and rapid and these incremental improvements are low cost compared to replacing the entire system. Capacity upgrades during the previous period confirmed this advantage. However, the methodology was to deploy a computer server integrated with storage when upgrading storage capacity. In some instances a new computer server is not required and thus scalable storage with non-local disks will be investigated. Specifically, utilizing DIII-D's existing large network-attached storage (NAS) system with an incremental storage upgrade may be an even more cost effective approach in some instances. A detailed investigation of this approach will be taken including quantitative performance analysis (retrieving analyzed data). The goal is to provide the most cost effect storage for DIII-D that meets requirements. With the exponential growth in the amount of DIII-D's analyzed data (Fig. 7-4), this is a critical area for investigation of cost containment. The vast majority of this growth is fueled by changes to diagnostics either through existing systems that expand their data acquisition capability (e.g., faster digitizers, more memory, more channels) or new diagnostics installed onto DIII-D.

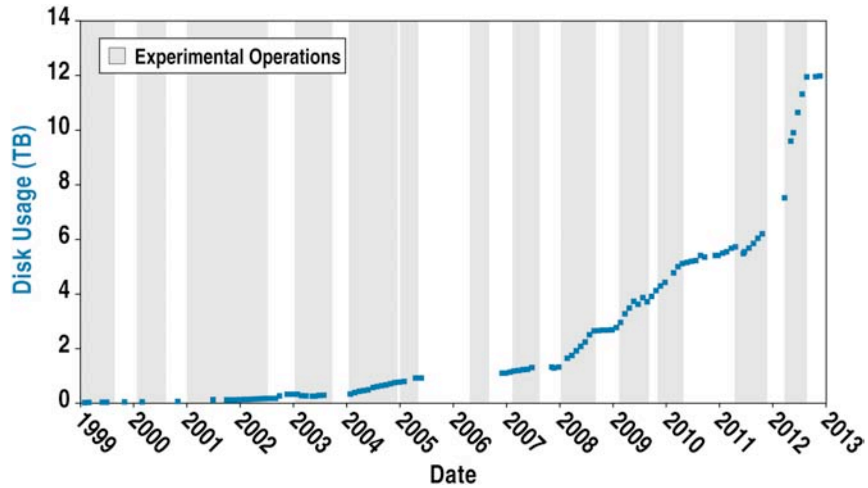

Fig. 7-4. The amount of analyzed data stored in MDSplus versus time. The rapid increase is due to diagnostics increasing their data acquisition capability and by the addition of new diagnostics to DIII-D.

New datasets are continually being added to the MDSplus data repository and the associated relational database. Such activity will of course continue and assistance will be provided as required to the scientific staff. The line of research in this proposal centered on an advanced 3D coil set and associated new diagnostics [e.g., fast ion loss detectors (FILD)] will allow detailed examination of the plasma's 3D structure. However, the successful completion of this line of research will require substantial additions to DIII-D's data storage capability including the ability to store 3D kinetic EFIT as well as data from new diagnostics and associated analysis codes. In addition to the diagnostic additions, work will continue on enhanced profile storage as well as time dependent data analysis storage with greater input flexibility (e.g., EFIT analysis with varying input files).

During operations, just after a pulse, the load on the MDSplus servers is severe because the number of clients (automatic analysis and interactive scientists) simultaneously connecting is large. To alleviate this load in random access memory (RAM) data caching will be investigated (Fig. 7-5). The concept is that data desired by a large number of clients (e.g., EFIT results) will be fetched once from MDSplus and then stored in a RAM-based data cache. Subsequent requests for this data will not go to MDSplus but to do the RAM data cache. Since reading data from RAM is ~1000 faster than from disk, where MDSplus data is stored, this will be very efficient and also help to alleviate the load on the MDSplus server. Taken to the extreme one could store all MDSplus data in RAM but this would be cost prohibitive. The goal of this work is to find an automated mechanism to accomplish the RAM storage and to understand how much of this storage is required to positively impact DIII-D's operation.

During the previous five-year period the usage of NoSQL (not only structured query language) databases has expanded within the computer industry. These are a broad class of database management systems that do not adhere to the relational database model (e.g., used by DIII-D's metadata catalogue described above) and are typically optimized for retrieve and append operations. During that same period there has been an increase in the usage of DIII-D's relational database with one table growing to 7.5 M records and 5 GB. At that size, with present hardware, queries can take several minutes to return a set of matching rows. Since a lot of these queries are not relational in nature (not joining tables together) they should naturally fit into the design of a NoSQL database that should have better performance. Additionally, if the NoSQL database is stored in RAM retrieval times can be fast enough to be considered truly interactive. With that speed, an interactive visualization application could be designed to visually examine these large repositories. Therefore a NoSQL solution will be explored; if its performance is beneficial, it will be deployed.

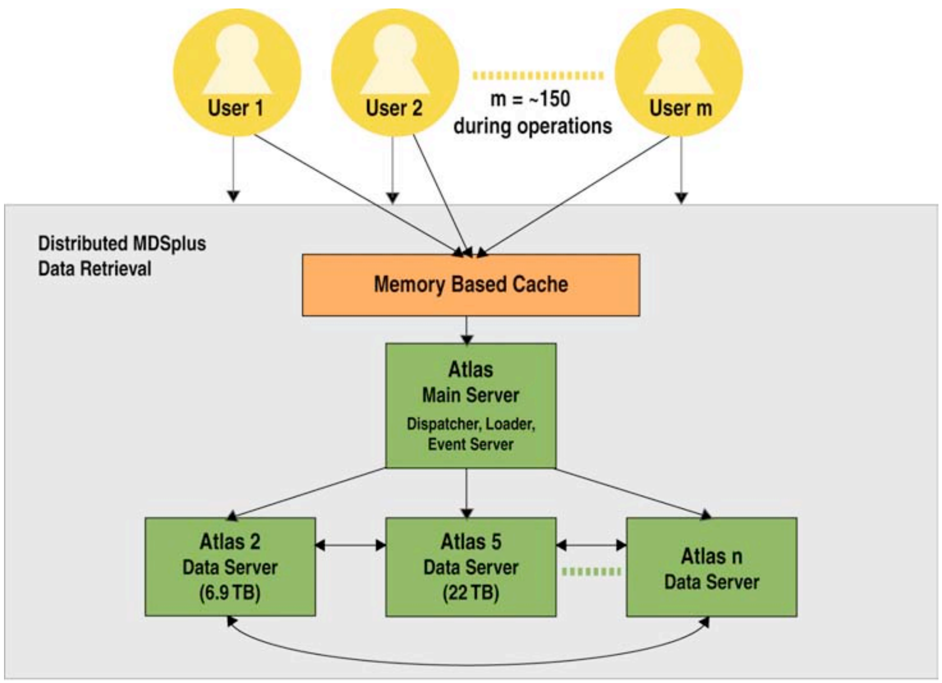

Fig. 7-5. Distributed MDSplus architecture allowed for continual exponential growth of the analyzed data repository. To alleviate high demand on the MDSplus system right after a shot's conclusion, an in-memory cache mechanism will be investigated for the most high demand data signals.

7.4. ANALYSIS INFRASTRUCTURE

DIII-D's data analysis infrastructure has grown over time to accommodate an increasingly diverse set of requirements. For example, as analysis codes have increased in number and their data interdependency has grown more complex, a methodology was required during tokamak operations to automatically start an action; e.g., to start a computer code when all of the input data is available. This was accomplished by deploying event and dispatching software that today controls over 100 computer codes to support between pulse data analysis. As complexity grows, monitoring must increasingly be done in an automated fashion. Building on previous work at DIII-D, the automatic monitoring of the entire data analysis infrastructure will be greatly expanded. The goal of this work is to allow rapid identification and resolution of infrastructure problems before they reach a critical stage. The vision is to use a browser-based dashboard to aggregate critical information into a unified view while also allowing a rapid drill down into greater detail. The types of monitored information can be quite diverse and include network services (e.g., HTTP), server host resources, and applications. This expanded monitoring will be done via DIII-D's existing Nagios® installation, an open source package design for infrastructure monitoring. One benefit of Nagios® is that it allows monitoring via remotely run scripts thereby allowing almost infinite customization that is critical for a very unique scientific research environment.

Another component of the data analysis infrastructure is the software codes that actually perform the analysis. To better monitor software quality a dedicated system for software regression testing will be deployed. For DIII-D, the intent of regression testing is to ensure that a code change has not introduced a fault that results in an incorrect answer. For very large codes, regression testing is an excellent method to determine whether a change in one part of the software affects other parts of the software and therefore the code's output. Previous work at DIII-D has shown that Nagios® can be used as the framework for this regression testing where deviations from code output from the known "truth" are reported as errors. The framework does not obviate the need for the physicist to decide the "truth" value and what amount of deviation is an error but it does provide an automated methodology to run the regression testing and report the results. Codes that already have manual regression testing will be easy to move into the framework. Authors of codes without such capability will be assisted as required.

During the previous period the Venus computational cluster was deployed mostly for interactive data analysis. However the need for batch computational resources including codes requiring a message passing interface (MPI) have put a strain on the Venus resource. As a result, the deployment of a companion batch computational cluster will be investigated and put into production. The aim is to have this driven from the existing Venus head node so as to give the DIII-D scientists one login node that allows both interactive and batch analysis. Modifications and enhancements to the existing Venus cluster will be investigated with the aim of decreasing response time and increasing overall data analysis efficiency.

As stated previously, the STAR computational cluster continues to be the main location for large between-pulse data analysis codes. This past period, the infrastructure for automated overnight analysis of long running codes on the days experimental data was put into production. Looking forward, the addition of new diagnostics as well as the desire to perform more time dependent calculations it is anticipated that the amount of codes run overnight will increase. Support will be given to this activity as required. The previously mentioned hardware additions to the STAR cluster will be sufficient to handle the increased overnight analysis load.

7.5. WEB TECHNOLOGY

Given the ubiquity of web browser clients on all operating systems and the typical ease of use, the usage of web technology at DIII-D has greatly increased (over 500 web access accounts) during the past five years. This usage has come in a variety of forms. Foremost, the adoption of the Wiki-based DIII-D web site has allowed the scientific team to be authors resulting in greatly increased content compared to funneling all changes through a single web master. Interactive graphics have also been introduced allowing rapid 2D visualizations of DIII-D data. Additionally, the Electronic logbook's web interface is commonly used during operations with over 200,000 entries now in the system. The DIII-D experimental web portal allows a customizable layout to remotely follow the day's experiment.

Looking forward, areas where client software can be transitioned away from custom installed applications to web-based systems will be examined. To facilitate this transition, the Protovis web graphics previously deployed (Fig. 7-6) will be upgraded to the current D3 library. This change along with enhanced data transmission protocol will allow larger datasets to be interactively visualized via the web browser. This will allow graphics to be added to many data pages (e.g., the experimental summary page) as well as a dedicated site for visualization. For remote participants, this can be an easier way to perform visualization work in comparison to logging into DIII-D computer systems or even locally installing visualization tools and associated libraries.

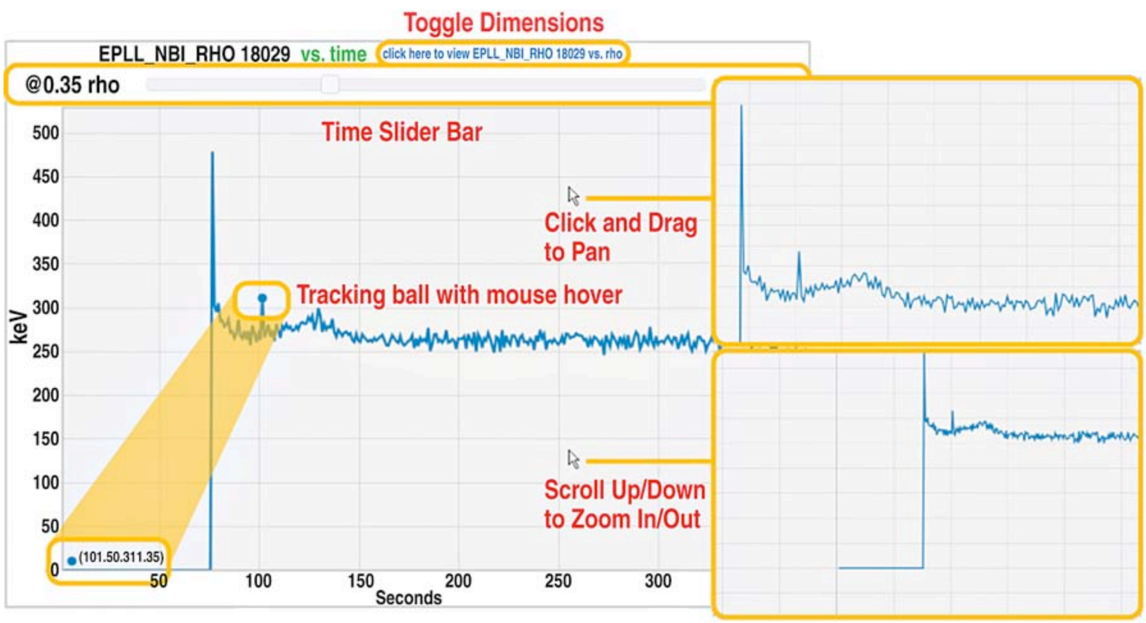

Fig. 7-6. Initial deployment of interactive (pan, zoom, slice, x/y value tracking, toggle dimensions) web-based graphics has proved valuable in a standalone fashion as well as when integrated with the electronic logbook. This deployment will be extended in the next five years by increasing the breadth of deployment as well as through functional upgrades.

The DIII-D experimental web portal will be upgraded to include real-time data displays that mirror what is done in the control room. Additionally the user interface will be enhanced to allow for greater customization. New capabilities will also be added to this site. In addition, the DIII-D mobile web site that was deployed in a beta form previously will be enhanced and upgraded to support more production usage. This site will be customized to smaller displays and slower networks yet will allow a scientist to monitor experimental operations.

The increase in complexity of data analysis requires a concurrent increase in both data and code documentation. It is envisioned that this documentation will include the traditional text form as well as tutorial-like videos. The later can take the form of a podcast that might be downloaded to a mobile device or just viewed directly in the web browser. This capability will be new for DIII-D yet it has been successfully used for on-line education and it should translate to simple information how-to for the scientific staff. Along with more documentation can come the difficulty in finding what is desired. Given the explosive growth of the DIII-D web site its design will be examined and, if required, a new layout will be deployed to enhance usability.

Looking forward, the need to continually upgrade software is anticipated not only for increased functionality but to maintain a high level of security. The public facing nature of the DIII-D web sites means that they are often targets for security breaches. As part of the overall DIII-D Cyber Security plan, these websites will be internally scanned on a regular basis to search for new vulnerabilities, and if found, they will be mitigated. Finally, as the dedicated hardware begins to reach end of life new systems will be put into production.

7.6. CONTROL ROOM AND REMOTE PARTICIPATION

During the previous five years, the fast majority of remote meetings and video/audio into the DIII-D control room were done using IP-based (H.323) videoconferencing. A new Polycom videoconferencing unit was deployed in the DIII-D control room to allow dedicated communication. Meeting rooms were upgraded as required and most of the videoconferencing usage relied on Energy Sciences Network's (ESnet) audio-video bridging service. Looking forward, the need to slowly upgrade this dedicated hardware is expected as existing systems reach end of life. Additionally, with the explosion of a variety of mobile devices, capability will be demonstrated to the scientific staff that allows them to join meetings and participate in discussions/experiments via tablets, phones, and laptops. As in the past, support will be provided in these areas to lower the burden for meeting participation.

Of course in a scientific setting like magnetic fusion research, remote participation is much more than just an audio-video connection. In the previous period, a new remote control room (RCR) was made operational near the offices of the DIII-D scientific staff (Fig. 7-7). Leveraging ideas used successfully in the DIII-D control room, new hardware and software techniques were deployed to allow for a more productive involvement in remote experimental operations. The RCR has been used for remote experimental participation with our EAST and KSTAR colleagues as well as being used directly in the DIII-D control room (about 2 miles away). For room communication the RCR is equipped with dedicated hardware for both H.323 and Skype communication. However, the real challenge in using this facility is the rapid access to experimental data (Fig. 7-8). If enough data is delayed, it is impossible for remote scientists to participate in the "scientific conversation" regarding what to do for the next shot. The focus on the next five years will be on techniques to reduce the wait-time for data. Leveraging ideas from ESnet on the Science DMZ, a similarly dedicated hardware system will be put in place that facilitates rapid data transfer over the wide area network (WAN). These techniques will be customized to our scientific workflow patterns and will include data pre-fetching and intelligent local data caching. Additionally, real-time-like displays will be introduced into the RCR to include plasma control data as well as plasma boundary information, similar to what is done in the DIII-D control room. Finally, general experimental monitoring will be enhanced through upgrades to the existing experimental web portals.

Toward the end of the present period, the original large display wall hardware (4:3 aspect ratio) was upgraded with higher resolution widescreen (16:9 aspect ratio) hardware. The change in aspect ratio and the increased total pixel count requires modification to the existing display software. This necessitated change will be taken advantage of to also increase the capability of the existing system. A unified design will be deployed that will have an enhanced layout along with larger fonts and different colors allowing greater visibility of the data to the entire control room. Additional data will be added including machine parameters to accompany the existing graphics, real-time boundary display, shot cycle information, and electronic logbook comments. The goal is that this large display can summarize the present state of the experiment to someone just walking into the control room as well as provide enough useful detail for the individual involved for the entire day.

Fig. 7-7. The existing DIII-D Remote Control Room used for KSTAR operations in 2011. Five large TVs face the scientific staff and 6 smaller 24 in. monitors display plasma control quantities (right).

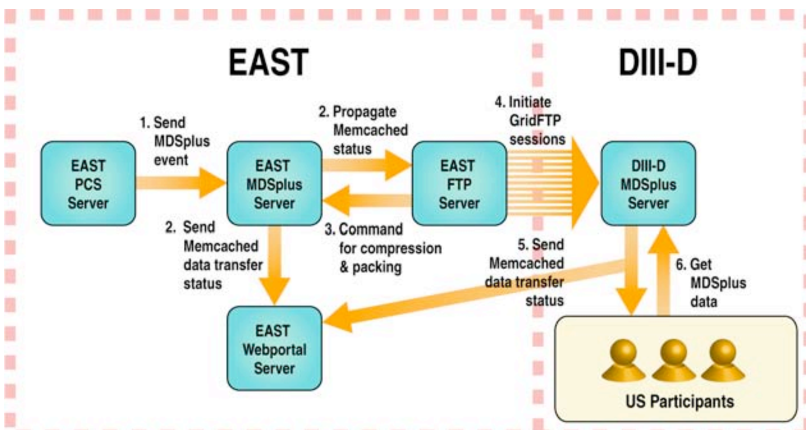

Fig. 7-8. Layout showing existing techniques utilized to attempt accelerated data transfer over the WAN. New techniques including the usage of intelligent caching will be deployed to the effective transfer time.

Below the large display wall are smaller displays that show real-time plasma control information. These displays act just like a digital oscilloscope and are vital for rapid understanding of any plasma control difficulties. The sociological behavior in the control room is for people to gather around these displays during the shot, point out areas of interest on these displays, and then return to their individual workstations to perform further data analysis. What if, when pointing out areas of interest, the displays were touch sensitive allowing direct interaction and further data discovery? Given the ubiquity of smart phones and tablets with their multi-touch screens, it seems a natural extension to investigate placing multi-touch systems in the control room for collaborative data analysis and discovery. General Atomics (GA) has experience in these devices elsewhere within the company and this capability will be demonstrated in the control room and evaluated for permanent deployment.

Throughout all of these activities, it is realized that the DIII-D scientist is presented with a large array of possible tools. Of particular interest will be developments that unify the number of different systems. The goal is to have one unified toolkit that can be used for a multitude of situations yet presents one simplified interface. Modules that support ad hoc and structured interpersonal communications, persistent collaboration environments along with shared displays and applications have the potential to significantly impact the efficiency of remote scientific participation. As the team works to deploy these new capabilities the aim will be to create as much of a unified interface as is possible.

7.7. USER EDUCATION AND TRAINING

Adding new tools or new capabilities to DIII-D's data analysis infrastructure is only beneficial if the scientific staff is made aware of their existence. To that end, the GA Friday science meeting will continue to be used for rapid communication to the staff. In addition, specific technology classes will be taught on an as needed basis to keep the researchers informed of these new capabilities. These will be similar to classes taught previously on IDL, object oriented programming, MDSplus, and a structured query language (SQL). Between these two extremes are short tutorials that will be recorded and made available via a web browser. Utilizing technology to record a computer screen, short demonstrations of capability can be recorded along with a voiceover for on-demand playback. These will all add to our reference library of information that available via the DIII-D web site.

7.8. REFERENCES FOR SECTION 7

[Abla 2010] G. Abla et al., Fusion Engin. Design **85**, 603 (2010).

[Farias 2012] G. Farias et al., Fusion Engin. Design **87**, 2081 (2012).

[Kalling 2011] R.C. Kalling et al., Fusion Engin. Design **86**, 399 (2011).

[Kim 2012] E.N. Kim et al., Fusion Engin. Design **87**, 2045 (2012).

[Schissel 2010] D.P. Schissel et al., Fusion Sci. Technol. **58**, 720 (2010).

[Schissel 2012] D.P. Schissel et al., Fusion Engin. Design **87**, 2194 (2012).

8. THE COLLABORATIVE NATIONAL PROGRAM

The DIII-D National Fusion Program is a highly collaborative multi-institutional research endeavor collaborating with more than 80 institutions worldwide. In large part, the DIII-D research program derives its strength from the diversity and capabilities of its national and international collaborating institutions and associated individuals. The funded scientific staff (full time equivalents) are evenly split between General Atomics (GA) and collaborating institutions and scientific collaborators have significant roles at all levels of the program. Consequently, the DIII-D Program has and will continue to invest significant resources to grow and maintain supportive and effective collaborations.

University participation is critically important to the U.S. fusion energy sciences program and to DIII-D. Our university partners bring a unique perspective to fusion research that greatly enriches the research program at major fusion facilities. University programs can maintain a sharp focus on key scientific questions, are better able to invest in developing new diagnostic techniques, and provide excellent preparation for next generation fusion scientists who will help the U.S. realize the full benefit of our participation in ITER. The facility investments included in the DIII-D Five-Year Program Plan will provide a research environment conducive to expanded University participation.

The DIII-D National Fusion Program maintains close linkage to key elements of the broader U.S. and international fusion science communities as part of its mission to optimize the tokamak approach to fusion energy. The DIII-D Program is strongly coupled to the U.S. Theory Program and to the growing number of topical centers which seek to apply the latest advances in numerical simulation to key challenges for fusion development. In addition to institutional topical science collaborations, the DIII-D Program also coordinates its research with other major U.S. and international fusion facilities, such as Germany's Axisymmetric Divertor Experiment Upgrade (ASDEX-U), C-Mod (MIT), China's Experimental Advanced Superconducting Tokamak (EAST), UK's Joint European Torus (JET), Japan Tokamak-60 Super Advanced (JT-60SA), the Korean Superconducting Tokamak Advanced Research (KSTAR), the National Spherical Torus Experiment (NSTX), and others. International collaborations are covered more fully in Section 9 of this document.

The DIII-D program actively participates in the ITER project on many levels and the DIII-D research plans address issues critical to the success of ITER. For example, each year the ITER Organization (IO) is invited to propose experiments and participate in the DIII-D experimental planning process and DIII-D routinely tests prototype diagnostics, hardware, and physics concepts for ITER with direct participation of members of the ITER Team. The U.S. Burning Plasma Organization (USBPO) coordinates U.S. research in support of ITER and potential next-step experiments; many DIII-D scientists serve in leadership positions within the USBPO, including Dr. Chuck Greenfield, who serves as the head of the USBPO.

8.1. SCOPE OF THE DIII-D FUSION PROGRAM

The DIII-D National Program evolved from the Doublet III device, which was constructed and initially operated by General Atomics in 1978. Collaboration has been a signature feature of the fusion effort at GA, starting with the Japan Atomic Energy Research Institute (JAERI), which invested significant money in the DIII-D facility and was provided half the run time in the period 1978–1984. This early large-scale collaboration set the GA fusion program on the course that has led to the present DIII-D

National Fusion Program which features a large number of diverse collaborations spanning the nation and the globe, as indicated in Fig. 8-1. These collaborations carry out the integrated DIII-D program mission. General Atomics provides most of the operations support.

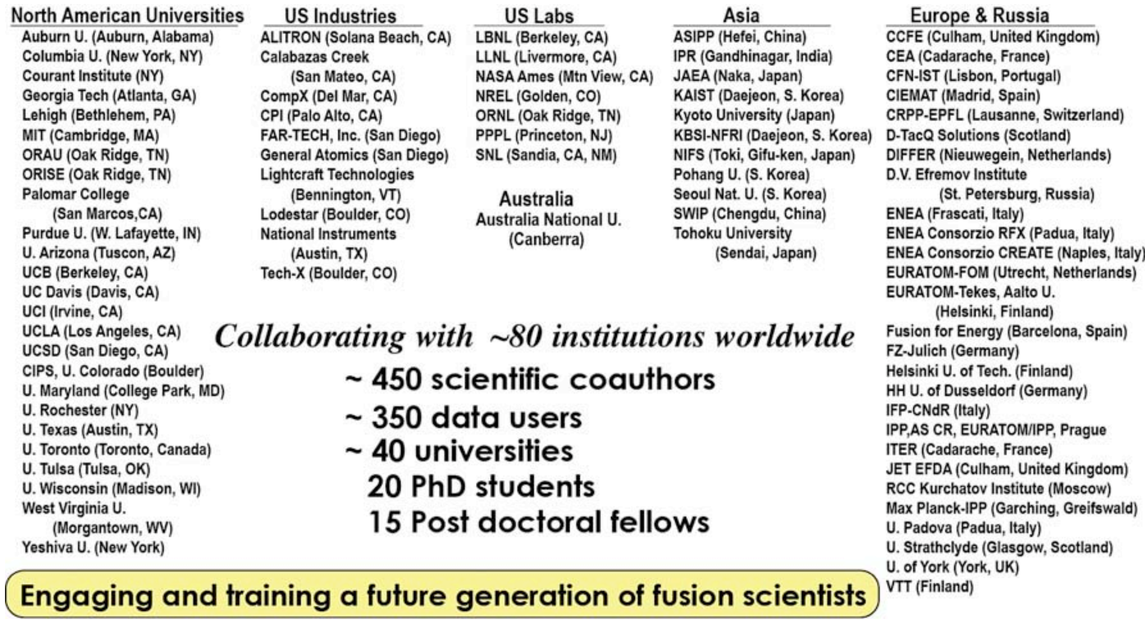

Fig. 8-1. National and international collaborations in support of the DIII-D research program.

In the present DIII-D National Fusion Program about 50% of the scientific staff (full time equivalents) are from collaborating institutions. The team ranges from undergraduates to senior scientists with three decades or more experience in fusion research. The DIII-D on-site research staff consists of approximately 80 full-time Ph.D. scientists, which includes 32 Fellows of the American Physical Society (APS) and 10 winners of the APS Excellence in Plasma Physics Award based on research carried out on DIII-D. The extended research team includes another 30 Fellows of the American Physical Society.

There are a total of 443 users of the facility (as measured by scientific authorship from 2011–2012), 121 from General Atomics and another 322 from other institutions which span the globe (Fig. 8-1). As shown, the list of 83 collaborating institutions (2012-13) includes:

- 26 universities in North America.
- 7 national laboratories in the U.S.
- 12 Institutions from Asia (including 1 from Australia).
- 28 Institutions from Europe and Russia.
- 10 High Technology Companies in the U.S.

8.1.1. The DIII-D National Team

The *core* of the DIII-D National Team consists of about 90 operating staff and ~85 research scientists. Over half of the scientists are from collaborating institutions and spend the majority of their time on site in San Diego. The majority of the operations staff are from GA (~10% of the FTEs are provided by collaborating institutions). The operating staff are responsible for the DIII-D tokamak and its major heating and current drive systems, as well as design, fabrication, and execution of facility improvements. The larger collaborating institutions have personnel on-site to assist with operation and maintenance of specific tokamak systems or larger diagnostic systems.

Many of the research scientists provide operations support for a broad range of scientific experiments involving the DIII-D tokamak. Such support includes diagnostic and data acquisition maintenance, diagnostic operation, system calibration, and data reduction/analysis. Collaborations have increased the diagnostic capability of DIII-D dramatically, enabling comprehensive measurements of plasma profiles, magnetohydrodynamic (MHD) modes, and plasma turbulence and transport which can be compared with numerical simulation in unprecedented detail. Future collaborations will continue this trend.

In addition to GA, there are nine major collaborating institutions that have broad programmatic responsibilities on multiple topics supported by on-site staff at DIII-D. Major collaborating institutions join with GA to form a DIII-D Executive Committee (DEC) to guide the program's strategic and near-term directions; further information on DEC may be found in Section 10. The programmatic responsibilities of these DIII-D collaborators are given in Table 8-1. University collaborations will be covered more fully in Section 8.3.

Table 8-1
Programmatic Responsibilities for Collaborating Institutions with Representation on the DIII-D Executive Committee 2012–2013

PPPL
- Rotation and momentum transport
- FW and ECH system support
- NTM control
- Active role in fast ion physics studies
- Boundary Physics
- CER and main-ion diagnostic support

LLNL
- Advanced Tokamak development
- RMP ELM-control research
- Current profile measurements with MSE
- Edge flow measurement and modeling
- IRTV and Divertor Thomson diagnostic support

ORNL
- Pellet ELM pacing hardware and experiments
- SXR imaging for RMP ELM control and 3D physics studies
- Disruption mitigation experiments: MGI, SPI
- Advanced tokamak scenario modeling
- FW system support and heating experiments

Columbia U.
- Leading role in resistive wall mode control
- Advanced tokamak development
- 3D field physics

UCLA
- Thrust and ITPA leadership
- Broad spectrum of turbulence measurements
- Anomalous electron transport
- LH-transition physics
- ITER prototype microwave diagnostics
- Advanced turbulence and density profile FIR and μwave diagnostics

UCSD
- Disruption mitigation studies, runaway electron dissipation, SXR and synchrotron emission studies
- H-mode transition physics
- Core transport model validation and experiments
- ELM control and fast edge probes
- SOL transport and flows
- DiMES, MiMES, and Dust production measurements

U. Wisconsin
- L-H transition physics, pedestal and core turbulence
- Turbulent transport model validation
- BES and UF CHERS fluctuation diagnostics
- Zonal flows and neoclassical MHD research

UC Irvine
- Fast ion physics
- Fast ion diagnostics
- Alfvén eigenmode stability

U. Texas
- Transport experiments and modeling
- Fine-scale (spatial, temporal) ECE T_e measurements

8.1.2. International Collaborations

The DIII-D international collaboration program continues to provide a broad source of innovative ideas and opportunities which support the DIII-D research program. Throughout, the DIII-D Program has benefited from the activities in many foreign collaborating institutions. The guiding principle of the DIII-D international collaboration program is to enhance the DIII-D research program through a combination of a detailed exchange of scientific information with foreign researchers and participation in experiments on other fusion facilities which complement current experiments carried out on DIII-D.

Section 9 provides a comprehensive overview of DIII-D international collaborations. The present and planned collaborations are closely related to the research areas of prime interest on DIII-D, namely the thrusts and topical research areas. Most international collaborative research involving DIII-D program scientists is supported out of DIII-D program funding, though General Atomics and some of its DIII-D partners receive separate funding to support specific research tasks at overseas facilities.

8.2. NATIONAL LEADERSHIP ROLE AND PROGRAM LINKAGES

A key element of this DIII-D Program Plan is to provide national program leadership arising from the DIII-D mission: ***optimization of the tokamak approach to fusion energy.*** The U.S. Department of Energy, Fusion Energy Sciences (DOE FES) program consists of a 10-year vision for magnetic fusion energy research, as quoted below (italics are ours):

- **ITER Research.** The U.S. has a strong research team hitting the ground on a completed ITER project in Cadarache. This team is capable of asserting world leadership in burning plasma science.
- **Fusion materials science.** The U.S. has made strides in fusion materials science and passed critical metrics in tokamak and spherical torus (ST) operations with national research teams. It has assessed technical risks associated with moderate vs. small aspect ratio and scope of mission, and is prepared to move beyond conceptual design of a *fusion nuclear science facility (FNSF).*
- **Extend the reach of plasma control science and plasma-wall interactions.** U.S. fusion research has successfully levered new international research opportunities, including program leadership, in long-pulse plasma control science and 3D physics. Opportunities also include the plasma-wall interaction science made possible with long pulses.
- **Validated predictive capability.** The U.S. is a world leader in integrated computation, validated by experiments at universities and labs. Such computation should be transformational, as it must reduce the risks associated with fusion development steps.

The DIII-D program therefore seeks to be a recognized positive influence for U.S. fusion research on many levels spanning all of these areas.

Ensuring the success of ITER is the highest priority of the DIII-D program. Participation in ITER is the central element of the U.S. fusion program, as "ITER represents an extraordinary commitment of funding and effort," according to FES Associate Director Dr. Edward Synakowski. In support of the U.S. commitment to ITER, the responsibility of the DIII-D National Team extends beyond simply conducting research on DIII-D, to actively engage and collaborate with the broader fusion research community. The DIII-D program is closely coupled to six national entities, groups, or research communities on an ongoing basis: (1) ITER; (2) the U.S. Burning Plasma Organization; (3) the U.S. Theory Program; (4) the Virtual Laboratory for Technology (VLT) and enabling technology groups, including scientists seeking to define the vision for a future FNSF as described in the 2010 Research Needs Workshop (ReNeW) report;

(5) other major fusion experiments; and (6) the Transport Task Force (TTF). We briefly describe these below.

8.2.1. DIII-D Research in Support of ITER

The DIII-D Research Program is committed to the success of the ITER experiment and to enabling the U.S. ITER Project Office to fulfill its commitments to the international ITER project. The DIII-D National Program is addressing key issues related to the design, construction, and operation of ITER. DIII-D capabilities allow researchers to simulate many aspects of ITER operation and research on DIII-D has led to expansion of ITER capabilities. ITER-related experiments are the largest single component of the FY11–FY12 experimental program – using approximately 50% of the run time in FY11–FY12 to address urgent issues such as edge localized mode (ELM) control, disruption mitigation, and scenario development as shown in Fig. 8-2, and explained in much greater detail in Sections 2–4

Fig. 8-2. DIII-D run-time allocation for FY13 showing balance between major program elements:

- ELM control and Pedestal (12.5 days)
- Disruption Mitigation (5 days)
- Burning Plasma Physics (9 days)
- Dynamics and Control Research (13.5 days)

The DIII-D National Fusion Program also supports the ITER Project by participating in the International Tokamak Physics Activity (ITPA), which regularly meets to discuss research needs for ITER, develop coordinated research plans to address those needs, and review results. Section 9 more fully describes DIII-D participation in ITPA activities.

Members of the DIII-D National Team are actively engaged with the international fusion community in conducting ITER-related R&D. Table 8-2 lists existing collaborations between DIII-D scientists and others related to ITER research and diagnostic development. These collaborations leverage the capabilities of the DIII-D facility in significant ways: e.g., U.S. research teams gain experienced international experts who bring fresh perspectives and new ideas with them, DIII-D data can be integrated into international databases more effectively, and U.S. scientists gain access to international facilities with the corresponding ability to conduct more comprehensive experiments. In addition to individual international collaborations related to ITER, DIII-D team members are active in the International Tokamak Physics Activity (ITPA) and lead several of the working groups. The DIII-D program is well represented at the biennial ITPA meetings and experimental proposals are developed that are aligned with ITPA research goals.

In the future, ITER's needs will shift from design-related issues to operational issues. It is expected that DIII-D will develop startup scenarios, develop experience operating in hydrogen, and simulate operation of the ITER control system. Hydrogen operation is important because the ITER research plan will include significant operation with hydrogen to minimize activation, whereas all high-power, high performance tokamaks have operated exclusively in deuterium for the past 20 years. We believe, as a result of these R&D activities in support of ITER, the DIII-D facility will provide excellent training for the next generation of scientists in the U.S. who will assume responsibility for conducting fusion experiments on ITER.

Table 8-2
Collaborations with DIII-D Related to ITER Research 2011–2012

Topic	Collaborating Institution	Key Collaborator	DIII-D Contact
Disruption database	MIT	R. Granetz	N. Eidietis
	NSTX	S. Gerhardt, S. Sabbagh	N. Eidietis
	JT-60U	Y. Kawano	N. Eidietis
	ASDEX	G. Pautasso	N. Eidietis
	MAST	A. Thornton	N. Eidietis
	JET	P. deVries, V. Riccardo	N. Eidietis
	TCV	J.-Y. Martin	N. Eidietis
	TEXTOR	M. Lehnen	N. Eidietis
	Tore Supra	F. Saint-Laurent	N. Eidietis
Disruption mitigation	UCSD	E. Hollmann,[a] V. Izzo,[a] J. Yu	E. Strait
	MIT	R. Granetz	E. Strait
	ORNL	L. Baylor, N. Commaux,[a] T. Jernigan[a]	E. Strait
Disruption modeling	UCSD	V. Izzo[a]	
ELM control for ITER	UCSD	R. Moyer,[a] D. Orlov[a]	T. Evans
	College of William & Mary	S. Mordijck	A. Leonard
	LLNL	M. Fenstermacher,[a] I. Joseph	A. Leonard
	PPPL	J. Menard, J.-K. Park	R. Maingi
	ASDEX-U	W. Suttrop	T. Evans
	MPI Greifswald	M. Jakubowski	T. Evans
	CEA-Cadarache	M. Becoulet, P. Garbet	T. Evans
	ITER IO	G. Huijsmans, A. Loarte, R. Pitts	T. Evans
	F4E	G. Saibene	T. Evans
	SNLA	J. Watkins[a]	T. Evans
	FZ Jülich	H. Frerichs, O. Schmitz, H. Stoschus M. Lehnen, Y. Liang, D. Reiter	T. Evans
	CFN-IST, Portugal	M.F. Nave	A. Leonard
	JET	C. Lowry	T. Evans
	LHD (NIFS)	K. Ida, S. Ohdachi, Y. Suzuki	T. Evans
	Heinrich-Heine Univ. Düsseldorf	A. Wingen	T. Evans
	CCFE (MAS)	A. Kirk	T. Evans
	ORISE	H. Stoschus[a]	C. Petty
	Georgia Tech.	W. Stacey	T. Evans
	ORNL	J. Canik, M. Shafer,[a] E. Unterberg[a]	T. Evans
ITER TBM Simulation	ITER IO	A. Loarte, J. Snipes	R. La Haye
	Multinational Team	W.W. Heidbrink, GJ. Kramer, N. Oyama, J-K. Park, K. Shinohara, J. Snipes, D.A. Spong, W.M. Solomon, T. Tala, V.D. Pustovitov	C. Greenfield
Magnetic diagnostics	KSTAR	J.G. Bak	E. Strait
	UCLA	J. Zhang[a]	C. Petty
Magnetic error fields, locked modes	Columbia U.	F. Volpe	
	PPPL	J. Menard, J.-K. Park	M. Lanctot
	ITER-TBM Task Force	J. Snipes	M. Lanctot
	Culham	T. Hender, D. Howell	M. Lanctot
	JET	C. Lowry	M. Lanctot
Neoclassical tearing Mode (NTM) physics and/or control	ASDEX-U	M. Maraschek, M. Reich, L. Urso, H. Zohm,	R. La Haye
	JET	P. Buratti, T. Hender, D. Howell	R. La Haye
	IFS	R. Fitzpatrick, F. Waelbroeck	R. La Haye
	Columbia U./NSTX	S. Sabbagh, F. Volpe	R. La Haye
	PPPL	R.A. Ellis, S. Gerhardt, J. Hosea	R. La Haye, J. Lohr
	U. Wisconsin	C.P. Hegna	R. La Haye
	U. Tulsa	D.P. Brennan	R. La Haye
	IPR- India	D. Raju, A. Sen, Y. Shankar	R. La Haye
	Tech-X Corp.	S. Kruger	R. La Haye
	Columbia U.	F. Volpe	E. Strait
	JAEA	A. Isayama	R. La Haye
Pellet injection studies	ORNL	L. Baylor, T. Jernigan,[a] N. Commaux[a]	K. Burrell
Plasma control	TRINITI	R. Khayrutdinov	D. Humphreys
	MIT	D. Whyte, S. Wolfe	D. Humphreys
Plasma rotation	CEA-Cadarache	L.-G. Eriksson, O. Meyer	J. deGrassie
	MIT	J. Rice	J. deGrassie
	PPPL	R. Bell, S. Kaye, W. Solomon	J. deGrassie
	JAEA	Yoshida	
	CFN-IST, Portugal	M.F.F. Nave	
	EURATOM-JET	P. de Vries	J. deGrassie
	UCSD	S. Mueller, W. Solomon	K. Burrell
	VTT	W. Solomon, T. Tala	K. Burrell
RWM Control for ITER	Columbia University	J. Berkery, J. Bialek, J. Hanson, G. Navratil	T. Luce
	PPPL	M. Okabayashi	T. Luce
	PPPL	M. Chance	L. Lao
	CCFE	Y. Q. Liu	L. Lao
	JAEA	G. Matsunaga, M. Takechi	R. Buttery
	Consorzio RFX	T. Bolzonella, L. Marelli, P. Martin, L. Piron, P. Piovesan, A. Soppelsa	R. Buttery
Sawtooth control	CRPP	O. Sauter	R. La Haye
	CCFE-Culham	I. Chapman	R. La Haye

[a]Onsite personnel.

8.2.2. DIII-D Support for the U.S. Burning Plasma Organization

The U.S. Burning Plasma Organization (USBPO) was created in 2006 to coordinate relevant U.S. fusion research with broad community participation "to advance the scientific understand of burning plasma and ensure the greatest benefit from a burning plasma experiment". DIII-D scientists were instrumental in setting up the organization. Dr. T.S. Taylor, the DIII-D Program Director, served as the first Deputy Director of the USBPO.

Dr. C. Greenfield of GA serves as Director of the USBPO, and Drs. R. Buttery and C. Wong of GA serve on the USBPO Council. Other DIII-D scientists serve as Topical Group leaders or deputy leaders:

- Dr. George McKee (U. Wisconsin) Confinement and Transport (Leader)
- Dr. Gary Staebler (GA) Confinement and Transport (Deputy Leader)
- Dr. David Pace (GA) Energetic Particles (Deputy Leader)
- Dr. Larry Baylor (ORNL) Fusion Engineering Science (Leader)
- Dr. Chris Holcomb (LLNL) Integrated Scenarios (Deputy Leader)
- Dr. Michael Walker (GA) Operations and Control (Leader)
- Dr. Egemen Kolemen (PPPL) Operations and Control (Deputy Leader)
- Dr. Tony Leonard (GA) Pedestal and Divertor/SOL (Leader)
- Dr. Rajesh Maingi (PPPL) Pedestal and Divertor/SOL (Deputy Leader)

In addition to supporting the USBPO by providing scientific management and leadership, the DIII-D program supports the USBPO by providing physics and engineering analysis in response to specific requests from the U.S. ITER Project Office, and by inviting ITER scientists to propose and to lead ITER-related experiments on DIII-D.

8.2.3. DIII-D Research and U.S. Theory Program

The DIII-D program prominently features close interactions between theorists and experimentalists both within the U.S. and worldwide. Theory motivates and guides formulation of experimental proposals and, conversely, DIII-D experimental observations are often used to guide development of theory and computational tools. Theorists are included in DIII-D near-term and long-term program planning and serve on the DIII-D Research Council. They are actively involved in the planning, execution and analysis of DIII-D experiments. This interaction together with systematic validation of theoretical predictions with experiments have led to the identification of a great deal of important new physics.

The GA Theory Group also hosts visitors and enables remote collaboration with numerous U.S. and worldwide theory programs, assists in training graduate students and post-docs, and develops and supports a well-integrated set of numerical tools (including TGYRO, GYRO, NEO, TGLF, GATO, ELITE, EFIT, ONETWO) which are used by an extensive group of users at DIII-D and around the world. The GA Theory Group and its collaborators focus on six areas of research:

- Magnetohydrodynamics
- Confinement and Transport
- Boundary Physics

- Heating, Current Drive, Energetic Particles, and Fueling
- Integrated Modeling
- Innovative Concepts

Seven members of the GA Theory group are APS Fellows, two have won the General Atomics Marshall N. Rosenbluth Award for Fusion Theory, and one has been awarded the American Physical Society John Dawson Award for Excellence in Plasma Physics Research.

Through its interactions with the GA Theory program and its on-site collaborators, the DIII-D program maintains close connection to the U.S. Scientific Discovery through Advanced Computing (SciDAC) program and other FES Theory program initiatives. Theory and simulation initiatives which feature strong connections to the DIII-D program include: Center for the Study of Plasma Microturbulence (CSPM), Center for Gyrokinetic Simulation of Energetic Particle Turbulence and Transport (GSEP), Edge Simulation Laboratory (ESL), Center for Edge Physics Simulation (EPSI), Center for Simulation of Wave-Plasma Interactions (CSWPI), Center for Extended MHD Modeling (CEMM), and Plasma Surface Interactions (PSI): Bridging from the Surface to the Micron Frontier through Leadership Class Computing. In addition, the GA Theory Program has also been awarded two ITER contracts to model disruption and runaway electron mitigation by massive gas injection (MGI) and evaluation of plasma response to ELM-stabilization coils in ITER with the 3D MHD codes NIMROD and M3D-C1.

In the following, we give a brief description of our relationships with some of these projects:

- In connection with the Center for the Study of Plasma Microturbulence (CSPM), local and global GYRO simulations and multi-radii comparisons of DIII-D transport experiments have been performed.
- Through the Gyrokinetic Simulation of Energetic Particle Turbulence and Transport (GSEP) project, GYRO is being applied to simulate reversed-shear Alfvén eigenmodes and toroidal Alfvén eigenmodes in DIII-D and local energetic particle turbulent transport.
- Through the Edge Simulation Laboratory (ESL) project, the NEO kinetic neoclassical transport code was developed and is being applied to study neoclassical flows and transport in DIII-D experiments. ESL is also engaged on work to extend the GYRO code to enable more extensive gyrokinetic studies near the edge of DIII-D, and is developing the COGENT cross-separatrix gyrokinetic code to enable kinetic scrape-off layer (SOL) and divertor studies.
- The Center for Edge Plasma Simulation (EPSI) develops the XGC code and is engaged in studies of the plasma response to magnetic perturbations, neoclassical transport and edge orbit loss effects in DIII-D.
- In direct collaboration with the Center for Simulation of Wave-Plasma Interactions (CSWPI), ORBIT-RF is being further upgraded to interact with the TORIC and AORSA RF codes and applied to model the DIII-D fast wave (FW) experiments.
- The GA Theory group, working with the Center for Extended Magnetohydrodynamic Modeling (CEMM) project and the NIMROD team, put a large effort into linear and nonlinear ELM simulations and ELM stabilization by resonant magnetic perturbations (RMPs). Both M3D-C1 and NIMROD are being applied to simulate plasma response to RMP fields and their effects on ELMs.

- In direct collaboration with the CEMM effort, NIMROD has also been applied to simulate mitigated and unmitigated disruptions using improved radiation, runaway electron, and pellet/gas-jet penetration models. NIMROD simulations of disruption mitigation and runaway electron confinement by massive pellet injection (MPI) are being performed by V. Izzo (UCSD).

Serving in its role as a national fusion facility, DIII-D data is made available to theorists worldwide via a number of collaborations targeting some of the most challenging issues confronting fusion energy science. The GA Theory group and its collaborators are uniquely placed in this regard with its past history of leadership in this area. Both the theorists on-site and the experimental research staff are committed to helping collaborators in the U.S. Theory Program with access to the data for validation of theory. Infrastructures have been set up to facilitate this interaction, which produce a continuous dialogue between theory and experiment.

Close theory interactions occur throughout the DIII-D research program. In the following paragraphs, we give a brief description of interactions in some of these research areas:

Turbulence and Transport. Turbulence and transport studies on DIII-D have improved physics understanding and identified new challenges. The theory group at GA approaches the problem of transport in tokamak plasmas with full gyrokinetic simulations, as well as development of computationally faster theory-based transport models accurately fitted to these simulations, in order to predict plasma profiles self-consistent with sources. This work is greatly enhanced by the close relationship between Theory and the DIII-D National Tokamak Program, including extensive engagement in the planning and analysis of turbulence and transport experiments, as shown in Table 8-3. Detailed comparisons of both observed turbulent structures and transport in multiple channels to simulations have validated the accuracy of gyrokinetic simulations in many regimes, while also identifying areas where additional physics is needed, guiding ongoing theory development. Recently, a new spectral-shift paradigm for *ExB* Doppler shear and momentum transport was developed and implemented in the TGLF transport model. It has been successfully tested against DIII-D transport experiments.

Pedestal Physics and Control of Edge Localized Modes (ELMs). Gaining an understanding of ELMs, including onset conditions and dynamic evolution, has come to the fore as a critical issue for ITER and other burning plasma experiments, both because of the potential impact of ELM pulses on material surfaces, and because ELM onset places an effective constraint on the pressure at the top of the edge barrier (the ”pedestal height”), which strongly impacts core confinement and overall fusion performance. The GA Theory group has made important breakthroughs in physics understanding of ELMs and ELM-free operation over the past few years. In particular, the ELITE code and EPED pedestal height and width model, pioneered by GA in collaboration with the University of York, has continued to be quantified, elaborated, and extensively and successfully tested against experimental data from DIII-D and other tokamaks. Recently, the EPED model, together with plasma response calculations (see below), was applied to develop a new working model for RMP ELM suppression in which the penetrated perturbation field stops the inward propagation of the edge barrier before the peeling-ballooning mode becomes unstable when the resonant surfaces are in the proper location. This model was tested against discharges from DIII-D RMP experiments and serves to guide proposed new ELM-control experiments.

Table 8-3
Collaborations with DIII-D Related to Integrated Modeling 2012–2013

Topic	Collaborating Institution	Key Collaborator	DIII-D Contact
3D MHD	ORNL	S. Hirshmann	L. Lao
	PPPL	M. Zarnstorff	L. Lao
	Auburn University	J. Hanson	L. Lao
	ORNL	E. Lazarus[(a)]	L. Lao
	CRPP-Lausanne	A. Cooper	A. Turnbull
	Columbia University	A. Boozer	A. Turnbull
	IPR-India	R. Srinivasan	L. Lao
Edge stability	York University	H. Wilson	P. Snyder
	LLNL	X. Xu, M. Umansky, I. Joseph	P. Snyder
	JAEA	N. Oyama	L. Lao
Edge modeling	LLNL	G. Porter, M. Makowski,[(a)] D. Hill,[(a)] M. Rensink, T. Rognlien	R. Prater
	A. Alto Univ., Helsinki	M. Groth	A. Leonard
	UCSD	S. Krashenninikov, A. Pigarov	A. Leonard
Energetic particle stability	UC-Irvine	Z. Lin	R. Waltz
Equilibrium reconstruction (EFIT)	MIT/ALCATOR C-Mod	S. Wolfe	L. Lao
	Culham/MAST	L. Appel	L. Lao
	NFRI/KSTAR	K.I. You	L. Lao
	Columbia, PPPL/NSTX	S. Sabbagh	L. Lao
	JET	V. Drozdov, E. Solano	L. Lao
	ASIPP-Hefei	Q. Ren	L. Lao
	SWIP	J. Dong	L. Lao
	CEA Cadarache	W. Zwingmann	L. Lao
ICRF, ECH physics	MIT	M. Porkolab	R. Prater
Integrated Modeling	ASIPP-Hefei	G. Li,[(a)] Q. Ren,[(a)] W. Guo,[(a)] C. Pan[(a)]	L. Lao
	SWIP	A. Sun	L. Lao
	IPR-India	R. Srinivasan	L. Lao
	ORNL	J.M. Park,[(a)] M. Murakami	L. Lao/R. Prater
MHD analysis	University of Wisconsin	J. Callen	A. Turnbull
	UC Berkeley	X. Li	A. Turnbull
Neoclassical tearing modes	Univ. of Wisconsin	J. Callen, C. Hegna	R. La Haye
	JAEA	N. Hayashi, A. Isayama	R. La Haye
Neutral modeling	ORNL	L. Owen	R. Prater
Nonlinear MHD stability	NYU/Courant Inst.	P. Garabedian	A. Turnbull
Pellet ablation	Ukraine	R.V. Samulyak	P. Parks
Pedestal	AUG	C. Maggi	R. Groebner
	JET	M. Beurskens	T. Osborne
	MIT	J. Hughes	T. Osborne
	ORNL	R. Maingi	T. Osborne
	U. Wisconsin	J. Callen	R. Groebner
	Tech-X/FACETS	J. Cary	R. Groebner
Pedestal modeling	IPP-Garching	K. Hallatschek	J. Candy
	NYU	C.S. Chang	R. Moyer
Pedestal, neutrals	Georgia Tech.	W. Stacey	R. Groebner
Resistive MHD code development	FAR-TECH	S. Galkin[(a)]	A. Turnbull
	LANL	A. Glasser	A. Turnbull
Resistive and edge stability	MIT	L. Sugiyama	L. Lao
Resistive stability	Culham	Y. Liu	A. Turnbull
	PPPL	M. Chance	M. Chu
	U. of Tulsa	D. Brennan	L. Lao
RF modeling	CompX	R. Harvey, A.P. Smirnov	R. Prater
Test of theory-based transport models and turbulence simulations	U. Texas	K. Gentle	C. Petty
Transport Model Validation	UCSD	C. Holland[(a)]	R. Prater
	UCLA	T. Rhodes[(a)]	C. Petty
	U. Wisconsin	G. McKee[(a)]	C. Petty
	PPPL	R. Budny	R. Waltz

[(a)]Onsite personnel.

3D Fields for ELM and Rotation Control and Transport. Understanding the effects of 3D fields on plasma stability and transport is a top priority for DIII-D and ITER. Predictive modeling of these effects will require an improved understanding of transport in 3D fields. Significant new capabilities for 3D modeling have been developed in the past few years, and will play a greater role in theory and analysis going forward. Recently, M3D-C1 two-fluid modeling of plasma response including the electron temperature displacement and magnetic structures in the DIII-D plasma edge upon the application of 3D fields has been successfully compared against DIII-D Thomson and soft x-ray emission data. Nonlinear calculations with M3D-C1 are ongoing, and future comparisons with DIII-D are planned.

8.2.4. Role of DIII-D Research for Enabling Technologies, Contributions and Needs

Progress in fusion has been closely coupled to advances in enabling technology. DIII-D will continue to participate in developing enabling technologies critical to the future of the tokamak in burning plasma experiments [e.g., electron cyclotron heating (ECH) systems, radio frequency (rf) systems, and plasma-facing components (PFCs)]. DIII-D participation in the Virtual Laboratory for Technology (VLT) features strong connections to the Plasma Facing Components working group and to the Chamber Technologies working group. The DiMES and MiMES sample exposure and diagnostic systems are part of the VLT program activities and many collaborators participate in research using these systems.

The key need for enabling technology for DIII-D is reliable, long-pulse high power ($P_{tube} > 1.5$ MW) gyrotrons at 117.5 GHz. Long pulses are essential to control the current density profiles due to the long current diffusion times of the plasma. General Atomics and DIII-D supported testing of second-generation depressed collector tubes under the auspices of VLT. Communications and Power Industries (CPI) manufactured the depressed collector tube, and the DIII-D program provided the requisite supporting infrastructure and manpower to operate the system. In the future, 1.5 MW tubes will reduce the cost of ECCD system upgrades since fewer power supplies and control systems will be needed to achieve a given power level. The Advanced Tokamak program will directly benefit from the development of improved launchers to allow faster tracking for better MHD mode control and complete mode suppression with reduced ECCD power.

Plasma control and operations research is essential to the development of fusion energy in order to benefit from the latest advances in tokamak physics. Success in many advanced tokamak studies to date has been achieved transiently, e.g., using heating to control the resistive evolution of the ohmic current. Further progress needs active control tools to maintain the desired profiles of current density and plasma pressure for several resistive times. DIII-D has identified near term control needs for advanced tokamak development, which include off-axis neutral beam injection and electron cyclotron heating and current drive, and for profile control, active non-axisymmetric MHD mode control, divertor pumping for density control, and active real-time plasma feedback control algorithms.

Where possible, the DIII-D group develops, tests, and applies new control systems as a natural part of its research program. Over the past decade, the DIII-D team has exported its plasma control system (PCS) to the new EAST (China) and KSTAR (Korea) tokamaks, as well as to other tokamaks such as NSTX at Princeton Plasma Physics Laboratory (PPPL) and Pegasus at the U. of Wisconsin. DIII-D scientists plan to continue their collaboration with EAST and KSTAR to develop operating scenarios enabling long-pulse H-mode discharges in these superconducting tokamaks.

DIII-D scientists have been working with the Commissariat à l'Énergie Atomique (CEA)-Cadarache (Dr. D. Moreau), to test simultaneous pressure and current profile control algorithms suitable for use in ITER. These experiments are being closely monitored by the ITER Organization. The active control of plasma profiles necessitates internal measurements with feedback to heating, fueling, and current drive systems; future burning plasma experiments will add new challenges due to the presence of internal alpha heating and limited diagnostic capability.

Disruption avoidance and mitigation is also needed on next-generation experiments such as ITER; DIII-D is presently working with the fusion community to develop new techniques such as shattered pellet injection. Recent experiments to safely dissipate disruption-induced runaway electrons are benefitting from regular interaction with the ITER Organization. Table 8-4 lists active collaborations between the DIII-D program and other institutions related to Plasma Control, Operations, and Technology for ITER and beyond.

Plasma-facing materials will be key to the development of fusion energy over the long term. New materials are needed which are compatible with high performance tokamak operation and which exhibit a long lifetime in a nuclear environment with minimal tritium uptake. During FY11–FY12, DIII-D scientists within the Plasma Boundary Interfaces research area, working in collaboration with groups from C-Mod and NSTX, quantified how the divertor heat flux profile varied with toroidal field, heating power, plasma current, and machine size in order to develop a multi-machine U.S. database. This database will be combined with data from tokamaks in Europe to reduce uncertainty in predicting the divertor heat flux in ITER. High-Z material erosion was investigated in DIII-D using the DiMES materials sample exposure system; samples were analyzed at Sandia National Laboratory (SNL) and results were compared with simulations at Purdue University and at the University of Toronto. Table 8-5 lists on-going collaborations related to the plasma boundary interface.

8.2.5. Collaboration with Other U.S. Fusion Experiments

To serve the U.S. Fusion Program more fully, and benefit from the breadth of U.S. fusion research, the DIII-D Program maintains active collaborations with other magnetic confinement experiments in the U.S. Program. Other experiments provide new ideas, new physics insights, tests of concepts, and supporting information that are extremely valuable to the DIII-D Program. Consequently, the DIII-D Program, representing a large collaboration of institutions, seeks to assist these programs to succeed in their research endeavors where possible. Joint experimental work falls into three categories:

1. Collaborative. Teams may work together to transfer experience from one facility to another to expand overall capabilities and expertise. Research teams may travel to other facilities to achieve specific goals.
2. Complementary. Similar experiments performed on separate facilities to expand the parameter range and improve understanding. Close coordination on subsequent data analysis.
3. Confirmatory. A key element of scientific research involves reproducing key results on different experiments. This is especially valuable when developing understanding and testing new models. We describe below some of the present and past linkages that incorporate one or more of these types of collaborative research.

Table 8-4
DIII-D Collaborations Related to Plasma Control, Operations, and Technology 2012–2013

Topic	Collaborating Institution	Key Collaborator	DIII-D Contact
2D MHD control simulation	LLNL, Kurchatov	W. Meyer, V. Lukash	D. Humphreys
	Lehigh U.F4E-Barcelona	E.J. Schuster, M. Cavinato	M. Walker
	LLNL	W. Meyer, L. LoDestro	D. Humphreys
	Lehigh U.	E.J. Schuster	T. Luce
Amorphous silicon crystallization	NREL CCR	D. Young J. Nielsen	J. Lohr J. Lohr
Diagnostic mirror development	TEXTOR	A. Litnovsky	C. Wong
Dust collection and analysis	IPP-Garching	V. Rohde	C. Wong
EAST physics operator training	ASIPP-Hefei	Q. Yuan, B. Xiao, J. Qian, R. Zhang	A. Hyatt
EAST plasma control system	ASIPP-Hefei	J. Luo, H. Wang, B. Shen, B. Xiao, Q. Yuan, J. Qian	D. Humphreys
Equilibrium control	Lehigh U.	E. Schuster, M. Alsarheed	M. Walker
	PPPL	C. Rowley	M. Walker
HL-2M Design Review	ASIPP	Q. Li	C. Wong
ITER He cooled TBM design	SWIP	K.M. Feng	C. Wong
Joint PFC Experiments	ASIPP	G.N. Luo	C. Wong
KSTAR plasma control system	NFRI-Daejon	S.H. Hahn, J.-Y. Kim, M. Kwon, Y.K. Oh	D. Humphreys
MAST plasma control system	CCFE-Culham	G. McArdle	J. Ferron
Microwave applications	NASA Lightcraft Research		J. Lohr
Gyrotron development	CPI		J. Lohr
Microwave power measurements	Calabazas Creek Research		J. Lohr
Non-axisymmetric control	Consorzio-CREATE	A. Pironti, F. Villone	D. Humphreys
NSTX plasma control	PPPL	D. Gates, D. Mueller	J. Leuer, D. Humphreys
NSTX plasma control system	PPPL	D. Mastrovito, K. Erickson, E. Kolemen	J. Ferron
MST plasma control system	U. Wisconsin	A. Squitieri	J. Ferron
Pegasus plasma control system	U. Wisconsin	M. Bongard	D. Humphreys, J. Ferron
Plasma control for ITER	ITER IO, F4E-Barcelona	T. Casper, A. Winter, J. Snipes, M. Cavinato, A. Portone, F. Sartori	D. Humphreys
	MIT	I. Hutchinson, S. Wolfe	D. Humphreys
	NFRI-Daejon	J.-Y. Kim, H. Jhang	D. Humphreys
	PPPL	R. Hawryluk, D. Gates	D. Humphreys
	JET	G. Sips	D. Humphreys
	ITER IO	T. Casper	D. Humphreys
PMI modeling and benchmark	ASIPP	G.N. Luo	C. Wong
Profile control	CEA-Cadarache	D. Mazon, D. Moreau	P. Gohil, M. Walker
	Lehigh U.	E. Schuster	M. Walker
Real-time ECH launcher control	PPPL	R.A. Ellis, J. Hosea	J. Lohr
Silicon annealing	U. Wisconsin	K. Thompson	J. Lohr
SST-1 operator training	IPR-India	R. Daniel, R. Rajpal	D. Humphreys, P. Gohil

Table 8-5
DIII-D Collaborations Related to Plasma Boundary Interface 2011–2012

Topic	Collaborating Institution	Key Collaborator	DIII-D Contact
Edge/Divertor plasma modeling	LLNL	D.N. Hill[(a)], M. Makowski,[(a)] G. Porter, M. Rensink, T. Rognlien	A. Leonard
	A. Alto U, Helsinki	M. Groth	A. Leonard
	U. Toronto	D. Elder, P. Stangeby[(a)]	A. Leonard
	UCSD	S. Krashenninikov, A. Pigarov	A. Leonard
	William & Mary	S. Mordijck	E. Strait
Sputtering/surface erosion	LLNL	A. McLean	A. Leonard
	LLNL	S. Allen[(a)]	A. Leonard
	MIT	D. Whyte	A. Leonard
	Purdue University	J. Brooks	C. Wong
	SNL	R. Bastasz	C. Wong
	FZ-Jülich	A. Litnovsky	A. Leonard
	MPI-PP Jülich	V. Phillips	A. Leonard
	UCSD	D. Rudakov[(a)]	C. Wong
Divertor spectroscopy	ORNL	D. Hillis, R. Isler, E. Unterberg[(a)]	A. Leonard
Divertor visible imaging	LLNL	M. Fenstermacher[(a)]	A. Leonard
	U. Arizona	K. Crabtree	S. Allen
Hydrogenic retention	LLNL	S. Allen,[(a)] R. Ellis,[(a)] M. Groth	A. Leonard
	ORNL	E. Unterberg[(a)]	A. Leonard
	SNL	W. Wampler	S. Allen
	U. Toronto	J. Davis, B. Fitzpatrick, A. Haasz, P. Stangeby	S. Allen
PFC heat flux physics	LLNL	C. Lasnier,[(a)] M. Makowski[(a)]	A. Leonard
	FZ-Julich	R. Laenger, O. Schmitz	C. Lasnier
	MPI-PP Greifswald	M. Jakubowski	C. Lasnier
	ORNL	R. Maingi	C. Lasnier
	MIT	J. Terry	C. Lasnier
Midplane and X-point Langmuir probes	UCSD	J. Boedo,[(a)] R. Moyer,[(a)] D. Rudakov[(a)]	A. Leonard
Divertor Langmuir probes	SNL	J. Watkins[(a)]	A. Leonard
DiMES/MiMES	UCSD	D. Rudakov[(a)]	C. Wong
Edge fluctuations	UCSD	J. Boedo,[(a)] R. Moyer[(a)], D.L. Rudakov[(a)]	A. Leonard
Edge turbulence modeling	LLNL	M. Makowski,[(a)] M. Umansky	A. Leonard
PFC dust formation/transport	UCSD	A. Pigarov, D.L. Rudakov[(a)]	A. Leonard
Plasma flows	UCSD	J. Boedo[(a)]	A. Leonard
	LLNL	S. Allen,[(a)] T. Weber[(a)]	A. Leonard
	A. Aalto U., Helsinki	M. Groth	
	Australia National U.	J. Howard	S. Allen
Neutral modeling	ORNL	L. Owen	R. Prater

[(a)]Onsite personnel.

National Spherical Torus Experiment Upgrade (NSTX-U) is a large spherical torus (ST) at PPPL. NSTX-U is investigating scientific issues for the ST in relation to possibilities for a future FNSF. Scientists from NSTX-U collaborate with the DIII-D program to study fast-ion physics, resistive wall mode (RWM) stabilization, boundary physics, and MHD stability. Each year the NSTX-U, DIII-D, and ALCATOR C-Mod programs conduct joint experiments on specific topics of particular interest to DOE; efforts in 2012 focused on core transport and profile stiffness, and in 2013 will focus on high-performance small-ELM operating regimes.

NSTX-U is presently shut down for upgrade of its toroidal field, ohmic transformer, and neutral beam heating systems and is not scheduled to resume operations until early in FY15. In the interim, a number of NSTX-U scientists are conducting their research using the DIII-D facility. Once operations resume at NSTX-U, we anticipate resuming joint experiments addressing confinement, MHD-stability, and divertor physics, as well as specific topics in support of ITER.

ALCATOR C-Mod is one of the three major tokamak facilities in the U.S. Program. Located at the Massachusetts Institute of Technology (MIT), it complements research on the DIII-D tokamak with its high toroidal magnetic field and accompanying high-density operating capability. The ALCATOR C-Mod and DIII-D programs have a long history of productive collaborations that include participation in the DOE-FES Joint Research Targets. Notable results include pedestal scaling (ρ^* and ν^*), divertor heat flux profile scaling, and the physics of intrinsic torques and plasma rotation. Both groups have strong programs in divertor physics with theory and code support for divertor research and edge transport; DIII-D features all-carbon PFCs while C-Mod operates with high-Z boronized walls. The C-Mod and DIII-D programs both feature strong efforts in disruption mitigation. Due to the wide range in size and plasma parameters, DIII-D and ALCATOR C-Mod play important roles in dimensionless scaling experiments with the larger European JET and Japanese JT-60U tokamaks. Scientists from each program participate in a number of joint experiments.

Although future operation of ALCATOR C-Mod is uncertain (see the FY14 FES budget plan released February 2012), we look forward to continuing high-impact collaborations with the ALCATOR Team on disruption characterization and mitigation, ELMs and pedestal physics, ELM-free operating modes, divertor detachment, plasma-material interactions, and plasma rotation.

High Beta Tokamak — Extended Pulse (HBT-EP) is a small tokamak at Columbia University studying the issue of passive and active control of MHD kink modes. The research is pursuing the use of non-axisymmetric control coils and a newly installed high-resolution magnetic sensor array to: (1) quantify external kink dynamics and multimode response to applied magnetic perturbations, (2) develop and understand the relationship between control coil configuration and active feedback control effectiveness, and (3) explore advanced feedback control algorithms. Research staff at Columbia have played leading roles in carrying out DIII-D high-performance and resistive wall mode stability experiments, as well as development and application of the VALEN code for MHD control in DIII-D.

Pegasus is a small spherical torus experiment at the University of Wisconsin. Its research program is focused on noninductive startup and operation at high beta with high plasma elongation. GA provided design engineering and analysis help for the Pegasus vacuum vessel and provided the port extensions in order to assist in a more rapid startup of this device. GA assisted in providing DIII-D Plasma Control System technology to the Pegasus Team.

Madison Symmetric Torus (MST) is a proof-of-principle scale reversed field pinch (RFP) experiment at the University of Wisconsin. This program is focused on understanding and controlling the plasma dynamo that sustains the RFP configuration, developing dynamo-free current drive techniques, and deploying state-of-the-art plasma diagnostics to support research on MHD and plasma transport physics. MST has been a leader in developing spectroscopic techniques to measure motional Stark broadening to deduce the local $|\mathbf{B}|$ and thereby determine the current profile. The MST group has been working with the Atomic Database and Analysis Structure (ADAS) project, JET, and DIII-D researchers to improve the atomic model for the Stark effect used in MSE measurement. In FY12, scientists from the MST Team joined colleagues from the Reversed Field Experiment (RFX) device in Italy to conduct experiments on DIII-D using RWM feedback control to extend stable tokamak operation to $q_{95}<2$ for 0.4 s and sought to produce tokamak discharges with a stationary helical core, similar to those obtained in RFP experiments. Such collaborative experiments provide important tests for MHD theory development.

The **Fusion Facilities Coordinating Committee (FFCC)** was established in 1998 to facilitate improved coordination between the three major U.S. magnetic fusion facilities (DIII-D, NSTX, and C-Mod) as well as between the major U.S. facilities and major international facilities. Representative program leaders from the U.S. facilities meet together at least once per year at the FES with the relevant DOE program managers, the corresponding facility Program Advisory Committee (PAC) chairs, USBPO representatives, and ITER managers — typically, just before the annual FES Budget Planning meeting in March. Topics for discussion include operating schedules, research goals, national and international collaboration activities, and ITER-related research activities. Other FFCC meetings take place either by phone or in person throughout the year as needed. Dr. Earl Marmar from the MIT ALCATOR C-Mod is presently serving as chair of the FFCC. Each year the FFCC works with the DOE FES program managers to identify Joint Research Targets which utilize the unique capabilities of the three major U.S. tokamaks to conduct a coordinated research program addressing important topics in fusion science.

Joint Research Targets (Level 1 DOE FES fusion program milestones). The DOE FES program has established the practice of identifying one high-level milestone each year for conducting coordinated research among the three major U.S. facilities: DIII-D, NSTX, and C-Mod. Each year, FES managers and program representatives serving on the Fusion Facilities Coordinating Committee meet to discuss potential research topics which could best provide important high visibility results in a timely manner through coordinated research activities. Topics and quarterly targets are developed and chosen that reflect expected facility capabilities and FES/facility research priorities. Each program then adjusts its programmatic milestones to support the joint milestone and allocates sufficient resources (run time and scientific staff) to complete the work. The list of recent Joint Research Targets appears in Table 8-6.

Table 8-6
FES Joint Research Targets FY08–FY14

Fiscal Year	Title or Subject Area	Lead Program
2008	Plasma rotation and momentum transport, impact on plasma stability and confinement	DIII-D
2009	Particle control and hydrogenic retention	C-Mod
2010	Thermal transport in the SOL plasma	NSTX
2011	Pedestal structure: experiment and theory	FFCC chair
2012	Core Transport	C-Mod
2013	Stationary enhanced confinement regimes without large ELMs	DIII-D
2014	Plasma response to applied 3D magnetic fields in tokamaks	DIII-D

8.2.6. Collaborations with the Transport Task Force and the Broader Science Community

Effective participation from a wide range of institutions in the broader science community is vital for conducting a world-class research program using the capabilities of the DIII-D facility. The DIII-D Team invites, encourages, supports, and benefits from the many collaborations with universities, industry, and laboratories that address fundamental issues related to fusion science. A snapshot of such collaborations, appears in Table 8-7.

Within the U.S., the Transport Task Force (TTF) provides a highly visible and effective framework for organizing fundamental research related to fusion energy. The long-term goal of the U.S. Transport Task Force (TTF) is to develop

> "... a predictive understanding of plasma transport leading to transport control. A major emphasis is placed on the study and understanding of the underlying plasma turbulence and of profile stiffness. The importance of the pedestal in setting the boundary conditions for core transport is widely recognized. Turbulence studies are made possible by dramatic improvements in the ability to control and measure internal profiles and turbulence properties. Demonstrating our understanding requires multiple, successful, quantitative tests of theory, simulation and modeling using experiments in fusion-relevant plasmas."

The DIII-D program has been closely linked with the TTF since its inception. The work of the TTF requires the integration of many individuals, groups and machines, spread among a large number of institutions. The main vehicle for this integration is the annual meeting of the TTF at which participants present results, identify issues and discuss future plans. In recent years, an average of about ten DIII-D scientists have attended the yearly TTF meeting. More recently, the U.S. and EU Transport Task Forces hold joint meetings, alternating between U.S. and EU venues. DIII-D intends to maintain ongoing participation in and support for the U.S. Transport Task Force.

Table 8-7
DIII-D Collaborations Related to Selected Topics in Fusion Science Research 2011–2012

Topic	Collaborating Institution	Key Collaborator	DIII-D Contact
Aspect ratio scaling	PPPL	S. Kaye, W. Solomon[(a)]	C. Petty
Atomic physics modeling	U. Strathclyde	M. O'Mullane	T. Evans
Beam emission spectroscopy; transport	U. Wisconsin	G. McKee,[(a)] I. Uzun-Kaymak, Z. Yan[(a)]	C. Petty
Beam emission spectroscopy; analysis	UCSD	G. Tynan, C. Holland[(a)]	G. McKee
Dimensionless scaling	JET	D. McDonald	C. Petty
	MIT	M. Greenwald, S. Wolfe	C. Petty
	CCFE	M. Valovic	C. Petty
ECE diagnostic	U. Maryland	R. Ellis	C. Petty
	U. Texas	M. Austin,[(a)] K. Gentle	C. Petty
ECE Imaging diagnostic	UC Davis	C. Domier	R. Boivin
	PPPL	B. Tobias	R. Boivin
Edge current density	ORISE	H. Stoschus[(a)]	C. Petty
Fast-ion physics	UC Irvine	X. Chen,[(a)] W. Heidbrink, D. Liu, C. Muscatello,[(a)] E. Ruskov, Y. Zhu	C. Petty
	PPPL	R. Nazikian	C. Petty
	PPPL	N. Gorelenkov, G. Kramer, G. Fu	A. Turnbull
	UCSD	R. Moyer[(a)]	E. Strait
FIR scattering, high-*k* backscattering	UCLA	T. Carter, J. Hillesheim, X. Nguyen, T. Rhodes,[(a)] L. Schmitz, G. Wang,[(a)] L. Zeng[(a)]	C. Petty
Fluctuation diagnostics	U. Tokyo	S. Kado, T. Oishi	G. McKee
ICRF fast ions	U.C. Irvine	W. Heidbrink	R. Pinsker
L-H transition physics	UCSD	D. Rudakov[(a)], R. Moyer[(a)]	K. Burrell
	U. Wisconsin	G. McKee,[(a)] Z. Yan[(a)]	K. Burrell
Leader of UCLA effort; member of DIII-D EC	UCLA	W.A. Peebles	C. Petty
Neoclassical tearing mode physics	York University	H. Wilson	R. La Haye
	CRPP-Lausanne	O. Sauter	R. La Haye
	U. Tulsa	D. Brennan	R. La Haye
	Tech-X Corp.	S. Kruger	R. La Haye
	Pohang University	M. Park	R. La Haye
	UCLA	T. Carter	R. La Haye
Neutral effect on L-H transition	ORNL	L. Owen	R. Groebner
Phase contrast imaging	MIT	A. Marinoni,[(a)] C. Rost[(a)]	K. Burrell
Plasma rotation	PPPL	W.M. Solomon[(a)]	K. Burrell
	U. Wisconsin	J. Callen, A. Cole, C. Hegna	R. La Haye
	EURATOM-ENEA, Frascati	M. Zerbini	C. Petty
	CEA-Cadarache	L.-G. Eriksson, O. Meyer	J. deGrassie
	MIT	J. Rice	J. deGrassie
	PPPL	S. Kaye. R. Bell	J. deGrassie
	JAEA	Yoshida	
	CFN-IST, Portugal	M.F.F. Nave	
	EURATOM-JET	P. de Vries	J. deGrassie
	UCSD	S. Mueller	J. deGrassie
L-H and core barrier physics	UCLA	E. Doyle[(a)], L. Schmitz, G. Wang[(a)]	C. Petty
Sawtooth physics	ORNL	E. Lazarus[(a)]	C. Petty
	CRPP-Lausanne	O. Sauter	R. Pinsker
	PPPL	B. Tobias[(a)]	C. Petty
Theory of transport barrier formation and fluctuation suppression	UCSD	P. Diamond	K. Burrell

[(a)]Onsite personnel.

The most complete understanding of plasma transport is obtained by an integration of theory and experiment, which is often accomplished by comparisons of experimental data with the predictions of theory-based simulation codes. The DIII-D tokamak has extensive capability for measuring simultaneously a number of fundamental plasma and turbulence properties, allowing comparisons with theory and simulation to unprecedented detail. Proposed upgrades to electron heating systems will provide unique opportunity to change the nature of the plasma heating and to vary the thermal gradients while observing changes in plasma turbulence. Experiments planned for FY14–FY18 will provide comprehensive data sets to compare with numerical simulation.

8.3. UNIVERSITY PARTICIPATION: TRAINING SCIENTISTS FOR FUSION RESEARCH IN THE ITER ERA

The DIII-D Team takes seriously its role as a steward of plasma physics, its responsibility to maintain a world class scientific research facility, and its duty to help recruit and train tomorrow's fusion scientists. The DIII-D program supports scientific education and training at four levels: science education and teacher training in secondary schools, undergraduate education at colleges and universities, graduate education leading to the Ph.D., and professional training through post doctoral fellowships. The participation of graduate students, post docs, and scientists from a wide range of institutions is essential to advancing fusion science across a broad front using the capabilities of the DIII-D facility.

Many universities participate in the DIII-D program, funded by one or more: (1) direct grants from the DOE FES as part of the overall DIII-D program, (2) subcontracts from GA and/or other DIII-D collaborators, and (3) other direct grants from DOE awarded through a special-topic peer review process (e.g., diagnostic awards). This participation added breadth to the DIII-D research program which would be unobtainable otherwise, and it strengthens university programs by providing exciting research opportunities for students and faculty. The experience young people gain while working at a major fusion research facility like DIII-D prepares them for future leadership roles in universities, high technology industries, and national laboratories. Planning and executing experiments at DIII-D will provide the U.S. with the workforce needed to realize the benefits of participation in ITER. Table 8-8 lists ongoing university collaborations at DIII-D and their primary research interests. New ideas for collaboration are welcome from university programs across a broad range of topics.

Table 8-8
Primary Research Interests of DIII-D University Collaborators (2011–2012)

School	Primary Research Emphasis
Auburn University (AL)	3D Field physics and 3D plasma equilibrium and effect on confinement
CIPS, University of Colorado, Boulder	Plasma Transport Simulation, magnetic perturbations, plasma-shaping effects
College of William and Mary, Williamsburg, VA	ELM control, 3D magnetic perturbations, simulations and analysis
Columbia University (NY)	Resistive Wall Mode control, plasma response to 3D magnetic fields, high-beta plasmas, steady-state tokamak operation
Courant Institute, New York University	Edge pedestal modeling, edge transport effects, ELM effects, SOL modeling
Georgia Institute of Technology (Atlanta)	MHD theory, transport theory, particle transport and flows, pedestal structure
Lehigh University (Lancaster, PA)	Plasma Control algorithms, current and pressure profile evolution and control, ITER control algorithms
Massachusetts Institute of Technology	Phase contrast imaging diagnostic, short wavelength plasma turbulence, RF heating and current drive
Oak Ridge Institute of Science Education	3D field effects, soft X-ray imaging, atomic physics and boundary radiation,
Palomar College (San Marcos, CA)	High speed data acquisition for fusion research
Purdue University (IN)	Plasma-surface interactions, impurity sources and sinks, simulation of surface sputtering and erosion,
U. Arizona, Tucson	Polarization effects in optical systems, IR and visible optics for fusion research, image analysis and software
UC Berkeley	Motional Stark Effect diagnostics, 3D magnetic field structure
UC Davis	Microwave imaging diagnostic development, 2D mode structure of MHD instabilities
UC Irvine	Fast ion stability and transport, Energetic particle diagnostics, TAE and RSAE mode structure and stability
UC Los Angeles	Plasma transport, plasma turbulence, L-H transition physics, ITER scenario development, wave profile and turb. diagnostics
UC San Diego	Edge probes, SOL flows and turbulent transport, L-H transition physics, surface erosion & analysis, dust generation & transport
U. Maryland	Microwave measurements, ITER ECE diagnostic prototyping
U. Rochester (NY)	MHD stability calculations. MISK code development, Resistive Wall Mode stability
U. Texas (Austin)	ECE electron temperature profile measurements, ITER ECE development, internal transport barriers
U. Toronto	Plasma surface interactions, impurity transport, SOL profiles, plasma detachment, edge flows, SOL Langmuir probes
U. Tulsa (OK)	Nonlinear MHD, resistive MHD simulations, energetic particle effects, flow shear and two-fluid effects on stability
U. Wisconsin (Madison)	Beam emission spectroscopy diagnostic, turbulent flows, L-H transition physics, RMP ELM suppression effects
West Virginia University (Morgantown)	Particle transport, plasma fueling, edge plasma optical diagnostics, neutral source measurements and analysis

8.3.1. Opportunities for Undergraduate Students

General Atomics is actively involved in the National Undergraduate Fellowship (NUF) Program in Plasma Physics and Fusion Engineering, which is administered by the Science Education program of the Princeton Plasma Physics Laboratory. This program provides about 25 summer internships to outstanding undergraduate students. Typically, DIII-D hosts 6–10 students each summer. From the results of student evaluations, it is clear that DIII-D has provided these students with a valuable learning experience that has proved to be a strong motivator for their pursuit of advanced degrees in fusion science. The program is a valuable tool for recruiting sharp new graduate students who may one day lead research on ITER.

8.3.2. Opportunities for Graduate Students

Universities which participate in the DIII-D program use the facility as a training ground for graduate students. Sixty-six students have performed research at the GA fusion facility leading to the award of an advanced degree; 20 students are presently engaged in graduate studies involving DIII-D. Some students may be full time at the DIII-D site designing, installing, and using diagnostic systems or analyzing DIII-D data, such as those shown in Fig. 8-3. All students are provided opportunities to present their work at science meetings. Others may work at their university writing analysis codes or developing theories, explaining plasma phenomena observed on DIII-D. Should ALCATOR C-Mod cease operating in FY13, we expect a significant increase in graduate students from MIT. Tables 8-9 and 8-10 show a list of present and past Ph.D. candidate students at DIII-D (as of ~ January 1, 2013).

Fig. 8-3. DIII-D hosts many graduate students, providing a wide range of research experiences. Left: David Eldon (UCSD), Center: Cedric Tsui (U. Toronto), Right: Colin Chrystal (UCSD)

Table 8-9
Present (FY13) Graduate Students at DIII-D

	Graduate Student	Affiliation	Topic
1.	J. Barton	Lehigh U.	Current profile control
2.	N. Bolte	UCI	Passive FIDA measurements of fast ion loss
3.	D. Boyer	Lehigh U.	Kinetic/burn control
4.	C. Chrobak	UCSD	Plasma Material Interactions and erosion
5.	C. Chrystal	UCSD	Investigation of poloidal rotation
6.	T. Collart	Georgia Tech.	Investigation of neoclassical rotation model
7.	D. Eldon	UCSD	Edge pedestal Thomson scattering
8.	B. Fitzpatrick	U. Toronto	Hydrogenic retention (oxygen bake)
9.	J.P. Floyd	Georgia Tech.	Theoretical model for plasma rotation
10.	R. Laengner	FZ Jülich	Divertor material migration with RMP
11.	N. Logan	Princeton U.	IPEC
12.	W. Shi	Lehigh U.	Integrated control
13.	L. Stagner	UCI	Bayesian inference of fast ion distribution
14.	D. Thompson	U. Wisconsin	BES – detector development
15.	D. Truong	U. Wisconsin	Multifield Turbulence & GAM structure
16.	C. Tsui	U. Toronto	Oxygen bake, C^{13} experiments
17.	W. Wehner	Lehigh U.	Rotation profile control
18.	T. Wilkes	Georgia Tech.	Edge Transport Differences during RMP
19.	J. Zhang	UCLA	Magnetic Fluctuation Polarimetry
20.	L. Yu	UCD	ECE bursts during ELMs

Table 8-10
Past Graduate Students at DIII-D

	Graduate Student	Affiliation	Topic
1.	S. Angelini	MIT	Disruption Modeling
2.	N. Antoniuk-Pablant	UCSD	B-Stark diagnostic
3.	C. Bae	Georgia Tech.	Theoretical model for plasma rotation
4.	Q. Boney	Hampton University	Divertor impurity diagnostic
5.	E. Carolipio	UCI	TAE mode studies
6.	S. Coda	MIT	CO_2 phase image interferometer
7.	K. Comer	U. Wisconsin	MHD studies
8.	D. Content	Johns Hopkins	Bolometers and visible bremsstrahlung
9.	R. Deranian	U. Wales	Plasma control
10.	M. Donales	Hampton University	Divertor impurity diagnostic
11.	J. Dorris	MIT	Phase Contrast Imaging
12.	H. Duong	UCI	Fast ion bursts
13.	D. Elder	U. Toronto	OEDGE modeling of C^{13} experiments
14.	C. Estrada-Mila	UCSD	Turbulent transport simulations
15.	D. Finkenthal	UCB	He transport
16.	J. Fitzpatrick	UCB	TAE mode analysis
17.	C. Fransson	Chalmers U.	Plasma control
18.	H. Frerichs	FZ Jülich	3D fluid modeling of RMP
19.	Z. Friis	Georgia Tech.	Thermal instabilities
20.	R. Gatto	UCB	Heat pinch modeling
21.	B. Grierson	Columbia	Interchange Turbulence in Dipole Plasma
22.	W. Guo	ASIPP	Integrated modeling
23.	S. Harrison	U. Wisconsin	Plasma surface interactions
24.	J. Hillesheim	UCLA	Multi-frequency Doppler reflectometry
25.	W. Howl	UCSD	MHD reconstruction
26.	D. Hua	UCB	ITG modes and energy confinements
27.	M. Jakubowski	U. Wisconsin	Beam emission diagnostics
28.	A. James	UCSD	Disruption-induced runaway electrons
29.	S. Janz	U. Maryland	ECE diagnostic bolometers
30.	O. Katsuro-Hopkins	Columbia U.	RWM feedback control modeling
31.	F. Kelly	Georgia Tech.	Radiation modeling
32.	K.W. Kim	UCLA	Fast density profiles reflectometry
33.	J. King	UCB (LLNL)	Fast response, digital MSE
34.	S. Kruger	U. Wisconsin	Flow shear effects on MHD
35.	T. Le Hecka	UCLA	Microwave reflectometry
36.	M. Lanctot	Columbia U.	RWM feedback control
37.	J.H. Lee	UCLA	Fast wave studies
38.	B. Leslie	U. Wisconsin	Beam emission spectroscopy
39.	Y. Luo	UCI	Beam ion studies
40.	A. McLean	U. Toronto	Plasma surface interactions
41.	B. Modi	UCB	Turbulence modeling
42.	S. Mordijck	UCSD	2D modeling of edge transport
43.	C. Muscatello	UCI	Fast ion transport
44.	Y. Mu	U. Toronto	Hydrocarbon fragmentation modeling
45.	E. Nardon	CCFE-MAST	ELM control by stochastic fields
46.	Q. Nguyen	UCB	UEDGE development
47.	C. Pan	ASIPP	Integrated modeling
48.	Y-S. Park	Seoul National U.	NTM detection and control
49.	M. Perry	Johns Hopkins	Impurity transport
50.	D. Pretty	Australia National U	Stochastic edge mag. field studies
51.	Chuang Ren	U. Wisconsin	Plasma rotation
52.	Q. Ren	ASIPP	Integrated modeling
53.	C. Rettig	UCLA	Microturbulence studies
54.	R. Rubilar	Georgia Tech.	Radiation modeling
55.	G. Sager	U. Illinois	Data analysis program
56.	M. Shafer	U. Wisconsin	Turbulence & flow during ITB formation
57.	P. Shriwise	U. Wisconsin	Velocimetry and BES fluctuation studies
58.	R. Stockdale	Princeton U.	Perturbative transport experiments
59.	H. Stoschus	FZ Jülich	Electron transport with rotating RMP
60.	B. Tobias	UCD	ECE imaging
61.	W. Wang	UCI	Neoclassical transport studies
62.	G. Watson	UCI	ICRF Studies
63.	A. White	UCLA	T_e fluctuation diagnostic
64.	B. Zaniol	U. Padova	Impurity ion flow in divertor
65.	A. Zwicker	Johns Hopkins	Multi-layer mirror spectrometer
66.	Q. Yuan	ASIPP	Plasma Control and Operations

8.3.3. Opportunities for Post Doctoral Fellowships

Postdoctoral fellowships provide important opportunities for developing future leaders in fusion research. Fifteen post doctoral fellows are conducting research connected with the DIII-D facility. These fellows are offered the opportunity to fully participate in all areas of the DIII-D program, with activities ranging from diagnostic development and numerical simulation to serving as a DIII-D tokamak physics operator. Post docs propose experiments and the run time priority of such experiments are carefully considered as part of DIII-D's commitment to their success. Scientists holding postdoctoral fellowships at universities have also furthered their scientific training at the GA fusion facility. Tables 8-11 and 8-12 list present (~ January 1, 2013) and past post doctoral fellows, their affiliation, and their research subject. Most of those completing fellowships at DIII-D have remained in the U.S. fusion program.

8.3.4. Opportunities for Expanded University Partnerships

The DIII-D program welcomes new ideas for collaboration from university programs across the nation. Members of the DIII-D Team work regularly with principal investigators as they prepare applications for grants, starting from the earliest planning phases through providing letters of support for the grant application. General Atomics and other DIII-D program participants explicitly partner with university programs where appropriate. Once in place, new collaborations receive on-site office space, administrative and computer support, as well as support for diagnostic installation, operation, and repair.

Table 8-11
Present (FY13) Post-Doctoral Fellows at DIII-D

	Post Doctoral Fellows	Affiliation	Topic
1.	D. Battaglia	PPPL	3D magnetics and particle transport
2.	X. Chen	UCI	EP instabilities using FIPA
3.	T. Fouquet	ORISE	Integrated modeling
4.	H. Frerichs	FZ Julich	3D edge transport modeling
5.	E. Li	U. Texas	Electron cyclotron emission
6.	D. Liu	UCI	FIDA analysis
7.	A. Marinoni	MIT	Phase contrast Imaging
8.	O. Meneghini	ORISE	Integrated modeling
9.	J. Munoz	ORISE	Divertor spectroscopy
10.	E. Olofsson	Columbia U.	Locked mode control
11.	C. Paz-Soldan	ORISE	3D magnetic field effects
12.	D. Shiraki	Columbia U.	Tearing mode torque balance
13.	H. Stoschus	ORISE	Edge current measurement with Li beam
14.	B. Tobias	PPPL	ECE imaging
15.	A. Wingen	ORISE	3D fields and synthetic SXR diagnostics

Table 8-12
Past Post-Doctoral Fellows at DIII-D

	Post Doctoral Fellows	Affiliation	Topic
1.	M. Austin	U. Maryland	ECE diagnostics
2.	E. Bass	ORISE	Gyrokinetic code for energetic particles
3.	E. Belli	ORISE	Edge gyrokinetic simulations
4.	D. Brennan	ORISE	MHD
5.	A. Brizard	UCB	Transport analysis
6.	N. Commaux	ORAU (ORNL)	Pellet injection
7.	A. Cole	U. Wisconsin	Non-resonant field error effects
8.	J. Cutherbertson	SNLA	Divertor Langmuir probe measurements
9.	J. Dorris	MIT	Phase Contrast Imaging
10.	N. Eidietis	ORISE	Plasma control
11.	D. Ernst	Princeton	Transport studies
12.	C. Fenzi	France/U. Wisconsin	Beam emission spectroscopy
13.	N. Ferraro	ORISE/DOE	Resistive MHD-edge
14.	A. Garofalo	Columbia U.	Wall stabilization
15.	G. Garstka	U. Maryland	ECE diagnostics
16.	T. Gianakon	U. Wisconsin	MHD theory and modeling
17.	D. Gray	UCSD	Disruption and coherent mode studies
18.	B. Grierson	PPPL	Main-ion rotation measurements
19.	M. Groth	LLNL	Boundary physics
20.	W. Guo	ASIPP	Plasma simulation
21.	D. Gupta	U. Wisconsin	Beam emission spectroscopy
22.	J. Hanson	Columbia U.	MHD mode control
23.	E. Hollmann	UCSD	Disruption and coherent mode studies
24.	C. Holcomb	LLNL	MSE diagnostic
25.	C. Holland	ORISE/UCSD	Turbulence studies
26.	B. Hudson	ORISE	Edge current measurement
27.	Y. Jeon	ORISE	Integrated modeling
28.	I. Joseph	UCSD	RMP ELM control
29.	O. Katsuro-Hopkins	Columbia U.	RWM Feedback Control Modeling
30.	J. Kinsey	Lehigh	Transport modeling
31.	M. Kissick	U. Wisconsin	Heat pulse propagation
32.	S. Kruger	U. Wisconsin	MHD studies
33.	K. Kupfer	ORISE	RF current drive
34.	T. Kurki-Suonio	UCB	Transport analysis
35.	M. Lanctot	LLNL	3D field effects, MSE and current profile control
36.	R. Lehmer	UCSD	Divertor physics and turbulence
37.	G. Li	ASIPP	Integrated modeling
38.	R. Maingi	ORISE	Divertor physics
39.	A. McLean	ORNL	Hydrogenic retention
40.	G. McKee	ORNL	Divertor spectroscopy
41.	O. Meyer	CEA Cadarache	Charge exchange recombination spectroscopy
42.	S. Mueller	UCSD	Momentum transport and intrinsic rotation
43.	D. Orlov	UCSD	3D fields and ELM control modeling
44.	P. O'Shea	MIT	Phase contrast imaging
45.	J.M. Park	ORNL	Integrated modeling
46.	D. Pace	UCI	Energetic Particle Research
47.	D. Ponce	ORISE	Thomson scattering
48.	H. Reimerdes	Columbia	Resistive wall mode stabilization
49.	Q. Ren	ASIPP	Integrated modeling
50.	C. Rost	MIT	Phase contrast imaging
51.	D. Rudakov	UCSD	Edge turbulence and transport studies
52.	O. Schmitz	FZ Julich	Divertor DiMES camera
53.	M. Shafer	ORISE	Divertor spectroscopy and ELM control
54.	W. Solomon	PPPL	CER diagnostics
55.	A. Sontag	ORNL	MHD studies
56.	J. Squire	ORISE	X-ray diagnostic
57.	F. Turko	ORISE	Resistive MHD in AT scenarios
58.	R. Srinivasan	IPR-India	Integrated modeling
59.	E.A. Unterberg	ORNL	Edge spectroscopy
60.	I. Uzun-Kaymak	U. Wisconsin	UFIT
61.	M. Van Zeeland	ORISE	CO2 interferometer
62.	F. Volpe	ORISE	Structure of magnetic islands
63.	M. Wade	ORISE	Helium transport
64.	G. Wang	UCLA	Transport studies/diagnostics
65.	T. Weber	LLNL	Edge plasma flows
66.	A. White	ORISE	Validation of Gyrokinetic Transport Codes
67.	D. Whyte	CCFM/Canada/UCSD	Divertor physics
68.	Z. Yan	U. Wisconsin	Beam emission spectroscopy
69.	J. Yu	UCSD	Disruption studies
70.	L. Zeng	UCLA	Transport studies/diagnostics

Collaborations often start at a very informal level through technical discussion at workshops and conferences. Each year at the American Physical Society/Division of Plasmas Physics (APS/DPP) meeting, the DIII-D program distributes a CD with copies of posters and talks presented at the meeting. Through print media distributed at the APS/DPP meeting, and through its website, the DIII-D program also advertises opportunities for collaborative research and makes available a contact list to facilitate inquiries and further dialogue. Access to DIII-D data is remarkably straightforward for university students, post docs, and scientists even at this earliest stage of dialogue.

Each year the DIII-D program invites proposals for experiments during a Research Opportunities Forum at General Atomics. Videoconferencing capabilities and a website make it possible to participate and propose ideas for experiments without traveling to San Diego. Typically, many more proposals are received than can be accommodated by the available run time; nonetheless, all proposals for run time are given serious consideration. Proposals related to completing research required to complete a graduate thesis have high visibility in the selection process.

Each year during the Research Opportunities Forum, the DIII-D program invites experimental proposals for the Torkil Jensen Award. The award prize is experimental time on the DIII-D tokamak to conduct innovative experiments and, in some situations, travel funds to participate in the experiment. Proposers need not be formally affiliated with the DIII-D program, but are encouraged to partner with program scientists. Dr. Torkil Jensen was an internationally recognized Theoretical Physicist at General Atomics known for his creative thinking on a wide range of plasma physics topics related to magnetic confinement fusion. The Torkil Jensen Award is open to both U.S. and international graduate students, post doctoral fellows, and staff scientists at universities, private industries, and national laboratories. Now in its fifth year, 50 proposals have been received and evaluated, with one or two run days awarded to the winners each year. There are three criteria for the award:

1. Potential for transformational new results.
2. Potential for producing high visibility, high impact science.
3. Collaborative effort (national or international partners).

The selection committee consists of a mix of on-site and collaborating DIII-D scientists. Travel funding for university participants is made available on a case-by-case basis.

Table 8-13 defines three broad categories of university participation and lists needs representative of those that could be addressed by new or expanded formal university collaborations. The list is a representation of possible topical areas to be explored and will change as needed with each new research advancement. Inquiries from universities are welcome. Further dialogue on this topic with university programs and with the DOE FES is planned.

Table 8-13
Areas of Potential Additional University Collaboration

Activity	Needs/Opportunities
Diagnostic Instrumentation	• ELM effects • 3D field effects • Disruption-induced runaway electrons • Internal magnetic field measurements • Turbulence and magnetic fluctuation measurements • SOL/Divertor ion temperature and flow • Divertor radiation loss and detachment • Erosion/redeposition • Plasma rotation (impurity and main ion)
Experiment and Analysis	• Pedestal width • Main ion particle transport • Disruption heat loads • Disruption-induced runaway electron dissipation • ELM losses • 3D field effects • Divertor detachment
Theory and Modeling	• Synthetic diagnostic development • Intrinsic rotation • Error field screening effects • Scenario modeling • SOL/divertor conditions and scaling • Extended MHD: rotation, flows, fast ions, two fluid effects • Pedestal width and core/edge coupling • ELM losses

9. INTERNATIONAL PARTNERSHIPS

9.1. INTRODUCTION

The DIII-D program, described in earlier sections, will provide compelling and essential progress toward the scientific basis for fusion energy. DIII-D is also an important part of the world's fusion portfolio (Fig. 9-1), with a high degree of complementarity between DIII-D and its international partners. The main premise of the international collaboration program at DIII-D is to advance the science of fusion plasma physics through interaction with these partners in such a manner as to accelerate the progress towards fusion energy realization. A key element of process is the establishment of joint experimental teams to use both DIII-D and the collaborating international facility to address critical issues. Areas of collaboration include: (a) addressing design and operational issues for ITER, (b) testing and advancing the capabilities of plasma control techniques through applications on multiple machines; (c) broadening the physics basis with predictive capability for fusion energy, and (d) training and broadening the experience of research staff for the future. The detailed collaborative exchanges provide the building blocks for advancing fusion energy science worldwide, particularly in preparing for and supporting international next-step experiments starting with ITER. The range of scientific exchanges is very broad and covers a large number of plasma physics topics (Section 9.4).

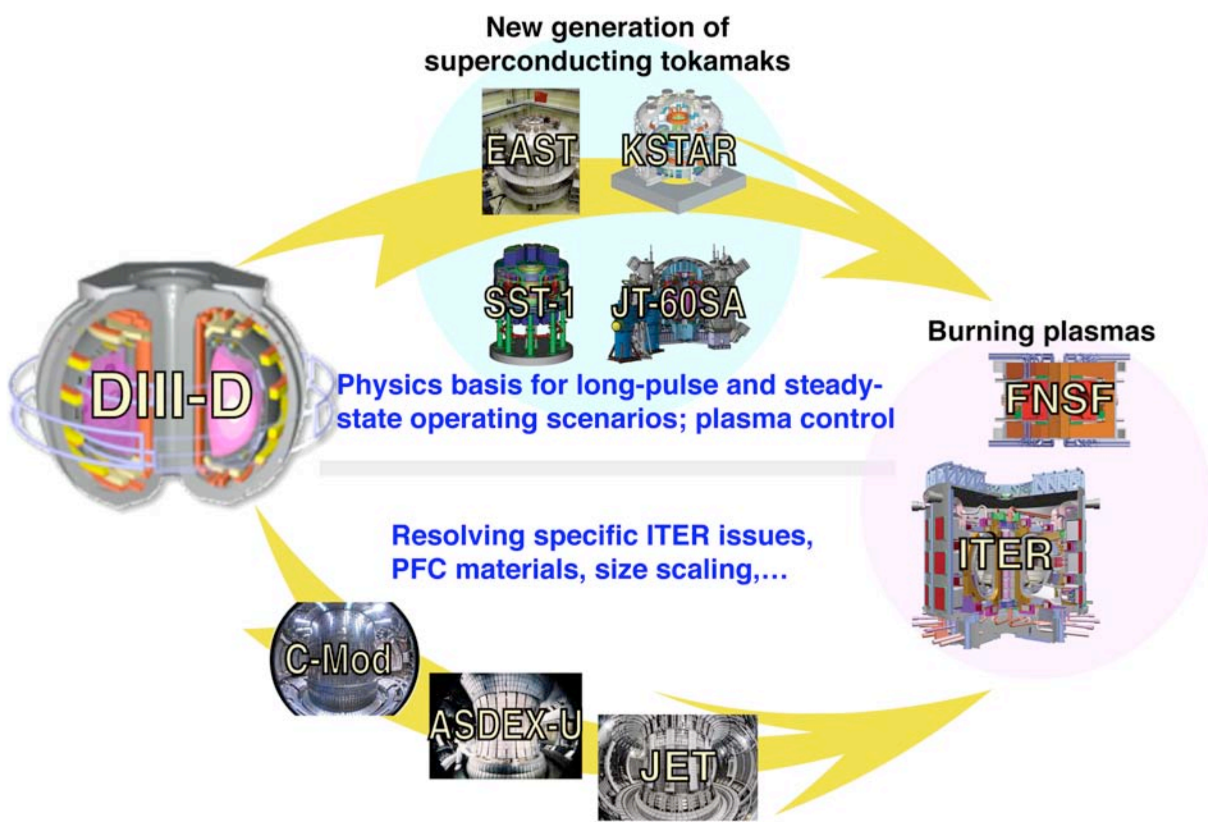

Fig. 9-1. DIII-D is an important element of the world fusion portfolio, and of an anticipated Long-Pulse, High Performance Initiative, wherein long-pulse scenarios developed in DIII-D can be tested at long-pulse and with metal walls. With our international partners we are developing a basis for operation of future burning plasma devices that will be central to the development of fusion energy.

A major emphasis of the international collaborations is addressing ITER high-priority research needs. Much of the high priority research is proposed, planned and executed through the International Tokamak Physics Activity (ITPA). Through experiments and regular meetings, the ITPA is effective for providing focus on important topics and joint analysis and discussion to accelerate progress. The ITER Organization (IO) and the Science and Technology Advisory Committee (STAC) also provide important direction and guidance on research efforts supporting ITER.

The present and future activities planned in the DIII-D international collaboration program are detailed in this section and are highlighted in Table 9-1. This list covers a broad range of topics, including personnel exchanges to prepare and perform joint experiments; the development of software and hardware components for specific applications, such as plasma control and auxiliary heating systems; the development of remote participation capabilities; the development of tools for data analysis and modeling; and work on technical and advisory committees. These collaborations will continue to expand on activities with long established fusion facilities, such as the European Fusion Development Agreement – Joint European Torus (EFDA-JET) and Germany's Axisymmetric Divertor Experiment Upgrade (ASDEX-U) Tokamak, as well as the new generation of superconducting, long-pulse tokamaks that are earlier in their development or currently under construction.

High priority within this international program will be a Long-Pulse, High-Performance (LPHP) Initiative. This LPHP Initiative will synergistically combine DIII-D's experience and expertise in scenario development and the expanding capability worldwide of superconducting tokamaks [Experimental Advanced Superconducting Tokamak (EAST), Korean Superconducting Tokamak Advanced Research (KSTAR), Japan Tokamak-60 Super Advanced (JT-60SA), and India's Steady State Tokamak (SST-1)]. A significant challenge for the fusion program is to demonstrate that high performance plasmas can be extended to times long compared to characteristic discharge times, such as the current redistribution time and plasma wall equilibration time. DIII-D has world-leading capabilities in plasma control and scenario development, and a comprehensive diagnostic set to evaluate and understand the complex interaction of the profiles. Joint experimental teams would demonstrate access to short-pulse sustainment and physics understanding on DIII-D, and then extend the scenarios to long pulse on the superconducting devices (Fig. 9-2). ITER scenarios and more advanced steady-state scenarios would be included. Because of the near-term capability of EAST, the initiative would initially focus on DIII-D/EAST.

Table 9-1
Collaborative Activities Described in this Section

Section	Collaborative Activity	Status and Plans
9.2	**Collaboration with other tokamak facilities**	• Scientific personnel exchanges for performing joint experiments data analysis and modeling • Remote participation in joint experiments at foreign facilities • Hardware and diagnostic development of prime areas of research
	9.2.1. EAST	— Plasma control — Long-pulse operating scenarios — In-kind hardware improvements to DIII-D
	9.2.2 KSTAR	— Plasma control — Long-pulse operating scenarios — H-mode physics
	9.2.3 JAEA/JT-60U/JT-60SA	— Long-pulse operating scenarios — Magnetohydrodynamic (MHD) stability — Transport
	9.2.4 EFDA-JET	— ITER-Like Wall studies — Joint experiments on high performance steady state plasmas, NTM and RWM studies, hybrid plasma development, real-time profile control and ITB studies — Possible DT campaign
	9.2.5 ASDEX-U	— Joint experiments on RWM ELM control, energetic particle physics, pedestal studies and divertor/scrape off layer (SOL) studies
	9.2.6 Tore Supra	— Burst Disk for disruption mitigation — Profile control
	9.2.7 Kurchatov Institute	— Helicon current drive
	9.2.8 MAST/TCV/TEXTOR	— RWM ELM control — 3D physics — Diagnostic Development
9.3	**International Tokamak Physics Activity (ITPA)**	• Active involvement of DIII-D personnel in ITPA topical groups — Propose and execute joint experiments with other fusion facilities — Perform data analysis and prepare reports of scientific results
9.4	**International Cooperative Agreements**	• Develop framework for carrying out collaborative activities
9.5	**International Investment in DIII-D**	• Scientific exchanges • Direct investment in DIII-D capabilities by international partners
9.6	**Infrastructure to Support Long-Distance Collaborations**	• Open data access policy • Tools for accessing data • Tools for remote participation

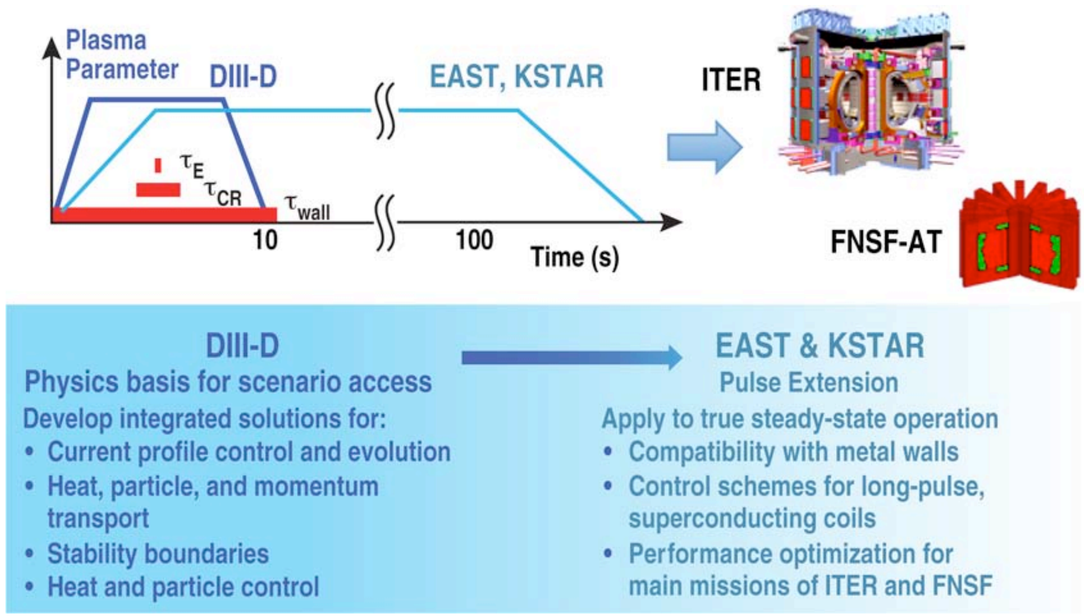

Fig. 9-2. The Long-Pulse, High Performance Initiative will focus on extending steady-state scenarios developed in DIII-D to true steady-state operating in collaborating superconducting tokamaks.

9.2. COLLABORATION WITH OTHER TOKAMAK FACILITIES

Below are described some of the proposed joint activities with DIII-D's international partners. Many of these activities fall under a general theme of long-pulse, high performance (LPHP) tokamak, which is proposed as an international initiative aiming to demonstrate the promise of these modes of operation as a basis for future devices including ITER's high gain mission, ITER's steady-state mission, a Fusion Nuclear Science Facility (FNSF), and ultimately a DEMOnstration power plant (DEMO).

Within the international LPHP initiative, joint experimental teams would develop appropriate operating scenarios on DIII-D, including both inductive and steady-state, and scenarios for ITER's high gain and high fluence missions. DIII-D's part in this would include developing plasma control techniques, applicability of various actuators (heating and current drive, shaping, 3D fields,…), a physics understanding of the complex interaction of profiles using the full set of diagnostics, and full integrated scenario demonstrations sustained for a few resistive times. The most promising scenarios could be exported to superconducting devices such as EAST, KSTAR, JT-60SA, and SST-1 for extension to long-pulse operation and assessments of the scenarios' compatibility with device-specific heating and current drive schemes and plasma facing components (PFCs). This will provide the first opportunities to study these operating scenarios under stationary conditions with regard to the core (possible in DIII-D) and the plasma's interactions with the wall (not possible with DIII-D alone).

It would be easy to look at this initiative as an effort where DIII-D starts the process, turns over the results to our partners with superconducting devices, and then our part is complete. However, the process here is envisioned a little bit differently. Although DIII-D does not have the long-pulse capabilities of its partners, this facility will, in the foreseeable future, maintain a level of flexibility that will be unmatched in the world program. This will enable bringing the results of tests in superconducting devices back to DIII-D as a guide for further development. Also, this effort is envisioned as being done by multi-institutional and multi-national Teams, so these efforts will deliver valuable experience to the Fusion Energy Sciences (FES) community that should eventually be applied to development of a DEMO program with major U.S. involvement.

It is also noted that the collaborations described here are carried out both by personnel exchanges and via remote collaboration. To support this, a "remote control room" (see Section 7.6) has recently been built and outfitted at General Atomics (GA). This capability, which can serve as a model for international efforts such as ITER, has been extensively exploited and will continue to be one of the essential tools for international collaboration.

9.2.1. EAST

The collaboration with the EAST tokamak, hosted by the Chinese Academy of Science Institute of Plasma Physics (ASIPP) in Hefei, China, has been the most active over the last several years. EAST is a superconducting tokamak, and represented a major advance in both the Chinese and world fusion programs when first commissioned. DIII-D and GA have provided extensive assistance in plasma control, heating systems, and the benefit of long experience with tokamak physics, that have helped to bring success to the EAST program. In return, DIII-D has received a loan of in-kind hardware including a primary power transformer and the lower divertor shelf installed on DIII-D in 2006.

During the next several years, we look forward to continuing and expanding our collaboration with EAST. EAST is presently not operating (2013) and is undergoing significant upgrades for their auxiliary power capability, adding neutral beams, additional lower hybrid current drive (LHCD), and additional ion cyclotron radio frequency (ICRF) power. We anticipate that EAST will reach a point in the next several years where it can begin testing the long-pulse scenarios that DIII-D is developing and characterizing; the next phase of the aforementioned LPHP Initiative.

The DIII-D Team is discussing a partnership with ASIPP which provides expert scientific assistance to EAST in exchange for support of upgrades on DIII-D. The collaboration plan includes providing continued assistance with plasma control on EAST, providing expert assistance in the planning and execution of experiments on EAST, operation time on DIII-D, specifically supporting scenario development on EAST, and support and training of Chinese scientists working on DIII-D. It is proposed that EAST/ASIPP provide hardware components that support the DIII-D facility capability improvements in Section 2.3. This includes 4 quadrant power supplies and manufacture of the 24 coils for the 3D coil set; high voltage transformers (4 rectifier transformers, 4 auto-transformers, and 4 arc filament transformers) for increasing the neutral beam power; two step-up transformers for EC power supplies; and gyrotron controls, stands and tank, and water manifolds for 3 gyrotron systems.

9.2.2. KSTAR

KSTAR, in Daejeon, Korea, is the other currently operating major superconducting tokamak. It has demonstrated several important milestones, including 15-second H-mode and RMP ELM suppression. As is the case regarding EAST, KSTAR is still a relatively new device, and it is to be anticipated that its capabilities will continue to increase significantly over the next several years.

DIII-D has also had a long and fruitful collaboration with KSTAR. The DIII-D Plasma Control group has been instrumental in bringing up KSTAR so that it could begin to make important contributions to the world fusion program, and this collaboration has expanded with KSTAR’s capabilities. As the capabilities increase further, we anticipate KSTAR contributing to the LPHP Initiative.

9.2.3. JAEA/JT-60U/JT-60SA

The collaboration with the Japan Atomic Energy Agency (JAEA), formerly known as the Japan Atomic Energy Research Institute (JAERI), has been the longest and most extensive in the history of the DIII-D research program. The collaborative agreement started in 1978 during the first year of operations on Doublet III and over nearly the last 30 years has provided a source of both financial contributions and scientific manpower that has significantly enhanced the DIII-D research program. With the advent of the JT-60U fusion facility, the areas of collaboration with DIII-D were greatly increased, particularly in the fields of Advanced Tokamak (AT) science and steady state, integrated performance optimization. With the termination of Japan’s JT-60U program, the collaboration has continued at a slower pace, with JAEA participation in a wide range of scientific areas on DIII-D.

Currently, JAEA is focused on construction of JT-60SA, a superconducting tokamak being built in collaboration with the European Union (EU) as part of their “Broader Approach.” The U.S. is currently not a party in JT-60SA, and so there is little formal participation. Also, first plasma is not expected in JT-60SA until 2019, outside of the interval covered by this plan.

However, there is significant alignment in the interests of the DIII-D Team and those of its JAEA colleagues, and significant complementarity between the capabilities of the DIII-D facility and the focus of the JT-60SA on long-pulse, high performance, steady-state. The JAEA group has continued to participate in DIII-D experiments and we expect continued participation during the cooperative agreement, especially in the areas of advanced steady-state operation.

9.2.4. EFDA-JET

The administration of the JET fusion device is organized under the European Fusion Development Agreement (EFDA) and is operated primarily as a user facility for member associations within EFDA. As such, experiments to be performed on JET are first proposed through the various association institutes and then prepared and executed by specific task forces comprised of visiting scientists from the association institutes. The main collaborative activities between DIII-D and JET have been centered on performing joint experiments at both facilities although collaborations have also been extended to diagnostic development and modeling efforts. The large majority of joint experiments are proposed through the ITPA organization and the collaborative exchanges between DIII-D and JET are primarily performed under the framework of the International Energy Agency Implementing Agreement (IEA IA) on Co-operation on Tokamak Programmes (CTP).

In the past, the main areas of interaction between DIII-D and JET have been: (a) development of high performance, steady-state operating scenarios; (b) neoclassical tearing mode (NTM) and resistive wall mode (RWM) studies; (c) hybrid operating scenario development; (d) ELM mitigation and pedestal studies; (e) real-time profile control and internal transport barrier (ITB) studies. Collaboration on these topics will continue with experiments on DIII-D and JET. Since installing their “ITER-Like Wall” (ILW), the JET program focused on operational issues providing data to the ITER program on the behavior of tokamaks with a tungsten divertor and beryllium wall. It is expected that as operational experience is gained with the ITER-like wall, cooperation on a broader range of topics on JET will continue.

As JET has many similarities with DIII-D, other than its larger dimensions and first wall materials, ITER will benefit strongly from the continuation of a variety of paired studies between the two devices. In particular, disruption mitigation and operating scenario development are two areas where this collaboration may make an important contribution. In addition, JET has proposed a deuterium and tritium (DT) campaign. If it is funded, there is strong interest in participating.

9.2.5. ASDEX-U

ASDEX-U, in Garching, Germany, is very similar to DIII-D in many respects. Its main contrast with DIII-D is that for the last several years, ASDEX-U has operated with a tungsten coating on its walls. DIII-D and ASDEX-U have a long history of collaborating in a variety of areas.

ASDEX-U has moved past its initial operations with the tungsten wall, and is carrying out a broad physics program studying H-mode access, ELM mitigation, disruption mitigation, energetic particle physics, to name a few. Recent areas of collaboration between DIII-D and ASDEX-U have been in RMP ELM control, divertor heat flux width, and energetic particle physics.

Comparative studies between DIII-D (an all carbon PFC device) and ASDEX-U in the above named research areas will endeavor to resolve the virtues of the various PFC materials used. This collaboration will continue as part of the LPHP Initiative.

9.2.6. Tore Supra

Tore Supra (Cadarache, France) is currently not expected to operate again prior to its upgrade to the Tore Supra WEST (W Environment in Steady-state Tokamak, where "W" is the chemical symbol of tungsten) device, which will be a superconducting, shaped, tokamak with tungsten walls. The Tore Supra Team had been actively engaged in disruption mitigation experiments using burst disks, a technique not attempted in any other device. DIII-D and the Tore Supra group are collaborating with the intention of deploying the Tore Supra burst disks on DIII-D, targeting 2014 for tests of the technique in DIII-D.

The longstanding collaboration on active control of plasma profiles with the CEA (Commissariat à l'Énergie Atomique, France), Tore Supra's home institution, should continue as well.

9.2.7. Kurchatov Institute

Collaborators at the Kurchatov Institute (located in Moscow, Russia) have recently proposed implementing a very high harmonic fast wave (500 MHz) helicon source for efficient off-axis current drive. If successful, this technique is a potential contributor to the development of steady-state scenarios, because the current drive efficiency is more than twice that of neutral beam injection (NBI) and ECCD. Calculations indicate that this current drive scheme would be effective on ITER and the Fusion Nuclear Science Facility – Advanced Tokamak (FNSF-AT). The Kurchatov Institute has proposed to provide klystrons and transmission lines for this experiment.

9.2.8. MAST/TCV/TEXTOR

The DIII-D research program is actively engaged with many other fusion programs around the world, which cannot all be mentioned in detail here. However, of these the most notable are the interactions with the UK's Mega-Ampere Spherical Tokamak (MAST), Switzerland's Tokamak a Configuration Variable (TCV), and Germany's Torus Experiment for Technology Oriented Research (TEXTOR). The work with MAST focuses on plasma control and RMP ELM control. DIII-D scientists assisted in the development of a charge exchange diagnostic system at TCV.

Although TEXTOR is no longer operating, an active collaboration on 3D magnetic fields and their application to RMP ELM control will continue.

9.3. INTERNATIONAL TOKAMAK PHYSICS ACTIVITIY

The DIII-D research program is actively engaged with the workings and plans of the International Tokamak Physics Activity (ITPA). The ITPA organization is presently supported through the ITER Organization and is a joint activity of fusion programs in the U.S., EU, Japan, Korea, China, India and Russia. The ITPA aims to provide cooperation on the tokamak physics R&D activities in order to develop the physics basis for burning tokamak plasmas. The internationally coordinated research activities within the ITPA are separated into topical physics groups and are performed on a voluntary basis. The purpose of these topical groups is to: (a) propose joint experiments to advance the understanding of fusion plasma physics; (b) assimilate data from these experiments and coordinate the analysis and prepare reports on the results; (c) organize, manage and update qualified databases in the different areas of fusion physics; (d) develop theoretical models and simulation codes to explain and reproduce experimental results; (e) integrate the R&D results towards improving the plasma performance and developing the operational scenarios for burning plasmas; (f) identify and resolve the key diagnostics issues associated with the control and analysis of burning plasma experiments.

The DIII-D research program is closely involved with the ITPA and makes strong contributions on many ITPA tasks, particularly with regard to the proposal and execution of ITPA joint experiments. For the DIII-D experimental program for 2012, out of the 51 experiments performed, roughly 33 were allocated for ITPA related experiments. Table 9-2 shows the breakdown of the experiments according to the research topics. The close involvement with the ITPA is also reflected in the U.S. membership of the ITPA Topical groups and leadership, which is shown in Table 9-3. The names highlighted in red are closely involved with the DIII-D program and reflect the strong contribution of the DIII-D program to this important international activity.

The DIII-D program will continue to place a high emphasis on performing ITPA tasks within its research program and further adapt to the high priority tasks, as well as the evolution of the ITPA organization itself, in light of the greater requirements and influence of the ITER Organization.

Table 9-2
General and ITPA-Related Experiments Performed on DIII-D in 2012

Thrust or Topical Science Area	Total Experiments	ITPA Experiments
ELM Control: 3D Field-Induced Transport	6	4
Burning Plasma Physics	10	6
Dynamics and Control	20	16
Boundary and Pedestal Physics	13	7
Torkil Jensen Award	2	0
	51	33

Table 9-3
U.S. Members of the ITPA Topical Groups (DIII-D Team members in red)

Topical Group	Members	Topical Group	Members
Coordinating Committee	S. Eckstrand C. Greenfield J. Wilson	**MHD, Disruptions, and Control**	R. Granetz J. Harris (Stellarator Rep) V. Izzo S. Jardin S. Sabbagh E. Strait (Chair) F. Waelbroeck J. Wesley
Diagnostics	S. Allen R. Boivin D. Brower D. Hillis D. Johnson B. Stratton J. Terry	**Pedestal and Edge Physics**	C.S. Chang M. Fenstermacher J. Hughes R. Maingi (Deputy Chair) A. Pankin T. Rognlien P. Snyder
Energetic Particle Physics	B. Breizman E. Fredrickson G. Fu W. Heidbrink D. Pace D. Spong S. Wukitch	**Scrape-Off-Layer and Divertor**	R. Doerner A. Leonard B. Lipschultz C. Skinner P. Stangeby M. Umansky D. Whyte
Integrated Operation Scenarios	P. Bonoli S. Gerhardt A. Hubbard C. Kessel T. Luce (Deputy Chair) J.-M. Park R. Prater	**Transport and Confinement**	P. Diamond E. Doyle S, Kaye G. McKee D. Mikkelsen C. Petty J. Rice

9.4. INTERNATIONAL COOPERATIVE AGREEMENTS

To carry out experiments internationally, appropriate umbrella agreements are required. DIII-D and most of its collaborators are party to the International Energy Agency Implementing Agreement (IEA IA) on Co-operation on Tokamak Programmes (CTP), which includes the ITER Organization and all of the ITER parties with the exception of Russia. In addition, there are bilateral agreements between the U.S., Europe, Japan, Korea, and China. The majority of DIII-D's international collaborations fall under the auspices of one or more of these agreements.

9.5. INTERNATIONAL INVESTMENT IN DIII-D

DIII-D's international partners demonstrate their enthusiasm for participating in the DIII-D research program through their investments, both in scientific exchanges and direct investment in device capabilities. These investments are viewed as a way of leveraging the program's support by the DOE.

A wealth of scientific exchanges have been and continue to be carried out under the auspices of the ITPA and CTP as well as through bilateral agreements. Table 9-4 lists recent exchanges from the beginning of FY12 through the present, indicating collaborative activity in many different topical areas. Table 9-5 shows the full list of international collaborating institutions during the last five years.

Table 9-4
A Broad Range of Personnel Exchanges Enhance International Collaborations and Joint Experiments (FY12 and FY13)

To DIII-D		From DIII-D	
Plasma Control System Development S.H. Hahn (NFRI) H. Han (NFRI) W. Lee (NFRI) S.-Y. Park (KNFRC) J. Qian (ASIPP) B. Xiao (ASIPP) S.-W. Yoon (NFRI) M. Yu (NFRI) R. Zhang (IPP) **ITER PCS** L. Zabeo (ITER) **Profile Control** F. Liu (CEA) D. Moreau (CEA) **Axisymmetric Control** J. Snipes (ITER) A. Winter (ITER) **Divertor Control** J. Snipes (ITER) **Disruption Mitigation** G. Papp (Chalmers U) **MHD Stability** J.-G. Bak (NFRI) P. Martin (RFX) P. Piovesan (RFX) **RWM Stabilization** G. Matsunaga Komuro (JAEA) **Pedestal and QH-mode studies** L. Aho-Mantila (MPI) M. Beurskens (CCFE) M. Nave (Euratom) S. Odachi (NIFS)	**Long Pulse Scenarios Development** S.H. Kim (Seoul Nat U) **Divertor Design** C.L. Dube (IPR) **Vacuum Systems** Z. Khan (IPR) **Diagnostic Development** M.K. Chowdhuri (IPR) J. Howard (ANU) M. Kumar (IPR) Q. Zang (IPR) C. Zhou (USTC) **Resonant Magnetic Perturbation Studies** K. Ida (NIFS) M. Leconte (NFRI) A. Wingen (Dusseldorf) Y. Zuzuki (NIFS) **Transport Physics** Y.-C. Kim (Oxford) T. Tokuzawa (NIFS) K.P. Wood (UK) M. Zerbini (ENEA) **Boundary Physics** M. Groth (Aalto U.) M. Hellwig (Jülich) A. Litnovskiy (Jülich) **Energetic Particle Physics** M. Garcia-Munoz (MPI) M. Salewski (Danish Tech U) **RF Physics** R. Maggiora (Politecnico) E. Testa (Politecnico)	**Diagnostic Development (EAST, HL-2A, KSTAR)** G. McKee (Wisconsin) B. Tobias (PPPL) **Advanced Inductive Scenarios (JET)** T. Luce (GA) **Long Pulse Scenario Development (KSTAR)** J.-M. Park (ORNL) **Boundary and 3D Physics (TEXTOR)** E. Unterberg (ORNL) **Diagnostic Development (EAST)** E. Doyle (UCLA) **Diagnostic Development (CIEMAT)** E. Hollmann (UCSD) **Resonant Magnetic Perturbation Studies (MAST)** T. Evans (GA) S. Mordijck (Wm. & Mary) R. Moyer (UCSD) **Tokamak operation (RFX-Mod)** T. Luce (GA)	**Energetic Particles (ASDEX-U)** D. Pace (GA) M. Van Zeeland (GA) **Energetic Particle Physics (EAST)** W. Heidbrink (UCI) Y. Zhu (UCI) **Energetic Particle Physics (Danish Technical U)** W. Heidbrink (UCI) **Plasma Control System Development (EAST)** B. Penaflor (GA) M. Walker (GA) **Plasma Control System Development (KSTAR)** B. Penaflor (GA) M. Walker (GA) **ITER CODAC Design (ITER)** G. Abla(GA) J. Ferron (GA) D. Humphreys (GA) G. Jackson (GA) D. Schissel (GA) M. Walker (GA)

Table 9-5
DIII-D Maintains a Large Number of Active International Collaborations (2008–2012)

Europe

Aalto U. (Helsinki, Finland)
CEA (Cadarache, France)
CFN-IST (Lisbon, Portugal)
Chalmers U. (Göteberg, Sweden)
CIEMAT (Madrid, Spain)
Consorzia RFX (Padua, Italy)
CRPP (Lausanne, Switzerland)
EFDA (Brussels, Belgium)
F4E (Barcelona, Spain)
FOM (Utrecht, The Netherlands)
Frascati (Frascati, Lazio, Italy)
FZ-Jülich (Jülich, Germany)
Heinrich-Heine U (Dusseldorf, Germany)
Helsinki U. (Helsinki, Finland)
IFP-CNdR (Milan, Italy)
IPP (Greifswald, Germany)
IPP AS CR (Prague, Czechslovakia)
IST (Lisbon, Portugal)
ITER (Cadarache, France)
JET-EFDA (Culham, England)
Kharkov IPT (Ukraine)
Max Planck (Garching, Germany)
U. Dusseldorf (Dusseldorf, Germany)
UKAEA (Culham, United Kingdom)
U. Naples (Naples, Italy)
U. Rome (Italy)
U. Strathclyde (Glasgow, Scotland)
U. York (York, England)

Japan

Kyoto U. (Kyoto)
JAEA (Naka, Ibaraki-ken)
NIFS (Toki, Gifu-ken)
Tsukuba U. (Tsukuba)

Russia

Efremove Institue (St. Petersburg)
Ioffe (St. Petersburg)
Keldysh (Udmurtia, Moscow)
Kurchatov Institute (Moscow)
Moscow State (Moscow)
St. Petersburg State Poly (St. Petersburg)
TRINITI (Troitsk)
Inst. of Applied Physics (Nizhny Novgorod)

Other International

Australia National U. (Canberra, AU)
ASIPP (Hefei, China)
IPR (Gandhinager, India)
NFRI (Daejeon, S. Korea)
Pohang U. (S. Korea)
Seoul Nat. U. (S. Korea)
SWIP (Chengdu, China)
U. Toronto (Toronto, Canada)

In addition, some international partners have chosen to invest directly in improving DIII-D's capabilities to carry out cutting-edge research. One prominent example was the contributions of divertor hardware made by the EAST Team as part of their collaboration with DIII-D. This Five-Year Plan includes additional partner investments, some of which are listed in Table 9-6.

Table 9-6
Proposed Investments in DIII-D Capabilities

Partner	Contribution	Scientific Benefit
ASIPP/EAST	Four-quadrant control power supplies	3D physics, RMP ELM control
	3D coils	3D physics, RMP ELM control
	High voltage power supplies and transformers	Additional NBI and ECH heating power
CEA/Tore Supra	Burst disks	Enables test of disruption mitigation technique
Russian Federation/ Kurchatov Institute	Helicon current drive source	Enables test of promising method for driving off-axis current

9.6. INFRASTRUCTURE TO SUPPORT LONG-DISTANCE COLLABORATIONS

DIII-D has an open data access policy, offering full access to data as it is collected and analyzed for all collaborators regardless of nationality. This access is conditional upon signing the data access agreement, which can be found at https://diii-d.gat.com/ssl_form/datausage/.

DIII-D has also deployed a suite of tools for accessing the facility via web, videoconferencing, and data sharing tools. Tools have also been prepared for remote participation by DIII-D staff in research at partner facilities, most notably a Remote Control Room located at General Atomics. Please refer to Section 7 for a complete description of the available tools.

10. DIII-D GOVERNANCE

Effective governance is an essential component of the DIII-D National Fusion Program, both for efficient management and for supporting a world-class multi-institutional fusion energy research program. Governance includes defining overall roles and responsibilities, establishing an open program planning process that nurtures both efficiency and innovation, coordinating research activities among the partners, and reporting and publication of results. Professional development is an important consideration here, since the strength of the DIII-D program resides in the motivated creativeness of the participants.

The structures, linkages, and processes described here provide a snapshot of a dynamic organization that began with the Doublet-III project (1978–1984), which featured a major collaboration with the Japan Atomic Energy Agency (JAEA) in Naka, Japan. DIII-D participants provide continuous feedback and suggestions for improvement in what is a very open and collaborative environment. The present way of doing business builds upon this past experience and reflects the broad-based input provided by team members.

10.1. ROLES AND RESPONSIBILITIES

General Atomics (GA) is the host institution for the DIII-D National Fusion Facility. Dr. Mickey Wade is the Director of the DIII-D National Fusion Program. As an employee of General Atomics, he is responsible for the facility and for oversight of the DIII-D National Fusion Program. Dr. Arnie Kellman is Director of DIII-D Operation, is also an employee of General Atomics and is responsible for safe day-to-day operation of the facility along with system maintenance, refurbishments, and upgrade activities. The Director of the DIII-D Experimental Science Division, Dr. Richard Buttery, is responsible for the execution of the DIII-D Research Program. Dr. David Hill, Deputy Director of the DIII-D Program, is an employee of Lawrence Livermore National Laboratory (LLNL) and a member of the Livermore-GA collaboration team. Dr. Charles Greenfield, an employee of General Atomics, serves as Assistant Director of the DIII-D National Program and is responsible for the ITER and International Research. Dr. Greenfield is also head of the U.S. Burning Plasma Organization (USBPO).

The DIII-D Team. The DIII-D Program is an open program with extensive national and international collaborations. The DIII-D National Team consists of 83 collaborating institutions, including 7 U.S. national laboratories, 26 universities in North America, and 10 U.S. companies in the private sector. International members include 11 institutions in Asia, 1 in Australia, and 28 in Europe and Russia. Presently, the full-time scientific staff consists of a nearly equal mix of General Atomics scientists and scientists from other institutions.

DIII-D Executive Committee (DEC). The DIII-D Executive Committee generally meets quarterly to advise the DIII-D Director on a broad range of programmatic issues such as long-range program planning. The DEC also addresses institutional issues related to managing the DIII-D Team, such as invited talks at major conferences, operational scheduling, and budgets. DEC membership consists of senior representatives (and their alternates) from General Atomics and major collaborators, including Princeton Plasma Physics Laboratory (PPPL), LLNL, Oak Ridge National Laboratory (ORNL), Columbia University, the University of Texas, the University of California Los Angeles (UCLA), and the University of California San Diego (UCSD). Many members participate by video or teleconference to reduce travel expenses. The membership of the 2013 DIII-D Executive Committee is shown in Table 10-1.

Table 10-1
DIII-D Executive Committee Membership and Affiliations

Chair: Mickey Wade (GA)	**Vice Chair:** David Hill (LLNL)	
Steve Allen (LLNL)	Ken Gentle (U. Texas)	Jerry Navratil (Columbia U.)
Max Austin (U. Texas)	Charles Greenfield (GA)	Raffi Nazikian (PPPL)
Rejean Boivin (GA)	Jeremy Hanson (Columbia U.)	Tony Peebles (UCLA)
Richard Buttery (GA)	Don Hillis (ORNL)	Terry Rhodes (UCLA)
Vincent Chan (GA)	Eric Hollmann (UCSD)	George Tynan (UCLA)
Edward Doyle (UCLA)	Arnie Kellman (GA)	Zeke Unterberg (ORNL)
Max Fenstermacher (LLNL)	George McKee (U. Wisconsin)	Randy Wilson (PPPL)
Ray Fonck (U. Wisconsin)	Richard Moyer (UCSD)	

DIII-D Program Advisory Committee (PAC). The DIII-D Program Advisory Committee is composed of 14 experts in the field not directly involved in the DIII-D Program, as shown in Table 10-2. It reports to the GA Vice-President for Magnetic Fusion Energy (MFE). The PAC meets openly at least once per year, responding to specific charges, which generally seek their comment on the Experimental Plan for the coming year and other issues prominent at the time (e.g., they were asked to comment on this Five-Year Program Plan during its development). Formally, their report is given to the Vice-President for MFE, though it is shared with the U.S. Department of Energy (DOE) and broadly distributed to members of the DIII-D Team.

Table 10-2
FY13 Program Advisory Committee Members and Affiliations

Prof. Riccardo Betti, U. Rochester	**Dr. Myeun Kwon**, KSTAR – NFRI, Korea
Prof. Dylan Brennan, U. Tulsa	**Dr. Wayne Meier**, LLNL
Dr. David Campbell, ITER Organization, Cadarache	**Dr. Jerry Hughes**, ALCATOR C-Mod, MIT
Professor Cary Forest, U. Wisconsin, Madison	**Professor Mark Koepke**, West Virginia University
Dr. Takaaki Fujita, JT-60SA (JAEA)	**Dr. Francois Waelbroeck**, U. Texas, Austin
Dr. Stefan Gerhardt, PPPL	**Dr. Yuanxi Wan**, ASIPP Heifei, China
Dr. Lorne Horton, EFDA JET Project	**Dr./Prof. Hartmut Zohm**, Max Planck Institute, Garching

Research Council. The Research Council (RC) is a large multi-institutional advisory group (27 members for FY13) chaired by the DIII-D Deputy Program Director. It is composed of scientists at all levels representing the various research areas, program management structures, and major collaborators. Its principal role is to advise and assist the DIII-D Director and his staff on matters relating to development and execution of the experimental program, such as goals and objectives, relative research and hardware priorities, topical balance, and run-time allocations. Table 10-3 lists the members of the FY13 Research Council.

Table 10-3
FY13 Research Council Members and Affiliations

Chair: David Hill (LLNL)	**Vice Chair:** Punit Gohil (GA)	
Experimental Coordinator: Max Fenstermacher (LLNL)	**Assist. Experimental Coordinator:** Dan Thomas (GA)	
Steve Allen (LLNL)	Arnie Kellman (GA)	Phil Snyder (GA Theory)
Richard Buttery (GA)	Tony Leonard (GA)	Wayne Solomon (PPPL)
Edward Doyle (UCLA)	Tim Luce (GA)	Ted Strait (GA)
Andrea Garofalo (GA)	Rajesh Maingi (ORNL)	Tony Taylor[a] (GA)
Charles Greenfield (GA)	George McKee (U. Wisc.)	Zeke Unterberg (ORNL)
Jeremy Hanson (Columbia U.)	Richard Moyer (UCSD)	Mike Van Zeeland (GA)
Eric Hollmann (UCLA)	Raffi Nazikian (PPPL)	Mickey Wade (GA)
Dave Humphreys (GA)	Craig Petty (GA)	

[a]Ex Officio.

Experimental Science Division and Physics Groups. The Experimental Science Division is responsible for developing and executing the overall DIII-D Research Plan. This Division is composed of three physics groups:

1. Dynamics and Control
2. Boundary and Pedestal Physics
3. Burning Plasma Physics

This high-level structure is aligned closely both with DIII-D's long-term research objectives and with the research needs of the DOE Fusion Energy Sciences (FES), as outlined in the 2010 Fusion Energy Science Advisory Committee (FESAC) Research Needs Workshop (ReNeW) report. The scientific content and expertise within these groups is broad topically and institutionally, so each is divided into Topical Area Working Groups. All scientists and students participating in on-site research are assigned to one of the three Physics Groups.

The **Dynamics and Control Group,** led by Dr. Wayne Solomon of the Princeton Plasma Physics Laboratory, is responsible for developing the physics basis for integrated operating scenarios for ITER and the Fusion Nuclear Science Facility (FNSF). This integration includes research in the areas of scenario development, plasma control, stability, disruptions, and heating/current drive. This group also provides the physics operators supporting DIII-D experiments.

The **Burning Plasma Physics Group**, led by Dr. Craig Petty of General Atomics, is responsible for advancing the predictive capability of critical physics phenomena in burning plasmas. Activities of the group include core transport and turbulence, L-H transition physics, and energetic particle research. Validation of comprehensive physics models in the areas of transport and energetic particles is a key focus of this group.

The **Boundary and Pedestal Physics Group**, with co-leaders Rajesh Maingi (PPPL) and Tony Leonard (GA), is responsible for developing an improved physics basis and control solutions for the pedestal and boundary regions. Activities of this group will include research on pedestal structure, edge localized mode (ELM) control, scrape-off-layer physics, and plasma-material interactions.

Specific research activities in the Experimental Science Division are organized and executed by **Topical Area Working Groups** and by **Task Forces**. Topical Area Working Groups are organized within each of the three Experimental Science Physics Groups, but may draw participants from across the organization (including the General Atomics Theory group). Task Forces address near-term high priority research that is cross-cutting in nature, which is best managed by a team of experts specifically assembled for the task at hand. Both types of groups are responsible for experimental planning, execution, and data analysis. Working Group leaders report to their Physics Group Leader, while the Task Forces report directly to the Division Director. Leadership of Task Forces and Working groups constitutes a significant programmatic responsibility, which often leads to increased leadership opportunities for DIII-D program scientists, including those from universities and other collaborating institutions. Figure 10-1 shows the Working Group and Task Force structure for FY13.

DIII-D Operations Division. This group is responsible for the safe and efficient operation, maintenance, refurbishment, and upgrades of the DIII-D facility. They oversee all the major hardware systems on DIII-D, including the auxiliary heating and current drive systems, the DIII-D vessel and coil systems, all major power supplies, vacuum systems, water systems, and cryogenic systems. This division is organized into six groups: Tokamak Operations, Mechanical Systems, Neutral Beam Systems, Electron Cyclotron Systems, Fast Wave Systems, and Electrical Systems. Staff from the major collaborators (PPPL, LLNL and ORNL) are responsible for a number of significant hardware systems and serve in key support positions within the Operations Division.

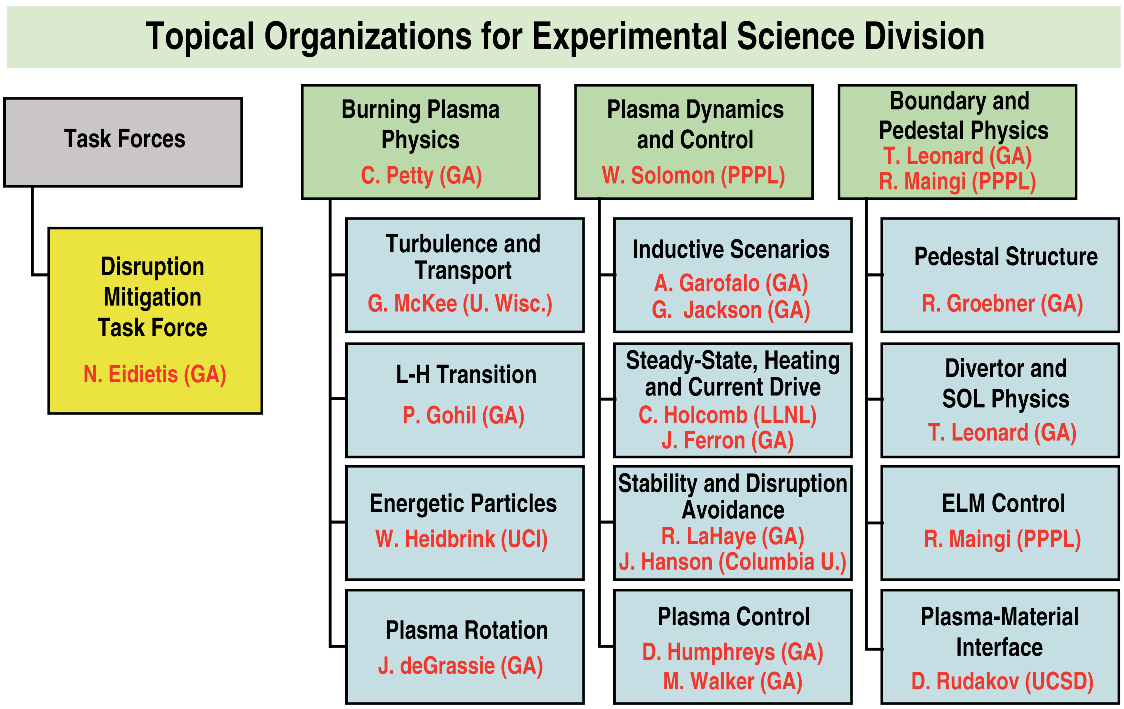

Fig. 10-1. Line Management organization of the DIII-D Experimental Science Division. Task Forces are formed regularly to address high visibility, high priority research topics and report directly to the Division Leader. The Disruption Task Force is new for 2013.

Theory Division within the Magnetic Fusion Energy Group at General Atomics. The DIII-D program relies on and benefits from close connection to theory; direct support is provided for theory effort on pedestal physics and ELM control, transport simulation, MHD stability, and disruption modeling. DIII-D scientists participate in a broad range of collaborations with theorists from around the U.S. and abroad. The DIII-D program provides data for validating new theory and models; conversely, theory motivates and guides planning for many DIII-D experiments. The theory group at GA includes scientists from other institutions (e.g., UCSD) who spend a majority of their year onsite at GA. The theorists work closely with the DIII-D program, providing not only general theory support, but also extending to key data analysis codes such as EFIT and the ONETWO profile analysis codes and simulation tools such as the NIMROD resistive MHD and XGC0 PIC edge plasma codes. Members of the theory group (both GA and non-GA staff) serve on both the DEC and the Research Council.

10.2. PROGRAM PLANNING

Planning for the DIII-D National Program is carried out in partnership with DIII-D management, DIII-D collaborators, and the DOE-FES Program, with input provided by the broader (national and international) fusion community. Program plans range from daily experiments to this Five-Year Program Plan. Both General Atomics and its DIII-D collaborators provide regular reporting to DOE. In this section, we outline the planning process at various levels, starting from the longer-term perspective moving to more near-term focus.

1. A **Five-Year Program Plan** is prepared every five years through open interaction of the DIII-D Team with the international fusion community and the DOE-FES Program:
   a. A draft Five-Year Plan is prepared by the DIII-D National Team. Multi-institutional teams are formed to develop various possible program elements for inclusion in the Five-Year Plan.
   b. The draft plan is presented to the DIII-D Program Advisory Committee for their consideration. Their feedback may lead to changes in the proposed plan.
   c. GA proposes the five-year research program to the DOE FES. Companion documents from the major collaborators, which lay out the planned contributions of the collaborator, are also submitted to provide a complete view of the proposed five-year DIII-D National Program to the FES program management.
   d. A formal GA proposal for a Cooperative Agreement, with content based on the Five-Year Plan, is reviewed by a panel appointed by the DOE FES.
   e. Once in place, the Cooperative Agreement between GA and the DOE may be updated to make it consistent with evolution of the national program priorities and with technical developments in the international fusion effort.
2. An **Annual Experimental Plan** is prepared as follows:
   a. The Experimental Science Division summarizes the previous year's results at the DIII-D Year-End Review, which is an open meeting featuring remote participation to national and international participants. This meetings provides the technical basis to begin developing the experimental plan for the next fiscal year's operation.
   b. High level research goals covering the next 1-3 years are put forward for consideration by the DIII-D Research Council and the full research team.
   c. Following the initial discussion of possible research goals, the DIII-D Director works with the staff to identify high priority research topics and then provides initial guidance for allocating 80% of experimental time among the research topics. Special Task Forces may be created to address a particular topic. The remaining 20% of the run time is reserved for allocation in mid-year following an evaluation of progress on the achieving research goals.
   d. An international Research Opportunities Forum (ROF) provides the opportunity for the community to propose experiments within the thrust and topical areas. The schedule is arranged to facilitate interactive remote participation from across the U.S., Asia, and Europe. A special session is organized to hear and discuss proposals from the ITER Organization in Cardarache, France.

e. Based on the proposals, Task Force and Working Group leaders work with groups interested in the specific research area to prepare detailed experimental plans. These plans are presented to the Research Council for final review of the overall program balance.

f. The DIII-D Executive Committee (Section 10.1) and the international DIII-D Advisory Committee (Section 10.1) also review the draft experimental plan.

g. The Experimental Plan is reviewed on a monthly basis during tokamak operations, taking into account changing hardware availability and DIII-D or national program priorities as provided by the OFES, the USBPO, or the ITER Project Office.

3. **Monthly and Daily Experimental Planning** is managed by the DIII-D Experimental Coordinator in consultation with the Director of DIII-D Operations, the Director of the Experimental Science Division, and program scientists.

10.3. FUNDING OF RESEARCH ON DIII-D

DIII-D National Fusion Program participants receive funding from seven different pathways:

1. The major participating laboratories in the DIII-D Team [GA, PPPL, LLNL, ORNL, Sandia National Laboratory Albuquerque (SNLA)] receive their funding directly from the DOE-FES Program.
2. GA issues subcontracts to universities and industries for specialized diagnostics and technical services.
3. Universities, laboratories, and private industry receive direct support to participate in the DIII-D research program in response to specific funding opportunity announcements from DOE or the National Science Foundation (NSF); e.g., diagnostic competitions, joint projects between DOE and other government agencies, Early Career Awards or Young Investigator Awards, and Small Business Innovative Research (SBIR) awards. Major university participants on DIII-D presently receiving DOE funding include UCSD, UCLA, U. Texas, Columbia U., U. Wisconsin, and Georgia Tech.
4. Private industry may support a collaboration using corporate funding. These are usually focused on targeted technology, product, or application development.
5. Funding for international collaborators traveling to DIII-D is generally provided by their home institution (e.g., salary and travel), though in some cases, the DIII-D Project provides local transportation and housing for short periods of time. DOE is changing its emphasis and management of outgoing international collaborations in response to a recent advisory panel report. Further details regarding international collaborations may be found in Section 9.

10.4. REPORTING DIII-D PROGRAM ACTIVITIES

1. DIII-D issues weekly highlights to the broader fusion research community on program activities. These highlights are available on the Web at https://diii-d.gat.com/diii-d/Weekly.
2. Each year the American Physical Society Division of Plasma Physics (APS/DPP) solicits press releases from its membership to highlight at its annual meeting. The DIII-D program supplies a number of announcements suitable for general release.
3. The DOE FES regularly requests research highlights from the DIII-D program for posting on the DOE FES public Website.
4. DOE conducts quarterly reviews of the program. GA and major collaborators report on facility operations, technical accomplishments, budgets, safety matters, and outstanding issues.
5. The DIII-D Program Director holds monthly videoconferences with the DOE-FES Research Division Director, Dr. James Van Dam.
6. The annual Experiment Plan is submitted to DOE in the second quarter of the fiscal year.
7. DIII-D program activities are discussed at meetings of the Fusion Facilities Coordinating Committee (FFCC) for coordination with other major U.S. facilities such as the National Spherical Torus Experiment (NSTX) at PPPL and ALCATOR C-Mod at MIT.
8. DIII-D program plans for the next two fiscal years are presented each year (typically in March) to the DOE-FES program managers at a meeting at Germantown in both talks and in printed reports.
9. DIII-D program activities are discussed extensively at meetings of the USBPO. DIII-D results frequently form the core technical content of USBPO reports and recommendations.
10. DIII-D results are presented at the biennial International Tokamak Physics Activity (ITPA) workshops which are organized under the umbrella of ITER.
11. DIII-D is a major contributor to national and international fusion and plasma physics meetings and conferences including the APS, the European Physical Society (EPS), the International Atomic Energy Agency (IAEA), the Plasma Surface Interactions (PSI) and to many special workshops, such as the annual MHD Workshop.
12. DIII-D research results are reviewed and published in many scientific, technical, and engineering journals. An extensive bibliography of DIII-D publications resulting from the previous Five-Year Cooperative Agreement appears in Section 12 at the end of this document.
13. The GA DIII-D Website at https://fusion.gat.com/global/DIII-D provides an extensive collection of public information about the DIII-D program.

10.5. DIII-D SAFETY PROGRAM

DIII-D Management is committed to maintaining an Environmental, Health and Safety (EH&S) program that places high value on ensuring the protection of life, the environment, and the facility. The highest priority is placed on the safety of personnel, collaborators, visitors, students and contractors working on-site. Because of the multi-institutional nature of the program and the complexity of the facility, an integrated and comprehensive approach toward EH&S issues was developed. As part of this integrated effort, the DIII-D program has assisted the GA corporate EH&S group that provides professional and licensed guidance and assistance in the areas of Health Physics and Radiation Safety, Industrial Hygiene, Industrial Safety, Environmental Health and Compliance. GA corporate provides training, reviews all hazardous tasks, maintains a database of Material Safety Data Sheets (MSDSs) for chemicals at the DIII-D site, and participates in all incident reviews at the DIII-D site.

In addition to GA management and GA corporate EH&S, the safety program is a broad-based program that emphasizes communication among all program participants and enables input from all levels of staff. The DIII-D safety engineer and Operations Director are assisted by the MFE Safety Committee consisting of members of all operation groups, technicians, engineers, research staff, diagnostic staff, with participation from the collaborating scientific staff. Standing committees for electrical, chemical, and laser safety are available to provide guidance and review of hazardous tasks. Safety issues are routinely discussed at weekly science meetings, daily status meetings, and management staff meetings. The DIII-D Safety Officer also interacts with the safety personnel from the other fusion laboratories in the U.S. and participates in an international Fusion Safety Working group that visits and inspects other world fusion laboratories.

At its heart, the safety program at DIII-D is based on the principles and core functions of Integrated Safety Management (ISM). A brief description of how each of the ISM principles are implemented at DIII-D and customized to this multi-institutional facility is described below.

1. Responsibility of DIII-D Line Management for Safety of all staff and workers.
    a. Managers, including supervisors, are responsible for safety of personnel and for maintaining a safe work environment in the area under their control.
    b. All personnel that work at the DIII-D site, whether permanently sited here or on temporary visits (students, visiting scientists) are assigned to a GA line manager who is responsible for reviewing their job assignments, safety training needs, and providing the needed training. There is no distinction made in the safety needs or training of GA and non-GA staff.
    c. All levels of management are responsible for safety and are delegated the necessary authority to implement safety policies and procedures.
    d. Safety is discussed at all staff meetings of the Program Director and Operations Director. Incidents are discussed and metrics on training compliance levels are provided to management at each staff meeting.

2. All staff, including line managers, task leaders, and employees have clear and well-defined roles and responsibilities in the safety program.
   a. GA line managers are responsible for providing the required safety training for the work and ensuring that safe work practices are followed.
   b. Functional Supervisors are responsible for daily supervision of staff. For collaborators, these are often from their home institutions.
   c. Task Leads are responsible for getting work done safely. They must analyze the job, identify hazards, plan the work, and review safety issues with the workers and notify management of specialized training required for their staff working on these tasks.
   d. All DIII-D staff (GA and non-GA collaborators, students, permanent, temporary, on-site or visiting) are responsible for working safely and completing all training identified for their job classification.
   e. All employees have the authority to stop work if there is a safety issue. They must not perform work if they feel they are not adequately trained.
   f. Additional roles and responsibilities are assigned to tasks specific to DIII-D Operations, such as Chief Operator, Radiation Management Officer, Test Coordinator, Pit Coordinator, and the DIII-D Safety Engineer.
3. Appropriate training provided for job responsibilities.
   a. There is an extensive training program at the corporate level and the DIII-D program level. Numerous training courses for non-DIII-D specific tasks are provided by the GA corporate EH&S group, such as forklift training, cranes, confined space entry, ergonomics, first aid, CPR, Lock-Out-Tag-Out, Qualified Electric Worker, and Hazard Communication/Hazardous Waste. Training and oversight in the use of Personal Protective Equipment (PPE), (e.g., SCBA air respirators) is also provided by GA corporate.
   b. DIII-D Safety Officer can determine if training provided by home institutions is accepted as DIII-D required training.
   c. Training for tasks associated with DIII-D specific tasks is formally identified in the job hazard analysis documents described below. These include hazards associated with DIII-D specific hazards (microwaves, high voltage, cryogenics, etc.) and DIII-D specific equipment.
   d. An on-line training database covering the training records of all DIII-D personnel is maintained that allows workers at all levels to keep track of their training and of the training of those who report to them. Training requirements are reviewed quarterly by all line managers and monthly reminders are sent out to all staff and management reminding them of upcoming classes and soon-to-be-expired training.
   e. A limited set of on-line classes for required training are available. Additional on-line classes are being developed to improve access for part-time visiting staff. On-line registration for classes is available.

   f. All staff, including short-term visiting researchers receive on-site safety orientations and are trained in DIII-D work procedures if their work at the facility extends beyond participation in experiments using control-room data terminals.

4. Balanced priorities.

   a. Consideration of EH&S needs are integrated into all activities of a project starting with the planning stage. Identification and mitigation plans of all hazards and safety issues must be addressed at the conceptual design review.

   b. Safety considerations are a higher priority than either schedule or budget issues and staff is reminded of this repeatedly. Good project planning is emphasized and is essential to avoiding undue pressure on staff. Adequate time for performing repairs, maintenance, and upgrades is built into the facility schedule.

5. Identification of safety and environmental standards and requirements.

   a. DIII-D is subject to a wide range of Federal, State, County, City, GA corporate, and DOE requirements.

   b. A Policy and Procedures Manual exists and is updated periodically to reflect new and updated regulations.

6. Hazard controls are tailored to DIII-D operations.

   a. A key element of our safety program is a Hazardous Work Authorization (HWA). This is the primary process to review tasks for hazards, compliance with safety regulations, and to specify plans for eliminating or mitigating the hazards. Hazards are described for each subtask of a process/project and a discussion of engineering controls, administrative controls, or PPE is included in the document. The document is reviewed by DIII-D management, the DIII-D safety committee and safety engineer, and GA corporate EH&S group.

   b. GA corporate EH&S input is included early in the design process for new equipment and new processes.

   c. All DIII-D personnel involved in the task are identified on the HWAs and trained in the job hazards and the control methods for the hazards.

   d. Formal Site Access Control procedures have been developed to provide personnel safety during different modes of operational status of the facility. The DIII-D access control system provides a graded approach to safety depending on the hazard level.

7. Operations authorization.

   a. Readiness reviews are held for new equipment and address both personnel and equipment safety before starting a new piece of equipment or existing equipment is modified.

   b. HWAs require the approval of both DIII-D and corporate management and the DIII-D Safety Committee.

   c. Work performed in the DIII-D machine hall is reviewed for safety and requires a Pit Work Authorization approved by the DIII-D Operations Division Director.

   d. All work performed in the machine hall is inspected daily by the machine pit coordinator.

Feedback and continuous improvement is a key feature of the DIII-D safety program. This involves regularly scheduled lab and office inspections, formal reporting and investigations of all incidents and near-misses to identify and prevent root causes of incidents, Significant Event Reviews, and annual reviews of all HWAs. Periodic safety audits are also held. A recent Safety Review of the entire DIII-D safety program with three levels of management was held to examine safety culture, identify gaps in the safety program, and develop an action plan to address the gaps. Input for this review was provided from small meetings of all DIII-D staff.

Because of production of neutrons, gamma and x-rays, there is an active radiation management program at DIII-D that is directed by the Manager of Tokamak Operations and reviewed by the GA Health Physics group. In addition to staying well within regulatory dose limits, the DIII-D program follows the ALARA (as low as reasonably achievable) principle. Consistent with this principle, radiation production is minimized (consistent with good research operations). Daily and long-term work schedules are adjusted for both in- and ex-vessel work to minimize dose exposure.

This comprehensive safety program ensures that the DIII-D facility is a safe environment to effectively perform experiments for both on-site and off-site visiting scientists.

10.6. MANAGEMENT OF THE COLLABORATIVE NATIONAL TEAM

10.6.1. General Principles of Collaboration

The following principles serve as guidelines for conducting institutional collaboration on the DIII-D Program:

1. Advancement of the DIII-D Program is held by all participating institutions to be essential for advancement of U.S. fusion energy science and to be in the interests of all DIII-D program participants.
2. Collaborators will accord high priority to their DIII-D commitments, both in the use of resources and in the assignment of personnel. GA will recognize that collaborating personnel assigned to DIII-D activities have additional responsibilities in their home programs.
3. In support of the DIII-D Program objectives, collaborators may assume lead responsibilities in defined areas and participation in other areas which may be spelled out in an institutional Memoranda of Understanding (MOU). "Lead responsibility" does not imply sole responsibility. In those areas where it does not hold a lead, a party may elect to retain significant minority participation sufficient to develop and sustain expertise in the area. These lead or support roles will be based on consensus assessments of capability and party needs by the program leadership. Individuals or groups which wish to collaborate on DIII-D should negotiate with the institution having recognized lead task responsibility. Cases of disagreement should be called to the attention of the director and Executive Committee. Institutions having lead responsibility for a task are not to delegate responsibility to another party without approval of the director.
4. GA will have sole responsibility for operating the DIII-D tokamak, though it counts on support from collaborating institutions. If a collaborator has a lead role involving an auxiliary hardware system on DIII-D, they may undertake the responsibility to operate that system. The scope of the collaborator's responsibility regarding design, construction, and operation of systems will be documented.
5. In order for the DIII-D Program to accomplish its programmatic objectives while providing individual researchers opportunities to pursue rewarding research, it is generally expected the participants will carry out both an agreed-upon research program and DIII-D program-related support tasks (e.g., leading research groups, preparing and presenting reports to DOE, operating a diagnostic, analyzing data, or assisting in research planning).
6. All data, raw or analyzed, will be considered the property of the DIII-D Program and will be accessible to others in the program. The rights of first authorship and lead responsibility will be respected. It is expected that GA staff and collaborators operating diagnostics or doing specialized analysis will provide data into defined DIII-D databases on a routine basis and to other members of the program when requested. Such contributions will be acknowledged appropriately.
7. Subject to DOE's technical data rights and patent rights, all data and results from the DIII-D Program will be freely shared and acknowledged between the collaborating parties. In general, all publications or reports must go through the standard GA DIII-D review cycle. However, in the case that the subject work is principally done by collaborating personnel using collaborators

equipment and codes, the publication or report may be submitted through the collaborating institution's review process. In such cases, a copy must be provided for timely courtesy review by the responsible DIII-D research area coordinator and division director. DIII-D division directors will make the determination of the appropriate review channel. Publications and reports will clearly identify that the work was done on the DIII-D tokamak and acknowledge DOE funding support. Detailed requirements for presentation formats, use of logos, and issues related to invited talks and papers will be managed by the DIII-D Program Director with review by the DIII-D Executive Committee.

8. DOE data and patent rights, as specified in GA's contract with DOE, will take precedence in all work done on or derived from DIII-D.
9. All GA data which GA identifies as proprietary will be protected by individual collaborators and collaborators' institutions.
10. Collaborating institutions are expected to participate in all DIII-D related DOE and community reviews.

10.6.2. Documents Governing Active Collaborations

MOUs are written between GA and major collaborators. MOUs generally cover the historical background that led to the collaboration, the institutional goals and requirements of both parties for participating in the collaboration, the principles and agreed upon procedures for the collaboration, and a definition of lead and participatory roles for the collaborator. The MOU is signed by the program leaders of GA and the collaborating institution.

10.6.3. Approval Process for Project Activities

A graded approach is used for Project Management involving the DIII-D facility. All DIII-D participants, as well as outside technical specialists, may review project plans and provide advice. Progress, costs, and schedules for special projects are reported at DOE Quarterly Reviews. DIII-D Program tasks for both GA and collaborators are summarized in common master schedules and milestones. A manual describing the work procedures for DIII-D tasks and projects is available for all DIII-D personnel and collaborators. This manual describes a sequence of procedures which establish a uniform approach to developing and maintaining new capabilities at DIII-D including designing, engineering, fabricating, installing, and maintaining hardware and equipment on the DIII-D tokamak or any of its related systems. Procedures are also included to guide the performance of work in the machine pit and within the facility. Depending on the complexity of the proposed task, the review and approval process may include a:

- Physics Validation Review describing research need and proposed actions to address the need.
- Conceptual Design Review to lay out the proposed technical approach.
- Preliminary Design Review to assess design features and overall plan at an early stage.
- Final Design Review to assess all elements of the design prior to beginning work.
- Operational Readiness Review to assess status of all systems, controls, and training prior to commissioning the system.

These work procedures undergo periodic review and updating.

10.6.4. Budget Planning for DIII-D Projects

Budgets for program tasks are generated by all tasks managers working with the DIII-D Planning and Control Group and submitted to the DIII-D program director for distribution to the Executive Committee and the DOE as needed. Task priorities are set by the DIII-D program director in consultation with the DIII-D Executive Committee and in accordance with GA's contractual requirements with the DOE. Resource disbursements are made with input from collaborating DIII-D program leaders. The Executive Committee may also make recommendations on program priorities of collaborators. Disagreements between parties will be arbitrated by DOE when they cannot be resolved by the Institutional Leadership.

10.6.5. Program Reporting

GA will submit all required plans and reports identified in its contract with DOE. GA will prepare a DIII-D Experimental Plan each year that details all planned experiments for that year including those to be performed by collaborators. It will be reviewed quarterly in conjunction with the DOE Quarterly Contract Review and updated as needed. The Plan will be prepared by the DIII-D Experiment Coordinator with input from the Experimental Science Division. Before submission to DOE for approval, it will be reviewed and approved by the DIII-D Program Director.

Technical program reports will be submitted quarterly as part of the DOE Quarterly Review or as needed. An Annual Technical Report and Final Contract Technical Report will also be submitted. An overall Management Plan will be submitted after contract award. At the beginning of the contract and on a quarterly basis thereafter, GA will submit management status and summary reports. Annually, GA will submit a milestone schedule plan, cost plan, and milestone schedule status report. DOE may also require a program review at the midpoint of this Five-Year Cooperative Agreement.

11. ACCOMPLISHMENTS AND HISTORY OF THE DIII-D PROGRAM

11.1. OVERVIEW

The DIII-D National Fusion Program is recognized to be one of the most productive fusion research programs in the world as measured in terms of the impact of results, in uncovering fundamental phenomena, in the overall number of publications, citations, and awards. These contributions have been made over a wide range in plasma science and fusion technology. The DIII-D results have had a large impact on the direction of worldwide magnetic fusion research and progress toward fusion energy. An essential ingredient in this success has been the integration of contributions from a wide range of collaborators from around the world together with the participation of DIII-D staff in research at other facilities throughout the world. Currently the DIII-D program is strengthened by collaborations from 99 institutions around the world. The influence of DIII-D results can be seen in the design of some of the present operating tokamaks in the world, including the Mega-Ampere Spherical Tokamak (MAST), the National Spherical Torus Experiment (NSTX), the Korean Superconducting Tokamak Advanced Research (KSTAR), and China's Experimental Advanced Superconducting Tokamak (EAST), and in the design of ITER.

The present five-year program (2009–2013) being completed has continued this high-level of productivity — enabled by new hardware and diagnostic capabilities that have come on line during this period. In this section, we highlight some of the past DIII-D accomplishments as a prologue to future DIII-D success in fusion research and in the program's capability to deliver on the proposals and plans detailed in this document.

11.2. DIII-D ACCOMPLISHMENTS

The DIII-D Tokamak program at General Atomics (GA) has made many scientific contributions to the worldwide fusion effort. The prescient pursuit of shaped plasmas drove the pioneering shape control techniques that were rewarded in record plasma beta values and reactor-relevant fusion triple products, $nT\tau$, demonstrating that a stable reactor core can exist. The hallmark of the DIII-D Research Program is the integration of magnetic fusion focused scientific research and advanced plasma control techniques into new operating scenarios aimed at optimizing the tokamak, providing improved regimes for ITER, and developing high performance scenarios for an advanced tokamak (AT). In the present five-year plan the DIII-D program focused on validating the physics basis for the ITER design by providing critical physics solutions for key issues to ensure ITER's success. These particular ITER contributions are detailed in Section 11.7.

Table 11-1 lists significant DIII-D contributions to burning plasma research. Many of these results are now the basis of every day experimental operation at DIII-D, while others continue to be refined and developed further because of their importance for ITER and the design of follow on tokamak reactors.

Operational hallmarks of the DIII-D program over the years have been reliability, flexibility, and adaptability. Since the Department of Energy (DOE) established metrics for the operational performance of the U.S. magnetic fusion facilities in 2001 DIII-D has surpassed each yearly target for run time. DIII-D was designed to be highly flexible in experimental capability, having very good diagnostic access and, of course, the ability to control a wide range of plasma shapes. The fact that a DIII-D plasma shape can be programmed to emulate the shape of virtually any tokamak operating worldwide has been invaluable in determining the dependence of key plasma parameters on machine size, and magnetic field strength. This capability has been used for numerous scaled "wind tunnel" comparisons of phenomena between DIII-D and other tokamaks, both larger and smaller physically.

Table 11-1
Major DIII-D Contributions to Tokamak Plasma Research

- Pioneered non-circular toroidal plasmas in the tokamak.
- Developed magnetohydrodynamic (MHD) equilibrium analysis for non-circular plasmas based on magnetic measurements, the pressure profile, the current profile and rotation. The DIII-D equilibrium code "EFIT" is now used by institutions throughout the world for shaped tokamaks.
- Established the open poloidal divertor shape to effectively manage the flow of impurities from the plasma core.
- Developed active divertor plasma pumping to allow control of the particle inventory.
- Optimized plasma shaping for simultaneous high plasma performance and divertor control of the heat and particle flux.
- Exported the DIII-D-developed digital plasma control system to divertor tokamak groups throughout the world.
- Demonstrated fast wave (FW) radio frequency (rf) current drive (CD) and validated theory.
- Pioneered millimeter wave gyrotron system implementation and launching technology.
- Demonstrated electron cyclotron heating (ECH) and current drive (ECCD), and validated theory.
- Used ECCD to suppress and control deleterious neoclassical tearing modes.
- Combined an understanding of the roles of plasma shape and internal profiles for stability to demonstrate discharges that satisfy the high gain goals of burning plasma conditions.
- Stabilized resistive wall modes (RWMs) with feedback controlled non-axisymmetric magnetic perturbation coils, thereby increasing the accessible plasma β.
- Identified toroidal Alfvén eigenmodes and their role in transporting fast ion energy out of the plasma.
- Pioneered the use of non-dimensional transport scaling experiments for plasma characterization, thereby providing a scientifically sound basis for projecting present results to future burning plasmas.
- Experimentally verified the role of *ExB* velocity shear in stabilizing turbulence, creating transport barriers, and thereby increasing plasma confinement.
- Demonstrated effective techniques for avoiding and mitigating disruptions.
- Discovered that edge localized modes (ELMs) can be stabilized by the application of small non-axisymmetric resonant magnetic perturbations (RMPs).
- Demonstrated that rapid injection of frozen deuterium pellets can trigger more rapid smaller ELMs and bring the resulting pulsed heat load down to tolerable levels for ITER.
- Discovered the QH-mode of operation, having no ELMs, and demonstrated that it is compatible with burning plasma capabilities.
- Developed a coherent, predictive theoretical model for H-mode pedestal stability, informed by a very large body of DIII-D experimental results.
- Identified, motivated, and demonstrated the value of the AT concept for enhancing the value of a power producing burning tokamak reactor.

Regarding the adaptability of the program two recent examples of DIII-D rapid response to emergent ITER needs are described. First, through international ITER meetings it became apparent to DIII-D plasma operational experts that the designed ITER shape control system would not be adequate to achieve the plasma ramp-up and ramp-down scenarios being planned, without encountering likely disruptions. Experiments were soon initiated in DIII-D that verified this to be the case, and then went on to develop other ramping scenarios that could be achieved by a somewhat upgraded ITER shaping coil system, that became the redesign from the original.

In the second, ITER made a request to DIII-D seeking any possible experiment that could be done to evaluate potential problems that might arise from the ITER Test Blanket Modules (TBMs) which will contain ferritic material, thereby adding non-axisymmetric magnetic perturbations. In a relatively short time, a TBM "mock-up" was fabricated that could be inserted into one of the large DIII-D ports, mimicking the actual TBM fields with two electromagnet coils. Experiments were performed, and the modest modifications in plasma parameters were measured. Further experiments have shown that there is a potential to obviate the effects of the ITER TBMs with appropriately designed compensating coils. For both of these ITER rapid response efforts in DIII-D the results have been disseminated at international meetings and published in archival journals.

11.3. HISTORY OF THE DIII-D PROGRAM

The General Atomics Tokamak Program has a history of creative concept development. The program began in 1968 with the Doublet I device, the first tokamak with a highly noncircular cross section, using solid copper walls to shape the plasma. Experiments on this device showed the doublet configuration to be magnetically and dynamically stable. These successes led in 1971 to the larger Doublet II device, also with solid copper walls. Doublet II was reconfigured in 1974 to use external coils to replace the copper walls. The new device was named Doublet IIA, and it pioneered the use of external coils to shape a wide range of highly noncircular plasmas and maintain them in nondecaying magnetic configurations.

The success of these experiments led to construction of the Doublet III device, completed in 1978. In the first years of operation, it was the largest operating tokamak in the world and attained the highest plasma current levels recorded at that time (2.2 MA). Experiments with a broad range of plasma configurations demonstrated the importance of elongation and shape control. Dee-shaped plasmas proved easiest to form and were projected to reach β values adequate for viable power plants. Diverted dee-shaped plasmas were also effective in achieving reduced impurity levels and enhanced confinement.

These successes led to the reconstruction of the Doublet III tokamak into a large dee-shaped cross section capable of a wide range of plasma shapes and divertor configurations. The device was renamed DIII-D in 1986. DIII-D rapidly reached currents of over 3 MA and achieved superior levels of confinement and β. DIII-D set and still holds the record of 13% beta for a conventional aspect ratio tokamak. Another significant numerical achievement was reaching a value of the fusion triple product $nT\tau$ of 7×10^{20} keV-s/m^3 corresponding to an equivalent fusion gain of 0.3.

In the late 1980s and early 1990s, DIII-D contributed, with other world tokamaks, to developing an understanding of routine tokamak performance that projected to a successful burning plasma experiment. The main parametric dependences of plasma confinement were found to be common among the various tokamaks, allowing the development of confinement scaling laws which implied a common underlying physics for the results and which allowed empirical extrapolation to burning plasma experiments. The limits to the stable operating space were understood and the empirical beta limit was in accord with Troyon scaling and also in agreement with theory. These developments allowed the definition of the standard tokamak operating space as given by an H factor of 2 for conventional ELMing H-mode operation and a normalized beta of 2 for the beta limit. This physics basis was and is adequate to project to burning plasma experiments and ultimately fusion reactors.

However, the DIII-D Team realized that the tokamak as a magnetic confinement configuration had potentially much more to offer than this nominal performance. In the early 1990s, modes of enhanced confinement considerably above the nominal H=2 scaling were being achieved. Theory calculations implied that normalized beta values up to perhaps 6 might be possible with wall stabilization, strong shaping, and broad pressure profiles. The DIII-D Team coined the term "Advanced Tokamak" to capture that package of research issues aimed at finding out just what the limits of the tokamak configuration could be as a magnetic confinement device. Since that time a major emphasis of the DIII-D Program has been Advanced Tokamak physics. With the stabilization of the resistive wall mode, operation above the free boundary limit has been realized. Advanced Tokamak research is also closely aligned with the requirements for steady state, since a high bootstrap current fraction requires a high normalized beta and enhanced confinement at lower plasma current than is given by H=2. Discharges with 100% noninductive current have been obtained that project to Q=5 in ITER for durations in excess of several energy confinement times, and 90% noninductive discharges have been obtained for approximately a current redistribution time of 2 s. We are confident that sustaining these "steady-state" discharge conditions at 100% noninductive plasma current for several current redistribution times can be accomplished with additional co-injected neutral beam injection (NBI), off-axis neutral beam injection (OANBI) current drive, and ECCD. Advanced Tokamak research is now a major effort in many of the world tokamaks and is the main goal for a number of new and tokamaks, EAST (China, first plasma 2006), KSTAR (Korea, first plasma 2008), and Japan's Tokamak-60 Super Advanced (JT-60SA).

The importance of ITER in DIII-D research is clearly evident, especially in the research results of the last Five-Year Program Plan. Innovative solutions to the ELMs in ITER have been developed with the QH-mode and ELM suppression with resonant magnetic perturbations. New high performance operating scenarios have been developed for ITER, such as the advanced inductive and hybrid scenarios, that potentially provide higher Q in ITER or longer pulse duration for reactor-specific research in the Phase II of ITER, for example evaluating test blanket modules.

11.4. THE U.S. FUSION PROGRAM COMMITS TO BURNING PLASMAS

The U.S. magnetic fusion program has moved into the new era of burning plasmas devices. This commitment and vision have given an even greater focus to DIII-D research and technological developments in support of this new paradigm. In this, and following sections we describe how the DIII-D program has been adapted accordingly, recent results in support of ITER, and how work in this Present Five Year Plan is the basis for the forward looking Five-Year Plan that has been presented in the previous sections of this document.

ITER is a U.S. Presidential Initiative. ITER is the most important element of the U.S. fusion effort, and the success of ITER is the highest priority of the DIII-D Program. The U.S. and six other international parties have agreed to build ITER, an international Tokamak "to demonstrate the scientific and technological feasibility of fusion energy." The intent for the U.S. to move forward with ITER came in

2003, and the ITER Organization became a legal entity in November 2007. ITER construction is now a reality, and this is the most significant change in the U.S. Fusion Program over the last decade. The U.S. ITER Project Offices was formed at Oak Ridge National Laboratory (ORNL) to be responsible for the U.S. contributions to ITER construction. The U.S. Burning Plasma Organization (USBPO) was formed to advance burning plasma science and provide the coordination of the U.S. scientific efforts for ITER and burning plasmas. The DIII-D Program maintains close ties with these new U.S. organizations.

Relatively soon after the ITER Agreement, a Fusion Energy Science Advisory Committee (FESAC) report identified significant gaps beyond ITER in being able to harness fusion power. At this time, General Atomics was actively involved in developing a strategy for a Fusion Development Facility (FDF) that specifically addresses many of the gaps identified. It was recognized that the physics basis needed for FDF was the development of the basis for steady-state AT scenarios. Thus, the 2009–2013 DIII-D program maintained a vigorous effort in AT physics supporting the Fusion Development Facility/Fusion Nuclear Science Facility Advanced Tokamak (FDF/FNSF-AT) concept.

Again, in short order (2009), the DIII-D Program was honed as a result of the U.S. program's Research Needs Workshop (ReNeW), held to survey the issues identified in previous studies and begin to develop research needs required to make fusion a practical energy source. The resulting ReNeW report divided the program into 4 themes and 18 thrusts, the themes being: (1) Burning Plasmas in ITER, (2) Creating, Predictable, High Performance Steady-State Plasmas, (3) Taming the Plasma-Material Interface, and (4) Harnessing Fusion Power. It was realized that the DIII-D program could address the first three themes, while an FDF is required for the fourth. DIII-D program plans began to conform accordingly. The step to FDF-AT also became a U.S. priority. In 2010, Fusion Energy Science (FES) (E. Synakowski) presented an "Emergent FES Vision," in which he described the future program referring specifically to these four themes and articulating an urgent need for a Fusion Nuclear Science Facility Advanced Tokamak.

Additionally, plasma operation is well underway in two superconducting tokamaks in ITER-partner countries, EAST (China), 2006, and KSTAR (South Korea), 2008. The capabilities of these devices are rapidly advancing. DIII-D has had a long and productive cooperative scientific program with both facilities. We believe there is an opportunity in the near future for making rapid progress in demonstrating burning plasma relevant very long-pulse high performance discharges. We are working together with the China's Academy of Sciences Institute of Plasma Physics (ASIPP) to establish a *long-pulse initiative* where joint teams focus on accessing and developing an understanding of high performance discharges on DIII-D and then extending them to 100s of seconds on EAST. This provides an opportunity to accelerate progress on steady-state discharges and provides a firm basis for continued partnership between DIII-D and EAST/ASIPP.

11.5. CONTINUITY OF THE DIII-D MISSION

The DIII–D Program mission statement adopted in this new Five-Year Plan is

> ***To establish the scientific basis for the optimization of the tokamak approach to fusion energy production.***

This is the same mission statement as in the 2009–2013 program plan. We feel strongly that this statement captures the essence of the DIII-D Program intent, maintaining a strong focus on excellent science, focusing on innovation and optimization — with all brought to bear on the goal of an attractive fusion energy solution. Our primary goal is to maintain a strong effort in ensuring progress and success in the pursuit of fusion energy: this often translates into pursuing research to answer a specific research and development (R&D) question needed for ITER. Our focus on science is two-fold. First, addressing a research objective based on solid scientific principles and background is the most effective process to resolve the R&D issues and make progress toward fusion energy. Second, the most effective way (often the only way) to translate the knowledge gained on DIII-D to future devices is through scientific understanding and validated models. In this quest for fusion power, our aim is to do excellent science. The focus upon an energy goal determines the proper high impact science to pursue.

While focusing on achieving energy production, we are at the same time looking for opportunities to improve the tokamak concept. The DIII-D's past contributions in increased beta and performance with plasma shape, stable sustained operation above the free boundary kink limit, development of advanced performance scenarios with profile and shape, understanding of improved transport and stability with plasma rotation, and suppression of ELMs with resonant magnetic perturbations are excellent examples of transformational research that has improved the tokamak concept as a fusion energy device.

With the completion of the ITER design in 2007, and a need to resolve specific design issues for ITER, a significant emphasis of our research in the 2009–2013 plan was on ITER issues. For the new 2014–2018 Five-Year plan, we have adopted two major objectives as themes:

1. Provide access to and prepare for burning plasmas in ITER, and
2. Prepare the path to fusion energy beyond ITER.

The near term DIII-D program focus will be heavily influenced by the research needs of ITER. The first of these goals recognizes the importance of the success of ITER in the U.S. and international program, and also recognizes that the time for impact on ITER design choices is drawing to a close and that preparing for operation on ITER will become increasingly important. Thus, the near term DIII-D program will continue to focus on finding and optimizing solutions for disruptions on ITER and ELM control. However, developing and understanding operational scenarios with ITER-like conditions will become increasingly important in the DIII-D research efforts. ITER-like conditions will include, ITER shape, $T_e/T_i \sim 1$, $\nu_e^* \sim 0.02$, $\beta_N{\sim}2$, and low neutral beam (NB) input torque.

The second DIII-D theme is aimed at developing the physics basis for driven (low bootstrap fraction) advanced tokamak scenarios suitable for a Fusion Nuclear Science Facility (FNSF). This will include addressing other high priority issues such as handling the high heat flux in an FNSF. An FNSF will require significantly higher neutron fluence than ITER, and the DIII-D vision of FNSF is a medium aspect ratio device that operates high performance and in steady-state, FSNF-AT. In this five-year period, DIII-D research will inform the decision on the configuration of the FNSF, either AT or ST. The second goal also includes developing the physics basis for AT operation in DEMO.

Building on a sound and tested scientific foundation is the most reliable and most effective way to advance fusion energy. This embodies doing "science with a purpose." Continuing to advance fundamental understanding and predictive capability of fusion science is the foundation for making progress toward fusion energy and succeeding in our two major objectives.

11.6. FACILITY OPERATION AND DEVELOPMENT – PRESENT INTO THE FUTURE

The 2009–2013 Five-Year plan laid out an ambitions plan for increasing the scientific and operational capabilities of the DIII-D facility. Although the Plan had requested funding for 21 weeks of operation each year, we were scheduled to operate a total of 59 weeks for the first four years. For the first four completed years, DIII-D successfully operated at 108% of the commitment for this period, with 63.7 weeks of operation over 4 years. This included maintaining the successful operational output through the period of the Long Torus Opening II, in which the 150 deg beamline was removed and reinstalled to be tilt-able from on axis to ~ r/a = 0.5, and significant new diagnostics were added. With the addition of American Recovery and Reinvestment Act (ARRA) funds, a significant number of the hardware upgrades were implemented by innovative scheduling of the research operations and facility maintenance. The major upgrades include:

1. Increase the number electron cyclotron (EC) gyrotrons from 6 to 8 with the new gyrotrons at 1.2 and 1.5 MW nominal output. All of the gyrotrons are capable of 10 s operation. The latter, 1.5 MW tube was designed with corporate funds, has been ordered, and is being manufactured. A new power supply and launcher were built to operate gyrotrons 7 and 8.
2. Reorient the one beamline to inject from planar (on axis) to 16.5 deg off-axis (r/a ~0.5). Angle of injection can be changed in approximately 30 minutes.
3. Add a major new array of magnetic sensors for 3D fields, > 100 probes.
4. Add new and upgrade existing diagnostics; high resolution edge Thomson scattering (TS), X-point x-ray camera, main ion charge exchange, electron cyclotron emission (ECE) imaging, and others.
5. Build a magnetic mock-up of the ITER test blanket module and complete experiments to evaluate performance under the TBM perturbed field, infrared (IR) and visible periscope diagnostics.
6. Add Remote steerable mirrors to the EC system to enable real-time feedback control of ECCD to stabilize tearing modes.

These items were added while maintaining approximately 16 weeks of operation, high availability, ~80%, and excellent scientific productivity. In addition to the enhancements listed above, a significant number of diagnostics were refurbished to maintain their usefulness and productivity.

11.6.1. EC Systems

During this 2009 five-year cooperative agreement, one 1.2 MW gyrotron and the power supply for gyrotrons 7 and 8 were funded by the ARRA. A second 1.2 MW gyrotron was ordered by National Aeronautics and Space Administration (NASA) and DIII-D is now pursuing a “permanent” loan of that gyrotron. Both of these 1.2 MW gyrotrons operated at 110 GHz with depressed voltage collectors. During this period, a new 1.5 MW, 117.5 GHz gyrotron was designed using GA Corporate funds. Princeton Plasma Physics Laboratory (PPPL) and GA together are funding the purchase and installation of the new 1.5 MW gyrotron. In 2012, one of the 1 MW gyrotrons failed with a leak in the collector. Presently, DIII-D has 5 (1 MW class), 2 (1.2 MW class) and 1 (1.5 MW class) gyrotrons.

This Five-Year program plan (2014–2018) will continue to increase the EC capability of the DIII-D tokamak. The plan is to add two (1.5 MW) tubes with socket, transmission line, launcher, and power supply. In addition, the plan is to replace the weakest of the 1 MW tubes. This will bring the total number of gyrotrons up to 10 with EC injected power to ~ 8.5 MW.

11.6.2. Neutral Beam Systems

During the last five-year contract period, the 150 deg beamline was disassembled and removed from the pit area and re-installed with the capability to elevate off-axis from 0 to 16.5 deg. The entire beamline (70,000 lb) is elevated by hydraulics, and the cryo lines and high voltage electrical lines had to engineered to be moveable with the beamline. As part of this work, a number of sources were masked (limits the cross section of the beam) and the DIII-D team continues to rebuild and refurbish ion sources as needed. This work was completed on schedule. This reorientation of the beamline allowed injection of up to 5 MW of NB off-axis allowing extension of high q_{min} AT discharges. In addition, this off-axis injection enabled control of the fast ion population and important research in fast ion transport and fast ion stability. An important part of the past five-year effort was to re-establish eight-ion source operation, with the addition of one more power supply source.

This five-year program plan calls for changing another beamline for off-axis injection, and increasing the voltage of 5 ion sources to provide up to 12 MW off-axis, 19 MW co injection, and 5 MW counter injection.

11.6.3. Internal Non-axisymmetric Coil Set

In the 2009 five-year plan, additional internal non-axisymmetric coils were planned for the inner wall to evaluate RMP ELM mitigation. The project proved to be more difficult and costly than was thought, and was terminated.

In this Five-Year Program, we plan to first acquire two sets of power supplies with which the I-coils can be controlled independently. This will enable better control over the RMP field, and rotation of n=2 field to evaluate stabilization of ELMs. This will also improve the capability for error field correction, resistive wall mode, and neoclassical toroidal viscosity studies. We plan to install a set of non-axisymmetric coils in the final year of this Five-Year Program, most likely on the outer wall.

11.6.4. Divertor Thermal

With ARRA funds, we have added IR cameras, including a periscope to be able to view a large area of the inside vessel wall, to better monitor the heat flux.

In this Five-Year Program Plan, we plan to replace the graphite tiles in the divertor region with carbon fiber composite tiles sufficient to handle 120 MJ 10 s pulses.

11.6.5. Diagnostics

A significant number of new diagnostics have been implemented in the 2009–2013 Five-Year Program, including: high-resolution edge Thomson Scattering, X-point x-ray camera, 3D magnetic diagnostic set, divertor swing probe, main ion charge-exchange recombination (CER), and ECE imaging. In addition a large number of refurbishments were undertaken, such as new magnetic integrators, rebuilding of the main Thomson system with additional high power lasers, etc.

In this five-year plan, we are planning a significant number of new diagnostic systems to maintain leadership in fusion science experiments (see Section 8).

11.6.6. Fast Wave Systems

During this Five-Year Plan, significant effort was expended to demonstrate fast wave heating of H-mode plasmas with good performance. Much of the effort was expended on getting the system to operate reliably. Because of the narrow scrape-off layer, the rf loading of H-mode plasmas is decreased. Reducing the gap between the plasma and antenna (by moving the antenna closer, and the plasma closer) and local gas puffing did increase the loading, but also typically negatively impacted the plasma performance. Primarily because of the decreased budget in 2013, the FW system has been mothballed for at least 1 year, and one of three antennas has been removed.

This five-year program plan calls for operation of the 0 and 180 deg systems. In cooperation with the Russians, we are evaluating testing a helicon wave system, which has the potential of very high CD efficiency at large minor radius.

11.6.7. Disruption Mitigation Systems

The 2009 Five-Year aimed to test several material delivery techniques for disruption mitigation: shattered pellet, shell pellet, and rupture disc, as well as continue evaluating the massive gas injection (MGI). The shattered pellet was most successful. The shell pellet hardware was installed, but successful tests still remains to be done. Producing and controlling a runaway electron channel was successfully demonstrated, providing the capability to experimentally evaluate dissipation of the channel.

In the 2014–2018 Five-Year Plan, new diagnostics are planned to more accurately measure the energy and spatial distribution of the runaway electron channel. In cooperation with Tore Supra, we plan to install and evaluate rupture discs on DIII-D. Additional MGI, up to 3, will be installed to evaluate the symmetry of the radiation during the thermal and current quench.

11.7. SCIENTIFIC ACCOMPLISHMENTS IN THE PERIOD 2009–2013 AND PROJECTIONS TO THE NEW RUN PERIOD

Here we identify some of the accomplishments from the present period that apply directly to the four major technical objectives for the new 2014–2018 period. Topical areas with significant present period results are indicated as bold bullets and those underlined indicate the major thrusts for the 2014–2018 Program Plan

11.7.1. Provide Physics Basis to Resolve Remaining ITER Design Issues

- **<u>Develop and qualify ELM control solutions for ITER</u>**
  - — DIII-D has significantly expanded the region of ELM suppression with RMP coils. Suppression has been observed with both n=3 and n=2, at ITER-relevant collisionality. Using one row of coils, suppression has been extended to q_{95} ~ 3.15. A number of other experiments have demonstrated ELM mitigation with non-axisymmetric coils, Germany’s Axisymmetric Divertor Experiment Upgrade (ASDEX-U), KSTAR and Joint European Torus (JET). The ASDEX-U mitigation at high density/collisionality is very similar to initial observations on DIII-D, and joint experiments have found similar results with n=2.

— DIII-D has new diagnostic capabilities to better evaluate the plasma response to the RMP: X-point x-ray, high resolution TS, and an edge reflectometer. Combining new experimental techniques, measurements, and modeling, a new paradigm is emerging in which a small island at the top of the pedestal prohibits the further expansion of the width of the pedestal, providing stability. The proposed new power supplies and a new coil set that allows rotation of n up to 4, will improve the control of the spectrum and the capability to diagnose the plasma response.

— DIII-D discovered the so-called quiescent H-mode, an H-mode without ELMs, originally accessed by counter-I_p directed NBI. The operating regime has been expanded to low torque and positive torque, and to ITER-relevant q_{95}. Good plasma performance at ITER-relevant low positive torque is achieved.

— Pellet pacing on DIII-D at 60 Hz (3 guns at 20 Hz) has demonstrated a factor of 10 decrease in peak heat flux at the divertor resulting from the ELMs. Optimization of the size and speed of the pellets is ongoing.

- **Meet the disruption challenge for ITER**

— DIII-D has demonstrated several delivery techniques for disruption mitigation. In the next Five-Year Plan, we will compare the delivery techniques: MGI, shell pellet, shattered pellet, and rupture disc.

— DIII-D has demonstrated production and control of a runaway electron channel. With new diagnostics, in the next Five-Year Plan, we will attempt to measure experimentally the dissipation of the runaways.

11.7.2. Enhance Confidence in ITER Achieving Q=10 Objective

- **Error field control and locked modes**

— Locked mode evaluation with a proxy field has demonstrated the importance of total plasma response and non-resonant components of the error field.

— 2014–2018 Five-Year Plan will further develop plasma response models and test compensation with individually powered sectors of the I-coil or C-coil. We will continue investigating and understanding the field resulting from the ITER TBM.

- **Neoclassical tearing mode stabilization**

— Necessary to reduce the risk of disruption and avoid reduction of energy confinement and fusion output in ITER.

— Experiments during the last five years have demonstrated real-time feedback of the location of the ECCD deposition using fast mirrors. Future experiments will move toward routine implementation of this capability.

- **Improve confidence in transport predictions in the burning plasma regime**

— DIII-D has evaluated non-nuclear scenarios for rapid start-up in ITER.

— Recent experiments have developed ITER scenarios with low torque and $T_e/T_i \sim 1$, and developed QH-mode as an ITER scenario option.

— Future ITER scenario research will focus on improving physics understanding and confidence in transport predictions at ITER-relevant beta, collisionality, input torque, and with dominant electron heating, in both ITER pulsed and steady-state scenarios.

- **Toroidal Rotation**

— Toroidal rotation has a large impact on both the transport and stability of tokamak plasmas, and must be understood and accurately modeled to have confidence in transport predictions.

— Enabled by the variable torque provided by the co-counter NBIs, a careful examination of the intrinsic torque in DIII-D showed a weak scaling of intrinsic torque with device size. The experiment indicated the dominant torque in ITER would be the neutral beam torque, and that the ITER-equivalent torque on DIII-D (that which would drive the same rotation) would be very small by typical NBI utilization, about 1 N-m or less. This work motivates the development of scenarios at low torque and evaluation of transport and stability at low torque/rotation.

— Rotation will remain critical part of developing transport predictions in the burning plasma regime.

- **Pedestal predictions**

— The pedestal sets the boundary for the core transport, and the understanding and predictability of the boundary is crucial to predict the performance of the tokamak.

— The 2009–2013 Five-Year Program plan was strongly focused on measuring the pedestal characteristics and together with the theory effort, generating a first-principle model to predict the pedestal width and height. This effort was the focus of the 2011 U.S. facilities joint research target. A new code was developed (EPED1) based on the peeling ballooning mode limiting the pedestal height, and the kinetic ballooning limiting the pedestal width. The code compares well with data from the three U.S. facilities and worldwide facilities in the International Tokamak Physics Activity (ITPA) database. Key fluctuations were identified with characteristics of kinetic ballooning modes, and the temporal evolution of the pedestal is also consistent with kinetic ballooning predictions.

— The high resolution edge Thomson scattering (funded by ARRA) was key in enabling the detailed pedestal physics.

— The research in 2014–2018 will include optimization of the pedestal conditions to enhance the performance of the tokamaks.

- **Fast Ion Physics**

— The behavior of fast ions in ITER significantly impacts the overall energy gain, and potential local damage to the first wall.

— The 2009–2013 research plan increased the ability to measure the fast ion population, the instabilities, and the fast ion loss with new diagnostics, fast ion D-alpha (FIDA), ECE imaging system (ECEI), and fast ion loss detector (FILD); and new control tools, primarily the OANBI to modify the fast ion population and also impact the fast ion velocity distribution.

— Experiments during the 2009 Five-Year plan confirmed a number of model results, for example the importance of rotation and fluid effects on the spatial shape of the perturbation. The growth of Alfven modes were observed to be consistent with changes in the gradient of the fast ions, modified with the OANBI. It was also found that the turbulent transport of the ions was not significant and not expected to be significant in ITER.

— Experiments with an ITER test blanket mockup showed heating of the module front surface consistent with detailed loss calculations in the perturbed field, limited primarily to conditions when Alfven modes were present.

— The 2014–2018 plan will continue to test models of fast particle loss, with and without perturbing fields.

11.7.3. Prepare the Physics Basis for Defining the Path for Fusion Energy Beyond ITER

- **Demonstrate the potential of high beta steady-state operation beyond ITER,** required for attractive fusion energy production

  — Access and sustainment of high q_{min} discharges: in the 2009–2013 Five-Year Plan, using the OANBI, DIII-D has sustained elevated q_{min} scenarios for 3 sec (2 τ_R), with β_N ~ 3.5, limited only by the duration of the auxiliary systems. These discharges have broad current profiles and are significantly below the ideal wall limit: beta is limited by available co-current heating power, and some reduction in confinement.

  — Staged progress: Additional OANBI, and increased EC and co-beam power should allow higher beta and 100% non-inductive in the 2014–2018 plan. We expect to develop steady-state scenarios for ITER, β_N ~ 3.5, then FNSF, β_N ~ 3.5 – 4, and suitable for DEMO, β_N ~ 5.

  — Transport in high q_{min} discharges: In the 2009–2013 experiment, significant effort was expended to understand the complex interaction between the current profile, and the resulting transport and bootstrap current. The global confinement was observed to decrease with increasing q_{min}. While the thermal confinement (and transport) remained consistent with good H-mode confinement. Predictions of increased pressure limits and reduced transport with increasing $\rho_{q\mathrm{min}}$ will be tested in the 2014–2018 plan with additional off-axis NBI and ECCD, in close interaction with continued efforts to gain predictive understanding of the transport in these regimes.

- **Resistive wall mode control.**

  — ITER steady-state scenarios with broad current profiles can be susceptible to the RWM.

  — Experiments have shown stabilization of the resistive wall mode by fast ions and thermal ions consistent with theory.

  — Recent experiments have demonstrated stabilization of the current driven kink at q=2.

  — Ongoing DIII-D experiments will evaluate to what extent the RWM is stabilized by fast ions, and thermal ions, and evaluate stable operation below q=2.

- **Develop advanced heat dispersal techniques for next-step devices**
  - DIII-D has established that the scrape-off layer width in attached plasmas varies with 1/IP. This work was part of a Joint U.S. Facility Research Target. When combined with other facilities in the U.S. and abroad, the dependence is $1/B_P$, illustrating potential narrow widths high heat flux in ITER and future devices. In DIII-D detached plasmas, more relevant to ITER operation, the heat flux footprint is observed to be much broader: experiments to determine the scaling of the heat flux width for detached plasmas remain to be done.
  - In the 2009–2013 program period, DIII-D explored two new divertor configurations; the Snowflake and open vessel Super-X. Peak heat flux was reduced by a factor of 2.5 in the Snowflake with the divertor still attached, and further heat flux reduction as divertor detaches.
  - The proven capability to vary the magnetic geometry will be further exploited in the 2014–2018 Plan, together with improved diagnostics to test and validate divertor models, especially highly collisional and radiative edge plasmas, and to optimize the divertor geometry for heat flux reduction and plasma performance.

12. BIBLIOGRAPHY FY08 THROUGH FY12

12.1. PUBLICATIONS FOR FY12

Allen, S.L., Meier, E.T., Weber, T.R., Hill, D.N., Meyer, W.H., Porter, G.D., Howard, J., “Impurity Flow Measurements in DIII-D using Coherence Imaging Spectroscopy,” Bull. Am. Phys. Soc. **57**, 311 (2012).

Allen, S.L., Soukhanovskii, V.A., Osborne, T.H., Kolemen, E., Boedo, J.A., Brooks, N.H., Fenstermacher, M.E., Groebner, R.J., Hill, D.N., Hyatt, A.W., Lasnier, C.J., Leonard, A.W., Makowski, M.A., Meyer, W.H., McLean, A.G., Petrie, T.W., Ryutov, D. and Watkins, J.G., “Initial Snowflake Divertor Physics Studies on DIII-D,” Synopsis presented at the 24th IAEA Fusion Energy Conf., San Diego, California, October 8–13, 2012; General Atomics Report GA-A27435 (2012).

Austin, M.E., Li, E., Ellis, R.F., “Using ECE Measurements to Assess Equilibrium Reconstructions on DIII-D,” Bull. Am. Phys. Soc. **57**, 143 (2012).

Azari, A., Eidietis, N.W., “Halo Currents in the DIII-D Tokamak,” Bull. Am. Phys. Soc. **57**, 166 (2012).

Bae, C., Stacey, W.M., Solomon, W.M., “Comparison of an Extended Rotation Theory with Experiment,” Bull. Am. Phys. Soc. **57**, 139 (2012).

Bak, J.-G., Kim, H.S., Lee, S.G., Lee, K.D., Ko, W.H., Kim, J., Jeon, Y.M., Kim, W.C., Bae, Y.S., Strait, E.J., La Haye, R.J., Buttery, R.J., Wade, M.R., Park, J.K., Hanson, J.M., “Study on Sawtooth and ELM activities in DIII-D and KSTAR Plasmas,” Bull. Am. Phys. Soc. **57**, 143 (2012).

Balunas, W.K., Pinsker, R.I., Diem, S.J., Kaufman, M.C., Unterberg, E.A., Nagy, A., “Diagnosis of Local Plasma Conditions within an ICRF Antenna on DIII-D,” Bull. Am. Phys. Soc. **57**, 167 (2012).

Barton, J.E., Boyer, M.D., Shi, W., Wehner, W.P., Schuster, E., Luce, T.C., Ferron, J.R., Walker, M.L., Humphreys, D.A., Penaflor, B.G., and Johnson, R.D., “First-Principles Model-Based Closed-Loop Control of the Current Profile Dynamic Evolution on DIII-D,” Proc. 24th IAEA Fusion Energy Conf., San Diego, California, October 8–13, 2012, Paper EX/P2-09; General Atomics Report GA-A27395 (2012).

Barton, J.E., Boyer, M.D., Shi, W., Wehner, W.P., Schuster, E., Luce, T.C., Ferron, J.R., Walker, M.L., Humphreys, D.A., Penaflor, B.G., Johnson, R.D., “First-Principles Model-Based Closed-Loop Control of the Current Profile Dynamic Evolution on DIII-D,” Synopsis presented at the 24th IAEA Fusion Energy Conf., San Diego, California, October 8–13, 2012; General Atomics Report GA-A27251 (2012).

Bass, E.M., and Waltz, “Gyrokinetic Simulation of Global and Local Alfvén Eigenmodes Driven by Energetic Particles in a DIII-D Discharge,” Phys. Plasmas **20**, 012508 (2013); General Atomics Report GA-A27344 (2012).

Bass, E.M., Waltz, R.E., “Gyrokinetic Simulation of Global and Local Alfvén Eigenmodes Driven by Neutral Beam Injection in DIII-D,” Bull. Am. Phys. Soc. **57**, 140 (2012).

Battaglia, D.J., Chang, C.S., Grierson, B.A., Solomon, W.M., Boedo, J.A., deGrassie, J.S., “Calculation of Intrinsic Edge Rotation Using XGC0,” Bull. Am. Phys. Soc. **57**, 310 (2012).

Baylor, L.R., “Reduction of ELM Intensity on DIII-D by On-demand Triggering With High Frequency Pellet Injection and Implications for ITER” Invited Bull. Am. Phys. Soc. **57**, 293 (2012).

Baylor, L.R., Commaux, N., Jernigan, T.C., Combs, S.K., Meitner, S.J., Brooks, N.H., Evans, T.E., Fenstermacher, M.E., Isler, R.C., Lasnier, C.J., Moyer, R.A., Osborne, T.H., Parks, P.B., Snyder, P.B., Strait, E.J., Unterberg, E.A., Loarte, A., "High Frequency ELM Pacing by Pellet Injection on DIII-D and Implications for ITER," Proc. 39th European Physical Society Conf. on Plasma Physics, Stockholm, Sweden, July 2–6, 2012, Paper O4.113; General Atomics Report GA-A27333 (2012).

Baylor, L.R., Commaux, N., Jernigan, T.C., Meitner, S.J., Brooks, N.H., Combs, S.K., Evans, T.E., Fenstermacher, M.E., Lasnier, C.J., Moyer, R.A., Osborne, T.H., Parks, P.B., Strait, E.J., Unterberg, E.A., and Loarte, A., "Experimental Demonstration of High Frequency ELM Pacing by Pellet Injection on DIII-D and Extrapolation to ITER," Proc. 24th IAEA Fusion Energy Conf., San Diego, California, October 8–13, 2012, Paper EX/6-02; General Atomics Report GA-A27414 (2012).

Baylor, L.R., Jernigan, T.C., Commaux, N., Combs, S.K., Meitner, S.J., Brooks, N.H., Evans, T.E., Fenstermacher, M.E., Lasnier, C.J., Moyer, R.A., Osborne, T.H., Parks, P.B., Strait, E.J., Unterberg, E.A., Loarte, A., "Experimental Demonstration of High Frequency ELM Pacing by Pellet Injection on DIII-D and Extrapolation to ITER," Synopsis presented at the 24th IAEA Fusion Energy Conf., San Diego, California, October 8–13, 2012; General Atomics Report GA-A27253 (2012).

Belli, E.A., and Candy, J., "Full Linearized Fokker-Planck Collisions in Neoclassical Transport Simulations," Plasma Phys. Control. Fusion **54**, 015015 (2012); General Atomics Report GA-A27101 (2011).

Belli, E.A., Boedo, J.A., Candy, J., Cohen, R.H., Colella, P., Dorf, M.A., Dorr, M.R., Hittinger, J.A., Mccorquodale, P.W., Rognlien, T.D., Snyder, P.B., "Eulerian Simulations of Neoclassical Flows and Transport in the Tokamak Plasma Edge and Outer Core," Synopsis presented at the 24th IAEA Fusion Energy Conf., San Diego, California, October 8–13, 2012; General Atomics Report GA-A27235 (2012).

Belli, E.A., Candy, J., "Non-axisymmetry Effects in Neoclassical Transport Simulations," Bull. Am. Phys. Soc. **57**, 63 (2012).

Boedo, J.A., Tynan, G.R., Rudakov, D.L., Yan, Z., McKee, G.R., Manz, P., Schmitz, L., Groebner, R.J., Rhodes, T.L., Wang, G., Diamond, P., and The DIII-D Team, "The Role of the Radial Electric Field, Reynolds Stress and Zonal Flows in the L-H Transition in DIII-D," Proc. 39th European Physical Society Conf. on Plasma Physics, Stockholm, Sweden, July 2–6, 2012, Paper P5.035; General Atomics Report GA-A27340 (2012).

Bolte, N.G., Heidbrink, W.W., Unterberg, E.A., "Measurements and Modeling of Fast-ion Light From Edge Neutrals," Bull. Am. Phys. Soc. **57**, 141 (2012).

Burrell, K.H., and Muñoz Burgos, J.M., "Kinetic Theory for Charge-Exchange Spectroscopy: Effects of Magnetic and Electric Fields on the Distribution Function after Charge-Exchange," Phys. Plasmas **19**, 072507 (2012); General Atomics Report GA-A27213 (2012).

Burrell, K.H., Garofalo, A.M., Solomon, W.M., Fenstermacher, M.E., "ELM-free, Quiescent H-mode Operation in DIII-D Under Reactor-relevant Conditions Using Non-Axisymmetric Magnetic Fields from Coils Outside the Toroidal Field Coil," Bull. Am. Phys. Soc. **57**, 208 (2012).

Burrell, K.H., Garofalo, A.M., Solomon, W.M., Fenstermacher, M.E., Orlov, D.M., Osborne, T.H., Park, J.-K., and Snyder, P.B., "Quiescent H-mode Operation Using Torque from Non-Axisymmetric, Non-Resonant Magnetic Fields," Proc. 24th IAEA Fusion Energy Conf., San Diego, California, October 8–13, 2012, Paper EX/P4-08; General Atomics Report GA-A27397 (2012).

Burrell, K.H., Garofalo, A.M., Solomon, W.M., Fenstermacher, M.E., Osborne, T.H., Park, J.-K., Schaffer, M.J., Snyder, P.B., "Reactor-Relevant Quiescent H-Mode Operation Using Torque From Non-Axisymmetric Non-Resonant Magnetic Fields," Phys. Plasmas **19**, 056117 (2012); General Atomics Report GA-A27177 (2011).

Buttery, R.J., Boozer, A.H., Ferraro, N.M., Hanson, J.M., La Haye, R.J., Liu, Y.Q., Park, J.-K. Remerdes, H., Schaffer, M.J., Snipes, J.A., Strait, E.J., and the DIII-D Team “Addressing the Error Field Correction Challenge for ITER,” Proc. 39th European Physical Society Conf. on Plasma Physics, Stockholm, Sweden, July 2–6, 2012, Paper P2.066; General Atomics Report GA-A27347 (2012).

Buttery, R.J., Boozer, A.H., Liu, Y.Q., Park, J.-K., Ferraro, N.M., Amoskov, V., Gribov, Y., La Haye, R.J., Lamzin, E., Menard, J.E., Schaffer, M.J., Strait, E.J., and the DIII-D Team, “New Challenges for Error Field Correction,” Synopsis presented at the 24th IAEA Fusion Energy Conf., San Diego, California, October 8–13, 2012; General Atomics Report GA-A27245 (2012).

Buttery, R.J., Boozer, A.H., Liu, Y.Q., Park, J.-K., Ferraro, N.M., Amoskov, V., Gribov, Y., La Haye, R.J., Lamzin, E., Menard, J.E., Schaffer, M.J., Strait, E.J., and The DIII-D Team, “Addressing New Challenges for Error Field Correction,” Proc. 24th IAEA Fusion Energy Conf., San Diego, California, October 8–13, 2012, Paper EX/P4-31; General Atomics Report GA-A27440 (2012).

Buttery, R.J., Boozer, A.H., Liu, Y.Q., Park, J.-K., Ferraro, N.M., Amoskov, V., Gribov, Y., La Haye, R.J., Lamzin, E., Menard, J.E., Schaffer, M.J., Strait, E.J., and The DIII-D Team, “The Limits and Challenges of Error Field Corrections for ITER,” presented at the 54th Annual Mtg. of the APS Division of Plasma Physics, Providence, Rhode Island, October 29–November 2, 2012 in Phys. Plasmas **19**, 056111 (2012); General Atomics Report GA-A27191 (2012).

Buttery, R.J., Ferraro, N.M., La Haye, R.J., Schaffer, M.J., Strait, E.J., Hanson, J.M., Park, J.-K., Reimerdes, H., “Resolving the Physics of Error Field Correction Through Error Field Proxy Experiments in DIII-D,” Bull. Am. Phys. Soc. **57**, 141 (2012).

Candy, J., “Theory, Verification and Validation of Finite-Beta Gyrokinetics,” Invited Bull. Am. Phys. Soc. **57**, 72 (2012).

Cengher, M., Lohr, J., Gorelov, Y.A., Ponce, D., Moeller, C.P., “Operational Performance of the ECH System on DIII-D,” Bull. Am. Phys. Soc. **57**, 313 (2012).

Chandler, E., Unterberg, E.A., Shafer, M.W.,Wingen, A., “Benchmarking and Optimizing Techniques for Inverting Images of DIII-D Soft X-Ray Emissions,” Bull. Am. Phys. Soc. **57**, 166 (2012).

Chapman, I.T., La Haye, R.J., Buttery, R.J., Heidbrink, W.W., Jackson, G.L., Muscatello, C.M., Petty, C.C., Pinsker, R.I., Tobias, B.J., Turco, F., “Sawtooth Control Using Electron Cyclotron Current Drive in ITER Demonstration Plasmas in DIII-D,” Plasma Phys. Control. Fusion **53**, 124003 (2011); General Atomics Report GA-A27163 (2011).

Chen, X., Fisher, R.K., Pace, D.C., García-Muñoz, M., Chavez, J.A., Heidbrink, W.W., Van Zeeland, M.A., “Near Midplane Scintillator-Based Fast Ion Loss Detector on DIII-D,” presented at the 19th High Temperature Plasma Diagnostics Conf., Monterey, California, May 6–10, 2012 in Rev. Sci. Instrum. **83**, 10D707 (2012); General Atomics Report GA-A27298 (2012).

Chen, X., Heidbrink, W.W., Fisher, R.K., Pace, D.C., Petty, C.C., Van Zeeland, M.A., “Neutral Beam-ion Prompt Loss Induced by Alfvén Eigenmodes in DIII-D,” Bull. Am. Phys. Soc. **57**, 207 (2012).

Choi, M., Chan, V.S., Pinsker, R.I., Muascatello, C.M., Green, D.C., and RF SciDAC, “Modeling of Large Orbit Fast Ion Distribution Evolution with Multiple Frequency Fast Wave Heating,” Proc. 39th European Physical Society Conf. on Plasma Physics, Stockholm, Sweden, July 2–6, 2012, Paper P4.143; General Atomics Report GA-A27339 (2012).

Choi, M., Ferraro, N.M, Lao, L.L., Chan, V.S., “Effects of magnetic perturbations and plasma response on loss of fast ions to the wall in DIII-D and ITER,” Bull. Am. Phys. Soc. **57**, 140 (2012).

Chrobak, C.P., Chamberlain, F., Lee, R.L., Holtrop, K.L., Taylor, P.L., Jackson, G.L., Wall, D., Buchenauer, D.A., Mills, B.E., "Survey and Cleaning of Metal Contamination in Graphite Plasma-Facing Tiles in DIII-D," Bull. Am. Phys. Soc. **57**, 312 (2012).

Chrobak, C.P., Van Zeeland, M.A., Moyer, R.A., Yu, J.H., "Restoring Transmission of Irradiated Image Fiber Bundles," presented at the 19th High Temperature Plasma Diagnostics Conf., Monterey, California, May 6-10, 2012 in Rev. Sci. Instrum. **83**, 10E514 (2012); General Atomics Report GA-A27314 (2012).

Chrystal, C., Burrell, K.H., Grierson, B.A., Groebner, R.J., Kaplan, D.H., "Calculation of Impurity Poloidal Rotation from Measured Poloidal Asymmetries in the Toroidal Rotation of a Tokamak Plasma," presented at the 19th High Temperature Plasma Diagnostics Conf., Monterey, California, May 6-10, 2012 Rev. Sci. Instrum. **83**, 10D501 (2012); General Atomics Report GA-A27290 (2012).

Chrystal, C., Burrell, K.H., Solomon, W.M., Grierson, B.A., "A Method for Measuring Poloidal Rotation in the DIII-D Tokamak," Bull. Am. Phys. Soc. **57**, 309 (2012).

Commaux, N., Baylor, L.R., Jernigan, T.C., Humphreys, D.A., Eidietis, N.W., Parks, P.B., Wesley, J.C., Lasnier, C.J., Hollmann, E.M., Izzo, V.A., Moyer, R.A., "Particle assimilation study during shattered pellet injection on DIII-D," Bull. Am. Phys. Soc. **57**, 207 (2012).

DeBoo, J.C., Petty, C.C., White, A.E., Burrell, K.H., Doyle, E.J., Hillesheim, J.C., Holland, C., McKee, G.R., Rhodes, T.L., Schmitz, L., Smith, S.P., Wang, G., Zeng, L., "Electron Profile Stiffness and Critical Gradient Studies," Phys. Plasmas **19**, 082518 (2012); General Atomics Report GA-A27189 (2012).

deGrassie, J.S., Evans, T.E., Snyder, P.B., Fenstermacher, M.E., Lanctot, M.J., Moyer, R.A., Orlov, D.M., Nazikian, R., Solomon, W.M., "Single-row versus double-row RMP ELM suppression in DIII-D," Bull. Am. Phys. Soc. **57**, 136 (2012).

Diem, S.J., Unterberg, E.A., Hillis, D.L., Horton, A.R., Ryan, P.M., Murakami, M., Jaeger, E.F., Green, D.L., Rasmussen, D.A., Kaufman, M.C., Pinsker, R.I., Nagy, A., "Dependence of ICRF Antenna Loading on ELM Frequency, Type and Size," Bull. Am. Phys. Soc. **57**, 312 (2012).

DIII-D Research Team, "DIII-D Year 2012 Experiment Plan," General Atomics Report GA-A27328 (2012).

Doyle, E.J., Zeng, L., Evans, T.E., McKee, G.R., Mordijck, S., Moyer, R.A., Peebles, W.A., Petty, C.C., Rhodes, T.L., Staebler, G.M., "Particle Transport Results from Collisionality Scans And Perturbative Experiments on DIII-D," Synopsis presented at the 24th IAEA Fusion Energy Conf., San Diego, California, October 8–13, 2012; General Atomics Report GA-A27237 (2012).

Doyle, E.J., Zeng, L., Staebler, G.M., Evans, T.E., Luce, T.C., McKee, G.R., Mordijck, S., Moyer, R.A., Peebles, W.A., Petty, C.C, Rhodes, T.L., "Particle transport results from collisionality scans and perturbative experiments on DIII-D," Proc. 24th IAEA Fusion Energy Conf., San Diego, California, October 8–13, 2012, Paper EX/P3-26; General Atomics Report GA-A27445 (2012).

Eidietis, N.W., Commaux, N., Hollmann, E.M., Humphreys, D.A., Jernigan, T.C., Moyer, R.A., Strait, E.J., Van Zeeland, M.A., Wesley, J.C., Yu, J.H., "Control of Post-Disruption Runaway Electron Beams in DIII-D," presented at the 53rd Annual Mtg. of the APS Division of Plasma Physics, Salt Lake City, Utah, November 14–18, 2011 in Phys. Plasmas **19**, 056109 (2012); General Atomics Report GA-A27184 (2011).

Elder, J.D., Lisgo, S., Leonard, A.W., Stangeby, P.C., Boedo, J.A., Bray, B.D., Brooks, N.H., Fenstermacher, M.E., Reiter, D., Rudakov, D.L., Unterberg, E.A., Watkins, J.G., "Detailed OEDGE Modeling of Core-Pedestal Fueling in DIII-D," presented at the 20th Int. Conf. on Plasma-Surface Interactions in Controlled Fusion Devices, Aachen, Germany, May 21–25, 2012 to be published in J. Nucl. Mater.; General Atomics Report GA-A27332 (2012).

Elder, J.D., Stangeby, P.C., Leonard, A.W., Bray, B.D., Brooks, N.H., Boedo, J.A., Rudakov, D.L., Watkins, J.G., Unterberg, E.A., Lasnier, C., "OEDGE Assessment of Pressure and Power Balance Methods for Separatrix Identification," Bull. Am. Phys. Soc. **57**, 311 (2012).

Eldon, D., Bray, B.D., Deterly, T.M., Liu, C., Watkins, M., Groebner, R.J., Leonard, A.W., Osborne, T.H., Snyder, P.B., Boivin, R.L., Tynan, G.R., "Initial Results of the High Resolution Edge Thomson Scattering Upgrade at DIII-D," presented at the 19th High Temperature Plasma Diagnostics Conf., Monterey, California, May 6-10, 2012 in Rev. Sci. Instrum. **83**, 10E343 (2012); General Atomics Report GA-A27291 (2012).

Eldon, D.P., Tynan, G.R., Groebner, R.J., Osborne, T.H., Bray, B.D., Boivin, R.L., Nazikian, R., "Evaluating pedestal gradients and scale lengths without functional fits in order to test for non-diffusive transport processes," Bull. Am. Phys. Soc. **57**, 309 (2012).

Evans, T.E., "ELM Mitigation Techniques," presented at the 20th Int. Conf. on Plasma-Surface Interactions in Controlled Fusion Devices, Aachen, Germany, May 21–25, 2012 to be published in J. Nucl. Mater.; General Atomics Report GA-A27310 (2012).

Evans, T.E., and the DIII-D Team, "Suppression and Mitigation of Edge Localized Modes in the DIII-D Tokamak With 3D Magnetic Perturbations," Proc. 21st Int. Toki Conf. on Integration of Fusion Science and Technology for Steady-State Operation, Toki-City, Japan, November 28–December 1, 2011; General Atomics Report GA-A27172 (2011).

Evans, T.E., Harris, J., Ida, K., Ohdachi, S., Shafer, M.W., Suzuki, Y., Tanaka, K., Unterberg, E.A., LHD Group, "Physics of Resonant Magnetic Perturbations in Toroidal Plasmas," Proc. Plasma Conf. 2011, Ishikawa Ongakudo, Japan, November 22–25, 2011; General Atomics Report GA-A27150 (2011).

Evans, T.E., Orlov, D.M., Wingen, A., Wu, W., Loarte, A., Casper, T.A., Schmitz, O., Saibene, G., Schaffer, M.J., "3D Vacuum Magnetic Field Modeling of the ITER ELM Control Coils during Standard Operating Scenarios," Synopsis presented at the 24th IAEA Fusion Energy Conf., San Diego, California, October 8–13, 2012; General Atomics Report GA-A27246 (2012).

Evans, T.E., Wu, W., Orlov, D.M., Wingen, A., Loarte, A., Casper, T.A., Schmitz, O., Saibene, G., "3D Vacuum Magnetic Field Modeling of the ITER ELM Control Coils During Standard Operating Scenarios," Bull. Am. Phys. Soc. **57**, 352 (2012).

Fenstermacher, M.E., Xu, X., Joseph, I., Lasnier, C.J., Meyer, W.H., Tobias, B.J., Zeng, L., "Validation of BOUT++ Nonlinear ELM Simulations Using Fast Measurements from DIII-D," Bull. Am. Phys. Soc. **57**, 138 (2012).

Fenstermacher, M.E., Xu, X.Q., Joseph, I., Lanctot, M.J., Lasnier, C.J., Meyer, W.H., Tobias, B.J., Zeng, L., Leonard, A.W., and Osborne, T.H., "Fast Pedestal, SOL, and Divertor Measurements from DIII-D to Validate BOUT++ Nonlinear ELM Simulations," presented at the 20th Int. Conf. on Plasma-Surface Interactions in Controlled Fusion Devices, Aachen, Germany, May 21–25, 2012 to be published in J. Nucl. Mater.; General Atomics Report GA-A27321 (2012).

Ferraro, N.M., "Calculations of Two-Fluid Linear Response to Non-Axisymmetric Fields in Tokamaks," Phys. Plasmas **19**, 056106 (2012); General Atomics Report GA-A27168 (2011).

Ferraro, N.M., Evans, T.E., Lao, L.L., Turnbull, A.D., Lanctot, M.J., Shafer, M.W., Unterberg, E.A., Nazikian, R., Moyer, R.A., Orlov, D.M., "Modeling Edge Plasma Response to 3D Fields in DIII-D," Bull. Am. Phys. Soc. **57**, 205 (2012).

Ferraro, N.M., Lao, L.L., Moyer, R.A., Orlov, D.M., Buttery, R.J., Evans, T.E., Lanctot, M.J., Snyder, P.B., Wade, M.R., "Edge Plasma Response to Non-Axisymmetric Fields in Tokamaks," Synopsis presented at the 24th IAEA Fusion Energy Conf., San Diego, California, October 8–13, 2012; General Atomics Report GA-A27247 (2012).

Ferron, J.R., "Progress Toward Fully Noninductive Discharge Operation in DIII-D Using Off-axis Neutral Beam Injection," Invited Bull. Am. Phys. Soc. **57**, 366 (2012).

Fisher, R.K., Pace, D.C., Kramer, G.J., Van Zeeland, M.A., Nazikian, R., Heidbrink, W.W., Garcia-Munoz, M., "First Experimental Observations of Beam Ion Losses Due to Energetic Particle Geodesic Acoustic Modes," Nucl. Fusion **52**, 123015 (2012); General Atomics Report GA-A27144 (2012).

Floyd, J.-P., Stacey, W.M., Groebner, R.J., "Evolution of Edge Pedestal Profiles Between ELMs," Bull. Am. Phys. Soc. **57**, 139 (2012).

Frerichs, H., Cahyna, P., Evans, T.E., Feng, Y., Reiter, D., Schmitz, O., "Impact of Screening of Resonant Magnetic Perturbations in 3D Edge Plasma Transport Simulations for DIII-D," submitted to J. Nucl. Mater; General Atomics Report GA-A27145 (2011).

Garofalo, A.M., Burrell, K.H., Solomon, W.M., Fenstermacher, M.E., Hanson, J.M., Lanctot, M.J., Okabayashi, M., Snyder, P.B., and The DIII-D Team, "High β, High Confinement, Stationary ELM-free Operation at Low Plasma Rotation," Proc. 39th European Physical Society Conf. on Plasma Physics, Stockholm, Sweden, July 2–6, 2012, Paper O2.102; General Atomics Report GA-A27343 (2012).

Garofalo, A.M., Chan, V.S., Canik, J.M., Sawan, M.E., Choi, M., Humphreys, D.A., Lao, L.L., Prater, R., Stangeby, P.C., St. John, H.E., and Turnbull, A.D., "A Fast-Track Path to DEMO Enabled by ITER and FNSF-AT," Proc. 24th IAEA Fusion Energy Conf., San Diego, California, October 8–13, 2012, Paper FTP/P7-35; General Atomics Report GA-A27432 (2012).

Garofalo, A.M., Chan, V.S., Choi, M., Humphreys, D.A., Kinsey, J.E., Lao, L.L., Snyder, P.B., St. John, H.E., Turnbull, A.D., Taylor, T.S., Canik, J.M., Sawan, M.E., Stangeby, P.C., "A Fast-Track Path to DEMO Enabled by ITER and FNSF-AT," Synopsis presented at the 24th IAEA Fusion Energy Conf., San Diego, California, October 8–13, 2012; General Atomics Report GA-A27236 (2012).

Gohil, P., and the DIII-D Team, "Overview of Recent DIII-D Experimental Results," Bull. Am. Phys. Soc. **57**, 205 (2012).

Gohil, P., Battaglia, D., de la Luna, E., Fenstermacher, M.E., Hughes, J., Kaye, S., Kirk, A., Ma, Y., Maingi, R., Martin, Y., McDonald, D.C., Meyer, H., Ryter, F., and the ITPA Topiccal Groups on Transport and Confinement and Pedestal and Edge Physics, and the Research Teams of ASDEX Upgrade, C-Mod, DIII-D, EFDA_JET, MAST and NSTX, "Assessment of the H-mode Power Threshold Requirements for ITER," Proc. 24th IAEA Fusion Energy Conf., San Diego, California, October 8–13, 2012, Paper ITR/P1-36; General Atomics Report GA-A27392 (2012).

Gohil, P., Battaglia, D., de la Luna, E., Fenstermacher, M.E., Hughes, J., Kaye, S., Kirk, A., Ma, Y., Maingi, R., Martin, Y., McDonald, D.C., Meyer, H., Ryter, F., and the ITPA Topical Groups on Transport and Confinement and Pedestal and Edge Physics, "Assessment of the H-Mode Power Threshold Requirements for ITER," Synopsis presented at the 24th IAEA Fusion Energy Conf., San Diego, California, October 8–13, 2012; General Atomics Report GA-A27250 (2012).

Gorelov, Y.A., Doane, J., Cengher, M., Lohr, J., Ponce, D., "Upgraded Waveguide Components for New 1.2 and 1.5 MW Gyrotrons on the DIII-D Tokamak," Bull. Am. Phys. Soc. **57**, 313 (2012).

Grierson, B.A., Burrell, K.H., Chrystal, C., Groebner, R.J., Kaplan, D.H., Heidbrink, W.W., Pablant, N.A., Solomon, W.M., Van Zeeland, M.A., "Active Spectroscopic Measurements of the Bulk Deuterium Properties in the DIII-D Tokamak," invited paper presented at the 19th High Temperature Plasma Diagnostics Conf., Monterey, California, May 6-10, 2012 in Rev. Sci. Instrum. **83**, 10D529 (2012); General Atomics Report GA-A27295 (2012).

Grierson, B.A., Burrell, K.H., Heidbrink, W.W., Lanctot, M.J., Pablant, N.A., Solomon, W.M., "Measurements of the Deuterium Ion Toroidal Rotation in the DIII-D Tokamak and Comparison to Neoclassical Theory," Phys. Plasmas **19**, 056107 (2012); General Atomics Report GA-A27179 (2011).

Grierson, B.A., Burrell, K.H., Heidbrink, W.W., Pablant, N.A., Solomon, W.M., "Measurement of Deuterium Ion Toroidal Rotation and Comparison to Neoclassical Theory in the DIII-D Tokamak," Synopsis presented at the 24th IAEA Fusion Energy Conf., San Diego, California, October 8–13, 2012; General Atomics Report GA-A27238 (2012).

Grierson, B.A., Burrell, K.H., Solomon, W.M., "Comparison of Deuterium Toroidal and Poloidal Rotation to Neoclassical Theory," Proc. 24th IAEA Fusion Energy Conf., San Diego, California, October 8–13, 2012, Paper EX/P3-19; General Atomics Report GA-A27398 (2012).

Grierson, B.A., Solomon, W.M., Burrell, K.H., DeGrassie, J.S., Boedo, J.A., "Toroidal and Poloidal Rotation of Deuterium Ions in DIII-D Intrinsic Rotation Conditions," Bull. Am. Phys. Soc. **57**, 310 (2012).

Groebner, R.J., Chang, C.S., Hughes, J.W., Maingi, R., Snyder, P.B., Xu, X.Q., Belli, E.A., Bray, B.D., Candy, J., Deterly, T.M., Ferraro, N.M., Kinsey, J.E., Leonard, A.W., Liu, C., Osborne, T.H., Ponce, D.M., Smith, S.P., Staebler, G.M., Waltz, R.E., Stacey, W.M., Fenstermacher, M.E., Joseph, I., Lasnier, C.J., Umansky, M.V., Wang, E.H-J., Churchill, R.M., Cziegler, I., Davis, E.M., Hubbard, A.E., Labombard, B., Lipschultz, B.L., Ma, Y., Rost, J.C., Sugiyama, L.E., Terry, J.L., Walk, J., White, A.E., Whyte, D.G., Wolfe, S.M., Canik, J.M., Lore, J.D., Sontag, A.C., Boyle, D.P., Diallo, A., Zweben, S.J., Watkins, J.G., Pankin, A.Y., Fulton, D.P., Lin, Z., Doyle, E.J., Rhodes, T.L., Schmitz, L., Zeng, L., Boedo, J.A., Diamond, P.H., Eldon, D.P., Parker, S.E., Wan, W., Elder, J.D., Callen, J.D., McKee, G.R., Yan, Z., "Improved Understanding of Physics Processes in Pedestal Structure, Leading to Improved Predictive Capability for ITER," Proc. 24th IAEA Fusion Energy Conf., San Diego, California, October 8–13, 2012, Paper EX/11-4; General Atomics Report GA-A27399 (2012).

Groebner, R.J., Chang, C.S., Hughes, J.W., Maingi, R., Snyder, P.B., Xu, X.Q., "Improved Understanding of Physics Processes in Pedestal Structure, Leading to Improved Predictive Capability for ITER," Synopsis presented at the 24th IAEA Fusion Energy Conf., San Diego, California, October 8–13, 2012; General Atomics Report GA-A27239 (2012).

Groebner, R.J., Snyder, P.B., Chang, C.S., Hughes, J.W., Maingi, R., Xu, X.Q., "Advances in Predictive Capability of Pedestal Structure from FY11 Joint Research Target," Bull. Am. Phys. Soc. **57**, 138 (2012).

Hanson, J.M., Berkery, J., Navratil, G.A., Sabbagh, S.A., Turco, F., Lanctot, M.J., Reimerdes, H., Chapman, I., Liu, Y., Okabayashi, M., Jackson, G.L., La Haye, R.J., Strait, E.J., "Effect of Fast Ion Distribution on Resistive Wall Mode Stability," Bull. Am. Phys. Soc. **57**, 142 (2012).

Hanson, J.M., Lanctot, M.J., Reimerdes, H., Chapman, I.T., In, Y., La Haye, R.J., Liu, Y., Navratil, G.A., Okabayashi, M., Strait, E.J., Solomon, W.M., Turco, F., "Probing Resistive Wall Mode Stability Using Off-Axis NBI," Synopsis presented at the 24th IAEA Fusion Energy Conf., San Diego, California, October 8–13, 2012; General Atomics Report GA-A27254 (2012).

Hanson, J.M., Turco, F., Lanctot, M.J., Berkery, J.W., Chapman, I.T., La Haye, R.J., Navratil, G.A., Okabayashi, M., Reimerdes, H., Sabbagh, S.A., and Strait, E.J., "Probing Resistive Wall Mode Stability Using Off-axis NBI," Proc. 24th IAEA Fusion Energy Conf., San Diego, California, October 8–13, 2012, Paper EX/P4-27; General Atomics Report GA-A27444 (2012).

Heidbrink, W.W., and the DIII-D Team, "Fast Ion Physics Enabled by Off-Axis Neutral Beam Injection," Synopsis presented at the 24th IAEA Fusion Energy Conf., San Diego, California, October 8–13, 2012; General Atomics Report GA-A27255 (2012).

Heidbrink, W.W., Chen, Xi, Van Zeeland, M.A., Grierson, B.A., Tobias, B.J., "Effect of Off-Axis Beam Injection on Alfvén Eigenmodes," Bull. Am. Phys. Soc. **57**, 140 (2012).

Heidbrink, W.W., Van Zeeland, M.A., Grierson, B.A., Muscatello, C.M., Park, J.M., Petty, C.C., Prater, R., Zhu, Y.B., "Initial Measurements of the DIII-D Off-Axis Neutral Beams," Nucl. Fusion **52**, 094005 (2012); General Atomics Report GA-A27208 (2012).

Hill, D.N., and the DIII-D Team, "DIII-D Overview – Research Toward Resolving Key Issues For ITER And Steady-State Tokamaks," Synopsis presented at the 24th IAEA Fusion Energy Conf., San Diego, California, October 8–13, 2012; General Atomics Report GA-A27257 (2012).

Hill, D.N., for the DIII-D Team, "Research Toward Resolving Key Issues for ITER and Steady-State Tokamaks," Proc. 24th IAEA Fusion Energy Conf., San Diego, California, October 8–13, 2012, Paper OV/1-1; General Atomics Report GA-A27442 (2012).

Hillesheim, J.C., "Observation of a Critical Gradient Threshold for Electron Temperature Fluctuations in the DIII-D Tokamak," Invited Bull. Am. Phys. Soc. **57**, 105 (2012).

Hillesheim, J.C., DeBoo, J.C., Peebles, W.A., Carter, T.A., Wang, G., Rhodes, T.L., Schmitz, L., McKee, G.R., Yan, Z., Staebler, G.M., Burrell, K.H., Doyle, E.J., Holland, C., Petty, C.C., Smith, S.P., White, A.E., Zeng, L., "Observation of a Critical Gradient Threshold for Electron Temperature Fluctuations in the DIII-D Tokamak," Phys. Rev. Lett. **110**, 045003 (2013); General Atomics Report GA-A27277 (2012).

Hillesheim, J.C., DeBoo, J.C., Peebles, W.A., Carter, T.A., Wang, G., Rhodes, T.L., Schmitz, L., McKee, G.R., Yan, Z., Staebler, G.M., Burrell, K.H., Doyle, E.J., Holland, C., Petty, C.C., Smith, S.P., White, A.E., Zeng, L., "Observation of a Critical Gradient Threshold for Electron Temperature Fluctuations in the DIII-D Tokamak," Proc. 39th European Physical Society Conf. on Plasma Physics, Stockholm, Sweden, July 2–6, 2012, Paper P5.045; General Atomics Report GA-A27336 (2012).

Hillesheim, J.C., Peebles, W.A., Carter, T.A., Schmitz, L., Rhodes, T.L., "Experimental Investigation of Geodesic Acoustic Mode Spatial Structure Intermittency and Interaction With Turbulence in the DIII-D Tokamak," Phys. Plasmas **19**, 02230 (2012); General Atomics Report GA-A27120 (2011).

Holcomb, C.T., Ferron, J.R., Luce, T.C., DeBoo, J.C., Park, J.M., White, A.E., Turco, F., Rhodes, T.L., Doyle, E.J., Schmitz, L., Van Zeeland, M.A., McKee, G.R., "The Effect of Safety Factor Profile on Transport in Steady-State, High-Performance Scenarios," Phys. Plasmas **19**, 032501 (2012); General Atomics Report GA-A26813 (2011).

Holcomb, C.T., Ferron, J.R., Turco, F., Luce, T.C., Politzer, P.A., Lanctot, M.J., Okabayashi, M., In, Y., Hanson, J.M., Petrie, T.W., La Haye, R.J., Hyatt, A.W., Osborne, T.H., Zeng, L., Doyle, E.J., Rhodes, T.L., Park, J.M., Zhu, Y., and Buttery, R.J., "Fully Noninductive Scenario Development in DIII-D Usig New Off-Axis Neutral Beam Injection Capability," Proc. 24th IAEA Fusion Energy Conf., San Diego, California, October 8–13, 2012, Paper EX/1-05; General Atomics Report GA-A27403 (2012).

Holcomb, C.T., Ferron, J.R., Turco, F., Luce, T.C., Politzer, P.A., Lanctot, M.J., Okabayashi, M., In, Y., Hanson, J.M., Petrie, T.W., La Haye, R.J., Hyatt, A.W., Osborne, T.H., Zeng, L., Doyle, E.J., Rhodes, T.L., Park, J.M., Zhu, Y., "Fully Noninductive Scenario Development in DIII-D Using New Off-Axis Neutral Beam Injection Capability," Synopsis presented at the 24th IAEA Fusion Energy Conf., San Diego, California, October 8–13, 2012; General Atomics Report GA-A27256 (2012).

Holcomb, C.T., Lanctot, M.J., Luce, T.C., Ferron, J.R., Buttery, R.J., Park, J.M., Turco, F., Hanson, J.M., Okabayashi, M., "High β_N steady state scenario development on DIII-D," Bull. Am. Phys. Soc. **57**, 310 (2012).

Holland, C., DeBoo, J.C., Rhodes, T.L., Schmitz, L., Hillesheim, J.C., Wang, G., White, A.E., Austin, M.E., Doyle, E.J., Peebles, W.A., Petty, C.C., Zeng, L., Candy, J., "Testing Gyrokinetic Simulations of Electron Turbulence," Nucl. Fusion **52**, 063028 (2012); General Atomics Report GA-A27136 (2011).

Holland, C., Kinsey, J.E., DeBoo, J.C., Burrell, K.H., Luce, T.C., Petty, C.C., White, A.E., Rhodes, T.L., Schmitz, L., Doyle, E.J., Hillesheim, J.C., McKee, G.R., Yan, Z., Smith, S.P., Wang, G., Zeng, L., Grierson, B.A., Mantica, P., Snyder, P.B., Waltz, R.E., Staebler, G.M., and Candy, J., "Validation Studies of Gyrofluid and Gyrokinetic Predictions of Transport and Turbulence Stiffness Using the DIII-D Tokamak," Proc. 24th IAEA Fusion Energy Conf., San Diego, California, October 8–13, 2012, Paper EX/P7-09; General Atomics Report GA-A27409 (2012).

Holland, C., Kinsey, J.E., DeBoo, J.C., Burrell, K.H., Petty, C.C., White, A.E., Rhodes, T.L., Schmitz, L., Doyle, E.J., Hillesheim, J.C., McKee, G.R., Yan, Z., Smith, S.P., Wang, G., Zeng, L., Snyder, P.B., Waltz, R.E., Staebler, G.M., Candy, J., "Validation Studies of Gyrofluid and Gyrokinetic Predictions of Transport and Turbulence Stiffness Using the DIII-D Tokamak," Synopsis presented at the 24th IAEA Fusion Energy Conf., San Diego, California, October 8–13, 2012; General Atomics Report GA-A27258 (2012).

Holland, C., Petty, C.C., Schmitz, L., Burrell, K.H., McKee, G.R., Rhodes, T.L., Candy, J., "Progress in GYRO Validation Studies of DIII-D H-mode Plasmas,"Nucl. Fusion **52**, 114007 (2012); General Atomics Report GA-A27159 (2011).

Hollmann, E.M., Austin, M.E., Boedo, J.A., Brooks, N.H., Commaux, N., Eidietis, N.W., Evans, T.E., Humphreys, D.A., Izzo, V.A., James, A.N., Jernigan, T.C., Loarte, A., Martin-Solis, J., Moyer, R.A., Muñoz-Burgos, J.M., Parks, P.B., Rudakov, D.L., Strait, E.J., Tsui, C., Van Zeeland, M.A., Wesley, J.C., and Yu, J.H., "Control and Dissipation of Runaway Electron Beams Created During Rapid Shutdown Experiments in DIII-D," Proc. 24th IAEA Fusion Energy Conf., San Diego, California, October 8–13, 2012, Paper EX/9-02; General Atomics Report GA-A27411 (2012).

Hollmann, E.M., Austin, M.E., Boedo, J.A., Brooks, N.H., Commaux, N., Eidietis, N.W., Evans, T.E., Humphreys, D.A., Izzo, V.A., James, A.N., Jernigan, T.C., Loarte, A., Martin-Solis, J., Moyer, R.A., Munoz-Burgos, J.M., Parks, P.B., Rudakov, D.L., Strait, E.J., Van Zeeland, M.A., Tsui, C., Wesley, J.C., Yu, J.H., "Control and Dissipation of Runaway Electron Beams Created During Rapid Shutdown Experiments in DIII-D," Synopsis presented at the 24th IAEA Fusion Energy Conf., San Diego, California, October 8–13, 2012; General Atomics Report GA-A27259 (2012).

Hollmann, E.M., Boedo, J.A., Brooks, N.H., Commaux, N., Eidietis, N.W., Evans, T.E., Humphreys, D.A., Izzo, V.A., Jernigan, T.C., Moyer, R.A., Muñoz-Burgos, J.M., Parks, P.B., Rudakov, D.L., Strait, E.J., Tsui, C., Van Zeeland, M.A., Wesley, J.C., Yu, J.H., "Disruption Runaway Electron Dissipation and Energy Distribution in DIII-D," Proc. 39th European Physical Society Conf. on Plasma Physics, Stockholm, Sweden, July 2–6, 2012, Paper P4.073; General Atomics Report GA-A27342 (2012).

Hollmann, E.M., Commaux, N., Eidietis, N.W., Humphreys, D.A., James, A.N., Jernigan, T.C., Parks, P.B., Wesley, J.C., Yu, J.H., Boedo, J.A., Brooks, N.H., Evans, T.E., Izzo, V.A., Moyer, R.A., Rudakov, D.L., Strait, E.J., Tsui, C., Van Zeeland, M.A., "Experiments on Disruption Runaway Electron Suppression in the DIII-D Tokamak," Proc. Plasma Conf. 2011, Ishikawa Ongakudo, Japan, November 22–25, 2011; General Atomics Report GA-A27148 (2011).

Izzo, V.A., "Impurity Mixing in Massive-Gas-Injection Simulations of DIII-D," Proc. 24th IAEA Fusion Energy Conf., San Diego, California, October 8–13, 2012, Paper TH/P3-13; General Atomics Report GA-A27393 (2012).

Izzo, V.A., "Impurity Mixing, Radiation Asymmetry, and Runaway Electron Confinement in MGI Simulations of DIII-D and ITER," Invited Bull. Am. Phys. Soc. **57**, 242 (2012).

Izzo, V.A., and Parks, P.B., "Impurity Mixing in Massive-Gas-Injection Simulations of DIII-D," Synopsis presented at the 24th IAEA Fusion Energy Conf., San Diego, California, October 8–13, 2012; General Atomics Report GA-A27247 (2012).

Izzo, V.A., Humphreys, D.A., Kornbluth, M., "Current Profile Effects on Runaway Electron Plateau Formation in Diverted DIII-D Discharges," Plasma Phys. Control. Fusion 54 095002 (YEAR?); General Atomics Report GA-A27146 (2011).

Jackson, G.L., Buttery, R.J., deGrassie, J.S., Doyle, E.J., Ferron, J.R., Hyatt, A.W., La Haye, R.J., Luce, T.C., Nazikian, R., Polizter, P.A., Solomon, W.M., Turco, F., Wade, M.R., "Long-Pulse Stability Limits of ITER Baseline Scenario" Proc. 24th IAEA Fusion Energy Conf., San Diego, California, October 8–13, 2012, Paper EX/P2-08; General Atomics Report GA-A27419 (2012).

Jackson, G.L., Chan, V.S., Stambaugh, R.D. "An Analytical Expression for the Tritium Burnup Fraction in Burning Plasma Devices" submitted to Fusion Sci. Technol.; General Atomics Report GA-A27221 (2012).

Jackson, G.L., Luce, T.C., Buttery, R.J., Hyatt, A.W., Ferron, J.R., La Haye, R.J., Politzer, P.A., Solomon, W.M., "Stability boundaries and development of the ITER baseline scenario," Bull. Am. Phys. Soc. **57**, 351 (2012).

Jackson, G.L., Turco, F., Luce, T.C., Buttery, R.J., Hyatt, A.W., Doyle, E.J., Ferron, J.R., La Haye, R.J., Politzer, P.A., Solomon, W.M., Wade, M.R., "Long-Pulse Stability Limits of ITER Baseline Scenario Plasmas in DIII-D," Synopsis presented at the 24th IAEA Fusion Energy Conf., San Diego, California, October 8–13, 2012; General Atomics Report GA-A27261 (2012).

James, A.N., Austin, M.E., Commaux, N., Eidietis, N.W., Evans, T.E., Hollmann, E.M., Humphreys, D.A., Hyatt, A.W., Izzo, V.A., Jernigan, T.C., La Haye, R.J., Parks, P.B., Strait, E.J., Tynan, G.R., Wesley, J.C., Yu, J.H., "Measurements of Hard X-ray Emission From Runaway Electrons in DIII-D," Nucl. Fusion **52**, 013007 (2012); General Atomics Report GA-A27064 (2011).

Jurewicz, J., Pace, D.C., Fisher, R.K., Van Zeeland, M.A., Holcomb, C.T., "Effect of Neutral Beam Parameters on Prompt Losses in Tokamaks," Bull. Am. Phys. Soc. **57**, 167 (2012).

Kim, E.N., Schissel, D.P., Abla, G., Flanagan, S. and Lee, X., "Web-Based (HTML5) Interactive Graphics for Fusion Research and Collaboration," Proc. 8th Tech. Mtg. on Control, Data Acquisition, and Remote Participation for Fusion Research, San Francisco, California, June 20–24, 2011 in Fusion Engin. Design **87**, 2045 (2012); General Atomics Report GA-A27113 (2011).

King, J.D., La Haye, R.J., Petty, C.C., Osborne, T.H., Lasnier, C.J., Groebner, R.J., Volpe, F.A.G., Lanctot, M.J., Makowski, M.A., Holcomb, C.T., Solomon, W.M., Allen, S.L., Luce, T.C., Austin, M.E., Meyer, W.H., Morse, E.C., "Hybrid-like 2/1 Flux-Pumping and Magnetic Island Evolution Due to Edge Localized Mode Neoclassical Tearing Mode Coupling in DIII-D," Phys. Plasmas **19**, 022503 (2012); General Atomics Report GA-A27069 (2011).

King, J.D., Strait, E.J., Boivin, R.L., La Haye, R.J., Lao, L.L., Battaglia, D.J., Logan, N.C., Hanson, J.M., Lanctot, M.J., Sontag, A.C., "Design of a 3D Magnetic Diagnostic System for DIII-D," Bull. Am. Phys. Soc. **57**, 183 (2012).

Koch, C.M., Thomas, D.M., Stoschus, H., "High Resolution Spectral Measurements of Lithium Beam-Induced Emission in Pedestal Region of DIII-D Plasmas," Bull. Am. Phys. Soc. **57**, 168 (2012).

Kolemen, E., Ellis, R.A., La Haye, R.J., Lohr, J., Noraky, S., Penaflor, B.G., Welander, A.S., "NTM Suppression and Avoidance at DIII-D Using Real-Time Mirror Steering," Bull. Am. Phys. Soc. **57**, 350 (2012).

Kolemen, E., Welander, A.S., La Haye, R.J., Eidietis, N.W., Humphreys, D.A., Lohr, J., Noraky, S., Penaflor, B.G., Prater, R., and Turco, F., "State-of-the-Art Neoclassical Tearing Mode Control in the DIII-D Using Real-Time Steerable Electron Cyclotron Current Drive Launchers," Synopsis presented at the 24th IAEA Fusion Energy Conf., San Diego, California, October 8–13, 2012; General Atomics Report GA-A27430 (2012).

Kramer, G.J., Budny, R.V., Ellis, R., Nazikian, R., McLean, A.G., Brooks, N.H., Schaffer, M.J., Van Zeeland, M.A., Heidbrink, W.W., Kurki-Suonio, T., Koskela, T., Shinohara, K., Snipes, J.A., Spong, D.A., "Localized Fast-Ion Induced Heat Loads in Test Blanket Module Mockup Experiments on DIII-D," Bull. Am. Phys. Soc. **57**, 140 (2012).

Kramer, G.J., Chen, L., Fisher, R.K., Heidbrink, W.W., Nazikian, R., Pace, D.C., Van Zeeland, M.A., "Fractional Resonances Between Waves and Energetic Particles in Tokamak Plasmas," Phys. Rev. Lett. **109**, 035003 (2012); General Atomics Report GA-A27207 (2012).

Kramer, G.J., McLean, A.G., Brooks, N.H., Budny, R.V., Ellis, R., Heidbrink, W.W., Kurki-Suonio, T., Nazikian, R., Koskela, T., Schaffer, M.J., Sinohara, K., Snipes, J.A., Spong, D.A., and Van Zeeland, M.A., "Observation of Localized Fast-Ion Heat Loads in Test Blanket Module Simulation Experiments on DIII-D," Proc. 24th IAEA Fusion Energy Conf., San Diego, California, October 8–13, 2012, Paper ITR/P1-32; General Atomics Report GA-A27415 (2012).

Kramer, G.J., McLean, A.G., Brooks, N.H., Budny, R.V., Ellis, R., Heidbrink, W.W., Kurki-Suonio, T., Nazikian, R., Koskela, T., Schaffer, M.J., Shinohara, K., Snipes, J.A., Spong, D.A., Van Zeeland, M.A., "Observation of Localized Fast-Ion Induced Heat Loads in Test Blanket Module Simulation Experiments on DIII-D," Synopsis presented at the 24th IAEA Fusion Energy Conf., San Diego, California, October 8–13, 2012; General Atomics Report GA-A27262 (2012).

La Haye, R.J., Strait, E.J., Lanctot, M.J., Paz-Soldan, C., "Model for Effect of Non-Resonant Error Field on Resonant Error Field Locking in Ohmic Plasmas in DIII-D," Bull. Am. Phys. Soc. **57**, 141 (2012).

Lanctot, M.J., Fenstermacher, M.E., Joseph, I., Buttery, R.J., Wade, M.R., Evans, T.E., Ferraro, N.M., deGrassie, J.S., Snyder, P.B., Nazikian, R., Moyer, R.A., Orlov, D.M., Hanson, J.M., Suttrop, W., Haskey, S., "Sustained Suppression of Type-I Edge Localized Modes with Dominantly n=2 Magnetic Fields in DIII-D," Bull. Am. Phys. Soc. **57**, 136 (2012).

Lanctot, M.J., Holcomb, C.T., Allen, S.L., Fenstermacher, M.E., Luce, T.C., "Pedestal Magnetic Field Measurements Using a Motional Stark Effect Polarimeter," presented at the 19th High Temperature Plasma Diagnostics Conf., Monterey, California, May 6-10, 2012 in Rev. Sci. Instrum. **83**, 10E319 (2012); General Atomics Report GA-A27300 (2012).

Lao, L.L., Ferraro, N.M., Buttery, R.J., Evans, T.E., La Haye, R.J., Strait, E.J., Turnbull, A.D., Wade, M.R., Guo, W., Lanctot, M.J., Lazarus, E.A., Sontag, A.C., Nazikian, R., Liu, Y.Q., "Test of Plasma Equilibrium Response against MHD Models Using Slowly Rotating 3D Magnetic Perturbations in DIII-D RMP Experiments," Bull. Am. Phys. Soc. **57**, 137 (2012).

Leonard, A.W., Elder, J.D., Canik, J.M., Groebner, R.J., Osborne, T.H., "Fueling with Edge Recycling to High Density in DIII-D," presented at the 20th Int. Conf. on Plasma-Surface Interactions in Controlled Fusion Devices, Aachen, Germany, May 21–25, 2012 to be published in J. Nucl. Mater.; General Atomics Report GA-A27324 (2012).

Leonard, A.W., Groebner, R.J., Osborne, T.H., Elder, J.D., "Fueling with edge recycling to high-density in DIII-D," Bull. Am. Phys. Soc. **57**, 312 (2012).

Leonard, A.W., Mahdavi, M.A., Lasnier, C.J., Petrie, T.W. and Stangeby, P.C., "Scaling Radiative Divertor Solutions to High Power in DIII-D," Nucl. Fusion **52**, 063015 (2012); General Atomics Report GA-A27057 (2011).

Leuer, J.A., Lee, R., Nagy, A. "A Magnetic Coil Levitation Simulator for Physics Exploration" submitted to Fusion Sci. Technol.; General Atomics Report GA-A27220 (2012).

Li, E., Austin, M.E., "Bursts in Electron Cyclotron Emission During ELMs and EHOs in Tokamaks," Bull. Am. Phys. Soc. **57**, 138 (2012).

Lietz, A.M., Jackson, G.L., Wu, W., Baylor, L.R., Commaux, N., "Modeling of Pellet Ablation and Deposition on Plasma Facing Surfaces," Bull. Am. Phys. Soc. **57**, 167 (2012).

Lohr, J., Cengher, M., Doane, J., Gorelov, Y.A., Moeller, C.P., Ponce, D., Noraky, S., Penaflor, B.G., Kolemen, E., "Upgrades for the ECH System on DIII-D," Bull. Am. Phys. Soc. **57**, 313 (2012).

Lohr, J., Cengher, M., Doane, J.L., Ellis, R.A., Gorelov, Y.A., Kolemen, E., Moeller, C.P., Noraky, S., Penaflor, B.G., Ponce, D.M., Prater, R., Shapiro, M., Tax, D., "Performance, Diagnostics, Controls and Plans for the Gyrotron System on the DIII-D Tokamak," Proc. 17th Joint Wkshp. on Electron Cyclotron Emission and Electron Cyclotron Resonance Heating, Deurne, The Netherlands, May 7–10, 2012; General Atomics Report GA-A27312 (2012).

Lore, J.D., Groebner, R.J., Osborne, T.H., Prater, R., "Comparison of Pedestal Structure and Confinement Properties in ECRH and NBI Heated H-modes in DIII-D," to be published in a Special Issue Nucl. Fusion; General Atomics Report GA-A27180 (2011).

Luce, T.C., Holland, C., Petty, C.C., Smith, S.P., Burrell, K.H., DeBoo, J.C., Kinsey, J.E., Marinoni, A., Austin, M.E., Doyle, E.J., and Zeng, L., "Experimental Tests of Stiffness in the Electron and Ion Energy Transport in the DIII-D Tokamak," Proc. 24th IAEA Fusion Energy Conf., San Diego, California, October 8–13, 2012, Paper EX/P3-18; General Atomics Report GA-A27416 (2012).

Makowski, M.A., Elder, D., Gray, T.K., Labombard, B., Lasnier, C.J., Leonard, A.W., Maingi, R., Osborne, T.H., Stangeby, P.C., Terry, J.L., Watkins, J.G., "Analysis of a Multi-Machine Database on Divertor Heat Fluxes," presented at the 54th Annual Mtg. of the APS Division of Plasma Physics, Providence, Rhode Island, October 29–November 2, 2012 in Phys. Plasmas **19**, 056122 (2012); General Atomics Report GA-A27183 (2011).

Makowski, M.A., Lasnier, C.J., Leonard, A.W., Elder, D., Osborne, T.H., Stangeby, P.C., "Models of SOL Transport and Their Relation to Scaling of the Divertor Heat Flux Width in DIII-D," presented at the 20th Int. Conf. on Plasma-Surface Interactions in Controlled Fusion Devices, Aachen, Germany, May 21–25, 2012 to be published in J. Nucl. Mater.; General Atomics Report GA-A27320 (2012).

Makowski, M.A., Lasnier, C.J., Nichols, J., Leonard, A.W., Osborne, T.H., Snyder, P.B., "Measurements and modeling of the divertor heat flux width in DIII-D," Bull. Am. Phys. Soc. **57**, 206 (2012).

Makowski, M.A., Leonard, A.W., Elder, D., Lasnier, C.J., Osborne, T.H., Stangeby, P.C., "Scaling of the Divertor Heat Flux Width in the DIII-D Tokamak," Synopsis presented at the 24th IAEA Fusion Energy Conf., San Diego, California, October 8–13, 2012; General Atomics Report GA-A27240 (2012).

Makowski, M.A., Leonard, A.W., Elder, J.D., Lasnier, C.J., Nichols, J., Osborne, T.H., Stangeby, P.C., Watkins, J.G., "Scaling of the Divertor Heat Flux Width in the DIII-D Tokamak," Proc. 24th IAEA Fusion Energy Conf., San Diego, California, October 8–13, 2012, Paper EX/P5-16; General Atomics Report GA-A27437 (2012).

Marinoni, A., Rost, J.C., Porkolab, M., Burrell, K.H., Candy, J., Luce, T., "Plasma Fluctuation Measurements in Ion Stiffness Experiments using Phase Contrast Imaging," Bull. Am. Phys. Soc. **57**, 206 (2012).

Martin, M.F., Stoschus, H., Thomas, D.M., Pace, D.C., "Edge Density Imaging Measurements of DIII-D Tokamak Plasmas using a Lithium Beam Probe and High Resolution Camera," Bull. Am. Phys. Soc. **57**, 167 (2012).

McCubbin, A.J., Smith, S.P., Ferraro, N.M., Callen, J.D., Meneghini, O., "Testing the Validity of the Neoclassical Toroidal Viscosity Model of Torque due to 3D Non-Resonant Magnetic Fields," Bull. Am. Phys. Soc. **57**, 166 (2012).

McKee, G.R., "Turbulence in Magnetically Confined Plasmas," Invited Bull. Am. Phys. Soc. **57**, 368 (2012).

McKee, G.R., Buttery, R.J., Evans, T.E., Holland, C., Moyer, R.A., Mordijck, S., Nazikian, R., Rhodes, T.L., Schmitz, O., Wade, M.R., Yan, Z., "Turbulence and Transport Response to Resonant Magnetic Perturbations in ELM-Suppressed Plasmas," Synopsis presented at the 24th IAEA Fusion Energy Conf., San Diego, California, October 8–13, 2012; General Atomics Report GA-A27264 (2012).

McKee, G.R., Fonck, R.J., Yan, Z., Holland, C., "Velocimetry Analysis of 2D Turbulence Imaging Data from Beam Emission Spectroscopy," Bull. Am. Phys. Soc. **57**, 307 (2012).

McKee, G.R., Yan, Z., Holland, C., Buttery, R.J., Evans, T.E., Moyer, R.A., Mordijck, S., Nazikian, R., Rhodes, T.L., Schmitz, O., Wade, M.R., "Turbulence and Transport Response to Resonant Magnetic Perturbations in ELM-Suppressed Plasmas on DIII-D," Proc. 24th IAEA Fusion Energy Conf., San Diego, California, October 8–13, 2012, Paper EX/P7-06; General Atomics Report GA-A27413 (2012).

McLean, A.G., Soukhanovskii, V.A., Brooks, N.H., Bray, B.D., Carlstrom, T.N., "Near infrared spectroscopy of the DIII-D divertor," Bull. Am. Phys. Soc. **57**, 311 (2012).

Meneghini, O., Smith, S.P., Lao, L.L., "Optimization of self-consistent DIII-D AT scenarios with the OMFIT framework," Bull. Am. Phys. Soc. **57**, 310 (2012).

Mordijck, S., Doyle, E.J., McKee, G.R., Moyer, R.A., Rhodes, T.L., Zeng, L., "Changes in Particle Transport as a Result of Resonant Magnetic Perturbations in DIII-D," Phys. Plasmas **19**, 056503 (2012); General Atomics Report GA-A27192 (2012).

Mordijck, S., Moyer, R.A., "Changes in Rotation and Rotational Shear by Resonant Magnetic Perturbations (RMPs)," Bull. Am. Phys. Soc. **57**, 137 (2012).

Mordijck, S., Moyer, R.A., McKee, G.R., "Changes in Density Fluctuations as a Result of Resonant Magnetic Perturbations Correlate With the Density Inverse Scale Length," Phys. Plasmas **19**, 024504 (2012); General Atomics Report GA-A27115 (2011).

Moreau, D., Schuster, E., Walker, M.L., Ferron, J.R., Humphreys, D.A., Barton, J.E., Boyer, D., Burrell, K.H., Flanagan, S.M., Gohil, P., Groebner, R.J., Hyatt, A.W., Johnson, R.D., La Haye, R.J., Liu, F., Lohr, J., Luce, T.C., Penaflor, B.G., Shi, W., Turco, F., Wehner, W., and ITPA-IOS Group Members and Experts, "Integrated Magnetic and Kinetic Control of Advanced Tokamak Scenarios on DIII-D Based on Data-Driven Models," Synopsis presented at the 24th IAEA Fusion Energy Conf., San Diego, California, October 8–13, 2012; General Atomics Report GA-A27265 (2012).

Moreau, D., Walker, M.L., Ferron, J.R., Liu, F., Schuster, E., Artaud, J.F., Barton, J.E., Boyer, M.D., Burrell, K.H., Flanagan, S.M., Garcia, J., Gohil, P., Groebner, R.J., Holcomb, C.T., Humphreys, D.A., Hyatt, A.W., Johnson, R.D., La Haye, R.J., Lohr, J., Luce, T.C., Nouailletas, R., Park, J.M., Penaflor, B.G., Shi, W., Turco, F., Wehner, W., and ITPA-IOS group members and experts, "Integrated Magnetic and Kinetic Control of Advanced Tokamak Scenarios Based on Data-Driven Models," Proc. 24th IAEA Fusion Energy Conf., San Diego, California, October 8–13, 2012, Paper ITR/P1-20; General Atomics Report GA-A27429 (2012).

Moyer, R.A., "Plasma Rotation and Radial Electric Field Response to Resonant Magnetic Perturbations in DIII-D," Invited Bull. Am. Phys. Soc. **57**, 295 (2012).

Moyer, R.A., Evans, T.E., Ferraro, N.M., Orlov, D.M., Van Zeeland, M.A., Wingen, A., Zeng, L. "Measurement of Plasma Boundary Displacement by n=2 Magnetic Perturbations Using Imaging Beam Emission Spectroscopy" submitted to Nucl. Fusion; General Atomics Report GA-A27315 (2012).

Muñoz Burgos, J.M., Leonard, A.W., Loch, S.D., Ballance, C.P., "Evaluation of an Improved Atomic Data Basis for Carbon in UEDGE Emission Modeling for L-mode Plasmas in DIII-D," presented at the 20th Int. Conf. on Plasma-Surface Interactions in Controlled Fusion Devices, Aachen, Germany, May 21–25, 2012 to be published in J. Nucl. Mater.; General Atomics Report GA-A27309 (2012).

Munoz Burgos, J.M., Schmitz, O., Loch, S.D., Ballance, C.P., "Hybrid Time Dependence/Independent Solution for the He I Line Ratio Temperature and Density Diagnostic for a Thermal Helium Beam With Application in the SOL Edge Regions in Tokamaks," Phys. Plasmas **19**, 012501 (2012); General Atomics Report GA-A26828 (2011).

Muscatello, C.M., "Measurements of Fast-Ion Transport by Mode-Particle Resonances on DIII-D" Nucl. Fusion. Nucl. Fusion **52**, 103022 (2012); General Atomics Report GA-A27200 (2012).

Muscatello, C.M., Heidbrink, W.W., Harvey, R.W., "Measurements of Resonant Transport of Fast Ions During a Sawtooth Crash," submitted to Phys. Plasmas as a Letter; General Atomics Report GA-A27151 (2011).

Muscatello, C.M., Heidbrink, W.W., Kolesnichenko, Ya.I., Lutsenko, V.V., Van Zeeland, M.A., Yakovenko, Yu.V., "Velocity-space studies of fast-ion transport at a sawtooth crash in neutral-beam heated plasmas," Plasma Phys. Control. Fusion **54**, 025006 (2012); General Atomics Report GA-A27058 (2010).

Nave, M.F.F., Burrell, K.H., Austin, M.E., deGrassie, J.S., Heidbrink, W.W., Osborne, T.H., Strait, E.J., Snyder, P.B., Van Zeeland, M.A., "Fishbone-Like Instability at the Edge of ELM-Free Quiescent H-Modes in DIII-D," Proc. 39th European Physical Society Conf. on Plasma Physics, Stockholm, Sweden, July 2–6, 2012, Paper P4.008; General Atomics Report GA-A27359 (2012).

Nazikian, R., for the RMP ELM Suppression Task Force, "Latest Results on Resonant Magnetic Perturbation (RMP) Induced ELM Suppression on DIII-D," Bull. Am. Phys. Soc. **57**, 205 (2012).

Okabayashi, M., Matsunaga, G., Ferron, J.R., deGrassie, J.S., Hanson, J.M., Heidbrink, W.W., Holcomb, C.T., In, Y., Jackson, G.L., Lanctot, M.J., La Haye, R.J., Liu, Y.Q., Luce, T.C., Pace, D.C., Solomon, W.M., Strait, E.J., Turnbull, A.D., Turco, F., Van Zeeland, M.A., "ELM-Like Events Excited by the Off-Axisfishbone Mode in the DIII-D Advanced Tokamak Regime," Proc. 39th European Physical Society Conf. on Plasma Physics, Stockholm, Sweden, July 2–6, 2012, Paper P2.034; General Atomics Report GA-A27331 (2012).

Okabayashi, M., Solomon, W.M., Matsunaga, G., Ferron, J.R., deGrassie, J.S., Jackson, G.L., La Haye, R.J., Luce, T.C., Pace, D.C., Strait, E.J., Turnbull, A.D., Van Zeeland, M.A., Hanson, J.M., Turco, F., Heidbrink, W.W., Holcomb, C.T., Lanctot, M.J., In, Y., Liu, Y.Q., "ELM-Like Events Excited by the Off-Axis-Fishbone Mode and Accompanied by Electron Density Snake," Bull. Am. Phys. Soc. **57**, 143 (2012).

Olstad, R.A., Callis, R.W., Cengher, M., Doane, J.L., Gorelov, Y.A., Grunloh, H.J., Moeller, C.P., Murphy, C.J., "Progress on Corrugated Waveguide Components Suitable for ITER ECH&CD Transmission Lines," Proc. 17th Joint Wkshp. on Electron Cyclotron Emission and Electron Cyclotron Resonance Heating, Deurne, The Netherlands, May 7–10, 2012; General Atomics Report GA-A27322 (2012).

Orlov, D., Evans, T.E., Moyer, R., Schaffer, M.J., Schmitz, O., Loarte, A., "Structure in ITER Due to In-Vessel ELM Control Coils," Fusion Engin. Design **87**, 1536 (2012); General Atomics Report GA-A27049, Rev. 1 (2011).

Orlov, D.M., Evans, T.E., Moyer, R.A., Schaffer, M.J., Schmitz, O., Loarte, A., "Analysis of Edge Magnetic Field Line Structure in ITER Due to In-Vessel ELM Control Coils," Fusion Engin. Design **87**, 1536 (2012); General Atomics Report GA-A27049 (2011).

Orlov, D.M., Moyer, R.A., Eldon, D., Evans, T.E., Ferraro, N.M., Van Zeeland, M.A., Wingen, A., Shafer, M.W., Unterberg, E.A., Grierson, B.A., Nazikian, R., "Comparison of Vacuum Model Predictions to Measurements in DIII-D RMP H-mode Discharges," Bull. Am. Phys. Soc. **57**, 136 (2012).

Osborne, T.H., Groebner, R.J., Smith, S.P., Snyder, P.B., Thomas, D.M., Boedo, J.A., Rhodes, T.L., Stoschus, H., Yan, Z., "Time Evolution of the H-mode Pedestal Characteristics in Type I ELM Discharges on DIII-D," Bull. Am. Phys. Soc. **57**, 205 (2012).

Pace, D.C., "Energetic Ion Transport and Neutral Beam Current Drive Reduction Due to Microturbulence in Tokamaks," Invited Bull. Am. Phys. Soc. **57**, 151 (2012).

Pace, D.C., Pinsker, R.I., Heidbrink, W.W., Fisher, R.K., Van Zeeland, M.A., McKee, G.R., García-Muñoz, M., "Scrape-Off Layer Ion Acceleration During Fast Wave Injection in the DIII-D Tokamak," Nucl. Fusion **52**, 063019 (2012); General Atomics Report GA-A27153 (2012).

Park, J.M., Ferron, J.R., Holcomb, C.T., Luce, T.C., Buttery, R.J., Lao, L.L., Prater, R,, Turco, F., Murakami, M., "Transport and Stability Characteristics of High q_{min} Steady-State Scenarios with Off-Axis NBI," Bull. Am. Phys. Soc. **57**, 207 (2012).

Park, J.M., Murakami, M., Petty, C.C., Heidbrink, W.W., Van Zeeland, M.A., Pace, D.C., Prater, R., Ferron, J.R., Osborne, T.H., Holcomb, C.T., Jackson, G.J., Petrie, T.W., Grierson, B.A., Murphy, C.J., Suzuki, T., "Validation of Off-axis Neutral Beam Current Drive Physics in the DIII-D Tokamak," Proc. 24th IAEA Fusion Energy Conf., San Diego, California, October 8–13, 2012, Paper EX/P2-13; General Atomics Report GA-A27422 (2012).

Park, J.M., Murakami, M., Petty, C.C., Heidbrink, W.W., Van Zeeland, M.A., Pace, D.C., Prater, R., Ferron, J.R., Osborne, T.H., Holcomb, C.T., Jackson, G.J., Petrie, T.W., "Validation of Off-axis Neutral Beam Current Drive Physics in the DIII-D Tokamak," Synopsis presented at the 24th IAEA Fusion Energy Conf., San Diego, California, October 8–13, 2012; General Atomics Report GA-A27241 (2012).

Parks, P.B., "Erratum and auxiliary remark: 'Equilibrium pellet and liquid jet shape under high ablation pressures' [Phys. Plasmas **5**, 1380 (1998) by P.B. Parks and M.N. Rosenbluth]," Phys. Plasmas **19**, 109901 (2012); Erratum General Atomics Report GA-A22772 (2012).

Paz-Soldan, C., Strait, E.J., La Haye, R.J., Buttery, R.J., Hanson, J.M., Lanctot, M.J., “Assessment of Error Field Control with the ‘n=1 Coil’,” Bull. Am. Phys. Soc. **57**, 142 (2012).

Petrie, T.W., Canik, J.M., Fenstermacher, M.E., Ferron, J.R., Groebner, R.J., Hill, D.N., Holcomb, C.T., Hyatt, A.W., Lasnier, C.J., Leonard, A.W., Luce, T.C., Mahdavi, M.A., Moyer, R.A., Osborne, T.E., Stangeby, P.C., Watkins, J.G. “Effect of Changes in Separatrix Magnetic Geometry on Divertor Behavior in DIII-D” Proc. 24th IAEA Fusion Energy Conf., San Diego, California, October 8–13, 2012, Paper EX/P5-12; General Atomics Report GA-A27405 (2012).

Petrie, T.W., Canik, J., Leonard, A.W., Mahdavi, M.A., Watkins, J.G., Buttery, R.J., Fenstermacher, M.E., Ferron, J.R., Groebner, R.J., Hill, D.N., Hyatt, A.W., Holcomb, C.T., Lasnier, C.J., Luce, T.C., Moyer, R.A., Stangeby, P.C., “Effect of Changes in Separatrix Magnetic Geometry on Divertor Behavior in DIII-D,” Post-Deadline Synopsis presented at the 24th IAEA Fusion Energy Conf., San Diego, California, October 8–13, 2012; General Atomics Report GA-A27266 (2012).

Petrie, T.W., Canik, J.M., Lasnier, C.J., Leonard, A.W., Mahdavi, M.A., Watkins, J.G., Fenstermacher, M.E., Ferron, J.R., Groebner, R.J., Hill, D.N., Hyatt, A.W., Holcomb, C.T., Luce, T.C., Moyer, R.A., Stangeby, v, “Effect of Separatrix Magnetic Geometry on Divertor Behavior in DIII-D,” presented at the 20th Int. Conf. on Plasma-Surface Interactions in Controlled Fusion Devices, Aachen, Germany, May 21–25, 2012 to be published in J. Nucl. Mater.; General Atomics Report GA-A27316 (2012).

Petrie, T.W., Leonard, A.W., Luce, T.C., Mahdavi, M.A., Holcomb, C.T., Fenstermacher, M.E., Hill, D.N., Lasnier, C.J., Canik, J., Watkins, J.G., Moyer, R.A., Stangeby, P.C., “Effect of Divertor Shaping on Divertor Plasma Behavior on DIII-D,” Bull. Am. Phys. Soc. **57**, 312 (2012).

Petty, C.C., DeBoo, J.C., Smith, S.P., Burrell, K.H., White, A.E., Hillesheim, J.C., Holland, C.H., “Electron Transport Stiffness and Heat Pulse Propagation on DIII-D,” Bull. Am. Phys. Soc. **57**, 206 (2012).

Petty, C.C., Guttenfelder, W., Holland, C., Kaye, S., Kinsey, J.E., McDonald, D.C., McKee, G.R., Vermare, L., Angioni, C., Bourdelle, C., Hoang, C., Imbeaux, F., Ryter, F., Urano, H., Valovic, M., and the ITPA Transport and Confinement Topical Group, “Implications of the Beta Scaling of Energy Confinement,” Synopsis presented at the 24th IAEA Fusion Energy Conf., San Diego, California, October 8–13, 2012; General Atomics Report GA-A27272 (2012).

Petty, C.C., Guttenfelder, W., Holland, C., Kaye, S.M., Kinsey, J.E., McDonald, D.C., McKee, G.R., Vermare, L., Angioni, C., Bourdelle, C., Hoang, G.T., Imbeaux, F., Ryter, F., Urano, H., Valovic, M., and The ITPA Transport and Confinement Topical Group, “ITER Implications of the Beta Scaling of Energy Confinement,” Proc. 24th IAEA Fusion Energy Conf., San Diego, California, October 8–13, 2012, Paper ITR/P1-30; General Atomics Report GA-A27427 (2012).

Pieronek, C.V., Tobias, B.J., Yu, L., Van Zeeland, M.A., “MHD Spectroscopy of Fusion Plasmas by ECE-Imaging of Reversed-Shear Alfvén Eigenmodes,” Bull. Am. Phys. Soc. **57**, 167 (2012).

Pinsker, R.I., Buttery, R.J., Luce, T.C., Porkolab, M., Diem, S., Kaufman, M., Ryan, P.M., Hosea, J.C., Nagy, A., Perkins, R., Solomon, W.M., Maggiora, R., Milanesio, D., “High Power Fast Wave Coupling and Heating in H-mode Plasmas on DIII-D,” Bull. Am. Phys. Soc. **57**, 312 (2012).

Pinsker, R.I., Milanesio, D., Maggiora, R., Commaux, N., Doyle, E.J., Hanson, G.R., Nagy, A., Porkolab, M., Ryan, P.M., Zeng, L., “Quantitative Comparison of Fast Wave Antenna Loading in DIII-D with Theoretical and Computational Models Incorporating Measured Profiles,” Proc. 39th European Physical Society Conf. on Plasma Physics, Stockholm, Sweden, July 2–6, 2012, Paper P2.053; General Atomics Report GA-A27359 (2012).

Prater, R., Buttery, R.J., DeBoo, J.C., Ferron, J.R., Garofalo, A.M., Holcomb, C.T., Jackson, G.L., La Haye, R.J., Lohr, J., Luce, T.C., Petty, C.C., Politzer, P.A., Solomon, W.M., Turco, F., "Applications of ECH on the DIII-D Tokamak and Projections for Future ECH Upgrades," Proc. 17th Joint Wkshp. on Electron Cyclotron Emission and Electron Cyclotron Resonance Heating, Deurne, The Netherlands, May 7–10, 2012; General Atomics Report GA-A27303 (2012).

Prater, R., Chan, V., Garofalo, A., "Improvement of Current Drive Efficiency in Projected FNSF Discharges," Bull. Am. Phys. Soc. **57**, 188 (2012).

Project Staff, "Fusion Energy Science Joint Facilities and Theory Research Target 2011, Final Report for the period October 1, 2010 through September 30, 2011," General Atomics Report GA-A27142 (2011).

Raum, P., Smith, S.P., Ferraro, N.M., Callen, J.D., Meneghini, O., "Investigating the Validity of the "Magnetic Flutter" Model of Tokamak Transport in the Presence of 3D External Magnetic Fields," Bull. Am. Phys. Soc. **57**, 166 (2012).

Reimerdes, H., Hanson, J.M., Oyama, N., Park, J.-K., Schaffer, M.J., Snipes, J.A., Strait, E.J., Tala, T., Buttery, R.J., Garofalo, A.M., In, Y., La Haye, R.J., Lanctot, M.J., Okabayashi, M., Orlov, D.M., Paz-Soldan, C., Salmi, A., Solomon, W.M., "Rotation Braking and Error Field Correction of the Test Blanket Module Induced Magnetic Field Error in ITER," Proc. 24th IAEA Fusion Energy Conf., San Diego, California, October 8–13, 2012, Paper EX/P4-09; General Atomics Report GA-A27434 (2012).

Riford, L.S., Cengher, M., Lohr, J., "Spectroscopic analysis of light emitted from gyrotron tubes," Bull. Am. Phys. Soc. **57**, 165 (2012).

Rost, J.C., Porkolab, M., Dorris, J.R., Marinoni, A., Burrell, K.H., "Phase Contrast Imaging Measurements of Short Wavelength Turbulence Generated by Shear in the QH-mode Edge on DIII-D," Bull. Am. Phys. Soc. **57**, 139 (2012).

Rudakov, D.L., Boedo, J.A., Moyer, R.A., Watkins, J.G., "Electron Temperature Fluctuations in DIII-D SOL," Bull. Am. Phys. Soc. **57**, 312 (2012).

Rudakov, D.L., Chrobak, C.P., Doerner, R.P., Krasheninnikov, S.I., Moyer, R.A., Umstadter, K.R., Wampler, W.R., Wong, C.P.C., "Arcing and Its Role in PFC Erosion and Dust Production in DIII-D," presented at the 20th Int. Conf. on Plasma-Surface Interactions in Controlled Fusion Devices, Aachen, Germany, May 21–25, 2012 to be published in J. Nucl. Mater.; General Atomics Report GA-A27317 (2012).

Rudakov, D.L., Stangeby, P.C., Brooks, N.H., Wampler, W.R., Brooks, J.N., Buchenauer, D.A., Elder, J.D., Fenstermacher, M.E., Hassanein, A., Lasnier, C.J., Leonard, A.W., McLean, A.G., Moyer, R.A., Okamoto, A., Sizyuk, T., Watkins, J.G., Wong, C.P.C., "Measurements of Net versus Gross Erosion of Molybdenum Divertor Surface in DIII-D," Proc. 24th IAEA Fusion Energy Conf., San Diego, California, October 8–13, 2012, Paper EX/P5-11; General Atomics Report GA-A27410 (2012).

Rudakov, D.L., Stangeby, P.C., Brooks, N.H., Wampler, W.R., Brooks, J.N., Buchenauer, D.A., Elder, J.D., Fenstermacher, M.E., Lasnier, C.J., Leonard, A.W., McLean, A.G., Moyer, R.A., Okamoto, A., Watkins, J.G., Wong, C.P.C., "Measurements of Net versus Gross Erosion of Molybdenum Divertor Surface in DIII-D," Synopsis presented at the 24th IAEA Fusion Energy Conf., San Diego, California, October 8–13, 2012; General Atomics Report GA-A27242 (2012).

Ryan, P.M., Green, D.L., Jaeger, E.F., Canik, J.M., Commaux, N., Diem, S.J., Hanson, G.R., Pinsker, R.I., Hosea, J.C., Nagy, A., Perkins, R.J., Taylor, G., "Study of Fast Wave Coupling Through the DIII-D Edge Plasma Using the AORSA Full Wave Code," Bull. Am. Phys. Soc. **57**, 313 (2012).

Sayer, M.S., Stacey, W.M., Floyd, J.-P., Groebner, R.J., “Evolution of Edge Pedestal Profiles Over the L-H Transition,” Bull. Am. Phys. Soc. **57**, 139 (2012).

Schissel, D.P., Abla, G., Flanagan, S., and Kim, E.N., “A New Remote Control Room for Tokamak Operations,” Proc. 8th Tech. Mtg. on Control, Data Acquisition, and Remote Participation for Fusion Research, San Francisco, California, June 20–24, 2011 in Fusion Engin. Design **87**, 2194 (2012); General Atomics Report GA-A27117 (2011).

Schmitz, L., Holland, C., Rhodes, T.L., Wang, G., Zeng, L., White, A.E., Hillesheim, J.C., Peebles, W.A., Smith, S.P., Prater, R., McKee, G.R., Yan, Z., Solomon, W.M., Burrell, K.H., Holcomb, C.T., Doyle, E.J., DeBoo, J.C., Austin, M.E., deGrassie, J.S., Petty, C.C., “Reduced Electron Thermal Transport in Low Collisionality H-mode Plasmas in DIII-D and the Importance of Intermediate/Small-Scale Turbulence,” Nucl. Fusion **52**, 023003 (2012); General Atomics Report GA-A27004 (2011).

Schmitz, L., Zeng, L., Rhodes, T.L., Hillesheim, J.C., McKee, G.R., Yan, Z., Peebles, W.A., Groebner, R.J., Burrell, K.H., Tynan, G.R., Doyle, E.J., Wang, G., “The Role of Zonal Flows and Predator-Prey Oscillations in the Formation of Core and Edge Transport Barriers,” Proc. 39th European Physical Society Conf. on Plasma Physics, Stockholm, Sweden, July 2–6, 2012, Paper P5.071; General Atomics Report GA-A27337 (2012).

Schmitz, L., Zeng, L., Rhodes, T.L., Hillesheim, J.C., Peebles, W.A., McKee, G.R., Yan, Z., Groebner, R.J., Burrell, K.H., Tynan, G.R., Boedo, J.A., Solomon, W.M., “The Role of Zonal Flows and Predator-Prey Oscillations in Triggering the L-H Transition and in Internal Transport Barriers,” Bull. Am. Phys. Soc. **57**, 308 (2012).

Schmitz, L., Zeng, L., Rhodes, T.L., Hillesheim, J.C., Peebles, W.A., Groebner, R.J., Burrell, K.H., Doyle, E.J., Solomon, W.M., Wang, G., “The Role of Zonal Flows and Predator-Prey Oscillations in the Formation of Core and Edge Transport Barriers,” Synopsis presented at the 24th IAEA Fusion Energy Conf., San Diego, California, October 8–13, 2012; General Atomics Report GA-A27243 (2012).

Schmitz, L., Zeng, L., Rhodes, T.L., Hillesheim, J.C., Peebles, W.A., Groebner, R.J., Burrell, K.H., McKee, G.R., Yan, Z., Tynan, G.R., Diamond, P.H., Boedo, J.A., Doyle, E.J., Grierson, B.A., Chrystal, C., Austin, M.E., Solomon, W.M., Wang, G., “The Role of Zonal Flows and Predator-Prey Oscillations in the Formation of Core and Edge Transport Barriers,” Proc. 24th IAEA Fusion Energy Conf., San Diego, California, October 8–13, 2012, Paper EX/P7-17; General Atomics Report GA-A27418 (2012).

Shafer, M.W., Unterberg, E.A., Orlov, D.M., Evans, T.E., Harris, J.H., Hillis, D.L., Mangi, R., Moyer, R.A., Nazikian, R., Wingen, A., “Experimental Imaging of Separatrix Splitting on DIII-D,” Nucl. Fusion **52**, 122001 (2012); General Atomics Report GA-A27311 (2012).

Shafer, M.W., Unterberg, E.A., Wingen, A., Harris, J.H., Hillis, D.L., Evans, T.E., Orlov, D.M., “Edge Soft X-Ray Imaging Measurements of 3D Plasma Response to Resonant Magnetic Perturbations,” Bull. Am. Phys. Soc. **57**, 205 (2012).

Shi, W., Wehner, W., Barton, J., Boyer, M.D., Schuster, E., Moreau, D., Walker, M.L., Ferron, J.R., “Data-driven Model-based Combined Magnetic and Kinetic Control on DIII-D,” Bull. Am. Phys. Soc. **57**, 311 (2012).

Smith, S.P., Callen, J.D., Groebner, R.J., Osborne, T.H., Leonard, A.W., Eldon, D., Bray, B.D., and The DIII-D Team, “Comparing Paleoclassical-Based Pedestal Model Predictions of Electron Quantities to Measured DIII-D H-Mode Profiles,” presented at the 13th Int. Wkshp. on H-mode Physics and Transport Barriers, Oxford, United Kingdom, October 10–12, 2011 in Nucl. Fusion **52**, 114016 (2012); General Atomics Report GA-A27160 (2012).

Smith, S.P., Luce, T.C., DeBoo, J.C., Petty, C.C., Burrell, K.H., Waltz, R.E., Staebler, G.M., Candy, J., Holland, C., Meneghini, O., White, A.E., Rhodes, T.L., Schmitz, L., Doyle, E.J., Hillesheim, J.C., Wang, G., Zeng, L., McKee, G.R., Yan, Z., "Probing Electron Temperature Critical Gradients in Experiment and Simulation," Bull. Am. Phys. Soc. **57**, 308 (2012).

Snyder, P.B., Beurskens, M.N.A., Groebner, R.J., Hughes, J.W., Maingi, R., Osborne, T.H., Walk, J.R., Wilson, H.R., Alcator C-Mod and DIII-D Teams, and JET-EFDA Contributors, "Developing and Testing the EPED Pedestal Model," Proc. 39th European Physical Society Conf. on Plasma Physics, Stockholm, Sweden, July 2–6, 2012, Paper P4.029; General Atomics Report GA-A27346 (2012).

Snyder, P.B., Groebner, R.J., Osborne, T.H., Hughes, J.W., Wilson, H.R., "Predicting and Optimizing Pedestal Height With the EPED Model," Bull. Am. Phys. Soc. **57**, 138 (2012).

Snyder, P.B., Osborne, T.H., Burrell, K.H., Candy, J., Groebner, R.J., Leonard, A.W., Nazikian, R., Orlov, D.M., Schmitz, O., Wade, M.R., and Wilson, H.R., "The EPED Pedestal Model: Extensions, Applications to ELM-Suppressed Regimes, and ITER Predictions," Post-Deadline Synopsis presented at the 24th IAEA Fusion Energy Conf., San Diego, California, October 8–13, 2012; General Atomics Report GA-A27268 (2012).

Snyder, P.B., Osborne, T.H., Burrell, K.H., Groebner, R.J., Leonard, A.W., Nazikian, R., Orlov, D.M., Schmitz, O., Wade, M.R., Wilson, H.R., "The EPED Pedestal Model and ELM-Suppressed Regimes: Studies of Quiescent H-mode and Development of a Model for ELM Suppression via Resonant Magnetic Perturbations," Phys. Plasmas **19**, 056115 (2012); General Atomics Report GA-A27201 (2011).

Solomon, W.M., Burrell, K.H., Buttery, R.J., deGrassie, J.S., Garofalo, A.M., Jackson, G.L., Luce, T.C., Petty, C.C., Politzer, P.A., Doyle, E.J., Turco, F., "Impact of Torque and Rotation in High Fusion Performance Plasmas," Bull. Am. Phys. Soc. **57**, 207 (2012).

Solomon, W.M., Burrell, K.H., Garofalo, A.M., Groebner, R.J., Lasnier, C.J., Makowski, M.A., Osborne, T.H., Reimerdes, H., deGrassie, J.S., Doyle, E.J., Evans, T.E., Fenstermacher, M.E., Jackson, G.L., Schaffer, M.J., "ELM Pacing Using Modulated Non-Axisymmetric Magnetic Fields on DIII-D," Nucl. Fusion **52**, 033007 (2012); General Atomics Report GA-A27045 (2011).

Solomon, W.M., Politzer P.A., Buttery, R.J., Ferron, J.R., Garofalo, A.M., Grierson B.A., Hanson, J.M., In, Y., Jackson, G.L., Holcomb, C.T., Kinsey, J.E., La Haye, R.J., Lanctot, M.J., Luce, T.C., Okabayashi, M., Petty, C.C., Turco, F., and Welander, A.S., "Access and Sustained High Performance in Advanced Inductive Discharges With ITER-Relevant Low Torque," Proc. 24th IAEA Fusion Energy Conf., San Diego, California, October 8–13, 2012, Paper EX/P2-01; General Atomics Report GA-A27412 (2012).

Solomon, W.M., Politzer, P.A., Buttery, R.J., Ferron, J.R., Garofalo, A.M., Hanson, J.M., In, Y., Jackson, G.L., Holcomb, C.T., La Haye, R.J., Lanctot, M.J., Luce, T.C., Okabayashi, M., Petty, C.C., Turco, F., Welander, A.S., "Access and Sustained High Performance in Advanced Tokamak Inductive Discharges with ITER-Relevant Low Torque," Synopsis presented at the 24th IAEA Fusion Energy Conf., San Diego, California, October 8–13, 2012; General Atomics Report GA-A27269 (2012).

Sontag, A.C., Harris, J.H., Shafer, M.W., Unterberg, E.A., Hanson, J.D., Lao, L.L., "3D Equilibrium Reconstruction of DIII-D Discharges using V3FIT," Bull. Am. Phys. Soc. **57**, 143 (2012).

St. John, H.E., Turnbull, A.D., Choi, M., Smith, S.P., Lao, L.L., Buttery, R.J., "Comparison of some turbulent confinement models for DIII-D, ARIES and FNSF," Bull. Am. Phys. Soc. **57**, 310 (2012).

Staebler, G.M., Waltz, R.E., Candy, J., Kinsey, J.E., "A New Paradigm for Suppression of Gyro-Kinetic Turbulence by Velocity Shear," Phys. Rev. Lett. **110**, 055003 (2013); General Atomics Report GA-A27226 (2012).

Staebler, G.M., Waltz, R.E., Candy, J., Kinsey, J.E., "Verification of the Spectral Shift Paradigm for ExB Shear Suppression of Transport," Bull. Am. Phys. Soc. **57**, 69 (2012).

Staebler, G.M., Waltz, R.E., Kinsey, J.E., and Solomon, W.M., "A New Paradigm for ExB Velocity Shear Suppression of Gyro-Kinetic Turbulence and the Momentum Pinch," Proc. 24th IAEA Fusion Energy Conf., San Diego, California, October 8–13, 2012, Paper TH/8-02; General Atomics Report GA-A27391 (2012).

Staebler, G.M., Waltz, R.E., Kinsey, J.E., Solomon, W.M., "A New Paradigm for ExB Velocity Shear Suppression of Gyro-Kinetic Turbulence and the Momentum Pinch," Synopsis presented at the 24th IAEA Fusion Energy Conf., San Diego, California, October 8–13, 2012; General Atomics Report GA-A27270 (2012).

Stagner, L., Heidbrink, W.W. , Salewski, M., "Towards Bayesian Inference of the Fast-Ion Distribution Function," Bull. Am. Phys. Soc. **57**, 141 (2012).

Stangeby, P.C., "Reduction of Net Erosion of High-Z Divertor Surface by Local Redeposition in DIII-D," Invited Bull. Am. Phys. Soc. **57**, 107 (2012).

Stangeby, P.C., "The Chodura Sheath for Angles of a Few Degrees Between the Magnetic Field and the Surface of Divertor Targets and Limiters," Nucl. Fusion **52**, 083012 (2012); General Atomics Report GA-A27116 (2011).

Stangeby, P.C., Rudakov, D.L., Wampler, W.R., Brooks, J.N., Brooks, N.H., Buchenauer, D.A., Elder, J.D., Hassanein, A., Leonard, A.W., McLean, A.G., Okamoto, A., Sizyuk, T., Watkins, J.G., Wong, C.P.C., "An Experimental Comparison of Gross and Net Erosion of Mo in the DIII-D Divertor," presented at the 20th Int. Conf. on Plasma-Surface Interactions in Controlled Fusion Devices, Aachen, Germany, May 21–25, 2012 to be published in J. Nucl. Mater.; General Atomics Report GA-A27302 (2012).

Stoschus, H., Thomas, D.M., Evans, T.E., Hudson, B., "Effect of Resonant Magnetic Perturbations on the Field Line Pitch Angle in the Pedestal of DIII-D," Bull. Am. Phys. Soc. **57**, 137 (2012).

Stoschus, H., Thomas, D.M., Hudson, B., Muñoz-Burgoz, J.M., Schweinzer, J., "Comparison of Collisional Radiative Models for Edge Electron Density Reconstruction from Li I (2s-2p) Emission Profiles," presented at the 19th High Temperature Plasma Diagnostics Conf., Monterey, California, May 6-10, 2012 in Rev. Sci. Instrum. **83**, 10D508 (2012); General Atomics Report GA-A27299 (2012).

Strait, E.J., Brooks, N.H., Buttery, R.J., La Haye, R.J., Schaffer, M.J., Reimerdes, H., Snipes, J.A., Hanson, J.M., Heidbrink, W.W., Zhu, Y., In, Y., Kramer, G.J., Okabayashi, M., Park, J.-K., Solomon, W.M., McLean, A.G., Oyama, N., Tala, T., "Test Blanket Module Mockup Experiments in DIII-D," Bull. Am. Phys. Soc. **57**, 352 (2012).

Thomas, D.M., "Beams, Brightness, and Background — Using Active Spectroscopy Techniques for Precision Measurements in Fusion Plasma Research," Phys. Plasmas **19**, 056118 (2012); General Atomics Report GA-A27185 (2011).

Thomas, D.M., Grierson, B.A., Muñoz Burgos, J.M., Van Zeeland, M.A., "Determination of Neutral Beam Energy Fractions from Collisional Radiative Measurements on DIII-D," presented at the 19th High Temperature Plasma Diagnostics Conf., Monterey, California, May 6-10, 2012 in Rev. Sci. Instrum. **83**, 10D518 (2012); General Atomics Report GA-A27294 (2012).

Thomas, D.M., Osborne, T.H., Groebner, R.J., Leonard, A.W., Stoschus, H., Koch, C.M., Martin, M.F., Makowski, M.A., "Pedestal Evolution Studies Using LIBEAM on DIII-D," Bull. Am. Phys. Soc. **57**, 139 (2012).

Tobias, B.J., Austin, M.E., Boom, J.E., Burrell, K.H., Classen, I.G.J., Domier, C.W., Luhmann, Jr., N.C., Nazikian, R.M., Snyder, P.B., “ECE-Imaging of the H-mode Pedestal,” presented at the 19th High Temperature Plasma Diagnostics Conf., Monterey, California, May 6-10, 2012 in Rev. Sci. Instrum. **83**, 10E329 (2012); General Atomics Report GA-A27292 (2012).

Tobias, B.J., Austin, M.E., Boom, J.E., Classen, I.G.J., Domier, C.W., Luhmann, Jr., N.C., Nazikian, R., Yu, L., “Intense Millimeter Wave Radiation from the H-mode Pedestal at ITER Relevant Collisionality,” Proc. 39th European Physical Society Conf. on Plasma Physics, Stockholm, Sweden, July 2–6, 2012, Paper P4.019; General Atomics Report GA-A27338 (2012).

Tobias, B.J., Bass, E.M., Classen, I.G.J., Domier, C.W., Grierson, B.A., Heidbrink, W.W., Luhmann Jr., N.C., Nazikian, R., Park, H.K., Spong, D.A., Van Zeeland, M.A., “Alfvèn Eigenmode Structure During Off-Axis Neutral Beam Injection,” Nucl. Fusion **52** 103009 (Year?); General Atomics Report GA-A27209 (2012).

Tobias, B.J., Domier, C.W., Luhmann, Jr., N.C., Austin, M.E., “ECE-Imaging of the H-mode Pedestal on DIII-D,” Bull. Am. Phys. Soc. **57**, 139 (2012).

Tooker, J.F., Huynh, P., Felch, K., Blank, M., Borchard, P., Caufman, S., “Gyrotron And Power Supply Developent for the Electron Cyclotron Heating System on DIII-D,” Proc. 27th Symp. on Fusion Technology, Liege, Belgium, September 24–28, 2012, accepted for publication in Fusion Engin. Design; General Atomics Report GA-A27373 (2012).

Tsui, C.K., Taussig, D.A., Watkins, M.G., Boivin, R.L., Stangeby, P.C., “Swinging Reciprocating Mach Probes for the High Field Side Scrape-Off Layer in DIII-D,” presented at the 19th High Temperature Plasma Diagnostics Conf., Monterey, California, May 6-10, 2012 in Rev. Sci. Instrum. **83**, 10D723 (2012); General Atomics Report GA-A27318 (2012).

Turco, F., Bialek, J.M., Hanson, J.M., Navratil, G.A., Sabbagh, S.A., Lanctot, M.J., Reimerdes, H., Liu, Y., “Resistive wall mode stability and plasma response modeling of DIII-D plasmas,” Bull. Am. Phys. Soc. **57**, 142 (2012).

Turco, F., Holcomb, C.T., Ferron, J.R., Luce, T.C., Politzer, P.A., Park, J.M., White, A.E., Brennan, D.P., Turnbull, A.D., Hanson, J.M., Okabayashi, M., In, Y., “Sensitivity of Transport and Stability to the Current Profile in Steady-State Scenario Plasmas in DIII-D,” presented at the 53rd Annual Mtg. of the APS Division of Plasma Physics, Salt Lake City, Utah, November 14–18, 2011 in Phys. Plasmas **19**, 122506 (2012); General Atomics Report GA-A27215 (2012).

Turnbull, A.D., “Comparisons of Linear and Nonlinear Plasma Response Models for Non-Axisymmetric Perturbations,” Invited Bull. Am. Phys. Soc. **57**, 295 (2012).

Unterberg, E.A., Shafer, M.W., Wingen, A., Harris, J.H., Hillis, D.L., Maingi, R., Evans, T.E., Farraro, N., “Measurements of Magnetic Topology During 3-D Magnetic Perturbations,” Bull. Am. Phys. Soc. **57**, 137 (2012).

Uzun-Kaymak, I.U., Fonck, R.J., McKee, G.R., “Turbulent Ion Temperature Fluctuation Measurements on DIII-D,” Bull. Am. Phys. Soc. **57**, 307 (2012).

Van Zeeland, M.A., Boivin, R.L., Brower, D.L., Carlstrom, T.N., Chavez, J.A., Ding, W.X., Feder, R., Johnson, D., Lin, L., O’Neill, R.C., Watts, C., “Conceptual Design of the Tangential Interferometer Polarimeter Density Measurements,” presented at the 19th High Temperature Plasma Diagnostics Conf., Monterey, California, May 6-10, 2012; General Atomics Report GA-A27301 (2012).

Van Zeeland, M.A., Gorelenkov, N.N., Heidbrink, W.W., Kramer, G.J., Spong, D.A., Austin, M.E., Fisher, R.K., Garcia Munoz, M., Gorelenkova, M., Murakami, M., Nazikian, R., Pace, D.C., Park, J.M., Tobias, B.J., White, R.B., “Alfvén Engenmode Stability and Fast Ion Loss in DIII-D and ITER Reversed Magnetic Shear Plasmas,” Nucl. Fusion **52**, 094023 (2012); General Atomics Report GA-A27216 (2012).

Van Zeeland, M.A., Heidbrink, W.W., Park, J.M., Prater, R., Holcomb, C.T., Austin, M.E., Ferron, J.R., Greenfield, C.M., Grierson, B.A., Hong, R.-M., Luce, T.C., McKee, G.R., Moyer, R.A., Murakami, M., Murphy, C.J., Muscatello, C.M., Pace, D.C., Petty, C.C., Raunch, J., Scoville, J.T., Solomon, W.M., Tobias, B.J., "Initial Off-Axis Beam Experiments in DIII-D," Proc. 39th European Physical Society Conf. on Plasma Physics, Stockholm, Sweden, July 2–6, 2012, Paper P2.068; General Atomics Report GA-A27335 (2012).

Volpe, F.A., La Haye, R.J., Lanctot, M.J., Mao, S., Prater, R., Strait, E.J., Welander, A.S., "Stabilization of Disruptive Locked Modes by Magnetic Perturbations and Electron Cyclotron Current Drive at DIII-D," Synopsis presented at the 24th IAEA Fusion Energy Conf., San Diego, California, October 8–13, 2012; General Atomics Report GA-A27271 (2012).

Wade, M.R., Nazikian, R., Battaglia, D., Buttery, R.J., deGrassie, J.S., Evans, T.E., Fenstermacher, M.E., Ferraro, N.M., Grierson, B.A., Hansen, J.M., Lanctot, M.J., McKee, G.R., Moyer, R.A., Orlov, D.M., Solomon, W.M., Schmitz, O., Shafer, M.W., Snyder, P.B., Unterberg, E.A., Wingen, A., Zeng, L., "Advances in the Physics Understanding of ELM Suppression Using Resonant Magnetic Perturbations in DIII-D," Proc. 24th IAEA Fusion Energy Conf., San Diego, California, October 8–13, 2012, Paper EX/3-1; General Atomics Report GA-A27441 (2012).

Wade, M.R., Nazikian, R., Buttery, R.J., deGrassie, J.S., Evans, T.E., Ferraro, N.M., McKee, G.R., Moyer, R.A., Orlov, D.M., Schmitz, O., Snyder, P.B., Zeng, L., "Advances in the Physics Understanding of ELM-Suppression Using Resonant Magnetic Perturbations in DIII-D," Synopsis presented at the 24th IAEA Fusion Energy Conf., San Diego, California, October 8–13, 2012; General Atomics Report GA-A27272 (2012).

Walker, M.L., and ITER Plasma Control Group, "Status of the ITER PCS Conceptual Design," Bull. Am. Phys. Soc. **57**, 187 (2012).

Waltz, R.E., "Nonlinear Theory of Drift-Cyclotron Kinetics and the Breakdown of Gyro-Kinetics," Phys. Plasmas **20**, 012507 (2013); General Atomics Report GA-A27360 (2012).

Waltz, R.E., "Search for the Missing L-mode Edge Transport and Possible Breakdown of Gyrokinetics," Invited Bull. Am. Phys. Soc. **57**, 105 (2012).

Waltz, R.E., Waelbroeck, F.L., "Gyrokinetic Simulations with External Resonant Magnetic Perturbations: Island Torque and Nonambipolar Transport with Plasma Rotation," Phys. Plasmas **19**, 032508 (2012); General Atomics Report GA-A27141 (2011).

Wang, G., Peebles, W.A., Rhodes, T.L., Hillesheim, J.C., Doyle, E.J., Schmitz, L., Zeng, L., Austin, M.E., Yan, Z., McKee, G.R., Nazikian, R., Petty, C.C., Burrell, K.H., Smith, S., Lanctot, M.J., "Geodesic Acoustic Mode Structure in DIII-D," Bull. Am. Phys. Soc. **57**, 308 (2012).

Watkins, J.G., Rajpal, R., Mandaliya, H., Watkins, M., Bovin, R.L., "Embedded Calibration System for the DIII-D Langmuir Probe Analog Fiber Optic Links," presented at the 19th High Temperature Plasma Diagnostics Conf., Monterey, California, May 6-10, 2012 in Rev. Sci. Instrum. **83**, 10D710 (2012); General Atomics Report GA-A27306 (2012).

Weber, T.R., Allen, S.L., and Howard, J., "C-III Flow Measurements with a Coherence Imaging Spectrometer," presented at the 19th High Temperature Plasma Diagnostics Conf., Monterey, California, May 6-10, 2012 Rev. Sci. Instrum. **83**, 10E102 (2012); General Atomics Report GA-A27280 (2012).

Weber, T.R., Porter, G.D., Meier, E.T., Allen, S.L., and Howard, J., "Impurity Flow Measurements at DIII-D Using a Coherence Imaging Spectrometer," presented at the 20th Int. Conf. on Plasma-Surface Interactions in Controlled Fusion Devices, Aachen, Germany, May 21–25, 2012 to be published in J. Nucl. Mater.; General Atomics Report GA-A27293 (2012).

Wehner, W., Shi, W., Schuster, E., Moreau, D., Walker, M.L., Ferron, J.R., "Data-Driven Modeling and Control of the Poloidal Flux Profile for Advanced Tokamak Scenarios in DIII-D," Bull. Am. Phys. Soc. **57**, 311 (2012).

Welander, A.S., La Haye, R.J., Penaflor, B.G., Lohr, J., Noraky, V., Prater, R., Eidietis, N.W., Humphreys, D.A., Kolemen, E., Turco, F., "Control of Neoclassical Tearing Modes in DIII-D," Bull. Am. Phys. Soc. **57**, 206 (2012).

Wesley, J.C., "USBPO Disruption Task: Critical Issues and Research Needs for the ITER DMS," Bull. Am. Phys. Soc. **57**, 350 (2012).

White, A.E., Pace, D.C., Heidbrink, W.W., Van Zeeland, M.A., Rhodes, T.L., McKee, G.R., Wang, G., Yan, Z., Hillesheim, J.C., Staebler, G.M., "Turbulent-Transport of Energetic Ions in Tokamak Plasmas with On-Axis Neutral Beam Injection," submitted to Nucl. Fusion; General Atomics Report GA-A27193 (2012).

Wilks, T., Stacey, W.M., Floyd, J.P., Evan, T.E., "Interpretative Modeling of RMP Effect on Edge Pedestal Transport," Bull. Am. Phys. Soc. **57**, 136 (2012).

Wingen, A., Unterberg, E.A., Shafer, M.W., Ferraro, N.M., Evans, T.E., "Influence of Plasma Response on Synthetic Soft X-ray Image for DIII-D," Bull. Am. Phys. Soc. **57**, 137 (2012).

Wong, C.P.C., "Fusion Technology Facility-Key Attributes and Interfaces to Technology and Materials," Proc. 24th IAEA Fusion Energy Conf., San Diego, California, October 8–13, 2012, Paper FTP/P1-30; General Atomics Report GA-A27394 (2012).

Wong, C.P.C., Abdou. M., Katoh, Y., Kurtz, R.J., Lumsdaine, A., Marriott, E. Merrill, B., Morley, N., Pint, B.A., Sawan, M.E., Smolentsev, S., Williams, B., Willms, R.S., Youssef, M. "Progress on DCLL Blanket Concept," presented at the 20th ANS Top. Mtg. on the Technology of Fusion Energy, Nashville, Tennesse, August 27–31, 2012 and to be published in Fusion Sci. Technol.; General Atomics Report GA-A27375 (2012).

Wong, C.P.C., Chan, V.S., Garofalo, A.M., Stambaugh, R., Sawan, M.E., Kurtz, R., Merrill, B., "Fusion Nuclear Science Facility-AT — A Material and Component Testing Device," presented at the 15th Int. Conf. on Fusion Reactor Materials, Charleston, South Carolina, October 16–22, 2011 in Fusion Sci. Technol. **62**, 283 (2012); General Atomics Report GA-A27154 (2011).

Wong, C.P.C., Chen, B., Hollmann, E.M., Rudakov, D.L., Wall, D., Tao, R., Wright, M., "Development Of Si-W Transient Tolerant Plasma Facing Material," presented at the 20th Int. Conf. on Plasma-Surface Interactions in Controlled Fusion Devices, Aachen, Germany, May 21–25, 2012 to be published in J. Nucl. Mater.; General Atomics Report GA-A27305 (2012).

Wong, Clement P.C., "Fusion Technology Facility — Key Attributes and Interfaces to Technology and Materials," Synopsis presented at the 24th IAEA Fusion Energy Conf., San Diego, California, October 8–13, 2012; General Atomics Report GA-A27273 (2012).

Yan, Z., Boedo, J.A., Diamond, P.H., Fonck, R.J., Gohil, P., Groebner, R.J., McKee, G.R., Osborne, T.H., Rudakov, R.L., Tynan, G. "Relating the L-H Power Threshold Scaling to Edge Turbulence Dynamics" Proc. 24th IAEA Fusion Energy Conf., San Diego, California, October 8–13, 2012, Paper EX/P7-05; General Atomics Report GA-A27401 (2012).

Yan, Z., McKee, G.R., Boedo, J.A., Rudakov, D.L., Diamond, P.H., Fonck, R.J., Groebner, R.J., Osborne, T.H., Gohil, P., "Relating the L-H Power Threshold Scaling to Edge Turbulence Dynamics," Synopsis presented at the 24th IAEA Fusion Energy Conf., San Diego, California, October 8–13, 2012; General Atomics Report GA-A27274 (2012).

Yan, Z., McKee, G.R., Boedo, J.A., Rudakov, D.L., Tynan, G.R., Diamond, P.H., Groebner, R.J., Osborne, T.H., Wang, G., Schmitz, L., “The Dynamics of Turbulence and Flow During the L-H Transition,” Bull. Am. Phys. Soc. **57**, 206 (2012).

Yu, L., Domier, C.W., Luhmann, Jr., N.C., Tobias, B.J., Austin, M.E.., “Characterization of Intense Bursts of mm-wave Emission Using New RF Spectrometer on the DIII-D Tokamak,” Bull. Am. Phys. Soc. **57**, 309 (2012).

Zeng, L., Doyle, E.J., Rhodes, T.L., Peebles, W.A., Staebler, G.M., Petty, C.C., McKee, G.R., “Particle Transport and Turbulence Dependence on Collisionality on DIII-D and Comparisons to GYRO and TGLF,” Bull. Am. Phys. Soc. **57**, 308 (2012).

Zhang, J., Peebles, W.A., Carter, T.A., Crocker, N.A., Doyle, E.J., Kubota, S., Rhodes, T.L., Wang, G., Zeng, L., “Initial tests of NSTX millimeter-wave polarimeter on DIII-D,” Bull. Am. Phys. Soc. **57**, 309 (2012).

Zhu, Y.B., Bortolon, A., Heidbrink, W.W., Celie, S.E., Roquemore, A.L., “Compact Solid-State Neutral Particle Analyzer in Current Mode,” presented at the 19th High Temperature Plasma Diagnostics Conf., Monterey, California, May 6-10, 2012 in Rev. Sci. Instrum. **83**, 10D304 (2012); General Atomics Report GA-A27296 (2012).

12.2. PUBLICATIONS FOR FY11

Bae, C., Stacey, W.M., Solomon, W.M., “Neoclassical Theory for Toroidal and Poloidal Rotation,” Bull. Am. Phys. Soc. **56**, 342 (2011).

Barton, J.E., Schuster, E., Walker, M.L., Humphreys, D.A., “Robust Control of the Spatial Current Profile in the DIII-D Tokamak,” Bull. Am. Phys. Soc. **56**, 299 (2011).

Baylor, L.R., Jernigan, T.C., Commaux, N., Meitner, S.J., Combs, S.K., Osborne, T.H., Parks, P.B., Strait, E.J., Fenstermacher, M.E., Lasnier, C.J., Moyer, R.A., Yu, J.H., “Pellet ELM Pacing Developments on DIII-D,” Bull. Am. Phys. Soc. **56**, 340 (2011).

Boedo, J.A., Belli, E.A., Hollmann, E.M., Solomon, W.M., Rudakov, D.L., Watkins, J.G., Prater, R., Candy, J., Groebner, R.J., Burrell, K.H., deGrassie, J.S., Lasnier, C.J., Leonard, A.W., Moyer, R.A., Porter, G.D., Brooks, N.H., Mueller, S.H., Tynan, G.R., Unterberg, E.A., “Poloidally and Radially Resolved Parallel Velocity Measurements in the DIII-D Boundary and Comparison to Neoclassical Computations,” Phys. Plasmas **18**, 032510 (2011); General Atomics Report GA-A26725 (2010).

Boedo, J.A., Schmitz, O., Reimerdes, H., Lao, L.L., Izzo, V.A., Lanctot, M.J., Osborne, T.H., Unterberg, E.A., Brooks, N.H., Evans, T.E., Hollmann, E.M., Groebner, R.J., Orlov, D.M., Watkins, J.G., Leonard, A.W., Lasnier, C.J., Moyer, R.A., Porter, G.D., Tynan, G.R., DIII-D Team, “Plasma Response to Applied Resonant Magnetic Perturbations in DIII-D,” Proc. 38th EPS Conf. on Plasma Physics, Strasborg, France, June 27–July 1, 2011, Paper P1.122; General Atomics Report GA-A27079 (2011).

Boyer, M.D., Barton, J.E., Schuster, E., Walker, M.L., Humphreys, D.A., “Backstepping Control of the Current Profile in the DIII-D Tokamak,” Bull. Am. Phys. Soc. **56**, 300 (2011).

Bray, B.D., Watkins, M., Liu, C., Deterly, T.M., Ponce, D.M., Eldon, D., “Edge Resolution and Laser Upgrades for the Thomson Scattering System at DIII-D,” Bull. Am. Phys. Soc. **56**, 344 (2011).

Burrell, K.H., “Neoclassical Toroidal Viscosity fro Non-Axisymmetric Magnetic Fields Allows ELM-free, Quiescent H-mode Operation in DIII-D Under Reactor-relevant Conditions,” Bull. Am. Phys. Soc. **56**, 358 (2011).

Buttery, R.J., “Tearing Under Stress — The Collusion of 3D Fields and Resistivity in Low Torque H-modes,” Bull. Am. Phys. Soc. **56**, 137 (2011).

Buttery, R.J., Boozer, A.H., Liu, Y.Q., Park, J.-K., Ferraro, N.M., Amoskov, V., Gribov, Y., La Haye, R.J., Lamzin, E., Menard, J.E., Schaffer, M.J., Strait, E.J., DIII-D Team, “The Limits and Challenges of Error Field Correction for ITER,” Presented at 5th IAEA Technical Meeting on Theory of Plasma Instabilities, Austin, Texas, September 5–7, 2011; General Atomics Report GA-A27135 (2011).

Buttery, R.J., Gerhardt, S., La Haye, R.J., Liu, Y.Q., Reimerdes, H., Sabbagh, S., Chu, M.S., Osborne, T.H., Park, J.-K., Pinsker, R.I., Strait, E.J., Yu, J.H., DIII-D Team, NSTX Team, “The Impact of 3-D Fields on Tearing Mode Stability of H-modes,” Nucl. Fusion **51**, 073016 (2011); General Atomics Report GA-A26982 (2011).

Callen, J.D., Cole, A.J., Mordijck, S., Moyer, R.A., “RMP Effects on Pedestal Structure and ELMs,” Bull. Am. Phys. Soc. **56**, 97 (2011).

Casper, T.A., Meyer, W.H., Jackson, G.L., Luce, T.C., Hyatt, A.W., Humphreys, D.A., Turco, F., “Validation of Thermal Transport Model Used for ITER Startup Scenario Predictions with DIII-D Experimental Data,” Nucl. Fusion **51**, 013001 (2011); General Atomics Report GA-A26379 (2010).

Cengher, M., Lohr, J., Gorelov, Y.A., Ponce, D., Moeller, C.P., “Performance Measurements for the ECH Transmission Lines on DIII-D,” Bull. Am. Phys. Soc. **56**, 341 (2011).

Chan, V.S., Stambaugh, R.D., Garofalo, A.M., Canik, J., Kinsey, J., Park, J.M., Peng, M.Y.K., Petrie, T.W., Porkolab, M., Prater, R., Sawan, M., Smith, J.P., Snyder, P.B., Stangeby, P.C., Wong, C.P.C., "A Fusion Development Facility on the Critical Path to Fusion Energy," Nucl. Fusion **51**, 083019 (2011); General Atomics Report GA-A26975 (2010).

Chen, X., Heidbrink, W.W., Fisher, R.K., Van Zeeland, M.A., Pace, D.C., Garcia-Munoz, M., "Coherent Beam-Ion Losses During Instabilities in DIII-D," Bull. Am. Phys. Soc. **56**, 343 (2011).

Choi, M., Pinsker, R.I., Muscatello, C.M., Chan, V.S., Heidbrink, W.W., Jaeger, E.F., "Modeling of Synergy Between 4th and 6th Harmonic Absorptions of Fast Waves on Injected Beams in DIII-D Tokamak," Proc. 19th Radio Frequency Powers in Plasmas, Newport, Rhode Island, June 1–3, 2011; General Atomics Report GA-A27077 (2011).

Chrobak, C.P., Moyer, R.A., Yu, J.H., Van Zeeland, M.A., "Restoring Transmission of Irradiated Image Fiber Bundles," Bull. Am. Phys. Soc. **56**, 344 (2011).

Chu, M.S., Lao, L.L., Schaffer, M.J., Evans, T.E., Strait, E.J., Liu, Y.Q., Lanctot, M.J., Reimerdes, H., Liu, Y., Casper, T.A., Gribov, Y., "Response of a Resistive and Rotating Tokamak to External Magnetic Perturbations Below the Alfven Frequency," Nucl. Fusion **51**, 073036 (2011); General Atomics Report GA-A26969 (2011).

Cole, A.J., Callen, J.D., Solomon, W.M., Garofalo, A.M., Hegna, C.C., Reimerdes, H., DIII-D Team, "Peak Neoclassical Toroidal Viscosity at Low Toroidal Rotation in the DIII-D Tokamak," Phys. Plasmas **18**, 055711 (2011); General Atomics Report GA-A27018 (2011).

Colio, R.A., Finkenthal, D.K., Deterly, T.M., "Improved Timing Sequence Generator on the DIII-D Tokamak," Bull. Am. Phys. Soc. **56**, 162 (2011).

Commaux, N., Baylor, L.R., Jernigan, T.C., Osborne, T.H., Parks, P.B., Fenstermacher, M.E., Lasnier, C.J., Moyer, R.A., Yu, J.H., "Study of the Heat Flux Induced by Pellet Triggered ELMs on the Divertor During Pacing Experiments on DIII-D," Bull. Am. Phys. Soc. **56**, 340 (2011).

DeBoo, J.C., Burrell, K.H., Petty, C.C., Smith, S.P., White, A.E., Holland, C., Doyle, E.J., Hillesheim, J.C., Rhodes, T.L., Schmitz, L., Wang, G., Zeng, L., McKee, G.R., "Electron Profile Stiffness and Critical Gradient Studies in an L-mode Discharge in DIII-D," Bull. Am. Phys. Soc. **56**, 341 (2011).

deGrassie, J.S., Buttery, R.J., Evans, T.E., Wade, M.R., Fenstermacher, M.E., Moyer, R.A., Orlov, D.M., Nazikian, R., Schmitz, O., "RMP ELM Suppression With a Single Row of Coils in DIII-D," Bull. Am. Phys. Soc. **56**, 295 (2011).

deGrassie, J.S., Mueller, S.H., Boedo, J.A., "Plasma Flow Due to a Loss Cone Distribution Centered Around the Outboard Edge in DIII-D," Nucl. Fusion **52**, 013010 (2011); General Atomics Report GA-A27026 (2011).

Donovan, D.C., Buchenauer, D.A., Watkins, J.G., Leonard, A.W., Lasnier, C.J., Stangeby, P.C., "Comparison of Sheath Power Transmission Factor for Neutral Beam Injection and Electron Cyclotron Heated Discharges in DIII-D," Bull. Am. Phys. Soc. **56**, 298 (2011).

Dwyer, B.L., Brooks, N.H., Lee, R.L., "Portable Rotating Discharge Plasma Device," Bull. Am. Phys. Soc. **56**, 162 (2011).

Eidietis, N.W., Humphreys, D.A., "A Diffusive Model for Halo Width Growth During VDEs," Nucl. Fusion **51**, 073034 (2011); General Atomics Report GA-A26983 (2011).

Elder, J.D., Stangeby, P.C., Leonard, A.W., Fenstermacher, M.E., Boedo, J.A., Rudakov, D.L., Bray, B.D., Brooks, N.H., Watkins, J.G., Unterberg, E.A., "Detailed OEDGE Modeling of Core-Pedestal Fueling in DIII-D," Bull. Am. Phys. Soc. **56**, 297 (2011).

Elder, J.D., Wampler, W.R., McLean, A.G., Stangeby, P.C., Allen, S.L., Bray, B.D., Brooks, N.H., Leonard, A.W., Unterberg, E.A., Watkins, J.G., "OEDGE Modeling of the DIII-D Double Null $^{13}CH_4$ Puffing Experiment," J. Nucl. Mater. **415**, S513 (2011); General Atomics Report GA-A26758 (2010).

Evans, T.E., "Pedestal Plasma Control With Small 3D Magnetic Fields," Bull. Am. Phys. Soc. **56**, 293 (2011).

Fenstermacher, M.E., Moyer, R.A., Osborne, T.H., "ELM Size and $v_{\perp e} \approx 0$ Location During RMP H-Mode Plasmas in DIII-D," Bull. Am. Phys. Soc. **56**, 294 (2011).

Ferron, J.R., Holcomb, C.T., Luce, T.C., Park, J.M., Politzer, P.A., Turco, F., DeBoo, J.C., Doyle, E.J., Hyatt, A.W., In, Y., La Haye, R.J., Murakami, M., Okabayashi, M., Petrie, T.W., Petty, C.C., Reimerdes, H., Rhodes, T.L., White, A.E., Zeng, L., "Design Parameters for DIII-D Steady-State Scenario Discharges," Proc. 38th EPS Conf. on Plasma Physics, Strasborg, France, June 27–July 1, 2011, Paper P1.089; General Atomics Report GA-A27086 (2011).

Ferron, J.R., Holcomb, C.T., Luce, T.C., Politzer, P.A., Turco, F., White, A.E., DeBoo, J.C., Doyle, E.J., Hyatt, A.W., La Haye, R.J., Murakami, M., Petrie, T.W., Petty, C.C., Rhodes, T.L., Zeng, L., "Optimization of the Safety Factor Profile for High Noninductive Current Fraction Discharges in DIII-D," Nucl. Fusion **51**, 063026 (2011); General Atomics Report GA-A26855 (2010).

Ferron, J.R., Luce, T.C., Politzer, P.A., DeBoo, J.C., La Haye, R.J., Holcomb, C.T., Lanctot, M.J., Turco, F., Park, J.M., In, Y. Okabayashi, M., "Off-Axis Neutral Beam Injection as a Tool for Expanding the Operating Space of DIII-D High f_{NI} Discharges," Bull. Am. Phys. Soc. **56**, 339 (2011).

Floyd, J.-P., Stacey, W.M., "Numerical Investigation of Solving the Generalized Diffusion Equation in the Edge Pedestal With Exended Diffusion Theory Codes," Bull. Am. Phys. Soc. **56**, 296 (2011).

Frerichs, H., Cahyna, P., Evans, T.E., Feng, Y., Reiter, D., Schmitz, O., "Impact of Screening of Resonant Magnetic Perturbations in 3D Edge Plasma Transport Simulations for DIII-D," submitted to Nucl. Fusion; General Atomics Report GA-A27145 (2011).

Galante, M.E., Magee, R.M., McCarren, D.W., Scime, E.E., Brooks, N.H., Boivin, B.L., "Measurements of Neutral Hydrogen Density in a Helicon Plasma," Bull. Am. Phys. Soc. **56**, 344 (2011).

Garofalo, A.M., Burrell, K.H., Park, J.-K., Solomon, W.M., Fenstermacher, M.E., Lanctot, M.J., "QH-Mode in Low Rotation, ITER-Similar Plasmas Using Static Non-Axisymmetric Magnetic Fields," Bull. Am. Phys. Soc. **56**, 97 (2011).

Garofalo, A.M., Solomon, W.M., Park, J.-K., Burrell, K.H., DeBoo, J.C., Lanctot, M.J., McKee, G.R., Reimerdes, H., Schmitz, L., Schaffer, M.J., Snyder, P.B., "Advances Toward QH-mode Viability for ELM-stable Operation in ITER," Nucl. Fusion **51**, 083018 (2011); General Atomics Report GA-A26978 (2011).

Gohil, P., DIII-D Team, "Overview of Recent DIII-D Experimental Results," Bull. Am. Phys. Soc. **56**, 96 (2011).

Gohil, P., Evans, T.E., Fenstermacher, M.E., Ferron, J.R., Osborne, T.H., Park, J.M., Schmitz, O., Scoville, J.T., Unterberg, E.A., "L-H Transition Studies on DIII-D to Determine H-mode Access for Operational Scenarios in ITER," Nucl. Fusion **51**, 103020 (2011); General Atomics Report GA-A26997 (2011).

Gorelov, Y.A., Lohr, J., Cengher, M., Ponce, D., Ellis, R.A., "Launchers on DIII-D," Bull. Am. Phys. Soc. **56**, 341 (2011).

Gorelov, Y.A., Lohr, J., Cengher, M., Ponce, D., Shapiro, M., Ellis, R.A., "Status Update on the DIII-D ECH System," Proc. 8th Int. Workshop on Strong Microwaves and Terahertz Waves – Sources and Applications, Nizhny Novgorod, Russia, July 9–16, 2011; General Atomics Report GA-A27076 (2011).

Greenfield, C.M., DIII-D Team, "DIII-D Contributions Toward the Scientific Basis for Sustained Burning Plasmas," Nucl. Fusion **51**, 094009 (2011); General Atomics Report GA-A27005 (2011).

Grierson, B.A., Burrell, K.H., Solomon, W.M., Pablant, N.A., Heidbrink, W.W., "Characterization of Neutral-Beam Induced D_alpha Emission on DIII-D," submitted to Nucl. Fusion; General Atomics Report GA-A27028 (2011).

Groebner, R.J., Snyder, P.B., Osborne, T.H., Smith, S.P., Leonard, A.W., Bray, B.D., Deterly, T.M., Liu, C., Boivin, R.L., deGrassie, J.S., Prater, R., Eldon, D., Rhodes, T.L., Zeng, L., Hillesheim, J.C., Yan, Z., McKee, G.R., "Testing Pedestal Models for Joint Research Target on DIII-D," Bull. Am. Phys. Soc. **56**, 97 (2011).

Hamming, B.W., Colio, R.A., Finkenthal, D.K., Van Zeeland, M.A., Deterly, T.M., "Effect of Clock Jitter on Plasma Density Measurements Relying on Direct Digital Demodulation Techniques," Bull. Am. Phys. Soc. **56**, 162 (2011).

Hanson, J.M., Berkery, J., Navratil, G.A., Sabbagh, S.A., Lanctot, M.J., Reimerdes, H., Chapman, I.T., Liu, Y., Okabayashi, M., In, Y., Jackson, G.L., Strait, E.J., Sieck, P.E., "Measuring Kinetic Contributions to Resistive Wall Mode Stability Using Active MHD Spectroscopy," Bull. Am. Phys. Soc. **56**, 98 (2011).

Hanson, J.M., Reimerdes, H., Lanctot, M.J., In, Y., La Haye, R.J., Jackson, G.L., Navratil, G.A., Okabayashi, M., Sieck, P.E., Strait, E.J., "Feedback Control of the Proximity to Marginal Stability Using Active MHD Spectroscopy," Nucl. Fusion **52**, 013003 (2012); General Atomics Report GA-A27041 (2011).

Heidbrink, W.W., Austin, M.E., Fisher, R.K., Garcia-Munoz, M., Matsunaga, G., McKee, G.R., Moyer, R.A., Muscatello, C.M., Okabayashi, M., Pace, D.C., Shinohara, K., Solomon, W.M., Strait, E.J., Van Zeeland, M.A., Zhu, Y.B., "Characterization of Off-Axis Fishbones," Plasma Phys. Control. Fusion **53**, 085028 (2011); General Atomics Report GA-A27010 (2011).

Heidbrink, W.W., McKee, G.R., Smith, D.R., Bortolon, A., "Beam Emission Spectroscopy Diagnostics Also Measure Edge Fast-Ion Light," Plasma Phys. Control. Fusion **53**, 085007 (2011); General Atomics Report GA-A26912 (2011).

Hill, D.N., Porter, G.D., Rognlien, T.D., "Two Dimensional Transport Effects in the Tokamak Scrape-Off Layer Plasma," J. Nucl. Mater. **415**, S570 (2011); General Atonics Report GA-A26784 (2010).

Hillesheim, J.C., Peebles, W.A., Carter, T.A., Rhodes, T.L., Schmitz, L., DIII-D Team, "The Geodesic Acoustic Mode and Zonal Flows in DIII-D," Bull. Am. Phys. Soc. **56**, 342 (2011).

Holcomb, C.T., Ferron, J.R., Luce, T.C., DeBoo, J.C., Park, J.M., White, A.E., Turco, F., Rhodes, T.L., Doyle, E.J., Schmitz, L., Van Zeeland, M.A., McKee, G.R., "The Effect of Safety Factor Profile on Transport in Steady-State, High-Performance Scenarios," Phys. Plasmas **19**, 032501 (2012); General Atomics Report GA-A27913 (2011).

Holcomb, C.T., Lanctot, M.J., Ferron, J.R., Luce, T.C., Politzer, P.A., Turnbull, A.D., La Haye, R.J., Turco, F., Hanson, J.M., Park, J.M., Murakami, M., In, Y., Okabayashi, M., "High q_{min} Steady State Scenario Development Using Off-Axis Neutral Beam Injection on DIII-D," Bull. Am. Phys. Soc. **56**, 97 (2011).

Holland, C., Burrell, K.H., Petty, C.C., Candy, J., Holcomb, C.T., "Progress in GYRO Validation Studies of DIII-D H-mode Plasmas," Bull. Am. Phys. Soc. **56**, 341 (2011).

Holland, C., Schmitz, L., Rhodes, T.L., Peebles, W.A., Hillesheim, J.C., Wang, G., Zeng, L., Doyle, E.J., Smith, S.P., Prater, R., Burrell, K.H., Candy, J., Waltz, R.E., Kinsey, J.E., Staebler, G.M., DeBoo, J.C., Petty, C.C., McKee, G.R., Yan, Z., White, A.E., "Advances in Validating Gyrokinetic Turbulence Models Against L- and H-mode Plasmas," Phys. Plasmas **18**, 056113 (2011); General Atomics Report GA-A26961 (2010).

Hollmann, E.M., Arnoux, G., Commaux, N., Eidietis, N.W., Evans, T.E., Granetz, R.S., Huber, A., Humphreys, D.A., Izzo, V.A., James, A.N., Jernigan, T.C., Lehnen, M., Maddaluno, G., Paccagnella, R., Parks, P.B., Phillips, V., Reinke, M.L., Rudakov, D.L., Saint-Laurent, F., Sizyuk, V., Strait, E.J., Wesley, J.C., Wong, C.P.C., Yu, J.H., "Plasma-Surface Interactions During Tokamak Disruptions and Rapid Shutdowns," J. Nucl. Mater. **415**, S27 (2011); General Atonics Report GA-A26775 (2010).

Hollmann, E.M., Chousal, L., Fisher, R.K., Hernandez, R., Jackson, G.L., Lanctot, M.J., Pidcoe, S.V., Shankara, J., Taussig, D.A., "Soft X-ray Array System with Variable Filters for the DIII-D Tokamak," Rev. Sci. Instrum. **82**, 113507 (2011); General Atomics Report GA-A27132 (2011).

Hollmann, E.M., Parks, P.B., Humphreys, D.A., Brooks, N.H., Commaux, N., Eidietis, N.W., Evans, T.E., Isler, R.C., James, A.N., Jernigan, T.C., Munoz Burgos, J.M., Strait, E.J., Tsui, C., Wesley, J.C., Yu, J.H., "Measurement of Runaway Electron Beam Composition and Estimate of Resulting Collisional Decay of Runaway Electron Currents in DIII-D," Proc. 38th EPS Conf. on Plasma Physics, Strasborg, France, June 27–July 1, 2011, Paper P2.106; General Atomics Report GA-A27084 (2011).

Hollmann, E.M., Parks, P.B., Humphreys, D.A., Brooks, N.H., Commaux, N., Eidietis, N.W., Evans, T.E., Isler, R.C., James, A.N., Jernigan, T.C., Munoz, J., Strait, E.J., Tsui, C., Wesley, J.C., Yu, J.H., "Effect of Applied Toroidal Electric Field on the Growth/Decay of Plateau-Phase Runaway Electron Currents in DIII-D," Nucl. Fusion **51**, 103026 (2011); General Atomics Report GA-A27006 (2011).

Humphreys, D.A., Eidietis, N.W., Hyatt, A.W., Leuer, J.A., Luce, T.C., Strait, E.J., Walker, M.L., Welander, A.S., Wesley, J.C., Lodestro, L.L., Pearlstein, L.D., "Operating ITER Robustly Without Disruption," Bull. Am. Phys. Soc. **56**, 189 (2011).

In, Y., Jackson, G.L., Okabayashi, M., Chu, M.S., Hanson, J.M., La Haye, R.J., Kim, J.S., Lanctot, M.J., Liu, Y.Q., Marrelli, L., Martin, P., Piovesan, P., Piron, L., Reimerdes, H., Soppelsa, A., Strait, E.J., Svidzinski, V., "Error Field Correction in the Unstable Resistive Wall Mode (RWM) Regime," submitted to Nucl. Fusion; General Atomics Report GA-A26992 (2011).

In, Y., Okabayashi, M., Jackson, G.L., La Haye, R.J., Sieck, P.E., Strait, E.J., Hanson, J.M., Reimerdes, H., "Improved Error Field Correction in High Performance Plasmas," Bull. Am. Phys. Soc. **56**, 299 (2011).

Izzo, V.A., Hollmann, E.M., James, A.N., Yu, J.H., Humphreys, D.A., Lao, L.L., Parks, P.B., Sieck, P.E., Wesley, J.C., Granetz, R.S., Olynyk, G.M., Whyte, D.G., "Runaway Electron Confinement Modeling for Rapid Shutdown Scenarios in DIII-D, Alcator C-Mod and ITER," Nucl. Fusion **51**, 063032 (2011); General Atomics Report GA-A26972 (2010).

Jackson, G.L., Humphreys, D.A., Hyatt, A.W., Lohr, J., Luce, T.C., Yu, J.H., "Noninductive Plasma Initiation and Startup in the DIII-D Tokamak," Nucl. Fusion **51**, 083015 (2011); General Atomics Report GA-A26967 (2011).

Jackson, G.L., Luce, T.C., Politzer, P.A., Joffrin, E., "Access Conditions for Advanced Inductive Scenarios," Bull. Am. Phys. Soc. **56**, 339 (2011).

Jakubowski, M.W., Evans, T.E., Fenstermacher, M.E., Lasnier, C.J., Schmitz, O., Wolf, R.C., Baylor, L.R., Boedo, J.A., Burrell, K.H., deGrassie, J.S., Gohil, P., Mordijck, S., Laengner, R., Leonard, A.W., Moyer, R.A., Petrie, T.W., Petty, C.C., Pinsker, R.I., Rhodes, T.L., Schaffer, M.J., Snyder, P.B., Stoschus, H., Osborne, T.H., Orlov, D.M., Unterberg, E.A., Watkins, J.G., "Toroidally Resolved Structure of Divertor Heat Flux in RMP H-mode Discharges on DIII-D," J. Nucl. Mater. **415**, S901 (2011); General Atomics Report GA-A26761 (2010).

James, A.N., Hollmann, E.M., Izzo, V.A., Tynan, G.R., Yu, J.H., Austin, M.E., Commaux, N., Jernigan, T.C., Eidietis, N.W., Evans, T.E., Humphreys, D.A., Hyatt, A.W., La Haye, R.J., Strait, E.J., Wesley, J.C., "Measurements and Interpretation of Hard X-ray Emission From Runaway Electrons in DIII-D," Bull. Am. Phys. Soc. **56**, 298 (2011).

James, A.N., Hollmann, E.M., Yu, J.H., Austin, M.E., Commaux, N., Evans, T.E., Humphreys, D.A., Jernigan, T.C., Parks, P.B., Putvinski, S., Strait, E.J., Tynan, G.R., Wesley, J.C., "Pellet Interaction With Runaway Electrons," J. Nucl. Mater. **415**, S849 (2011); General Atomics Report GA-A26752 (2010).

Kalling, R.C., Evans, T.E., Orlov, D.M., Schissel, D.P., Maingi, R., Menard, J.E. and Sabbagh, S.A., "Accelerating the Numerical Simulation of Magnetic Field Lines in Tokamaks Using the GPU," Fusion Engin. Design **86**, 399 (2011); General Atomics Report GA-A26776 (2010).

King, J.D., La Haye, R.J., Petty, C.C., Osborne, T.H., Lasnier, C.J., Lanctot, M.J., Makowski, M.A., Holcomb, C.T., Allen, S.L., Morse, E.C., "Magnetic Island Evolution Due to ELM-NTM Coupling in DIII-D," Proc. 38th EPS Conf. on Plasma Physics, Strasborg, France, June 27–July 1, 2011, Paper P2.087; General Atomics Report GA-A27078 (2011).

King, J.D., Lasnier, C.J., Lanctot, M.J., Makowski, M.A., Holcomb, C.T., Allen, S.L., Meyer, W.H., La Haye, R.J., Petty, C.C., Osborne, T.H., Groebner, R.J., Luce, T.C., Volpe, F., Austin, M.E., Morse, E.C., "Hybrid-like Discharges With 2/1 Flux-Pumping Due to ELM-NTM Coupling in DIII-D," Bull. Am. Phys. Soc. **56**, 299 (2011).

King, J.D., Makowski, M.A., Holcomb, C.T., Allen, S.L., Hill, D.N., La Haye, R.J., Turco, F., Petty, C.C., Van Zeeland, M.A., Rhodes, T.L., Meyer, W.H., Geer, R., Morse, E.C. "MHD Interference With the Edge Pedestal Motional Stark Effect Diagnostic Due to Intensity and Sideband Fluctuations on DIII-D," Rev. Sci. Instrum. **82**, 033515 (2011); General Atomics Report GA-A26797 (2010).

Kramer, G.J., Fu, G.Y., Nazikian, R., Van Zeeland, M.A., Fisher, R.K., Heidbrink, W.W., Chen, L., Pace, D.C., "Simulation of Observed EGAM Induced Beam-Ion Losses in DIII-D," Bull. Am. Phys. Soc. **56**, 98 (2011).

La Haye, R.J., Buttery, R.J., Gerhardt, S.P., Sabbagh, S.A., "Rotation in the Plasma Flow Frame of Marginal Neoclassical Tearing Mode Islands in DIII-D and NSTX," Bull. Am. Phys. Soc. **56**, 298 (2011).

La Haye, R.J., Buttery, R.J., Gerhardt, S.P., Sabbagh, S.A., Brennan, D.P., "Aspect Ratio Effects on Neoclassical Tearing Modes From Comparison Between DIII-D and NSTX," Proc. 38th EPS Conf. on Plasma Physics, Strasborg, France, June 27–July 1, 2011, Paper P2.088; General Atomics Report GA-A27071 (2011).

La Haye, R.J., Petty, C.C., Politzer, P.A., DIII-D Team, "Influence of Plasma Flow Shear on Tearing in DIII-D Hybrids," Nucl. Fusion **51**, 053013 (2011); General Atomics Report GA-A26756 (2010).

Lanctot, M.J., Holcomb, C.T., Allen, S.L., Fenstermacher, M.E., King, J.D., Ferron, J.R., Luce, T.C., "Improvements to the Motional Stark Effect Diagnostic on DIII-D," Bull. Am. Phys. Soc. **56**, 343 (2011).

Lanctot, M.J., Reimerdes, H., Garofalo, A.M., Chu, M.S., Hanson, J.M., Liu, Y.Q., Navratil, G.A., Bogatu, I.N., In, Y., Jackson, G.L., La Haye, R.J., Okabayashi, M., Park, J.-K., Schaffer, M.J., Schmitz, O., Strait, E.J., "Measurements and Modeling of Three-Dimensional Equilibria in DIII-D," Phys. Plasmas **18**, 056121 (2011); General Atomics Report GA-A26964 (2011).

Lao, L.L., Chu, M.S., Turnbull, A.D., Wade, M.R., Ferraro, N.M., Izzo, V.A., Lazarus, E.A., Guo, W., Srinivasan, R., Liu, Y.Q., "Plasma Equilibrium Response to Slowly Rotating 3D Magnetic Perturbations in DIII-D RMP Experiments," Bull. Am. Phys. Soc. **56**, 295 (2011).

Lasnier, C.J., Allen, S.L., Fenstermacher, M.E., Hill, D.N., Weber, T.R., "Wide-Angle Tangential Viewing System for DIII-D," Bull. Am. Phys. Soc. **56**, 169 (2011).

Lasnier, C.J., Makowski, M.A., Boedo, J.A., Allen, S.L., Brooks, N.H., Hill, D.N., Leonard, A.W., Watkins, J.G., West, W.P., "Scaling of Divertor Heat Flux Profile Widths in DIII-D," J. Nucl. Mater. **415**, S353 (2011); General Atonics Report GA-A26750 (2010).

Lazarus, E.A., Evans, T.E., Fenstermacher, M.E., "Experiments and ELM-Suppression in Double-Null DIII-D Plasma," Bull. Am. Phys. Soc. **56**, 295 (2011).

Leonard, A.W., Mahdavi, M.A., Petrie, T.W., "An Isolated Divertor for Reactor Scale Tokamaks," Bull. Am. Phys. Soc. **56**, 297 (2011).

Leuer, J.A., Cunningham, G., Mueller, D., Brooks, N.H., Eidietis, N.W., Humphreys, D.A., Hyatt, A.W., Jackson, G.L., Lohr, J., Politzer, P.A., Pinsker, R.I., Prater, R., Taylor, P.L., Walker, M.L., Budny, R.V., Gates, D.A., Nagy, A., Hahn, S.-H., Oh, Y.-K., Yoon, S.-W., Yu, J.H., Murakami, M., Park, J.M., Sontag, A.C., "Solenoid-free Startup Experiments in DIII-D," Nucl. Fusion **51**, 063038 (2011); General Atomics Report GA-A26974 (2011).

Lohr, J., Blank, M., Borchard, P., Cauffman, S., Cengher, M., Doane, J.L., Ellis, R., Felch, K., Gorelov, Y.A., Moeller, C.P., Noraky, S., Ponce, D., Richenderfer, A., Shapiro, M., "Transmission Line Performance and Plans for the Gyrotron Complex on the DIII-D Tokamak," Proc. 36th Int. Conf. on Infrared, Millimeter, and Terahertz Waves, Texas, October 2–7, 2011, Houston; DOI: 10.1109/irmmw-THz.2011.6104797; General Atomics Report GA-A27107 (2011).

Lohr, J., Cengher, M., Gorelov, Y.A., Grunloh, H.J., Kellman, A.G., Pawley, C.J., McDaniel, W., O'Neill, R.C., Ponce, D., Prater, R., Tooker, J.F., Ellis, R.A. Blanck, M., Borchard, P., Felch, K., Cauffman, S., "Upgrade Plans and Performance of the DIII-D ECH System," Bull. Am. Phys. Soc. **56**, 341 (2011).

Luce, T.C., "Realizing Steady-State Tokamak Operation for Fusion Energy," Phys. Plasmas **18**, 030501 (2011); General Atomics Report GA-A26638 (2010).

Luce, T.C., Ferron, J.R., Holcomb, C.T., Turco, F., Politzer, P.A., Petrie, T.W., "Progress in Steady-State Scenario Development in the DIII-D Tokamak," Proc. 6th IAEA Technical Meeting on Steady-State Operation of Magnetic Fusion Devices, Vienna, Austria, December 6–10, 2010; General Atomics Report GA-A26981 (2011).

Magee, R.M., Galante, M.E., McCarren, D.W., Scime, E.E., Boivin, R.L., Brooks, N.H., "A TALIF Diagnostic for the DIII-D Tokamak," Bull. Am. Phys. Soc. **56**, 244 (2011).

Makowski, M.A., "Analysis of a Multi-Machine Database on Divertor Heat Fluxes," Bull. Am. Phys. Soc. **56**, 228 (2011).

Makowski, M.A., Lasnier, C.J., Leonard, A.W., Boedo, J.A., Watkins, J.G., Hill, D.N., "Comparison of Upstream T_e Profiles with Downstream Heat Flux Profiles and Their Implications on Parallel Heat Transport in the SOL in DIII-D," J. Nucl. Mater. **415**, S357 (2011); General Atomics Report GA-A26759 (2010).

Marinoni, A., Rost, J.C., Porkolab, M., Dorris, J.R., Burrell, K.H., "Imaging and Modeling DIII-D Core Turbulence by Means of the Phase Contrast Diagnostic," Bull. Am. Phys. Soc. **56**, 348 (2011).

McKee, G.R., Yan, Z., Schmitz, O., Buttery, R.J., Evans, T.E., Wade, M.R., Schmitz, L., Moyer, R.A., "Turbulence Dynamics During RMP-ELM Suppressed Discharges," Bull. Am. Phys. Soc. **56**, 295 (2011).

McLean, A.G., Stangeby, P.C., Bray, B.D., Brezinsek, S., Brooks, N.H., Davis, J.W., Isler, R.C., Kirschner, A., Laengner, R., Lasnier, C.J., Mu, Y., Munoz, J., Rudakov, D.L., Schmitz, O., Unterberg, E.A., Watkins, J.G., Whyte, D.G., Wong, C.P.C., "Quantification of Chemical Erosion in the DIII-D Divertor and Implications for ITER," J. Nucl. Mater. **415**, S141 (2011); General Atomics Report GA-A26805 (2010).

Meyer, O., Burrell, K.H., Chavez, J.A., Kaplan, D.H., Chrystal, C., Pablant, N.A., Solomon, W.M., "Masking a CCD Camera Allows Multi-chord Charge Exchange Spectroscopy Measurements at High-Speed on the DIII-D Tokamak," Rev. Sci. Instrum. **82**, 023114 (2011); General Atomics Report GA-A26694 (2010).

Mordijck, S., "Particle Transport Modification Due to Resonant Magnetic Perturbations on the DIII-D Tokamak," Bull. Am. Phys. Soc. **56**, 56 (2011).

Mordijck, S., Moyer, R.A., Kirk, A., Tamain, P., Temple, D., McKee, G.R., Nardon, E., "Comparison of Resonant Magnetic Perturbation Induced Particle Transport Changes in H-mode (DIII-D) and L-mode (MAST)," Plasma Phys. Control. Fusion **53**, 122001 (2011); General Atomics Report GA-A26768 (2011).

Moyer, R.A., Yu, J.H., Orlov, D.M., Chrobak, C., Mordijck, S., Van Zeeland, M.A., Evans, T.E., Wade, M.R., Chang, C.S., Waelbroeck, F.L., Callen, J.D., "Comparison of Plasma Response Model Predictions to Measurements in DIII-D RMP H-mode Discharges," Bull. Am. Phys. Soc. **56**, 294 (2011).

Mu, Y., Elder, J.D., Stangeby, P.C., McLean, A.G., "3D-DIVIMP(HC) Code Modeling of DIII-D DiMES Porous Plug Injector Experiments," J. Nucl. Mater. **415**, S145 (2011); General Atonics Report GA-A26737 (2010).

Mueller, S.H., Boedo, J.A., Burrell, K.H., deGrassie, J.S., Moyer, R.A., Rudakov, D.L., Solomon, W.M., "Experimental Investigation of the Role of Fluid Turbulent Stresses and Edge Plasma Flows for Intrinsic Rotation Generation in DIII-D H-mode Plasmas," Phys. Rev. Lett. **106**, 115001 (2011); General Atomics Report GA-A26907 (2011).

Mueller, S.H., Boedo, J.A., Burrell, K.H., deGrassie, J.S., Moyer, R.A., Rudakov, D.L., Solomon, W.M., Tynan, G.R., "Intrinsic Rotation Generation in DIII-D ELM-Free H-mode Plasmas," Proc. 38th EPS Conf. on Plasma Physics, Strasborg, France, June 27–July 1, 2011, Paper O4.119; General Atomics Report GA-A27092 (2011).

Mueller, S.H., Boedo, J.A., Burrell, K.H., deGrassie, J.S., Moyer, R.A., Rudakov, D.L., Solomon, W.M., Tynan, G.R., "Intrinsic Rotation Generation in ELM-free H-mode Plasmas in the DIII-D Tokamak, Part I Experimental Observations," Phys. Plasmas **18**, 072504 (2011); General Atomics Report GA-A27003 (2011).

Munoz Burgos, J.M., Brooks, N.H., Fenstermacher, M.E., Meyer, W.H., Unterberg, E.A., Schmitz, O., Loch, S.D., Balance, C.P., "Application of Collisional Radiative Modeling of Helium and Deuterium for Image Tomography Diagnostic of T_e, N_e, and N_D in the DIII-D Tokamak," Bull. Am. Phys. Soc. **56**, 344 (2011).

Munoz Burgos, J.M., Schmitz, O., Unterberg, E.A., Loch, S.D., Balance, C.P., "Implementation of a New Atomic Basis for the He I Equilibrium Line Ratio Technique for Electron Temperature and Density Diagnostic in the SOL for H-mode Plasmas in DIII-D," J. Nucl. Mater. **415**, S115 (2011); General Atonics Report GA-A26748 (2010).

Murakami, M., Park, J.M., Giruzzi, G., Garcia, J., Bonoli, P., Budny, R.V., Doyle, E.J., Fukuyama, A., Hayashi, N., Honda, M., Hubbard, A.E., Ide, S., Imbeaux, F., Jaeger, E.F., Luce, T.C., Na, Y.-S., Oikawa, T., Osborne, T.H., Parail, V., Polevoi, A., Prater, R., Sips, A.C.C., Snipes, J.A., St John, H.E., Snyder, P.B., Voitsekhovitch, I., ITPA Integrated Operation Scenario Group, "Integrated Modeling of Steady-State Scenarios and Heating and Current Drive Mixes for ITER," Nucl. Fusion **51**, 103006 (2011); General Atomics Report GA-A26984 (2011).

Murphy, C.J., Abrahim, M., Anderson, P.M., Chiu, H.K., Grunloh, H.J., Hansink, M.J., Holtrop, K.L., Hong, R.-M., Kellman, A.G., Kellman, D.H., Mauzey, P.S., Noraky, S., Pawley, C.J., Rauch, J., Scoville, J.T., Van Zeeland, M.A., Yip, H.H., Wood, R.L., Murakami, M., Park, J.M., Heidbrink, W.W., "Overview of DIII-D Off-Axis Neutral Beam Project," Proc. 24th IEEE/NPSS Symp. on Fusion Engineering, Chicago, Illinois, June 26–30, 2011; General Atomics Report GA-A27097 (2011).

Muscatello, C.M., Heidbrink, W.W., "Measurements of Fast-Ion Transport by Resonant Interaction of a Sawtooth Crash," Bull. Am. Phys. Soc. **56**, 343 (2011).

Okabayashi, M., deGrassie, J.S., Heidbrink, W.W., In, Y., Liu, Y.Q., Matsunaga, G., Reimerdes, H., Strait, E.J., Takechi, M., Jackson, G.L., Hanson, J.M., La Haye, R.J., Lanctot, M.J., Sieck, P.E., "Off-Axis Fishbone Modes and Excitation of RWM in DIII-D," Proc. 38th EPS Conf. on Plasma Physics, Strasborg, France, June 27–July 1, 2011, Paper P4.087; General Atomics Report GA-A27074 (2011).

Okabayashi, M., Heidbrink, W.W., In, Y., Matsunaga, G., Takechi, M., Strait, E.J., Jackson, G.L., La Haye, R.J., Sieck, P.E., Lanctot, M.J., Hanson, J.M., "Off-Axis-Fishbone Mode and Its Relevancy to the RWM Onsets," Bull. Am. Phys. Soc. **56**, 298 (2011).

Okabayashi, M., Matsunaga, G., deGrassie, J.S., Heidbrink, W.W., In, Y., Liu, Y.Q., Reimerdes, H., Solomon, W.M., Strait, E.J., Takechi, M., Asakura, N., Budny, R.V., Jackson, G.L., Hanson, J.M., La Haye, R.J., Lanctot, M.J., Manickam, J., Shinohara, K., "Off-Axis Fishbone-Like Instability and Excitation of Resistive Wall Mode in JT-60U and DIII-D," Phys. Plasmas **18**, 056112 (2011); General Atomics Report GA-A26947 (2011).

Orlov, D.M., Nogami, S., Moyer, R.A., Evans, T.E., Schaffer, M.J., Ferraro, N.M., Unterberg, E.A., Loarte, A., Lanctot, M.J., Fenstermacher, M.E., "Metrics to Quantify Magnetic Field Stochasticity for DIII-D and ITER Discharges," Bull. Am. Phys. Soc. **56**, 294 (2011).

Pace, D.C., Fisher, R.K., Garcia-Munoz, M., Heidbrink, W.W., McKee, G.R., Murakami, M., Muscatello, C.M., Nazikian, R., Park, J.M., Petty, C.C., Rhodes, T.L., Staebler, G.M., Van Zeeland, M.A., Waltz, R.E., White, R.B., Yu, J.H., Zhang, W., Zhu, Y.B., "Transport of Energetic Ions Due to Sawteeth, Alfven Eigenmodes, and Microturbulence," Nucl. Fusion **51**, 043012 (2011); General Atomics Report GA-A26965 (2011).

Pace, D.C., Fisher, R.K., Garcia-Munoz, M., Heidbrink, W.W., Van Zeeland, M.A., "Neutral Beam Ion Losses Due to Alfven Eigenmode Activity in the DIII-D Tokamak," Plasma Phys. Control. Fusion **53**, 062001 (2011); General Atomics Report GA-A26953 (2011).

Park, J.M., Murakami, M., Petty, C.C., Van Zeeland, M.A., Ferron, J.R., Osborne, T.H., Politzer, P.A., Prater, R., Heidbrink, W.W., Holcomb, C.T., Pace, D.C., "Off-Axis NBCD Experiments in DIII-D," Bull. Am. Phys. Soc. **56**, 96 (2011).

Penaflor, B.G., Piglowski, D.A., Johnson, R.D., McHarg Jr., B.B., “Custom Open Source Solutions for DIII-D Data Acquisition and Control Systems,” Proc. 8th IAEA Technical Committee Meeting on Control Data Acquisition and Remote Participation for Fusion Research, Livermore, California, June 20–24, 2011 in Fusion Engin. Design **87**(12), 1977 (2012); General Atomics Report GA-A27085 (2011).

Petrie, T.W., Evans, T.E., Fenstermacher, M.E., Mordijck, S., Brooks, N.H., Ferron, J.R., Hudson, B., Hyatt, A.W., Lasnier, C.J., Leonard, A.W., Luce, T.C., Moyer, R.A., Politzer, P.A., Schaffer, M.J., Snyder, P.B., Watkins, J.G., “First Results Examining the Compatibility of RMP ELM Suppression With the Radiating Divertor in DIII-D,” J. Nucl. Mater. **415**, S906 (2011); General Atomics Report GA-A26728 (2010).

Petrie, T.W., Ferron, J.R., Hyatt, A.W., Leonard, A.W., Luce, T.C., Politzer, P.A., Holcomb, C.T., Fenstermacher, M.E., Hill, D.N., Lasnier, C.J., Watkins, J.G., “Effect of Divertor Shaping on Plasma Performance and Divertor Power Loading on DIII-D,” Bull. Am. Phys. Soc. **56**, 297 (2011).

Petty, C.C., Austin, M.E., Brennan, D.P., Burrell, K.H., DeBoo, J.C., Doyle, E.J., Ferron, J.R., Garofalo, A.M., Hillesheim, J.C., Holcomb, C.T., Holland, C., Hyatt, A.W., In, Y., Jackson, G.L., Lohr, J., Politzer, P.A., Prater, R., Reimerdes, H., Rhodes, T.L., Schmitz, L., Smith, J.P., Solomon, W.M., Staebler, G.M., Takahashi, R., Turco, F., Turnbull, A.D., Van Zeeland, M.A., Wang, G., White, A.E., Zeng, L., “Contributions of Electron Cyclotron Waves to Performance in Advanced Regimes on DIII-D,” Proc. 19th Radio Frequency Powers in Plasmas, Newport, Rhode Island, June 1–3, 2011; General Atomics Report GA-A27072 (2011).

Petty, C.C., Ferron, J.R., Politzer, P.A., Prater, R., Van Zeeland, M.A., Park, J.M., Murakami, M., Heidbrink, W.W., Muscatello, C.M., Holcomb, C.T., Grierson, B.A., “Off-Axis Neutral Beam Current Drive on DIII-D,” Bull. Am. Phys. Soc. **56**, 339 (2011).

Petty, C.C., Jayakumar, R.J., Makowski, M.A., Holcomb, C.T., Humphreys, D.A., La Haye, R.J., Luce, T.C., Politzer, P.A., Prater, R., Wade, M.R., Welander, A.S., “Spatiotemporal Changes in the Pressure-Driven Current Densities on DIII-D Due to Magnetic Islands,” Nucl. Fusion **52**, 013011 (2011); General Atomics Report GA-A27033 (2011).

Pinsker, R.I., Luce, T.C., Politzer, P.A., Porkolab, M., Goulding, R.H., Hanson, G.R., Ryan, P.M., Hosea, J.C., Nagy, A., Wilson, J.R., Maggiora, R., Milanesio, D., Zeng, L., “Recent Results on Coupling Fast Waves to High Performance Plasmas on DIII-D,” Proc. 19th Radio Frequency Powers in Plasmas, Newport, Rhode Island, June 1–3, 2011, AIP Conf. Proc. **1406**, 313 (2011); General Atomics Report GA-A27104 (2011).

Pinsker, R.I., Ryan, P.M., Goulding, R.H., Hanson, G.R., Milanesio, D., Maggiora, R., Hosea, J.C., Nagy, A., Porkolab, M., Zeng, L., “Comparison of 3-D Modeling With Experimental Results on Fast Wave Antenna Loading in DIII-D,” Bull. Am. Phys. Soc. **56**, 98 (2011).

Politzer, P.A., “Scaling of Energy Confinement With Rotation for Advanced Inductive Plasmas in DIII-D,” Bull. Am. Phys. Soc. **56**, 239 (2011).

Ponce, D., Lohr, J., Tooker, J.F., O'Neill, R.C., Moeller, C.P., Doane, J.L., Noraky, S., Dubovenko, K., Gorelov, I.A., Cengher, M., Penaflor, B.G., Ellis, R.A., “ECH System Developments Including the Design of an Intelligent Fault Processor on the DIII-D Tokamak,” Fusion Engin. Design **86**, 785 (2011); General Atomics Report GA-A26849 (2010).

Prater, R., Lohr, J., DIII-D Physics Team, DIII-D Operations Team, “The Many Applications of ECH on the DIII-D Tokamak,” Proc. 8th Int. Workshop on Strong Microwaves and Terahertz Waves – Sources and Applications, Nizhny Novgorod, Russia, July 9–16, 2011; General Atomics Report GA-A27075 (2011).

Prater, R., Pinsker, R.I., Choi, M., Harvey, R.W., Petrov, Yu., Porkolab, M., “Effect of Hydrogen Minority on the Power Balance for Fast Wave Heating in DIII-D,” Bull. Am. Phys. Soc. **56**, 340 (2011).

Project Staff, “DIII-D Year 2011 Experiment Plan,” General Atomics Report GA-A27050 (2011).

Reimerdes, H., Buttery, R.J., Garofalo, A.M., In, Y., La Haye, R.J., Lanctot, M.J., Okabayashi, M., Park, J.-K., Schaffer, M.J., Strait, E.J., Volpe, F.A.G., “Error Field Tolerance and Error Field Correction Strategies Applicability to ITER,” Fusion Sci. Technol. **59**, 572 (2011); General Atomics Report GA-A26831 (2010).

Rhodes, T.L., Holland, C., Smith, S.P., White, A.E., Burrell, K.H., Candy, J., DeBoo, J.C., Doyle, E.J., Hillesheim, J.C., Kinsey, J.E., McKee, G.R., Mikkelsen, D., Peebles, W.A., Petty, C.C., Prater, R., Parker, S., Chen, Y., Schmitz, L., Staebler, G.M., Waltz, R.E., Wang, G., Yan, Z., Zeng, L., “L-Mode Validation Studies of Gyrokinetic Turbulence Simulations Via Multiscale and Multifield Turbulence Measurements on the DIII-D Tokamak,” Nucl. Fusion **51**, 063022 (2011); General Atomics Report GA-A26980 (2010).

Rhodes, T.L., Zeng, L., Doyle, E.J., Wang, G., Peebles, W.A., Schmitz, L., Hillesheim, J.C., Mordijck, S., Evans, T.E., McKee, G.R., Yan, Z., “Effect of Resonant Magnetic Perturbations on Fluctuations and Transport on DIII-D,” Bull. Am. Phys. Soc. **56**, 294 (2011).

Richenderfer, A., Cengher, M., Lohr, J., Moeller, C.P., “Mode Content and Transmission Measurements on Components of the ECH Transmission Lines on DIII-D,” Bull. Am. Phys. Soc. **56**, 162 (2011).

Rost, J.C., Porkolab, M., Dorris, J.R., Marinoni, A., Burrell, K.H., “Study of the Poloidal Variation of Edge Plasma Turbulence in QH-mode With PCI on DIII-D,” Bull. Am. Phys. Soc. **56**, 297 (2011).

Rudakov, D.L., Boedo, J.A., Moyer, R.A., Pitts, R., Leonard, A.W., Stangeby, P.C., Watkins, J.G., “Turbulent SOL Transport in Limited Versus Diverted L-mode Discharges in DIII-D,” Bull. Am. Phys. Soc. **56**, 297 (2011).

Rudakov, D.L., Boedo, J.A., Pitts, R.A., Jackson, G.L., Lasnier, C.J., Leonard, A.W., Moyer, R.A., Stangeby, P.C., Tynan, G.R., Watkins, J.G., “SOL Width and Transport in Limited Versus Diverted Discharges in DIII-D,” J. Nucl. Mater. **415**, S387 (2011); General Atonics Report GA-A26757 (2010).

Schmitz, L., Rhodes, T.L., Hillesheim, J.C., Peebles, W.A., Wang, G., Zeng, L., Holland, C., Burrell, K.H., DeBoo, J.C., Smith, S.P., Prater, R., deGrassie, J.S., Staebler, G.M., McKee, G.R., Solomon, W.M., “Dependence of Electron and Ion Transport on T_e/T_i in Low Collisionality QH-mode Plasmas,” Bull. Am. Phys. Soc. **56**, 342 (2011).

Schmitz, L., Zeng, L., Rhodes, T.L., Hillesheim, J.C., Doyle, E.J., Groebner, R.J., Peebles, W.A., Burrell, K.H., Wang, G., “The Role of Zonal Flow Predator-Prey Oscillations in Triggering the Transition to H-mode Confinement,” Phys. Rev. Lett. **108**, 155002 (2011); General Atomics Report GA-A27125 (2011).

Schmitz, O., Evans, T.E., Boedo, J.A., Fenstermacher, M.E., Jakubowski, M.W., Laengner, R., McLean, A.G., Orlov, D.M., Reimerdes, H., Watkins, J.G., Brooks, N.H., Lasnier, C.J., Frerichs, H., Reiter, D., Samm, U., Stoschus, H., Unterberg, E.A., DIII-D Team, TEXTOR Team, “The Influence of Three-Dimensional Stochastic Magnetic Boundaries on Plasma Edge Transport and the Resulting Plasma Wall Interaction,” J. Nucl. Mater. **415**, S886 (2011); General Atomics Report GA-A26778 (2010).

Scoville, J.T., “Recent and Future Upgrades to the DIII-D Tokamak,” Proc. 26th Symp. on Fusion Technology, September 27–October 1, 2010, Porto, Portugal, Fusion Engin. Design **86**, 651 (2011); General Atomics Report GA-A26846 (2010).

Scoville, J.T., Murphy, C.J., Hong, R.-M., “Commissioning of the Off-Axis Neutral Beamline on the DIII-D Tokamak,” Bull. Am. Phys. Soc. **56**, 300 (2011).

Shafer, M.W., Battaglia, D.J., Unterberg, E.A., Canik, J.M., Evans, T.E., Harris, J.H., Meitner, S.J., “Soft X-ray Imaging Design and Analysis Methods on DIII-D,” Proc. 20th Int. Toki Conf. on the Next 20 Years in Plasma and Fusion Research, Toki-City, Japan, December 7-10, 2010 published in Special Issue Plasma and Fusion Research: Regular Articles **6**, 2402041 (2011) (The Japan Society of Plasma Science and Nuclear Fusion Research 2011); General Atomics Report GA-A26977 (2011).

Shafer, M.W., Unterberg, E.A., Battaglia, D.J., Canik, J.M., Harris, J.H., Hillis, D.L., Maingi, R., Evans, T.E., “Edge Soft X-ray Imaging for Measurements of Magnetic Topology During 3-D Magnetic Perturbations,” Bull. Am. Phys. Soc. **56**, 296 (2011).

Shi, W., Wehner, W., Schuster, E., Walker, M.W., Huumphreys, D.A., “Robust Control of the Toroidal Rotation and Safety Factor Profiles in the DIII-D Tokamak,” Bull. Am. Phys. Soc. **56**, 300 (2011).

Smith, S.P., Groebner, R.J., Osborne, T.H., Leonard, A.W., Callen, J.D., “Testing the Paleoclassical Based Pedestal Model Against Measured DIII-D Pedestal Profiles,” Bull. Am. Phys. Soc. **56**, 296 (2011).

Snyder, P.B., Groebner, R.J., Hughes, J.W., Osborne, T.H., Beurskens, M., Leonard, A.W., Wilson, H.R., Xu, X.Q., “A First Principles Predictive Model of the Pedestal Height and Width - Development, Testing, and ITER Optimization With the EPED Model,” Nucl. Fusion **51**, 103016 (2011); General Atomics Report GA-A26993 (2011).

Solomon, W.M., Burrell, K.H., deGrassie, J.S., Garofalo, A.M., Moyer, R.A., Mueller, S.H., Petty, C.C., Reimerdes, H., “Characterization of Intrinsic Rotation Drive on DIII-D,” Nucl. Fusion **51**, 073010 (2011); General Atomics Report GA-A26979 (2011).

Solomon, W.M., Burrell, K.H., Garofalo, A.M., Groebner, R.J., Lasnier, C.J., Makowski, M.A., Osborne, T.H., Reimerdes, H., DeGrassie, J.S., Doyle, E.J., Evans, T.E., Fenstermacher, M.E., Jackson, G.L., Schaffer, M.J., “ELM Pacing Using Modulated Nonaxisymmetric Magnetic Fields on DIII-D,” Nucl. Fusion **52**, 033007 (2012); General Atomics Report GA-A27045 (2011).

Solomon, W.M., Okabayashi, M., Buttery, R.J., Ferron, J.R., Garofalo, A.M., Jackson, G.L., La Haye, R.J., Luce, T.C., Petty, C.C., Politzer, P.A., Welander, A.S., Hanson, J.M., In, Y., Lanctot, M.J., Turco, F., “Advanced Inductive Plasmas With Low Torque Startup,” Bull. Am. Phys. Soc. **56**, 99 (2011).

St John, H.E., Turnbull, A.D., Choi, M., Smith, S.P., Buttery, R.J., Lao, L.L., Snyder, P.B., “Physics Modeling of ARIES-AT,” Bull. Am. Phys. Soc. **56**, 340 (2011).

Stacey, W.M., “Ion Orbit Loss and X-Loss Effects on the Interpretation of Transport in the Edge Pedestal,” Bull. Am. Phys. Soc. **56**, 297 (2011).

Staebler, G.M., Waltz, R.E., Kinsey, J.E., Solomon, W.M., Belli, E.A., “Multi-Species Gyro-Kinetic Momentum Transport Modeling with the Trapped Gyro-Landau Fluid Model,” Proc. 38th EPS Conf. on Plasma Physics, Strasborg, France, June 27–July 1, 2011, Paper O4.122; General Atomics Report GA-A27082 (2011).

Stangeby, P.C., “Assessing Material Migration Through ^{13}C Injection Experiments,” J. Nucl. Mater. **415**, S278 (2011); General Atonics Report GA-A26769 (2010).

Stangeby, P.C., Elder, J.D., Boedo, J.A., Makowski, M.A., Lasnier, C.J., Leonard, A.W., “The Relation Between Upstream Radial Widths of n_e and T_e and Outer Target Power Width for H-mode Discharges in DIII-D,” Bull. Am. Phys. Soc. **56**, 98 (2011).

Stangeby, P.C., Leonard, A.W., “Obtaining Reactor-Relevant Divertor Conditions in Tokamaks,” Nucl. Fusion **51**, 063001 (2011); General Atomics Report GA-A26753 (2010).

Strait, E.J., Buttery, R.J., Garofalo, A.M., La Haye, R.J., Schaffer, M.J., Sieck, P.E., Volpe, F.A.G., Hanson, J.M., "Error Field Measurements Using the Torque on a Magntic Island," Bull. Am. Phys. Soc. **56**, 299 (2011).

Sutherland, D.A., Fisher, R.K., Pace, D.C., Heidbrink, W.W., Chen, X., "Studies of Prompt Losses From Neutral Beam Injection into DIII-D," Bull. Am. Phys. Soc. **56**, 163 (2011).

Svidzinski, V.A., In, Y., Kim, J.S., Chu, M.S., Liu, Y.Q., "Stability Analysis of Resistive Wall Mode in Rotating High-Beta Plasmas in DIII-D," Bull. Am. Phys. Soc. **56**, 298 (2011).

Thomas, D.M., "Beams, Brightness and Background — Using Active Spectroscopy Techniques for Precision Measurements in Fusion Plasma Research," Bull. Am. Phys. Soc. **56**, 58 (2011).

Tobias, B.J., Boivin, R.L., Boom, J.E., Classen, I.G.J., Domier, C.W., Donne, A.J.H., Heidbrink, W.W., Luhmann Jr, N.C., Munsat, T., Muscatello, C.M., Nazikian, R., Park, H.K., Spong, D.A., Turnbull, A.D., Van Zeeland, M.A., Yun, G.S., DIII-D Team, "On the Application of Electron Cyclotron Emission Imaging to the Validation of Theoretical Models of Magnetohydrodynamic Activity," Phys. Plasmas **18**, 056107 (2011); General Atomics Report GA-A26944 (2011).

Tobias, B.J., Classen, I.G.J., Domier, C.W., Heidbrink, W.W., Luhmann, Jr, N.C., Nazikian, R., Park, H.K., Spong, D.A., Van Zeeland, M.A., "Electron Cyclotron Emission Imaging of Fast Ion Induced Shearing of 2D Alfvén Eigenmodes," Phys. Rev. Lett. **106**, 075003 (2011); General Atomics Report GA-A26833 (2010).

Tobias, B.J., Domier, C.W., Luhmann Jr, N.C., Boom, J.E., Classen, I.G.J., Donne, A.J.H., Yun, G., Park, H.K., Nazikian, R.M., "Sawtooth Precursor Oscillations on DIII-D," IEEE Trans. Plasma Sci. **39**, 3022 (2011); General Atomics Report GA-A26929 (2011).

Tobias, B.J., Nazikian, R., Dormier, C.W., Luhmann, N.C., Austin, M.E., "ECE-Imaging of the H-mode Pedestal," Bull. Am. Phys. Soc. **56**, 146 (2011).

Tooker, J.F., Anastasi, D.D., Guzman, T.J., Huynh, P., McDaniel, W.L., Pawley, C.J., "Electron Cyclotron Heating Power Supplies on DIII-D," Fusion Engin. Design **86**, 801 (2011); General Atomics Report GA-A26847 (2010).

Turco, F., "Sensitivity of Transport and Stability to the Current Profile in Steady-State Scenario Plasmas in DIII-D," Bull. Am. Phys. Soc. **56**, 359 (2011).

Turco, F., Luce, T.C., Ferron, J.R., Holcomb, C.T., Brennan, D.P., DeBoo, J.C., White, A.E., Politzer, P.A., In, Y., "Transport and Stability of High-β_N High Noninductive Fraction DIII-D Discharges," Proc. 38th EPS Conf. on Plasma Physics, Strasborg, France, June 27–July 1, 2011, Paper P5.086; General Atomics Report GA-A27088 (2011).

Umstadter, K.R., Rudakov, D.L., Wampler, W.R., Watkins, J.G., Wong, C.P.C., "Effects of ELMs on Deuterium-Loaded-Tungsten Plasma Facing Components," J. Nucl. Mater. **415**, S83 (2011); General Atomics Report GA-A26762 (2010).

Unterberg, E.A., Allen, S.L., Brooks, N.H., Evans, T.E., Leonard, A.W., McLean, A.G., Watkins, J.G., Whyte, D.G., "Global Particle Balance Measurements in DIII-D H-mode Discharges," J. Nucl. Mater. **415**, S740 (2011); General Atomics Report GA-A26770 (2010).

Uzun-Kaymak, I.U., Fonck, R.J., McKee, G.R., Yan, Z., "Ion Temperaature and Toroidal Velocity Fluctuation Measurements Using Two-Point Ultra-Fast Charge Exchange Recombination Spectrometer (UF-CHERS)," Bull. Am. Phys. Soc. **56**, 343 (2011).

Van Zeeland, M.A., Austin, M.E., Gorelenkov, N.N., Fisher, R.K., Heidbrink, W.W., Kramer, G.J., Garcia-Munoz, M., Murakami, M., Nazikian, R., Pace, D.C., Park, J.M., Tobias, B.J., White, R.B., "Alfvén Eigenmode Stability and Fast Ion Transport in DIII-D and ITER Reversed Magnetic Shear Plasmas," Proc. 12th IAEA Technical Mtg. on Energetic Particles in Magnetic Confinement Systems, Austin, Texas, September 8–10, 2011; General Atomics Report GA–A27133 (2011).

Van Zeeland, M.A., Ferron, J.R., Hyatt, A.W., Murphy, C.J., Petty, C.C., Prater, R., Scoville, J.T., Heidbrink, W.W. Muscatello, C.M., Park, J.M., Murakami, M., Pace, D.C., Holcomb, C.T., Grierson, B.A., Tobias, B.J., Solomon, W.M., Moyer, R.A., "Initial Off-Axis Neutral Beam Checkout and Physics Experiments on DIII-D," Bull. Am. Phys. Soc. **56**, 96 (2011).

Van Zeeland, M.A., Heidbrink, W.W., Fisher, R.K., Garcia-Munoz, M., Kramer, G.J., Pace, D.C., White, R.B., Aekaeslompolo, S., Austin, M.E., Boom, J.E., Classen, I.G.J., da Graca, S., Geiger, B., Gorelenkova, M., Gorelenkov, N.N., Hyatt, A.W., Luhmann, N., Maraschek, M., McKee, G.R., Moyer, R.A., Muscatello, C.M., Nazikian, R., Park, H., Sharapov, S., Suttrop, W., Tardini, G., Tobias, B.J., Zhu, Y.B., DIII-D Team, ASDEX Upgrade Team, "Measurements and Modeling of Alfvén Eigenmode Induced Fast Ion Transport and Loss in DIII-D and ASDEX Upgrade," Phys. Plasmas **18**, 056114 (2011); General Atomics Report GA-A26963 (2011).

Wade, M.R., "Plasma Response and Transport Associated with RMP ELM Suppression on DIII-D," Bull. Am. Phys. Soc. **56**, 186 (2011).

Walker, M.L., "Model-Based Decoupling Control of Tokamak Plasmas," Proc. 2012 American Control Conf., Montreal, Canada, September 23, 2011; General Atomics Report GA-A27143 (2011).

Walker, M.L., Humphreys, D.A., Eidietis, N.W., Leuer, J.A., Welander, A.S., Koleman, N.W., "System Modeling, Validation, and Design of Shape Controllers for NSTX," Bull. Am. Phys. Soc. **56**, 247 (2011).

Wang, G., Peebles, W.A., Rhodes, T.L., DeBoo, J.C., Staebler, G.M., Hillesheim, J.C., Yan, Z., McKee, G.R., Petty, C.C., Solomon, W.M., Burrell, K.H., Doyle, E.J., Leonard, A.W., Schmitz, L., Van Zeeland, M.A., White, A.E., Zeng, L., "Multi-field/Multi-scale Turbulence Response to Electron Cyclotron Heating of DIII-D Ohmic Plasmas," Phys. Plasmas **18**, 082504 (2011); General Atomics Report GA-A27025 (2011).

Wang, G., Rhodes, T.L., Peebles, W.A., Hillesheim, J.C., Doyle, E.J., Schmitz, L., Zeng, L., Austin, M.E., Yan, Z., McKee, G.R., Petty, C.C., Burrell, K.H., DeBoo, J.C., Solomon, W.M., "Role of Edge Turbulence and Flows in the Density Dependence of the L-H Transition Power Threshold on DIII-D," Bull. Am. Phys. Soc. **56**, 296 (2011).

Weber, T.R.., Allen, S.L., Hill, D.N., Meyer, W.H., Porter, G.D., Howard, J., "C^{2+} Flow Measurement in DIII-D Using Coherence Imaging Spectro-Polarimetry," Bull. Am. Phys. Soc. **56**, 98 (2011).

Wehner, W., Shi, W., Xu, C., Schuster, E., Moreau, D., Mazon, D., Walker, M.L., Humphreys, D.A., "Data-Driven Modeling of the Toroidal Rotation and Safety Factor Profile Dynamics for AT Scenarios in DIII-D," Bull. Am. Phys. Soc. **56**, 300 (2011).

Welander, A.S., Eidietis, N.W., Humphreys, D.A., Hyatt, A.W., Leuer, J.A., Walker, M.L., "New Plasma Discharge Development Tools for the DIII-D Plasma Control System," Bull. Am. Phys. Soc. **56**, 299 (2011).

Wingen, A., Evans, T.E., Spatschek, K.H., "Dependence of a Current-Driven ELM Self-Amplification Process on the Plasma Shape," Nucl. Fusion **52**, 054018 (2012); General Atomics Report GA-A27063 (2011).

Wingen, A., Evans, T.E., Spatschek, K.H., "Effect of Thermoelectric Currents on the Magnetic Topology in DIII-D," Phys. Plasmas **18**, 042501 (2011); General Atomics Report GA-A26692 (2010).

Yan, Z., McKee, G.R., Boedo, J.A., Tynan, G.R., Diamond, P.H., Groebner, R.J., Osborne, T.H., Wang, G., Schmitz, L., "The Dynamics of Turbulence and Shear Flow Approaching the L-H Transition," Bull. Am. Phys. Soc. **56**, 97 (2011).

Yu, J.H., Smirnov, R.D., Rudakov, D.L., "Dust Appearance Rates During Neutral Beam Injection and After Oxygen Bake in the DIII-D Tokamak," J. Nucl. Mater. **415**, S1102 (2011); General Atonics Report GA-A26774 (2010).

Zeng, L., Doyle, E.J., Rhodes, T.L., Schmitz, L., Peebles, W.A., Evans, T.E., Mordijck, S., Moyer, R.A., McKee, G.R., Yan, Z., "Effects of Resonant Magnetic Field Perturbations on Density Profiles, Particle Transport, and Turbulence in DIII-D," Bull. Am. Phys. Soc. **56**, 97 (2011).

12.3. PUBLICATIONS FOR FY10

Abla, G., Fredian, T.W., Schissel, D.P., Stillerman, J.A., Greenwald, M.J., Stepanov, D. and Ciarlette, D.J., “Operation Request Gatekeeper – A Software System for Remote Access Control of Diagnostic Instruments in Fusion Instruments,” Proc. 18th Topl. Conf. on High Temperature Plasma Diagnostics, Wildwood, New Jersey, May 16–20, 2010 Rev. Sci. Instrum. **81**, 10E124 (2010); General Atomics Report GA-A26729 (2010).

Allen, S.L., Brooks, N.H., Dittmar, T., Ellis, R., Fenstermacher, M.E., Davis, J.W., Elder, J.D., Fitzpatrick, B., Haasz, A.A., Jackson, G.L., Leonard, A.W., Litnovsky, A., Mahdavi, M.A., McLean, A.G., Osborne, T.H., Politzer, P.A., Rudakov, D.L., Stangeby, P.C., Tsitrone, E., Tsui, C., Umstadter, K., Unterberg, E.A., Wampler, W.R., West, W.P., Whyte, D.G., “Particle Control and Transport Experiments in the DIII-D Tokamak With Graphite Walls,” Proc. 23rd IAEA Fusion Energy Conf., Daejeon Republic of Korea, October 11–16, 2010, Paper EXD/6-4; General Atomics Report GA-A26897 (2010).

Antar, G.Y., Krasheninnikov, S.I., Snyder, P.B., Moyer, R.A., Pugno, R., Gray, D.S., “The Spatio-Temporal Structure of Type I Edge Localized Modes Investigated by Fast Imaging on the DIII-D Tokamak,” Nucl. Fusion **49**, 032001 (2009); General Atomics Report GA-A26538 (2010).

Austin, M.E., Gentle, K.W., Petty, C.C., Rhodes, T.L., Schmitz, L., “Transport Analysis of Bat-eared T_e Profile Discharges in DIII-D,” Bull. Am. Phys. Soc. **55**, 345 (2010).

Bae, C., Stacey, W.M., “Neoclassical Rotation Theory for Toroidal and Poloidal Rotation Velocities Using Miller Equilibrium Analytical Flux Surface Geometry,” Bull. Am. Phys. Soc. **55**, 132 (2010).

Barton, J.E., Schuster, E., Walker, M.L., Humphreys, D.A., “Closed-Loop Simulation of Model-Based Current Profile Control with the DIII-D Plasma Control System,” Bull. Am. Phys. Soc. **55**, 131 (2010).

Bass, E.M., and Waltz, R.E., “Gyrokinetic Simulations of Energetic Particle Driven TAE/EPM Transport Embedded in ITG/TEM Turbulence,” Proc. 23rd IAEA Fusion Energy Conf., Daejeon Republic of Korea, October 11–16, 2010, Paper THW/P4-01; General Atomics Report GA-A26877 (2010).

Baylor, L.R., Commaux, N., Jernigan, T.C., Parks, P.B., Evans, T.E., Osborne, T.H., Strait, E.J., Fenstermacher, M.E., Lasnier, C.J., Moyer, R.A., Yu, J.H., “ELM Pacing by Pellet Injection on DIII-D and Extrapolation to ITER,” Proc. 37th European Physical Society Conf. on Plasma Physics, Dublin, Ireland, June 21–25, 2010, Paper P2.117; General Atomics Report GA-A26792 (2010).

Baylor, L.R., Jernigan, T.C., Commaux, N., Evans, T.E., Osborne, T.H., Parks, P.B., Strait, E.J., Fenstermacher, M.E., Lasnier, C.J., Moyer, R.A., Yu, J.H., “Pellet ELM Pacing Results from DIII-D,” Bull. Am. Phys. Soc. **55**, 63 (2010).

Boivin, R.L., Park, H.K., Vayakis, G., Conway, G., Hawkes, N., Hirsch, M., Sasao, M., Veschev, E.A., “R&D ITPA Activities in Support of Optimizing ITER Diagnostic Performance,” Proc. 23rd IAEA Fusion Energy Conf., Daejeon Republic of Korea, October 11–16, 2010, Paper ITR/P1-02; General Atomics Report GA-A26876 (2010).

Bray, B.D., Ponce, D.M., Liu, C., Deterly, T.M., Watkins, M., “Upgraded Thomson Scattering System at DIII-D,” Bull. Am. Phys. Soc. **55**, 134 (2010).

Brooks, N.H., Burrell, K.H., Isler, R.C., Meyer, O., Pablant, N.A., “Charge Exchange Recombination Detection of Low-Z and Medium-Z Impurities in the Extreme UV Using a Digital Lock-in Technique,” Rev. Sci. Instrum. **81**, 10D721 (2010); General Atomics Report GA-A26727 (2010).

Brooks, N.H., Taussig, D.A., Scime, E., Galante, M., “An LIF Diagnostic for Measurement of the Neutral Deuterium Profile in the SOL and Pedestal of DIII-D,” Bull. Am. Phys. Soc. **55**, 131 (2010).

Burrell, K.H., Belli, E.A., Solomon, W.M., Grierson, B.A., Wang, W., Rewoldt, G.W., "Impurity Poloidal Rotation in DIII-D Under Low Toroidal Field Conditions," Bull. Am. Phys. Soc. **55**, 156 (2010).

Buttery, R.J., Gerhardt, S., La Haye, R.J., Reimerdes, H., Sabbagh, S., Brennan, D.P., Chu, M.S., Liu, Y., Park, J.-K., Pinsker, R.I., Yu, J.H., "The Impact of 3D Fields on Tearing Mode Stability of H-Modes," Proc. 23rd IAEA Fusion Energy Conf., Daejeon Republic of Korea, October 11–16, 2010, Paper EXS/P5-01; General Atomics Report GA-A26890 (2010).

Buttery, R.J., La Haye, R.J., Reimerdes, H., "A New Resistive Response to 3-D Fields in Low Rotation H-modes," Bull. Am. Phys. Soc. **55**, 131 (2010).

Callen, J.D., "Paleoclassical Model of Pedestal Structure," Bull. Am. Phys. Soc. **55**, 130 (2010).

Callis, R.W., Doane, J.L., Grunloh, H.J., Kajiwara, K., Kasugai, A., Moeller, C.P. Oda, Y., Olstad, R.A., Sakamoto, K., Takahashi, K., "Testing of ITER-Class ECH Transmission Line Components at the JAEA Radio-Frequency Test Stand," Proc. 23rd IAEA Fusion Energy Conf., Daejeon Republic of Korea, October 11–16, 2010, Paper ITR/P1-09; General Atomics Report GA-A26850 (2010).

Cengher, M., Lohr, J., Gorelov, Y.A., Ponce, D., Moeller, C.P., Shapiro, M., "Improved Efficiency of the ECH Transmission Lines on DIII-D," Bull. Am. Phys. Soc. **55**, 345 (2010).

Cengher, M., Lohr, J., Ponce, D., Gorelov, Y.A., Moeller, C.P., Shapiro, M., "Transmission Line Power Measurements for the 110 GHz Electron Cyclotron Heating System on DIII-D and Gyrotron Operational Performance," 35th Int. Conf. on Infrared Millimeter and Terahertz Waves, Rome, Italy, September 5–10, 2010 in J. Infrared, Millimeter, and Terahertz Waves **32**, 1 (2010); General Atomics Report GA-A26817 (2010).

Choi, M., Green, D.L., Jaeger, E.F., Chan, V.S., Muscatello, C.M., Heidbrink, W.W., Liu, D., Harvey, R.W., Lao, L.L., Pinsker, R.I., Berry, L.A., Bonoli, P., Kim, S.H., and the RF-SciDAC Team, "Finite Orbit Monte-Carlo Simulation of Ion Cyclotron Resonant Heating Scenarios in DIII-D, NSTX, KSTAR and ITER," Proc. 23rd IAEA Fusion Energy Conf., Daejeon Republic of Korea, October 11–16, 2010, Paper THW/P7-06; General Atomics Report GA-A26870 (2010).

Chrobak, C.P., Taylor, P.L., Brooks, N.H., Jackson, G.L., Wall, D.R., Unterberg, E.A., Fitzpatrick, B., Davis, J.W., Haasz, A.A., McLean, A.G., Stangeby, P.C., Tsui, C., Umstadter, K.R., Allen, S.L., Wampler, W.R., "Thermo-Oxidation Experiments in the DIII-D Tokamak," Bull. Am. Phys. Soc. **55**, 133 (2010).

Chrystal, C., Burrell, K.H., Pablant, N.A., "Straightforward Correction for the Astigmatism of a Czeray-Turner Spectrometer," Rev. Sci. Instrum. **81**, 023503 (2010); General Atomics Report GA-A26552 (2009).

Chu, M.S., Garofalo, A.M., La Haye, R.J., Schaffer, M.J., Strait, E.J., Reimerdes, H., Liu, Y.Q., Casper, T.A., Gribov, Y., "Plasma Response to Complex External Magnetic Perturbations," Bull. Am. Phys. Soc. **55**, 131 (2010).

Chu, M.S., Lao, L.L., Schaffer, M.J., Evans, T.E., Strait, E.J., Liu, Y.Q., Lanctot, M.J., Reimerdes, H., Liu, Y., Casper, T.A., Gribov, Y., "Response of a Resistive and Rotating Tokamak to External Magnetic Perturbations Below the Alfvénic Frequency," Proc. 23rd IAEA Fusion Energy Conf., Daejeon Republic of Korea, October 11–16, 2010, Paper THS/P5-04; General Atomics Report GA-A26886 (2010).

Cole, A.J., Callen, J.D., Solomon, W.M., Garofalo, A.M., Hegna, C.C., Reimerdes, H., DIII-D Team, "Peak Neoclassical Toroidal Viscous Force in the DIII-D Tokamak," Proc. 37th European Physical Society Conf. on Plasma Physics, Dublin, Ireland, June 21–25, 2010, Paper O4.115; General Atomics Report GA-A26781 (2010).

Commaux, N., Baylor, L.R., Eidietis, N.W., Evans, T.E., Hollmann, E.M., Humphreys, D.A., Izzo, V.A., James, A.N., Jernigan, T.C., Parks, P.B., Wesley, J.C., Yu, J.H., “Novel Rapid Shutdown Strategies for Runaway Electron Suppression in DIII-D,” Proc. 23rd IAEA Fusion Energy Conf., Daejeon Republic of Korea, October 11–16, 2010, Paper EXS/P2-02; General Atomics Report GA-A26856 (2010).

Commaux, N., Baylor, L.R., Jernigan, T.C., Hollmann, E.M., Parks, P.B., Wesley, J.C., James, A.N., Humphreys, D.A., Yu, J.H., Combs, S.K., Meitner, S.J., Foust, C.R., “Disruption Mitigation Experiments Carried Out Using the New Shattered Pellet Injection on DIII-D,” Proc. 37th European Physical Society Conf. on Plasma Physics, Dublin, Ireland, June 21–25, 2010, Paper P4.116; General Atomics Report GA-A26787 (2010).

Commaux, N., Baylor, L.R., Jernigan, T.C., Hollmann, E.M., Parks, P.B., Humphreys, D.A., Wesley, J.C., Yu, J.H., “Demonstration of Rapid Shutdown Using Large Shattered Deuterium Pellet Injection in DIII-D,” Nucl. Fusion **50**, 025011 (2010); General Atomics Report GA-A26626 (2010).

Commaux, N., Pegourie, B., Baylor, L.R., Kochl, F., Parks, P.B., Jernigan, T.C., Geraud, A., Nehme, H., “Influence of the Low Order Rational q Surfaces on the Pellet Deposition Profile,” Nucl. Fusion **50**, 025011 (2010); General Atomics Report GA-A26496 (2009).

DeBoo, J.C., Holland, C., Rhodes, T.L., Schmitz, L., Wang, G., White, A.E., Austin, M.E., Doyle, E.J., Hillesheim, J.C., Peebles, W.A., Petty, C.C., Yan, Z., Zeng, L., “Probing Plasma Turbulence by Modulating the Electron Temperature Gradient,” Phys. Plasmas **17**, 056105 (2010); General Atomics Report GA-A26584 (2010).

DeBoo, J.C., Staebler, G.M., “Survey of Driftwave Linear Growth Rate Sensitivity to Gradient Scale Lengths,” Bull. Am. Phys. Soc. **55**, 346 (2010).

deGrassie, J.S., Boedo, J.A., Mueller, S.H., “Thermal Ion Orbit Loss and Intrinsic Toroidal Velocity Near the Last Closed Flux Surface,” Bull. Am. Phys. Soc. **55**, 131 (2010).

DIII-D Research Team, “DIII-D Year 2010 Experiment Plan,” General Atomics Report GA-A26635 (2010).

Dorris, J.R., Rost, J.C., Porkolab, M., Burrell, K.H., “Measurements of Short Wavelength Plasma Fluctuations Using the DIII-D Phase Contrast Imaging Diagnostic,” Bull. Am. Phys. Soc. **55**, 347 (2010).

Doyle, E.J., DeBoo, J.C., Ferron, J.R., Jackson, G.L., Luce, T.C., Murakami, M., Osborne, T.H., Park, J.-M., Politzer, P.A., Reimerdes, H., Budny, R.V., Casper, T.A., Challis, C.D., Groebner, R.J., Holcomb, C.T., Hyatt, A.W., La Haye, R.J., McKee, G.R., Petrie, T.W., Petty, C.C., Rhodes, T.L., Shafer, M.W., Snyder, P.B., Strait, E.J., Wade, M.R., Wang, G., West, W.P., Zeng, L., “Demonstration of ITER Operatonal Scenarios on DIII-D,” Nucl. Fusion **50**, 075005 (2010); General Atomics Report GA-A26404 (2010).

Doyle, E.J., DeBoo, J.C., Gohil, P., “Progress in Demonstration of the ITER Baseline Scenario on DIII-D,” Bull. Am. Phys. Soc. **55**, 344 (2010).

Eidietis, N.W., Humphreys, D.A., “Diffusive Model for Halo Width Growth During VDEs,” Proc. 23rd IAEA Fusion Energy Conf., Daejeon Republic of Korea, October 11–16, 2010, Paper EXS/P2-05; General Atomics Report GA-A26881 (2010).

Elder, J.D., Stangeby, P.C., Lasnier, C.J., Makowski, M.A., Boedo, J.A., Brooks, N.H., Leonard, A.W., Watkins, J.G., “Application of OEDGE to Transport Coefficient Extraction in DIII-D Joule Milestone Discharges,” Bull. Am. Phys. Soc. **55**, 133 (2010).

Eldon, D.P., Bray, B.D., Ponce, D.M., Chavez, A.J., Deterly, T.M., Groebner, R.J., Liu, C., Osborne, T.H., Snyder, P.B., "High Resolution Pedestal Thomson Scattering System at DIII-D," Bull. Am. Phys. Soc. **55**, 134 (2010).

Evans, T.E., "An Overview of Recent DIII-D ELM Control Experiments," Bull. Am. Phys. Soc. **55**, 128 (2010).

Evans, T.E., Wingen, A., Watkins, J.G., Spatschek, K.H., "A Conceptual Model for the Nonlinear Dynamics of Edge-Localized Modes in Tokamak Plasmas," Chapter 3 of Nonlinear Dynamics (2010) p. 59; General Atomics Report GA-A26557 (2009).

Fenstermacher, M.E., "Overview of Recent DIII-D Experimental Results," Bull. Am. Phys. Soc. **55**, 61 (2010).

Fenstermacher, M.E., Becoulet, M., Cahyna, P., Canik, J., Chang, C.S., Evans, T.E., Gohil, P., Kaye, S., Kirk, A., Liang, Y., Liang, Y., Loarte, A., Maingi, R., Schmitz, O., Suttrop, W., Wilson, H.R., "ELM Control by Resonant Magnetic Perturbations - Overview of Research by the PEP ITPA Group," Proc. 23rd IAEA Fusion Energy Conf., Daejeon Republic of Korea, October 11–16, 2010, Paper ITR/P1-30; General Atomics Report GA-A26859 (2010).

Ferron, J.R., Holcomb, C.T., Luce, T.C., Politzer, P.A., Turco, F., White, A.E., DeBoo, J.C., Doyle, E.J., Hyatt, A.W., La Haye, R.J., Murakami, M., Petrie, T.W., Petty, C.C., Rhodes, T.L., Zeng, L., "Optimization of the Safety Factor Profile for High Noninductive Current Fraction Discharges on DIII-D," Proc. 23rd IAEA Fusion Energy Conf., Daejeon Republic of Korea, October 11–16, 2010, Paper EXS/P2-06; General Atomics Report GA-A26875 (2010).

Ferron, J.R., Luce, T.C., Politzer, P.A., DeBoo, J.C., Petrie, T.W., Petty, C.C., La Haye, R.J., Smith, S.P., Holcomb, C.T., Turco, F., Murakami, M., Park, J.M., In, Y., Okabayashi, M., Doyle, E.J., Reimerdes, H., "Physics Issues for Extending the Pulse Length of High f_NI DIII-D Discharges," Bull. Am. Phys. Soc. **55**, 344 (2010).

Fisher, R.K., Pace, D.C., Garcia-Munoz, M., Boivin, R.L., Fredrickson, E.D., Heidbrink, W.W., Muscatello, C.M., Nazikian, R., Petty, C.C., Van Zeeland, M.A., Zhu, Y.B., "Measurements of Beam Ion Losses on DIII-D Due to MHD Instabilities," Proc. 37th European Physical Society Conf. on Plasma Physics, Dublin, Ireland, June 21–25, 2010, Paper P5.108; General Atomics Report GA-A26801 (2010).

Fisher, R.K., Pace, D.C., Garcia-Munoz, M., Heidbrink, W.W., Muscatello, C.M., Van Zeeland, M.A., Zhu, Y.B., "Scintillator-Based Diagnostics for Fast Ion Loss Measurements on DIII-D," Rev. Sci. Instrum. **81**, 10D307 (2010); General Atomics Report GA-A26741 (2010).

Fitzpatrick, B.W.M., Allen, S.L., Ellis, R., Tsui, C.K., Chrobak, C., Davis, J.W., Haasz, A.A., Stangeby, P.C., McLean, A.G., "Collateral Effects of Thermo-Oxidation on DIII-D In-Vessel Components and First Results from the In Situ Oxidation in DIII-D," Presented at the 19th Int. Conf. on Plasma Surface Interactions, San Diego, California, May 24–28, 2010; General Atomics Report GA-A26751 (2010).

Garofalo, A.M., Burrell, K.H., Lanctot, M.J., Reimerdes, H., Solomon, W.M., Schmitz, L., "Advances Toward QH-Mode Viability for ELM-Free Operation in ITER," Proc. 23rd IAEA Fusion Energy Conf., Daejeon Republic of Korea, October 11–16, 2010, Paper EXS/1-2; General Atomics Report GA-A26887 (2010).

Garofalo, A.M., Burrell, K.H., Osborne, T.H., Schaffer, M.J., Snyder, P.B., Solomon, W.M., Lanctot, M.J., Reimerdes, H., Rhodes, T.L., Schmitz, L., McKee, G.R., Yan, Z., "Improving Stability and Confinement of Slowly Rotating Tokamak Plasmas Using Static Nonaxisymmetric Magnetic Fields," Bull. Am. Phys. Soc. **55**, 64 (2010).

Garofalo, A.M., Solomon, W.M., Burrell, K.H., Reimerdes, H., Lanctot, M.J., Osborne, T.H., Schaffer, M.J., Schmitz, L., "Improving Stability and Confinement of Slowly Rotating Tokamak Plasmas Using Static Nonaxisymmetric Fields," submitted to Phys. Rev. Lett.; General Atomics Report GA-A26624 (2010).

Garofalo, A.M., Solomon, W.M., Park, J.-K., Burrell, K.H., DeBoo, J.C., Lanctot, M.J., McKee, G.R., Reimerdes, H., Schmitz, L., Schaffer, M.J., Snyder, P.B., "Advances Toward QH-mode Viability for ELM-stable Operation in ITER," Proc. 23rd IAEA Fusion Energy Conf., Daejeon Republic of Korea, October 11–16, 2010, Paper EXD/6-4; General Atomics Report GA-A26787 (2010).

Gohil, P., Evans, T.E., Fenstermacher, M.E., Ferron, J.R., McDonald, D.C., Osborne, T.H., Park, J.M., Schmitz, O., Scoville, J.T., Unterberg, E.A. "L-H Transition Studies on DIII-D to Determine H-Mode Access for Operational Scenarios in ITER," Proc. 23rd IAEA Fusion Energy Conf., Daejeon Republic of Korea, October 11–16, 2010, Paper EXC/2-4Ra; General Atomics Report GA-A26864 (2010).

Gohil, P., Evans, T.E., Schaffer, M.J., Fenstermacher, M.E., Schmitz, O., "L-H Transition Studies on DIII-D to Determine H-mode Access for Operational Scenarios in ITER," Bull. Am. Phys. Soc. **55**, 131 (2010).

Gohil, P., Jernigan, T.C., Osborne, T.H., Scoville, J.T., Strait, E.J., "The Torque Dependence of the H-Mode Power Threshold in Hydrogen, Deuterium, and Helium Plasmas in DIII-D," Nucl. Fusion **50** 064011 (2010); General Atomics Report GA-A26562 (2009).

Gorelov, Y.A., Lohr, J., Cengher, M., Ponce, D., "Alignment of RF Beams to the Waveguide Transmission Lines at DIII-D," Bull. Am. Phys. Soc. **55**, 345 (2010).

Greenfield, C.M., DIII-D Team, "DIII-D Contributons Toward the Scientific Basis for Sustained Burning Plasmas," Proc. 23rd IAEA Fusion Energy Conf., Daejeon Republic of Korea, October 11–16, 2010, Paper OV/1-4; General Atomics Report GA-A26869 (2010).

Grierson, B.A., Burrell, K.H., Solomon, W.M., Pablant, N.A., "Deuterium Velocity and Temperature Measurements on the DIII-D Tokamak," Rev. Sci. Instrum. **81**, 10D735 (2010); General Atomics Report GA-A26732 (2010).

Grierson, B.A., Solomon, W.M., Burrell, K.H., Pablant, N.A., "Main Ion Charge Exchange Spectroscopy for Ion Temperature and Rotation at DIII-D," Bull. Am. Phys. Soc. **55**, 133 (2010).

Groebner, R.J., Snyder, P.B., Osborne, T.H., Leonard, A.W., Rhodes, T.L., Zeng, L., Unterberg, E.A., Yan, Z., McKee, G.R., Lasnier, C.J., Boedo, J.A., Watkins, J.G., "Limits to H-mode Pedestal Pressure Gradient in DIII-D," Nucl. Fusion **50** 064002 (2010); General Atomics Report GA-A26565 (2009).

Hanson, J.M., Katsuro-Hopkins, O., Bialek, J., Reimerdes, H., In, Y., Lanctot, M.J., Navratil, G.A., Okabayashi, M., Strait, E.J., "Model-Based Feedback Control of Resistive Wall Modes Using External Coils," Proc. 37th European Physical Society Conf. on Plasma Physics, Dublin, Ireland, June 21–25, 2010, Paper P4.127; General Atomics Report GA-A26786 (2010).

Hanson, J.M., Reimerdes, H., Lanctot, M.J., Navratil, G.A., Jackson, G.L., La Haye, R.J., Sieck, P.E., Okabayashi, M., In, Y., "Feedback Control of Resistive Wall Mode Stability Using Neutral Beam Injection Heating," Bull. Am. Phys. Soc. **55**, 350 (2010).

Heidbrink, W.W., "Fast-Ion D_α Measurements of the Fast-Ion Distribution Function," Rev. Sci. Instrum. **81**, 10D727 (2010); General Atomics Report GA-A26740 (2010).

Heidbrink, W.W., Muscatello, C.M., Pace, D.C., Zhu, Y.B., Van Zeeland, M.A., Fisher, R.K., Solomon, W.M., Garcia-Munoz, M., "New Measurements of Fast-ion Transport," Bull. Am. Phys. Soc. **55**, 62 (2010).

Hillesheim, J.C., Peebles, W.A., Carter, T.A., Rhodes, T.L., Schmitz, L., DIII-D Team, "Geodesic Acoustic Mode Measurements in DIII-D," Bull. Am. Phys. Soc. **55**, 347 (2010).

Hillesheim, J.C., Peebles, W.A., Rhodes, T.L., Schmitz, L., White, A.E., Carter, T.A., "New Plasma Measurements With a Multichannel Milllimeter-wave Fluctuation Diagnostic System in the DIII-D Tokamak," Rev. Sci. Instrum. **81**, 10D907 (2010); General Atomics Report GA-A26734 (2010).

Holcomb, C.T., Ferron, J.R., Luce, T.C., DeBoo, J.C., White, A.E., Rhodes, T.L., Schmitz, L., Turco, F., "Transport Dependence on Safety Factor Profile in DIII-D Steady-state Discharges," Bull. Am. Phys. Soc. **55**, 345 (2010).

Holcomb, C.T., Ferron, J.R., White, A.E., Luce, T.C., DeBoo, J.C., Rhodes, T.L., Schmitz, L., Turco, F., "Dependence of Transport on the Safety Factor Profile in DIII-D Steady-State Scenarios," Presented at the 19th Int. Conf. on Plasma Surface Interactions, San Diego, California, May 24–28, 2010; General Atomics Report GA-A26783 (2010).

Holland, C., "Advances in Validating Gyrokinetic Turbulence Models in L- and H-mode Plasmas," Bull. Am. Phys. Soc. **55**, 191 (2010).

Hollmann, E.M., Commaux, N., Eidietis, N.W., Evans, T.E., Humphreys, D.A., James, A.N., Jernigan, T.C., Parks, P.B., Strait, E.J., Wesley, J.C., Yu, J.H., Austin, M.E., Baylor, L.R., Brooks, N.H., Izzo, V.A., Jackson, G.L., Van Zeeland, M.A., Wu, W., "Experiments in DIII-D Toward Achieving Rapid Shutdown With Runaway Electron Suppression," Phys. Plasmas **17**, 056117 (2010); General Atomics Report GA-A26593 (2009).

Hollmann, E.M., Commaux, N., Eidietis, N.W., Evans, T.E., Humphreys, D.A., James, A.N., Jernigan, T.C., Parks, P.B., Strait, E.J., Wesley, J.C., Wu, W., Yu, J.H., "Experiments on Rapid Shutdown Using Shell Pellets in DIII-D," Proc. 37th European Physical Society Conf. on Plasma Physics, Dublin, Ireland, June 21–25, 2010, Paper P4.131; General Atomics Report GA-A26788 (2010).

Hong, R.-M., Chiu, H.K., Grunloh, H.J., Kellman, A.G., Murphy, C.J., Scoville, J.T., "Development of a Neutral Beam Ion Source for Off-Axis Beam Injection and Long Pulse Operation," Proc. 26th Symp. on Fusion Technology, Porto, Portugal, September 27–October 1, 2010; General Atomics Report GA-A26835 (2010).

Hudson, B., Evans, T.E., Osborne, T.H., Petty, C.C., Snyder, P.B., Unterberg, E.A., "ELM Suppression by Resonant Magnetic Perturbation in High-Performance, Stationary Plasmas," Nucl. Fusion **50**, 045006 (2010); General Atomics Report GA-A26521 (2009).

Hudson, B., Evans, T.E., Osborne, T.H., Petty, C.C., Snyder, P.B., "ELM Suppression in DIII-D Hybrid Plasmas Using n=3 Resonant Magnetic Perturbations," Proc. 23rd IAEA Fusion Energy Conf., Daejeon Republic of Korea, October 11–16, 2010, Paper EXC/P5-02; General Atomics Report GA-A26857 (2010).

Hudson, B., Evans, T.E., Petty, C.C., Snyder, P.B., "Dependence of Resonant Magnetic Perturbation Experiments on the Plasma Shape," Nucl. Fusion **50**, 064005 (2010); General Atomics Report GA-A26566 (2010).

Humphreys, D.A., Eidietis, N.W., Evans, T.E., Hyatt, A.W., Leuer, J.A., Parks, P.B., Strait, E.J., Walker, M.L., Welander, A.S., Wesley, J.C., LoDestro, L.L., Pearlstein, L.D., Commaux, N., Jernigan, T.C., Hollmann, E.M., James, A.N., Yu, J.H., Evans, T.E., Hyatt, A.W., Leuer, J.A., Parks, P.B., Strait, E.J., Walker, M.L., Welander, A.S., Wesley, J.C., LoDestro, L.L., Pearlstein, L.D., Commaux, N., Jernigan, T.C., Hollmann, E.M., James, A.N., Yu, J.H., "ITER Current Channel Control Under Disturbances and Disruptions with Implications from DIII-D Experiments," Bull. Am. Phys. Soc. **55**, 131 (2010).

Hyatt, A.W., Ferron, J.R., Humphreys, D.A., Chamberlain, F.R., Johnson, R.D., Penaflor, B.G., Piglowski, D.A., Scoville, J.T., Walker, M.L., "Physics Operations With the DIII-D Plasma Control System," IEEE Trans. Plasma Sci. **38**, 434 (2010); General Atomics Report GA-A26495 (2009).

Hyatt, A.W., Humphreys, D.A., Luce, T.C., Taylor, P.L., "A Database Investigation of Advanced Tokamak Mode Disruptivity in DIII-D," Bull. Am. Phys. Soc. **55**, 349 (2010).

In, Y., Bogatu, I.N., Garofalo, A.M., Jackson, G.L., Kim, J.S., La Haye, R.J., Lanctot, M.J., Marrelli, L., Martin, P., Okabayashi, M., Reimerdes, H., Schaffer, M.J., Strait, E.J., "On the Roles of Direct Feedback and Error Field Correction in Stabilizing Resistive-Wall Modes," Nucl. Fusion **50**, 042001 (2010); General Atomics Report GA-A26559 (2009).

In, Y., Jackson, G.L., Okabayashi, M., Chu, M.S., Hanson, J.M., La Haye, R.J., Liu, Y.Q., Marrelli, L., Martin, P., Piovesan, P., Piron, L., Reimerdes, H., Soppelsa, A., Strait, E.J., "Error Field Correction in Unstable Resistive Wall Mode (RWM) Regime," Proc. 23rd IAEA Fusion Energy Conf., Daejeon Republic of Korea, October 11–16, 2010, Paper EXS/P5-07; General Atomics Report GA-A26863 (2010).

In, Y., Svidzinski, V., Kim, J.S., Okabayashi, M., Jackson, G.L., La Haye, R.J., Strait, E.J., Hanson, J.M., Lanctot, M.J., Reimerdes, H., Liu, Y.Q., "Magnetic Feedback-controlled Error-field Correction and RWM Stabilization," Bull. Am. Phys. Soc. **55**, 349 (2010).

Izzo, V.A., James, A.N., Hollmann, E.M., Yu, J.H., Humphreys, D.A., Wesley, J.C., Lao, L.L., Parks, P.B., Sieck, P.E., Whyte, D.G., Olynyk, G.J., Granetz, R.S., "Runaway Electron Confinement Modeling for DIII-D, Alcator C-Mod, and ITER," Proc. 23rd IAEA Fusion Energy Conf., Daejeon Republic of Korea, October 11–16, 2010, Paper THS/9-2; General Atomics Report GA-A26880 (2010).

Izzo, V.A., James, A.N., Yu, J.H., Hollmann, E.M., Parks, P.B., Lao, L.L., Wesley, J.C., Whyte, D.G., Olynyk, G., Granetz, R.S., "Runaway Electron Confinement Studies with NIMROD," Bull. Am. Phys. Soc. **55**, 348 (2010).

Jackson, G.L., Austin, M.E., deGrassie, J.S., Hyatt, A.W., Lohr, J., Luce, T.C., Prater, R., West, W.P., "Plasma Initiation and Startup Studies in the DIII-D Tokamak with Second Harmonic EC Assist," Fusion Sci. Technol. **57**, 27 (2010); General Atomoics Report GA-A26350 (2009).

Jackson, G.L., Humphreys, D.A., Casper, T.A., Hyatt, A.W., Leuer, J.A., Lohr, J., Luce, T.C., Van Zeeland, M.A., Yu, J.H., "DIII-D Experimental Simulation of ITER Scenario Access and Termination," Proc. 23rd IAEA Fusion Energy Conf., Daejeon Republic of Korea, October 11–16, 2010, Paper EXS/P2-11; General Atomics Report GA-A26858 (2010).

Jackson, G.L., Politzer, P.A., Humphreys, D.A., Casper, T.A., Hyatt, A.W., Leuer, J.A., Lohr, J., Luce, T.C., Van Zeeland, M.A., Yu, J.H., "Understanding and Predicting the Dynamics of Tokamak Discharges During Startup and Rampdown," Phys. Plasmas **17**, 056116 (2010); General Atomics Report GA-A26587 (2009).

James, A.N., Hollmann, E.M., Eidietis, N.W., Humphreys, D.A., Parks, P.B., Strait, E.J., Tynan, G.R., Wesley, J.C., "Thermal Quench Runaway Electron Generation and Post Current Quench Deconfinement Characteristics," Proc. 37th European Physical Society Conf. on Plasma Physics, Dublin, Ireland, June 21–25, 2010, Paper P2.150; General Atomics Report GA-A26791 (2010).

James, A.N., Hollmann, E.M., Izzo, V.A., Tynan, G.R., Humphreys, D.A., Parks, P.B., Strait, E.J., Wesley, J.C., "Generation and Stability of Runaway Electrons During Rapid-Shutdown in DIII-D," Bull. Am. Phys. Soc. **55**, 131 (2010).

Jernigan, T.C., Commaux, N., Baylor, L.R., Eidietis, N.W., Evans, T.E., Humphreys, D.A., Izzo, V.A., Parks, P.B., Wesley, J.C., Hollmann, E.M., James, A.N., Yu, J.H., “Rapid Shutdown Methods for Runaway Electron Suppression by Large Shattered Pellets and Massive Gas Injection in DIII-D,” Bull. Am. Phys. Soc. **55**, 131 (2010).

King, J.D., Makowski, M.A., Holcomb, C.T., Allen, S.L., Geer, R., Meyer, W.H., Hill, D.N., Pham, D., Morse, E.C., “A Digital Lock-in Upgrade of the Motional Stark Effect Diagnostic on DIII-D,” Rev. Sci. Instrum. **81**, 10D739 (2010); General Atomics Report GA-A26736 (2010).

King, J.D., Makowski, M.A., Holcomb, C.T., Allen, S.L., Hill, D.N., Meyer, W.H., Geer, R., Van Zeeland, M.A., Rhodes, T.L., Morse, E.C., “Measurement of Tearing Mode Structure and Evolution Through Fluctuation Analysis of the Motional Stark Effect Diagnostic Structure and Evolution Through Fluctuation Analysis of the Motional Stark Effect Diagnostic,” Bull. Am. Phys. Soc. **55**, 350 (2010).

Kinsey, J.E., Staebler, G.M., Candy, J., Waltz, R.E., “ITER Predictions Using the Gyro Verified and Experimentally Validated TGLF Transport Model,” Proc. 23rd IAEA Fusion Energy Conf., Daejeon Republic of Korea, October 11–16, 2010, Paper THC/3-03; General Atomics Report GA-A26874 (2010).

Kornbluth, M., Humphreys, D.A., Hyatt, A.W., Turnbull, A.D., Welander, A.S., Commaux, N., Jernigan, T.C., Hollmann, E.M., James, A.N., Yu, J.H., “Runaway Electrons in the Presence of MHD Instabilities in DIII-D,” Bull. Am. Phys. Soc. **55**, 172 (2010).

Kramer, G.J., Budny, R.V., Ellis, R., Heidbrink, W.W., Kurki-Suonio, T., Nazikian, R., Salmi, A., Schaffer, M.J., Shinohara, K., Snipes, J.A., Spong, D.A., Koskela, T., Van Zeeland, M.A. “Fast Ion Effects During Test Blanket Module Simulation Experiments in DIII-D,” Proc. 23rd IAEA Fusion Energy Conf., Daejeon Republic of Korea, October 11–16, 2010, Paper EXW/P7-10; General Atomics Report GA-A26892 (2010).

Kramer, G.J., Budny, R.V., Nazikian, R., Heidbrink, W.W., Kurki-Suonio, T., Salmi, A., Schaffer, M.J., Van Zeeland, M.A., Shinohara, K., Snipes, J.A., Spong, D.A., “Fast Ion Effects During Test Blanket Module Simulation Experiments in DIII-D,” Bull. Am. Phys. Soc. **55**, 375 (2010).

La Haye, R.J., Brennan, D.P., Buttery, R.J., Gerhardt, S.P., “slands in the Stream - The Effect of Plasma Flow on Tearing Stability,” Phys. Plasmas **17**, 056110 (2010); General Atomics Report GA-A26551 (2009).

La Haye, R.J., Buttery, R.J.,l Gerhardt, S.P., Sabbagh, S.A., Brennan, D.P., “Comparison of Aspect Ratio Effects on Neoclassical Tearing Modes Between DIII-D and NSTX,” Bull. Am. Phys. Soc. **55**, 198 (2010).

La Haye, R.J., Petty, C.C., Politzer, P.A., DIII-D Team, “Influence of Plasma Flow Shear on Tearing in DIII-D,” Proc. 37th European Physical Society Conf. on Plasma Physics, Dublin, Ireland, June 21–25, 2010, Paper P4.138; General Atomics Report GA-A26793 (2010).

Lanctot, M.J., “Measurement and Modeling of 3D Equilibria in DIII-D,” Bull. Am. Phys. Soc. **55**, 23 (2010).

Lanctot, M.J., Reimerdes, H., Garofalo, A.M., Chu, M.S., Liu, Y.Q., Strait, E.J., Jackson, G.L., La Haye, R.J., Okabayashi, M., Osborne, T.H., Schaffer, M.J., “Validation of the Linear Ideal MHD Model of Three-Dimensional Tokamak Equilibria,” Phys. Plasmas **17**, 030701 (2010); General Atomics Report GA-A26488 (2009).

Lao, L.L., Chu, M.S., Collier, A., Evans, T.E., Schaffer, M.J., Strait, E.J., Ren, Q., Srinivasan, R., Liu, Y., “Effects of 3D Magnetic Perturbations on DIII-D Reconstructed Equilibria,” Bull. Am. Phys. Soc. **55**, 129 (2010).

Lasnier, C.J., Makowski, M.A., Boedo, J.A., Brooks, N.H., Hill, D.N., Leonard, A.W., Watkins, J.G., "Scaling of Divertor Heat Flux Profile Widths in DIII-D," Proc. 23rd IAEA Fusion Energy Conf., Daejeon Republic of Korea, October 11–16, 2010, Paper EXD/P3-20; General Atomics Report GA-A26867 (2010).

Leonard, A.W., Mahdavi, M.A., Petrie, T.W., Lasnier, C.J., Stangeby, P.C., "Divertor Heat Flux Control Scaled to High Power," Bull. Am. Phys. Soc. **55**, 132 (2010).

Leuer, J.A., Cunningham, G., Mueller, D., Brooks, N.H., Eidietis, N.W., Humphreys, D.A., Hyatt, A.W., Jackson, G.L., Lohr, J., Politzer, P.A., Pinsker, R.I., Prater, R., Taylor, P.L., Walker, M.L., Budny, R.V., Gates, D., Nagy, A., Hahn, S.-H., Oh, Y.-K., Yoon, S.-W., Yu, J.H., Murakami, M., Park, J.M., Sontag, A.C., "Solenoid-Free Startup Experiments in DIII-D," Proc. 23rd IAEA Fusion Energy Conf., Daejeon Republic of Korea, October 11–16, 2010, Paper EXC/P2-03; General Atomics Report GA-A26854 (2010).

Leuer, J.A., Eidietis, N.W., Ferron, J.R., Humphreys, D.A., Hyatt, A.W., Jackson, G.L., Johnson, R.D., Penaflor, B.G., Piglowski, D.A., Walker, M.L., Welander, A.S., Yoon, S.W., Hahn, S.H., Oh, Y.K., Xiao, B.J., Wang, H.Z., Yuan, Q.P., Mueller, D., "Plasma Startup Design of Fully Superconducting Tokamaks EAST and KSTAR With Implications for ITER," IEEE Trans. Plasma Sci. **38**, 333 (2010); General Atomics Report GA-A26492 (2009).

Leuer, J.A., Xiao, B.J., Humphreys, D.A., Walker, M.L., Hyatt, A.W., Jackson, G.L., Mueller, D., Penaflor, B.G., Piglowski, D.A., Johnson, R.D., Welander, A.S., Yuan, Q.P., Wang, H.Z., Luo, J.R., East Team, "Tokamak Startup Modeling and Design for EAST First Plasma Campaign," Fusion Sci. Technol. **57**, 48 (2010); General Atomics Report GA-A26328 (2009).

Logan, N.C., Strait, E.J., Reimerdes, H., "Measurement of the Electromagnetic Torque in Rotating DIII-D Plasmas," Plasma Phys. Control. Fusion **52** 045013 (2010); General Atomics Report GA-A26456 (2009).

Lohr, J., Cengher, M., Doane, J.L., Gorelov, Y.A., Moeller, C.P., Ponce, D., Prater, R., "The Multiple Gyrotron System on the DIII-D Tokamak," J. Infrared, Millimeter, and Terahertz Waves **32**, 253 (2010); General Atomics Report GA-A26800 (2010).

Lohr, J., Cengher, M., Ponce, D., "Progress Report on the DIII-D ECH System," Bull. Am. Phys. Soc. **55**, 344 (2010).

Luce, T.C., "Role of ECH and ECCD in High-Performance Steady-State Scenarios," Proc. 16th Joint Workshop on Electron Cyclotron Emission and Electron Cyclotron Resonance Heating, Sanya, PR China, April 12–15, 2010 (World Scientific Publishing Co. Pte. Ltd., Singapore, Japan, 2010) p. 7; General Atomics Report GA-A26820 (2010).

Luce, T.C., Challis, C.D., Ide, S., Isayama, A., Joffrin, E., Kamada, Y., Politzer, P.A., Schweinzer, J., Sips, A.C.C., Stober, J., Giruzzi, G., Kessel, C.E., Murakami, M., Na, Y.-S., Park, J.M., Polevoi, A.R., Budny, R.V., Citrin, J., Garcia, J., Hayashi, N., Hobirk, J., Hudson, B.F., Imbeaux, F., McDonald, D.C., Parail, V.V., Petrie, T.W., Petty, C.C., Suzuki, T., Wade, M.R., "Development of Advanced Inductive Scenarios for ITER," Proc. 23rd IAEA Fusion Energy Conf., Daejeon Republic of Korea, October 11–16, 2010, Paper EXC/P3-05; General Atomics Report GA-A26898 (2010).

Luce, T.C., Politzer, P.A., Chalis, C.D., Joffrin, E., Solomon, W.M., "Confinement in Advanced Inductive Plasmas — Gyroradius and Rotation," Bull. Am. Phys. Soc. **55**, 61 (2010).

Maggi, C.F., Groebner, R.J., Angioni, C., Hein, T., Horton, L.D., Konz, C., Leonard, A.W., Petty, C.C., Sips, A.C.C., Snyder, P.B., Candy, J., Waltz, R.E., ASDEX Upgrade Team, DIII-D Team, "Pedestal and Core Confinement of Hybrid Scenario in ASDEX Upgrade and DIII-D," Nucl. Fusion **50** 025023 (2010); General Atomics Report GA-A26416 (2009).

Makowski, M.A., Lasnier, C.J., Porter, G.D., Hill, D.N., Leonard, A.W., Watkins, J.G., "Comparison of Measured Heat Flux Profiles with UEDGE Simulations of H-mode Discharges in DIII-D," Bull. Am. Phys. Soc. **55**, 132 (2010).

McKee, G.R., Yan, Z., Fonck, R.J., Uzun-Kaymak, I.U., Rhodes, T.L., Schmitz, L., Holland, C., White, A.E., "Variation of Turbulence and Transport with the T_e/T_i Ratio in H-mode Plasmas," Bull. Am. Phys. Soc. **55**, 63 (2010).

Mordijck, S., Moyer, R.A., Doyle, E.J., Zeng, L., Schmitz, L., Unterberg, E.A., Commaux, N., Gentle, K.W., Reimerdes, H., "Modeling Experimental Changes in Particle Transport From Resonant Magnetic Perturbations (RMPs) Using SOLPS5," Bull. Am. Phys. Soc. **55**, 129 (2010).

Moyer, R.A., Mordijck, S., Rost, J.C., McKee, G.R., Rhodes, T.L., Doyle, E.J., Zeng, L., Schmitz, L., Evans, T.E., "Impact of Resonant Magnetic Perturbations (RMPs) on Turbulence Drive, Damping, and Transport," Bull. Am. Phys. Soc. **55**, 63 (2010).

Mueller, S.H., "Evidence of an Edge Momentum Source in DIII-D H-mode Plasmas and Role of the Reynolds Stress for Intrinsic Rotation," Bull. Am. Phys. Soc. **55**, 238 (2010).

Munoz Burgos, J.M., Schmitz, O., Unterberg, E.A., Loch, S.D., Balance, C.P., "Time Dependent Solution for the He I Line Ratio Electron Temperature and Density Diagnostic in TEXTOR and DIII-D," Bull. Am. Phys. Soc. **55**, 134 (2010).

Murakami, M., Park, J.M., Giruzzi, G., Garcia, J., Bonoli, P., Budny, R.V., Doyle, E.J., Fukuyama, A., Hayashi, N., Honda, M., Hubbard, A., Ide, S., Imbeaux, F., Jaeger, E.F., Luce, T.C., Na, Y.-S., Oikawa, T., Osborne, T.H., Parail, V., Polevoi, A., Prater, R., Sips, A.C.C., Snipes, J.A., St John, H.E., Snyder, P.B., Voitsekhovitch, I., "Integrated Modeling of Steady-State Scenarios and Heating and Current Drive Mixes for ITER," Proc. 23rd IAEA Fusion Energy Conf., Daejeon Republic of Korea, October 11–16, 2010, Paper ITR/P1-35; General Atomics Report GA-A26896 (2010).

Muscatello, C.M., Heidbrink, W.W., Pace, D.C., Zhu, Y., Kolesnichenko, Ya.I., Lutsenko V.V., Yakovenko, Yu.V., Van Zeeland, M.A., Fisher, R.K., Tobias, B.J., "Sawtooth-induced Fast-ion Transport in the DIII-D Tokamak: Observations and Comparison to Theory," Bull. Am. Phys. Soc. **55**, 348 (2010).

Namasondhi, P., Holland, C., Prater, R., DeBoo, J.C., Candy, J., Staebler, G.M., White, A.E., "Quantifying Statistical Uncertainty in Tokamak Transport Modeling," Bull. Am. Phys. Soc. **55**, 172 (2010).

Nazikian, R., "On the Identification of Interferometer Signals in High-k Scattering Data," Bull. Am. Phys. Soc. **55**, 347 (2010).

Okabayashi, M., "Off-axis Fishbone-like Instability and Excitation of the Resistive Wall Mode (RWM) in JT-60U and DIII-D Devices," Bull. Am. Phys. Soc. **55**, 290 (2010).

Orlov, D.M., Evans, T.E., Moyer, R.A., Schaffer, M.J., Schmitz, O., "Numerical Analysis of Resonant Magnetic Perturbations for ELM Control in ITER," Proc. 37th European Physical Society Conf. on Plasma Physics, Dublin, Ireland, June 21–25, 2010, Paper P2.150; General Atomics Report GA-A26789 (2010).

Orlov, D.M., Moyer, R.A., Evans, T.E., Schaffer, M.J., Schmitz, O., "Numerical Analysis of Resonant Magnetic Perturbations ELM Control in ITER," Bull. Am. Phys. Soc. **55**, 376 (2010).

Osborne, T.H., Horton, L.D., Frassinetti, L., Groebner, R.J., Leonard, A.W., Lomas, P., Nunes, I., Saarelma, S., Scannell, R., Snyder, P.B., Zarzoso, D., Balboa, I., Bray, B.D., Flanagan, J., Giroud, C., Giovannozzi, R.E., Kempenaars, M.A.H., Loarte, A., de la Luna, E. Maddison, G., Maggi, C., McDonald, D.C., McKee, G.R., Pasqualotto, R., Saibene, G., Sartori, R., Solano, E.R., Yan, Z., Zabeo, L. DIII-D Team, JET-EFDA Team, "Scaling of H-mode Pedestal and ELM Characteristics in the JET and DIII-D Tokamaks," Proc. 23rd IAEA Fusion Energy Conf., Daejeon Republic of Korea, October 11–16, 2010, Paper EXC/2-1; General Atomics Report GA-A26911 (2010).

Pablant, N.A., Burrell, K.H., Groebner, R.J., Holcomb, C.T., Kaplan, D.H., "Measurements of the Internal Magnetic Field Using the B-Stark Motional Stark Effect Diagnostic on DIII-D," Rev. Sci. Instrum. **81**, 10D729 (2010); General Atomics Report GA-A26744 (2010).

Pablant, N.A., Grierson, B.A., Burrell, K.H., Groebner, R.J., Kaplan, D.H., Holcomb, C.T., "Improved Spectral Fitting Models for the B-Stark Diagnostic at DIII-D," Bull. Am. Phys. Soc. **55**, 134 (2010).

Pace, D.C., Fisher, R.K., Garcia-Munoz, M., Darrow, D.S., Heidbrink, W.W., Muscatello, C.M., Nazikian, R., Van Zeeland, M.A., Zhu, Y.B., "Modeling the Response of a Fast Ion Loss Detector Using Orbit Tracing Techniques in a Neutral Beam Prompt Loss Study on the DIII-D Tokamak," Rev. Sci. Instrum. **81**, 10D305 (2010); General Atomics Report GA-A26731 (2010).

Pace, D.C., Fisher, R.K., Garcia-Munoz, M., Heidbrink, W.W., Lin, Z., McKee, G.R., Murakami, M., Muscatello, C.M., Nazikian, R., Park, J.M., Petty, C.C., Rhodes, T.L., Van Zeeland, M.A., Waltz, R.E., White, R.B., Yu, J.H., Zhang, W., Zhu, Y.B., "Transport of Energetic Ions Due to Microturbulence, Sawteeth, and Alfven Eigenmodes," Proc. 23rd IAEA Fusion Energy Conf., Daejeon Republic of Korea, October 11–16, 2010, Paper EXW/4-2; General Atomics Report GA-A26883 (2010).

Pace, D.C., Heidbrink, W.W., Muscatello, C.M., Zhu, Y.B., Fisher, R.K., Van Zeeland, M.A., Garcia-Munoz, M., "Pitch and Energy Resolved Fast Ion Losses in the DIII-D Tokamak," Bull. Am. Phys. Soc. **55**, 348 (2010).

Park, J.M., Doyle, E.J., Ferron, J.R., Holcomb, C.T., Jackson, G.L., Lao, L.L., Luce, T.C., Owen, L.W., Murakami, M., Osborne, T.H., Politzer, P.A., Prater, R., Snyder, P.B., "Experiment and Modeling of ITER Demonstration Discharges in the DIII-D Tokamak," Proc. 23rd IAEA Fusion Energy Conf., Daejeon Republic of Korea, October 11–16, 2010, Paper EXC/P2-05; General Atomics Report GA-A26899 (2010).

Payne, J., McCune, D., Prater, R., "Potential Application of a Graphical Processing Unit to Parallel Computations in the NUBEAM Code," Bull. Am. Phys. Soc. **55**, 173 (2010).

Petrie, T.W., Brooks, N.H., Evans, T.E., Ferron, J.R., Luce, T.C., Politzer, P.A., Schaffer, M.J., Snyder, P.B., Fenstermacher, M.E., Lasnier, C.J., Rensink, M.E., Hudson, B., Watkins, J.G., Mordijck, S., "Compatibility of RMP ELM Suppression with Radiating Divertor in DIII-D," Bull. Am. Phys. Soc. **55**, 128 (2010).

Petrie, T.W., Evans, T.E., Brooks, N.H., Fenstermacher, M.E., Ferron, J.R., Hyatt, A.W., Luce, T.C., Lasnier, C.J., Mordijck, S., Politzer, P.A., Rensink, M.E., Schaffer, M.J., Snyder, P.B., Watkins, J.G., "Results from Radiating Divertor Experiments With RMP ELM Suppression," Proc. 23rd IAEA Fusion Energy Conf., Daejeon Republic of Korea, October 11–16, 2010, Paper EXD/P3-27; General Atomics Report GA-A26851 (2010).

Petty, C.C., DeBoo, J.C., Ferron, J.R., La Haye, R.J., Luce, T.C., Politzer, P.A., Prater, R., Wade, M.R., McKee, G.R., Vermare, L., Murakami, M., Doyle, E.J., "Dependence of DIII-D Hybrid Scenario on Dimensionless Parameters," Bull. Am. Phys. Soc. **55**, 344 (2010).

Petty, C.C., Evans, T.E., DeBoo, J.C., La Haye, R.J., Politzer, P.A., Allen, S.L., Doyle, E.J., Fenstermacher, M.E., Ferron, J.R., Hyatt, A.W., Jayakumar, R.J., Moyer, R.A., Osborne, T.H., "ELM Suppression in Hybrid Discharges Using n=3 Magnetic Perturbations on DIII-D," Nucl. Fusion **50**, 022002 (2010); General Atomics Report GA-A26282 (2009).

Petty, C.C., Lohr, J., Luce, T.C., Prater, R., Harvey, R.W., Smirnov, A.P., Austin, M.E., Makowski, M.A., "Effect of Particle Transport on the Measured Electron Cyclotron Current Drive Profile," Fusion Sci. Technol. **57**, 10 (2010); General Atomics Report GA-A26305 (2009).

Pinsker, R.I., Luce, T.C., Politzer, P.A., Porkolab, M., Baity, F.W., Gould, R.H., Hanson, J.M., Murakami, M., Ryan, P.M., Hosea, J.C., Nagy, A., Wilson, J.R., Maggiora, R., Milanesio, D., "High-Power Fast Wave Coupling Experiments in Advanced Regimes in DIII-D," Bull. Am. Phys. Soc. **55**, 62 (2010).

Pinsker, R.I., Mayoral, M.-L., Bobkov, V., Goniche, M., Hosea, J.C., Wukitch, S.J., Moriyama, S., Baity, F.W., Colas, L., Durodie, F., Ekedahl, A., Hanson, G.R., Jacquet, P., Lamalle, P., Monakhov, I., Murakami, M., Nagy, A., Nightingale, M., Noterdaeme, J.-M., Ongena, J., Porkolab, M., Ryan, P.M., Vrancken, M., Wilson, J.R., ASDEX Upgrade Team, "Experiments on Gas Puffing to Enhance ICRF Antenna Coupling," Proc. 37th European Physical Society Conf. on Plasma Physics, Dublin, Ireland, June 21–25, 2010, Paper O4.124; General Atomics Report GA-A26782 (2010).

Politzer, P.A., Challis, C.D., Joffrin, E., Luce, T.C., Beurskens, M., Buratti, P., Crisanti, F., DeBoo, J.C., Ferron, J.R., Giroud, C., Hobirk, J., Holcomb, C.T., Hyatt, A.W., Imbeaux, F., Jayakumar, R.J., Jenkins, I., Kinsey, J.E., La Haye, R.J., McDonald, D.C., Petty, C.C., Turco, F., Wade, M.R., "Understanding Confinement in Advanced Inductive Scenario Plasmas - Dependence on Gyroradius and Rotation," Proc. 23rd IAEA Fusion Energy Conf., Daejeon Republic of Korea, October 11–16, 2010, Paper EXC/P2-06; General Atomics Report GA-A26888 (2010).

Politzer, P.A., Jackson, G.L., Humphreys, D.A., Casper, T.A., Hyatt, A.W., Leuer, J.A., Lohr, J., Luce, T.C., Van Zeeland, M.A., Yu, J.H., "Experimental Simulation of ITER Discharge Rampdown in DIII-D," Proc. 37th European Physical Society Conf. on Plasma Physics, Dublin, Ireland, June 21–25, 2010, Paper P2.188; General Atomics Report GA-A26790 (2010).

Politzer, P.A., Jackson, G.L., Humphreys, D.A., Luce, T.C., Hyatt, A.W., Leuer, J.A., "Experimental Simulation of ITER Rampdown in DIII-D," Nucl. Fusion **50**, 035011 (2010); General Atomics Report GA-A26537 (2009).

Ponce-Marquez, D.M., Bray, B.D., Deterly, T.M., Liu, C., Eldon, D., "Thomson Scattering Diagnostic Upgrade on DIII-D," Rev. Sci. Instrum. **81**, 10D525 (2010); General Atomics Report GA-A26735 (2010).

Prater, R., deGrassie, J.S., Gohil, P., Osborne, T.H., Doyle, E.J., Zeng, L., "Confinement and Pedestal Characteristics in H-Mode With ECH Heating," Proc. 16th Joint Workshop on Electron Cyclotron Emission and Electron Cyclotron Resonance Heating, Sanya, PR China, April 12–15, 2010 (World Scientific Publishing Co. Pte. Ltd., Singapore, Japan, 2010) p. 143; General Atomics Report GA-A26763 (2010).

Prater, R., Groebner, R.J., Lohr, J., Politzer, P.A., Osborne, T.H., Austin, M.E., Doyle, E.J., Zeng, L., Harvey, R.W., White, A.E., "Some New Results From Electron Cyclotron Heating Experiments on DIII-D," Bull. Am. Phys. Soc. **55**, 344 (2010).

Reimerdes, H., Berkery, J.W., Lanctot, M.J., Chu, M.S., Garofalo, A.M., Hanson, J.M., In, Y., La Haye, R.J., Liu, Y.Q., Matsunaga, G., Navratil, G.A., Okabayashi, M., Sabbagh, S.A., Strait, E.J., "Non-Ideal Modifications of Three-Dimensional Equilibrium and Resistive Wall Mode Stability Models in DIII-D," Proc. 23rd IAEA Fusion Energy Conf., Daejeon, Republic of Korea, October 11–16, 2010, Paper EXS/5-4; General Atomics Report GA-A26862 (2010).

Rhodes, T.L., Holland, C.H., Smith, S.P., White, A.E., Burrell, K.H., Candy, J., DeBoo, J.C., Doyle, E.J., Hillesheim, J.C., Kinsey, J.E., McKee, G.R., Mikkelsen, D., Peebles, W.A., Petty, C.C., Prater, R., Parker, S., Chen, Y., Schmitz, L., Staebler, G.M., Waltz, R.E., Wang, G., Yan, Z., Zeng, L., "Validation Studies of Gyrokinetic Turbulence Simulations Via Multi-Sccale/Multi-Field Turbulence Measurements on the DIII-D Tokamak," Proc. 23rd IAEA Fusion Energy Conf., Daejeon, Republic of Korea, October 11–16, 2010, Paper EXC/7-2; General Atomics Report GA-A26889 (2010).

Rhodes, T.L., Peebles, W.A., Schmitz, L., Doyle, E.J., Hillesheim, J.C., Zeng, L., Wang, G., Holland, C.H., Tynan, G.R., White, A.E., McKee, G.R., Yan, Z., DeBoo, J.C., Burrell, K.H., Petty, C.C., Mikkelsen, D., "Multi-scale/Multi-field Turbulence Measurements to Rigorously Test Gyrokinetic Simulation Predictions on DIII-D," Bull. Am. Phys. Soc. **55**, 346 (2010).

Rost, J.C., Porkolab, M., Dorris, J.R., Burrell, K.H., "Study of Poloidal Variation and Radial Wavenumber of Edge Turbulence in L- and H-mode with PCI on DIII-D," Bull. Am. Phys. Soc. **55**, 347 (2010).

Rudakov, D.L., Boedo, J.A., Lasnier, C.J., Pitts, R.A., Stangeby, P.C., Leonard, A.W., McLean, A.G., Moyer, R.A., Tynan, G.R., Watkins, J.G., Wong, C.P.C., Yu, J.H., "Tests of ITER Limiter L-mode SOL Power Width Scaling in DIII-D," Proc. 37th European Physical Society Conf. on Plasma Physics, Dublin, Ireland, June 21–25, 2010, Paper P2.155; General Atomics Report GA-A26796 (2010).

Sanchez, A., Pinsker, R.I., Baity, F.W., Eguizabal, A., Fredd, E., Greenough, N., Nagy, A., "Improved RF Phase and Amplitude Detection for ICRF Heating Experiments," Bull. Am. Phys. Soc. **55**, 173 (2010).

Schaffer, M.J., "ITER Test Blanket Module Error Field Simulation Experiments," Bull. Am. Phys. Soc. **55**, 23 (2010).

Schaffer, M.J., Snipes, J.A., Gohil, P., de Vries, P., Evans, T.E., Fenstermacher, M.E., Gao, X., Garofalo, A.M., Gates, D.A., Greenfield, C.M., Heidbrink, W.W., Kramer, G.J., La Haye, R.J., Liu, S., Loarte, A., Nave, M.F.F., Osborne, T.H., Oyama, N., Park, J.-K., Ramasubramanian, N., Reimerdes, H., Saibene, G., Salmi, A., Shinohara, K., Spong, D.A., Solomon, W.M., Tala, T., Boedo, J.A., Chuyanov, V., Doyle, E.J., Jakubowski, M., Jhang, H., Nazikian, R.M., Pustovitov, V.D., Schmitz, O., Srinivasan, R., Taylor, T.S., Wade, M.R., You, K.-I., Zeng, L., DIII-D Team, "ITER Test Blanket Module Error Field Simulation Experiments at DIII-D," Proc. 23rd IAEA Fusion Energy Conf., Daejeon, Republic of Korea, October 11–16, 2010, Paper ITR/1-3; General Atomics Report GA-A26868 (2010).

Schissel, D.P, Abla, G., Fredian, T., Greenwald, M., Penaflor, B.G., Stillerman, J., Walker, M.L., and Ciarlette, D.J., "An Investigation of Secure Remote Instrument Control," Proc. 7th IAEA Tech. Mtg. on Control, Data Acquisition, and Remote Participation in Fusion Research, Aix-en-Provence, France, June 15–19, 2009 in Fusion Engin. Design **85**, 608 (2010); General Atomics Report GA-A26484 (2009).

Schissel, D.P., Abla, G., Flanagan, S., Kim, L., and Lee, X., "The Between-Pulse Data Analysis Infrastructure at the DIII-D National Fusion Facility," Fusion Sci. Technol. **58**, 720 (2010); General Atomics Report GA-A26703 (2010).

Schmitz, L., Holland, C., Rhodes, T.L., Wang, G., Hillesheim, J.C., Zeng, L., Peebles, W.A., Doyle, E.J., McKee, G.R., White, A.E., Burrell, K.H., DeBoo, J.C., deGrassie, J.S., Petty, C.C., "Electron Thermal Transport and Multi-scale Turbulence in Low Collisionality H-mode Plasmas," Bull. Am. Phys. Soc. **55**, 346 (2010).

Schmitz, L., Holland, C., Rhodes, T.L., Wang, G., Zeng, L., White, A.E., Hillesheim, J.C., Peebles, W.A., Smith, S.P., Prater, R., McKee, G.R., Solomon, W.M., Burrell, K.H., Doyle, E.J., DeBoo, J.C., Austin, M.E., deGrassie, J.S., Petty, C.C., "Reduced Electron Thermal Transport in Low Collisionality H-mode Plasmas in DIII-D and the Importance of Small-Scale Turbulence," Proc. 23rd IAEA Fusion Energy Conf., Daejeon, Republic of Korea, October 11–16, 2010, Paper EXC/P7-01; General Atomics Report GA-A26866 (2010).

Shafer, M.W., Battaglia, D.J., Unterberg, E.A., Canik, J., Hillis, D.L., Maingi, R., Evans, T.E., "2D Soft X-ray System for Imaging Magnetic Topology in the Pedestal Region on DIII-D," Bull. Am. Phys. Soc. **55**, 131 (2010).

Shafer, M.W., Battaglia, D.J., Unterberg, E.A., Evans, T.E., Hillis, D.L., Maingi, R. "2D Soft X-ray System on DIII-D for Imaging the Magnetic Topology in the Pedestal Region," Rev. Sci. Instrum. **81**, 10E534 (2010); General Atomics Report GA-A26749 (2010).

Sieck, P.E., Baylor, L.R., Evans, T.E., Leonard, A.W., Osborne, T.H., Strait, E.J., "Improving Diamagnetic Flux Temporal Resolution to Measure ELM Energy Loss," Bull. Am. Phys. Soc. **55**, 130 (2010).

Smith, S.P., Groebner, R.J., Staebler, G.M., Ferron, J.R., "Turbulence Studies at the Top of the Pedestal," Bull. Am. Phys. Soc. **55**, 130 (2010).

Snipes, J.A., Schaffer, M.J., Gohil, P., de Vries, P., Fenstermacher, M.E., Evans, T.E., Gao, X., Garofalo, A.M. Gates, D.A., Greenfield, C.M., Heidbrink, W.W., Kramer, G.J., Liu, S., Loarte, A., Nave, M.F.F., Oyama, N., Park, J-K., Ramasbramanian, N., Reimerdes, H., Saibene, G., Salmi, A., Shinohara, K., Spong, D.A., Solomon, W.M., Tala, T., Boedo, J.A., Budny, R., Chuyanov, V., Doyle, E.J., Jakubowski, M., Jhang, H., Nazikian R.M., Pustovitov, V.D., Schmitz, O., Osborne, T.H., Srinivasan, R., Taylor, T.S., Wade, M.R., You, K-I., DIII-D Team, "Results of ITER Test Blanket Module Mockup Experiments on DIII-D," Proc. 37th European Physical Society Conf. on Plasma Physics, Dublin, Ireland, June 21–25, 2010; General Atomics Report GA-A26807 (2010).

Snyder, P.B., Groebner, R.J., Hughes, J.W., Osborne, T.H., Beurskens, M.N., Leonard, A.W., Wilson, H.R., "A First Principles Predictive Model of the Pedestal Height and Width — Development, Testing, and ITER Optimizastion With the EPED Model," Proc. 23rd IAEA Fusion Energy Conf., Daejeon, Republic of Korea, October 11–16, 2010, Paper THS/1-1; General Atomics Report GA-A26891 (2010).

Snyder, P.B., Groebner, R.J., Leonard, A.W., Osborne, T.H., Hughes, J.W., Wilson, H.R., "Developing and Testing the EPED Pedestal Model," Bull. Am. Phys. Soc. **55**, 130 (2010).

Solomon, W.M., Burrell, K.H., deGrassie, J.S., Evans, T.E., Garofalo, A.M., Jackson, G.L., Osborne, T.H., Reimerdes, H., Lasnier, C.J., Makowski, M.A., Doyle, E.J., "ELM Pacing Using Modulated Magnetic Field Perturbations," Bull. Am. Phys. Soc. **55**, 130 (2010).

Solomon, W.M., Burrell, K.H., Garofalo, A.M., Kaye, S.M., Bell, R.E., Cole, A.J., deGrassie, J.S., Hahm, T.S., Jackson, G.L., Lanctot, M.J., Petty, C.C., Reimerdes, H., Sabbagh, S.A., Strait, E.J., Tala, T., Waltz, R.E., "Mechanisms for Generating Toroidal Rotation in Tokamaks Without External Momentum Input," Phys. Plasmas **17**, 056108 (2010); General Atomics Report GA-A26591 (2009).

Solomon, W.M., Burrell, K.H., Lanctot, M.J., Reimerdes, H., Solomon, W.M., Schmitz, L., "Characterization of the Effective Torque Profile Associated With Driving Intrinsic Rotation on DIII-D," Proc. 23rd IAEA Fusion Energy Conf., Daejeon, Republic of Korea, October 11–16, 2010, Paper EXC/3-5; General Atomics Report GA-A26882 (2010).

Stacey, W.M., Groebner, R.J., "Evolution of Edge Pedestal Transport Between ELMs," Bull. Am. Phys. Soc. **55**, 130 (2010).

Stagner, L., Heidbrink, W.W., Grierson, B.A., "A Reduced Model for Predicting Fast-ion D_α Light in Tokamaks," Bull. Am. Phys. Soc. **55**, 167 (2010).

Stangeby, P.C., "A Three-Dimensional Analytic Model for Discrete Limiters in ITER," Nucl. Fusion **50** 035013 (2010); General Atomics Report GA-A26525 (2009).

Stangeby, P.C., "Strong Suppression of Net Erosion of Graphite at Divertor Targets Due Strong Suppression of Net Erosion of Graphite at Divertor Targets Due to Prompt Local Deposto Prompt Local Deposition Caused by the Strong Electric Field of the Magnetic Pre-sheath," Bull. Am. Phys. Soc. **55**, 133 (2010).

Strait, E.J., Chu, M.S., Garofalo, A.M., La Haye, R.J., Schaffer, M.J., Reimerdes, H., Casper, T.A., Gribov, Y., "Error Field Measurement Techniques for ITER Using Plasma Response," Bull. Am. Phys. Soc. **55**, 375 (2010).

Sun, A.P., Dong, J.Q., Wang, A.K., Lao, L.L., St John, H.E., Prater, R., "Comparison of a Plasma Transport Analysis and Simulations in DIII-D and HL-2A ECH/ECCD H-mode Discharges," Bull. Am. Phys. Soc. **55**, 129 (2010).

Svidzinski, V.A., In. Y., Kim, J.S., Chu, M.S., Liu, Y.Q., "Rotation-compatible Resistive Wall Mode Modeling in Tokamaks Using Self-consistent Stability Code MARS," Bull. Am. Phys. Soc. **55**, 349 (2010).

Taylor, T.S., Buttery, R.J., "Addressing the New Challenges of Burning Plasma Physics With Dominant Electron Heating on DIII-D," Bull. Am. Phys. Soc. **55**, 343 (2010).

Tobias, B.J., "Electron Cyclotron Emission Imaging of MHD Activity on the DIII-D, TEXTOR, ASDEX-U, and KSTAR Tokamaks," Bull. Am. Phys. Soc. **55**, 107 (2010).

Turco, F., Luce, T.C., "Impact of the Current Profile Evolution on Tearing Stability of ITER Demonstration Discharges in DIII-D," Nucl. Fusion **50**, 095010 (2010); General Atomics Report GA-A26560 (2010).

Turco, F., Luce, T.C., Ferron, J.R., Politzer, P.A., Van Zeeland, M.A., Smith, S.P., Garofalo, A.M., Turnbull, A.D., Holcomb, C.T., White, A.E., Okabayashi, M., In, Y., Reimerdes, H., Brennan, D.P., Takahashi, R., "Impact of Current Profile on Transport and Stability in High Noninductive Fraction DIII-D Discharges," Bull. Am. Phys. Soc. **55**, 61 (2010).

Turnbull, A.D., "On the Relation Between 3-D Equilibrium and Stability," Bull. Am. Phys. Soc. **55**, 349 (2010).

Unterberg, E.A., Allen, S.L., Brooks, N.H., "Fuel Retention and Removal from the Carbon First-Wall in DIII-D," Bull. Am. Phys. Soc. **55**, 62 (2010).

Unterberg, E.A., Allen, S.L., Leonard, A.W., Brooks, N.H., Davis, J.W., Fitzpatrick, B.W.N., Haasz, A.A., Jackson, G.L., Mahdavi, M.A., Tsui, C.K., Umstadter, K.R., Stangeby, P.C., West, W.P., DIII-D Team, "Hydrogenic Retention Studies in DIII-D H-Mode Discharges," Proc. 37th European Physical Society Conf. on Plasma Physics, Dublin, Ireland, June 21–25, 2010, Paper P2.165; General Atomics Report GA-A26798 (2010).

Unterberg, E.A., Schmitz, O., Evans, T.E., Maingi, R., Brooks, N.H., Fenstermacher, M.E., Mordijck, S., Moyer, R.A., Orlov, D.M., "The Effects of an Open and Closed Divertor on Particle Exhaust During RMP ELM Suppression in DIII-D," Nucl. Fusion **50**, 034011 (2010); General Atomics Report GA-A26445 (2009).

Van Zeeland, M.A., "Alfvén Eigenmodes and Fast Ion Loss in the DIII-D and ASDEX-Upgrade Tokamaks," Bull. Am. Phys. Soc. **55**, 288 (2010).

Van Zeeland, M.A., Yu, J.H., Brooks, N.H., Heidbrink, W.W., Burrell, K.H., Groebner, R.J., Hyatt, A.W., Luce, T.C., Pablant, N.A., Solomon, W.M., Wade, M.R., "Active and Passive Imaging in the DIII-D Tokamak," Plasma Phys. Control. Fusion **52**, 045006 (2010); General Atomics Report GA-A26510 (2009).

Van Zeeland, M.A., Yu, J.H., Heidbrink, W.W., Brooks, N.H., Burrell, K.H., Chu, M.S., Hyatt, A.W., Nazikian, R., Pablant, N.A., Pace, D.C., Solomon, W.M., Wade, M.R., "Imaging Key Aspects of Fast Ion Physics in the DIII-D Tokamak," Nucl. Fusion **50**, 084002 (2010); General Atomics Report GA-A26590 (2009).

Van Zeeland, M.A., Yu, J.H., Heidbrink, W.W., Brooks, N.H., Burrell, K.H., Chu, M.S., Hyatt, A.W., Nazikian, R., Pablant, N.A., Pace, D.C., Solomon, W.M., Wade, M.R., "Imaging Key Aspects of Fast Ion Physics in the DIII-D Tokamak," Nucl. Fusion **50**, 084002 (2010); General Atomics Report GA-A26590 (2009).

Volpe, F.A.G., La Haye, R.J., Lohr, J., Prater, R., Strait, E.J., Welander, A.S., Lanctot, M.J., "Stabilization of Disruptive Locked Modes at DIII-D by Means of ECCD and Magnetic Perturbations," Bull. Am. Phys. Soc. **55**, 350 (2010).

Wang, G., Peebles, W.A., Rhodes, T.L., Hillesheim, J.C., Doyle, E.J., Schmitz, L., Zeng, L., White, A.E., Yan, Z., McKee, G.R., DeBoo, J.C., Petty, C.C., Burrell, K.H., Leonard, A.W., Staebler, G.M., Solomon, W.M. "Multi-field/Multi-scale Turbulence Response to EC Heating of DIII-D Ohmic Plasmas," Bull. Am. Phys. Soc. **55**, 346 (2010).

Watkins, J.G., Rudakov, D.L., Lasnier, C.J., Leonard, A.W., Pitts, R.A., Yu, J.H., Evans, T.E., Nygren, R.E., Stangeby, P.C., Wampler, W.R., "Main Chamber Plasma-Wall Interaction Studies in DIII-D in Support of ITER," Proc. 23rd IAEA Fusion Energy Conf., Daejeon Republic of Korea, October 11–16, 2010, Paper EXD/P3-36; General Atomics Report GA-A26895 (2010).

Wehner, W., Xu, C., Schuster, E., Walker, M.L., Humphreys, D.A., In, Y., "Tracking of Current and Rotation Profile Evolution in the DIII-D Tokamak via System Identification," Bull. Am. Phys. Soc. **55**, 132 (2010).

Welander, A.S., Humphreys, D.A., Walker, M.L., Gates, D.A., Kolemen, E., Xiao, B., "Linear Plasma Response Model Based on the Solution to a Perturbed Grad-Shafranov Equation," Bull. Am. Phys. Soc. **55**, 350 (2010).

Wesley, J.C., Commaux, N., Eidietis, N.W., Evans, T.E., James, A.N., Jernigan, T.C., Hollmann, E.M., Humphreys, D.A., Hyatt, A.W., Parks, P.B., Strait, E.J., Yu, J.H., "Control and Dissipation of Plateau-Phase Runaway Currents in DIII-D," Proc. 23rd IAEA Fusion Energy Conf., Daejeon Republic of Korea, October 11–16, 2010, PostDeadline Paper; General Atomics Report GA-A26901 (2010).

Wesley, J.C., deVries, P.C., Eidietis, N.W., Flanagan, S.M., Gerhardt, S.P., Granetz, R.S., Gribov, Y., Hender, T.C., Hollmann, E.M., Hyatt, A.W., Johnson, M.F., Kawano, Y., Lehnen, M., Lister, J., Martin, R., Menard, J., Pautasso, G., Reux, C., Riccardo, V., Sabbagh, S.A., Schissel, D.P., Saint-Laurant, F., Strait, E.J., Sugihara, M., "Disruption, Halo Current and Rapid Shutdown Database Activities for ITER," Proc. 23rd IAEA Fusion Energy Conf., Daejeon Republic of Korea, October 11–16, 2010, Paper ITR/P1-26; General Atomics Report GA-A26885 (2010).

White, A.E., Peebles, W.A., Rhodes, T.L., Holland, C.H., Wang, G., Schmitz, L., Carter, T.A., Hillesheim, J.C., Doyle, E.J., Zeng, L., McKee, G.R., Staebler, G.M., Waltz, R.E., DeBoo, J.C., Petty, C.C., Burrell, K.H., "Measurements of the Cross-Phase Angle Between Density and Electron Temperature Fluctuations and Comparison with Gyrokinetic Simulation," Phys. Plasmas **17**, 056103 (2010); General Atomics Report GA-A26588 (2010).

White, A.E., Peebles, W.A., Rhodes, T.L., Wang, G., Schmitz, L., Carter, T.A., Hillesheim, J.C., Doyle, E.J., Zeng, L., Holland, C.H., McKee, G.R., Staebler, G.M., Waltz, R.E., Candy, J. ,DeBoo, J.C., Petty, C.C., Burrell, K.H., "Correlation ECE Measurements of Turbulent Electron Temperature Fluctuations in DIII-D," Proc. 16th Joint Workshop on Electron Cyclotron Emission and Electron Cyclotron Resonance Heating, Sanya, PR China, April 12–15, 2010 (World Scientific Publishing Co. Pte. Ltd., Singapore, Japan, 2010) p. 168; General Atomics Report GA-A26777 (2010).

White, A.E., Schmitz, L., Peebles, W.A., Rhodes, T.L., Carter, T.A., McKee, G.R., Shafer, M.W., Staebler, G.M., Burrell, K.H., DeBoo, J.C., Prater, R., "Simultaneous Measurement of Core Electron Temperature and Density Fluctuations During Electron Cyclotron Heating on DIII-D," Phys. Plasmas **17**, 020701 (2010); General Atomics Report GA-A26410 (2009).

Wingen, A., Evans, T.E., Lasnier, C.J., Spatscheek, K.H., "Numerical Modeling of the Nonlinear ELM Cycle in Tokamaks," Phys. Rev. Lett. **104**, 175001 (2010); General Atomics Report GA-A26419 (2009).

Wingen, A., Evans, T.E., Spatschek, K.H., "Influence of the X-point Position on Structure Formation by Thermoelectric Currents," Proc. 37th European Physical Society Conf. on Plasma Physics, Dublin, Ireland, June 21–25, 2010, Paper P2.168; General Atomics Report GA-A26773 (2010).

Wong, C.P.C., Abdou, M., Dagher, M., Katoh, Y., Kurtz, R.J., Malang, S., Marriott, E.P., Merrill, B.J., Messadek, K., Morley, N.B., Pint, B.A., Sawan, M.E., Sharafat, S., Smolentsev, S., Sze, D.K., Willms, S., Ying, A., Youssef, M.Z., "An Overview of the US DCLL ITER TBM Program," Fusion Engin. Design **85**, 1129 (2010); General Atomics Report GA-A26555 (2009).

Wong, C.P.C., Chen, B., Rudakov, D.L., Hassanein, A., Rognlien, T.D., Kurtz, R., Evans, T.E., Leonard, A.W., McLean, A.G., "Plasma Facing Material Selection: A Critical Issue for Magnetic Fusion Power Development," Proc. 23rd IAEA Fusion Energy Conf., Daejeon Republic of Korea, October 11–16, 2010, Paper FTP/P1-31; General Atomics Report GA-A26873 (2010).

Yan, Z., "Pressure-Gradient-Limiting Instability Dynamics in the H-mode Pedestal on DIII-D," Bull. Am. Phys. Soc. **55**, 107 (2010).

Yan, Z., McKee, G.R., Groebner, R.J., Snyder, P.B., Osborne, T.H., Beurskens, M.N.A., Burrell, K.H., Evans, T.E., Moyer, R.A., Reimerdes, H. Xu, X., "Pedestal Turbulence Dynamics in ELMing and ELM-free H-mode Plasmas," Proc. 23rd IAEA Fusion Energy Conf., Daejeon Republic of Korea, October 11–16, 2010, Paper EXC/P3-05; General Atomics Report GA-A26865 (2010).

Zeng, L., Doyle, E.J., Rhodes, T.L., Schmitz, L., Peebles, W.A., Mordijck, S., deGrassie, J.S., "Particle Transport Analysis Using Modulated Gas Puff Technique in DIII-D," Bull. Am. Phys. Soc. **55**, 345 (2010).

Zhang, W., Heidbrink, W.W., Lin, Z., Pace, D.C., McCune, D., "Gyrokinetic Particle Simulations of Energetic Particle Transport by Drift Waves and of Toroidal Alfven Eigenmodes," Bull. Am. Phys. Soc. **55**, 348 (2010).

Zhu, Y.B., Heidbrink, W.W., Celle, S., "Solid State Neutral Particle Analyzer in Current Mode on DIII-D Tokamak," Bull. Am. Phys. Soc. **55**, 380 (2010).

Zhu, Y.B., Heidbrink, W.W., Schaffer, M.J., "Effect of Test Blanket Module on Triton Burn-up in DIII-D Tokamak," Bull. Am. Phys. Soc. **55**, 348 (2010).

12.4. PUBLICATIONS FOR FY09

Allen, S.L., Unterberg, E.A., Brooks, N.H., Mahdavi, M.A., Whyte, D.G., Davis, J.W., Haasz, A.A., Fitzpatrick, B., "Particle Control and Carbon Transport Experiments on DIII-D," Bull. Am. Phys. Soc. **54**, 57 (2009).

Anderson, P.M., "Mechanical Design of the Positioning System for DIII-D Off-Axis Neutral Beam," Proc. 23rd IEEE/NPSS Symp. on Fusion Engineering, San Diego, California, May 31–June 5, 2009; General Atomics Report GA-A26417 (2009).

Anderson, P.M., and Hong, R.M., "Mechanical Design for Modification of a Neutral Beam for Off-axis Injection," Fusion Engin. Design **84**, 526 (2009); General Atomics Report GA-A26202 (2008).

Austin, M.E., Gentle, K.W., Petty, C.C., Rhodes, T.L., Schmitz, L., Wang, G., "Heat Transport in Off-Axis EC-Heated Discharges in DIII-D," Bull. Am. Phys. Soc. **54**, 59 (2009).

Avril, A., Makowski, M.A., Umansky, M., Kalling, R., Schissel, D.P., "Visualization of Turbulence with OpenGL," Bull. Am. Phys. Soc. **54**, 161 (2009).

Axley, A., Pinsker, R.I., "Investigation of Ion Cyclotron Emissions on DIII-D During Neutral Bem Injection and Fast Wave Heating," Bull. Am. Phys. Soc. **54**, 160 (2009).

Baylor, L.R., Jernigan, T.C., Commaux, N., Evans, T.E., Parks, P.B., Fenstermacher, M.E., Moyer, R.A., Yu, J.H., "Pellet ELM Triggering Results and Pacing Prospects for DIII-D," Bull. Am. Phys. Soc. **54**, 163 (2009).

Boedo, J.A., "Edge Turbulence and SOL Transport in Tokamaks," J. Nucl. Mater. **390–391**, 29 (2009); General Atonics Report GA-A26173 (2008).

Bray, B.D., Deterly, T.M., Ponce, D.M., Liu, C., "Initial Operation of an Improved Thomson Scattering System at DIII-D," Bull. Am. Phys. Soc. **54**, 168 (2009).

Bray, B.D., West, W.P., Rudakov, D.L., "Dependence of Laser Measured Dust Densities in the SOL at DIII-D With Operational Configuration," J. Nucl. Mater. **390–391**, 96 (2009); General Atonics Report GA-A26126 (2008).

Brooks, N.H., Meyer, O., "Charge Exchange Recombination Detection of Low-Z Impurities in the Extreme UV Using Digital Lock-In Techniques," Bull. Am. Phys. Soc. **54**, 168 (2009).

Budny, R.V., Andre, R., Kessel, C.E., McCune, D., Jackson, G.L., Humphreys, D.A., Luce, T.C., Politzer, P.A., "Modeling Tokamak Discharges During Startup in DIII-D and Predictions for ITER," Bull. Am. Phys. Soc. **54**, 166 (2009).

Burby, J., Pinsker, R.I., Choi, M., "Comparison of Moderate to High Ion Cyclotron Absorption on Energetic Ions in NSTX and DIII-D," Bull. Am. Phys. Soc. **54**, 160 (2009).

Burrell, K.H., Osborne, T.H., Snyder, P.B., Groebner, R.J., Gohil, P., Fenstermacher, M.E., Solomon, W.M., "Quiescent H-mode Plasmas in DIII-D With Strong, Co-Current Edge Rotation," Bull. Am. Phys. Soc. **54**, 271 (2009).

Burrell, K.H., Osborne, T.H., Snyder, P.B., West, W.P., Fenstermacher, M.E., Groebner, R.J., Gohil, P., Leonard, A.W., Solomon, W.M., "Quiescent H-Mode Plasmas With Strong Edge Rotation in the Co-Current Direction," Phys. Rev. Lett. **102**, 155993 (2009); General Atomics Report GA-A26318 (2009).

Burrell, K.H., Osborne, T.H., Snyder, P.B., West, W.P., Fenstermacher, M.E., Groebner, R.J., Gohil, P., Leonard, A.W., Solomon, W.M., "Edge Pedestal Control in Quiescent H-mode Discharges in DIII-D Using Co- Plus Counter-Neutral Beam Injection," Nucl. Fusion **49** 085024 (2009); General Atomics Report GA-A26324 (2009).

Buttery, R.J., Challis, C.D., La Haye, R.J., Gerhardt, S.P., DIII-D Team, JET Team, NSTX Team, "Sensitivity of Tearing Mode Beta Limits to Rotation and Current Profile," Bull. Am. Phys. Soc. **54**, 235 (2009).

Callen, J.D., Groebner, R.J., Osborne, T.H., Canik, J.M., Owen, L.W., Pankin, A., Rafig, T., Rognlien, T.D., Stacey, W.M., "Analysis of Pedestal Transport," Bull. Am. Phys. Soc. **54**, 270 (2009).

Callis, R.W., Baylor, L.R., Parks, P.B., Alexander, N.B., Moeller, C.P., "Alternate Concepts for Generating High Speed DT Pellets for Fueling ITER," Fusion Engin. Design **84**, 526 (2009); General Atomics Report GA-A26261 (2008).

Callis, R.W., Doane, J.L., Grunloh, H.J., Kajiwara, K., Kasugai, A., Moeller, C.P., Oda, Y., Olstad, R.A., Sakamoto, K., Takahashi, K., "Design and Testing of ITER ECH and CD Transmission Line Components," presented at the 25th Symp. on Fusion Technology, Rostock, Germany, September 15–19, 2008; Fusion Engin. Design **84**(2–6), 526 (2009); General Atomics Report GA-A26198 (2008).

Campbell, G.L., Holtrop, K.L., "Design of the DIII-D Top Level Power Supply Control System for an Eighth Neutral Beam Ion Source," Proc. 23rd IEEE/NPSS Symp. on Fusion Engineering, May 31–June 5, 2009, San Diego, California; General Atomics Report GA-A26427 (2009).

Cengher, M., Lohr, J., Doane, J.L., Gorelov, I.A., Moeller, C.P., DeBoo, J.C., Leonard, A.W., Ponce, D., "Summary of RF Power Measurements on the ECH System on DIII-D," Bull. Am. Phys. Soc. **54**, 166 (2009).

Cengher, M., Lohr, J., Gorelov, I.A., Grosnickle, W.H., Ponce, D., Johnson, P., "Measurements of the ECH Power and of the Transmission Line Losses on DIII-D," Fusion Sci. Technol. **55**, 213 (2009); General Atomics Report GA-A26317 (2008).

Chiu, H.K., Hong, R.M., Scoville, J.T., "Calculated Beam Profiles for the DIII-D Off-Axis and Long Pulse Neutral Beam Upgrade," Proc. 23rd IEEE/NPSS Symp. on Fusion Engineering, San Diego, California, May 31–June 5, 2009; General Atomics Report GA-A26433 (2009).

Chu, M.S., Lao, L.L., Evans, T.E., Schaffer, M.J., Strait, E.J., Liu, Y.Q., Lanctot, M.J., Reimerdes, H., "Non-axisymmetric Plasma Response to External Magnetic Perturbations," Bull. Am. Phys. Soc. **54**, 162 (2009).

Commaux, N., Baylor, L.R., Jernigan, T.C., Evans, T.E., Humphreys, D.A., Parks, P.B., Van Zeeland, M.A., Wesley, J.C., Hollmann, E.M., James, A.N., Yu, J.H., "Disruption Mitigation Experiments Carried Out on DIII-D," Bull. Am. Phys. Soc. **54**, 303 (2009).

DeBoo, J.C., "Probing Plasma Turbulence by Modulating the Electron Temperature Gradient," Bull. Am. Phys. Soc. **54**, 138 (2009).

deGrassie, J.S., "Tokamak Rotation Sources, Transport and Sinks," Proc. 36th EPS Conf. on Controlled Fusion and Plasma Physics, Sofia, Bulgaria, June 29–July 3, 2009; General Atomics Report GA-A26481 (2009).

deGrassie, J.S., Burrell, K.H., Groebner, R.J., Solomon, W.M., "Toroidal Rotation With Near-Balanced NBI in DIII-D H-Mode Discharges," Bull. Am. Phys. Soc. **54**, 268 (2009).

deGrassie, J.S., Groebner, R.J., Burrell, K.H., Solomon, W.M., "Intrinsic Toroidal Velocity Near the Edge of DIII-D H-mode Plasmas," Nucl. Fusion **49** 085020 (2009); General Atomics Report GA-A26144 (2009).

Deterly, T.M., Bray, B.D., Hsieh, C.-L., Kulchar, J.A., Liu, C., Ponce, D.M., "The Design, Implementation and Preliminary Results of a New Photo Detector for the DIII-D Thomson Scattering Diagnostic," IEEE Trans. Plasma Sci. **38**, 1699 (2009); General Atomics Report GA-A26511 (2009).

Deterly, T.M., Bray, B.D., Hsieh, C.-L., Kulchar, J.A., Liu, C., Ponce, D.M., "Description and Preliminary Result of a New Photo Detector for the DIII-D Thomson Scattering Diagnostic," Proc. 23rd IEEE/NPSS Symp. on Fusion Engineering, San Diego, California, May 31–June 5, 2009; General Atomics Report GA-A26434 (2009).

DIII-D Research Team, "DIII-D Year 2009 Experimental Plan," General Atomics Report GA-A26394 (2009).

Doyle, E.J., DeBoo, J.C., Ferron, J.R., La Haye, R.J., Kinsey, J.E., Luce, T.C., Politzer, P.A., "Progress in Developing ITER Operational Scenarios on DIII-D," Bull. Am. Phys. Soc. **54**, 305 (2009).

Eidietis, N.W., Hollmann, E.M., Humphreys, D.A., Jernigan, T.C., Strait, E.J., Wesley, J.C., "Modeling and Measurement of Disruption Halo Current Evolution on DIII-D," Bull. Am. Phys. Soc. **54**, 164 (2009).

Elder, J.D., Stangeby, P.C., Lisgo, S., Leonard, A.W., Bray, B.D., Brooks, N.H., Fenstermacher, M.E., Groth, M., Boedo, J.A., Rudakov, D.L., Watkins, J.G., Unterberg, E.A., "OEDGE Modeling of Deuterium Recycling in DIII-D," Bull. Am. Phys. Soc. **54**, 273 (2009).

Evans, T.E., Wingen, A., Spatschek, K.H., Lasnier, C.J., "Simulations of Nonlinear ELM Instabilities in Tokamaks," Bull. Am. Phys. Soc. **54**, 272 (2009).

Evans, T.E., Yu, J.H., Jakubowski, M., Schmitz, O., Watkins, J.G., Moyer, R.A., "The Conceptual Model of the Magnetic Topology and Nonlinear Dynamics of ELMs," J. Nucl. Mater. **390–391**, 789 (2009); General Atonics Report GA-A26116 (2008).

Fenstermacher, M.E., "Overview of Recent DIII-D Experimental Results," Bull. Am. Phys. Soc. **54**, 57 (2009).

Fenstermacher, M.E., Buttery, R.J., Evans, T.E., Osborne, T.H., Schaffer, M.J., deGrassie, J.S., Gohil, P., Groebner, R.J., Moyer, R.A., DIII-D Team, "Physics of the Boundary Plasma During ELM Control with Resonant Magnetic Perturbations in ITER Similar Shaped Plasmas on DIII-D," J. Nucl. Mater. **390–391**, 793 (2009); General Atonics Report GA-A26114 (2008).

Ferron, J.R., Luce, T.C., Politzer, P.A., DeBoo, J.C., Petrie, T.W., Petty, C.C., La Haye, R.J., Holcomb, C.T., White, A.E., Turco, F., Doyle, E.J., Rhodes, T.L., Zeng, L., "Optimization of the Internal Magnetic Configuration for High Bootstrap Current Fraction and High Beta for Steady-state," Bull. Am. Phys. Soc. **54**, 165 (2009).

Fisher, R.K., Boivin, R.L., Garcia-Munoz, M., Heidbrink, W.W., Pace, D.C., Van Zeeland, M.A., Zhu, Y.B., "Fast Ion Loss Diagnostics on DIII-D," Proc. 36th EPS Conf. on Controlled Fusion and Plasma Physics, Sofia, Bulgaria, June 29–July 3, 2009; General Atomics Report GA-A26480 (2009).

Floyd, J.-P., Stacey, W.M., "Generalized Diffusion Theory Calculations of the Edge Pedestal Density Profile," Bull. Am. Phys. Soc. **54**, 274 (2009).

Friis, Z.W., Stacey, W.M., Leonard, A.W., Rensink, M.E., "Analysis of Neutral Recycling Fueling of the DIII-D Edge Pedestal," Bull. Am. Phys. Soc. **54**, 273 (2009).

Garofalo, A.M., Burrell, K.H., Cole, A.J., deGrassie, J.S., Jackson, G.L., Lanctot, M.J., Reimerdes, H., Solomon, W.M., DIII-D Team, "Plasma Rotation Driven by Static Nonresonant Magnetic Fields," Proc. 36th EPS Conf. on Controlled Fusion and Plasma Physics, Sofia, Bulgaria, June 29–July 3, 2009; General Atomics Report GA-A26463 (2009).

Garofalo, A.M., Burrell, K.H., Jackson, G.L., Cole, A.J., Solomon, W.M., Lanctot, M.J., Reimerdes, H., "Quiescent H-Mode Plasmas with Rotation Driven by Static Non-axisymmetric Fields," Bull. Am. Phys. Soc. **54**, 60 (2009).

Garofalo, A.M., Solomon, W.M., Lanctot, M.J., Burrell, K.H., DeBoo, J.C., deGrassie, J.S., Jackson, G.L., Park, J.-K., Reimerdes, H., Schaffer, M.J., Strait, E.J., DIII-D Team, "Plasma Rotation Driven by Static Nonresonant Magnetic Fields," Phys. Plasmas **16**, 056119 (2009); General Atomics Report GA-A26336 (2009).

Gohil, P., DIII-D Helium Plasma Team, "H-mode Power Threshold, ELM Characteristics and Control, and Plasma Startup in Helium Plasmas in DIII-D," Bull. Am. Phys. Soc. **54**, 268 (2009).

Gohil, P., Jernigan, T.C., Scoville, J.T., Strait, E.J., "The H-mode Power Threshold in Hydrogen Plasmas in DIII-D," Nucl. Fusion **49** 115004 (2009); General Atomics Report GA-A26360 (2009).

Gorelov, Y.A., Lohr, J., Cengher, M., Ponce, D., "Operational Experience with the Six Gyrotron System on DIII-D," Bull. Am. Phys. Soc. **54**, 166 (2009).

Groebner, R.J., Leonard, A.W., Snyder, P.B., Osborne, T.H., Maggi, C.F., Fenstermacher, M.E., Petty, C.C., Owen, L.W., "Progress Towards a Model for Predictive Pedestal Height in DIII-D," Nucl. Fusion **49** 085037 (2009); General Atomics Report GA-A26345 (2009).

Groebner, R.J., Osborne, T.H., Leonard, A.W., Fenstermacher, M.E., "Temporal Evolution of H-mode Pedestal in DIII-D," Nucl. Fusion **49**, 045013 (2009); General Atomics Report GA-A26139 (2008).

Groebner, R.J., Snyder, P.B., Osborne, T.H., Leonard, A.W., Rhodes, T.L., Zeng, L., Yan, Z., McKee, G.R., "Test of a Model for Limits to Pedestal Pressure Gradient in DIII-D," Bull. Am. Phys. Soc. **54**, 271 (2009).

Groth, M., Boedo, J.A., Brooks, N.H., Isler, R.C., Leonard, A.W., Porter, G.D., Watkins, J.G., West, W.P., Bray, B.D., Fenstermacher, M.E., Groebner, R.J., Moyer, R.A., Rudakov, D.L., Yu, J.H., Zeng, L., "Effect of Cross-Field Drifts and Core Rotation on Flows in the Main Scrape-Off Layer of DIII-D L-mode Plasmas," Nucl. Fusion **49** 115002 (2009); General Atomics Report GA-A27349 (2009).

Groth, M., Ellis, R.M., Brooks, N.H., Fenstermacher, M.E., Lasnier, C.J., Meyer, W.H., Moeller, J.M., "Measurements of Line Emission Profiles in the Main Scrape-Off Layer of the DIII-D Tokamak," Rev. Sci. Instrum. **80**, 033505 (2009); General Atomics Report GA-A26295 (2008).

Groth, M., Porter, G.D., Boedo, J.A., Brooks, N.H., Isler, R.C., West, W.P., Bray, B.D., Fenstermacher, M.E., Groebner, R.J., Leonard, A.W., Moyer, R.A., Rognlien, T.D., Watkins, J.G., Yu, J.H., "Measurements and Simulations of Scrape-Off Layer Flows in the DIII-D Tokamak," J. Nucl. Mater. **390–391**, 343 (2009); General Atomics Report GA-A26119 (2008).

Hanson, G.R., Commaux, N., Baity, F.W., Horton, A.R., Wilgen, J.B., Nagy, A., Pinsker, R.I., "Q-band AM Reflectometer on the DIII-D 285°-300° Fast Wave Antenna," Bull. Am. Phys. Soc. **54**, 169 (2009).

Hanson, J.M., Lanctot, M.J., Navratil, G.A., Reimerdes, H., Strait, E.J., "Measuring Resistive Wall Mode Stability in Real-time," Bull. Am. Phys. Soc. **54**, 162 (2009).

Holcomb, C.T., Ferron, J.R., Luce, T.C., Petrie, T.W., Politzer, P.A., Challis, C., DeBoo, J.C., Doyle, E.J., Greenfield, C.M., Groebner, R.J., Groth, M., Hyatt, A.W., Jackson, G.L., Kessel, C., La Haye, R.J., Makowski, M.A., McKee, G.R., Murakami, M., Osborne, T.H., Park, J.M., Prater, R., Porter, G.D., Reimerdes, H., Rhodes, T.L., Shafer, M.W., Snyder, P.B., Turnbull, A.D., West, W.P., "Plasma Shape Optimization for Steady-State Tokamak Development in DIII-D," Proc. 36th EPS Conf. on Controlled Fusion and Plasma Physics, Sofia, Bulgaria, June 29–July 3, 2009; General Atomics Report GA-A26494 (2009).

Holcomb, C.T., Ferron, J.R., Luce, T.C., Petrie, T.W., Politzer, P.A., Challis, C., DeBoo, J.C., Doyle, E.J., Greenfield, C.M., Groebner, R.J., Groth, M., Hyatt, A.W., Jackson, G.L., Kessel, C., La Haye, R.J., Makowski, M.A., McKee, G.R., Murakami, M., Osborne, T.H., Park, J.M., Prater, R., Porter, G.D., Reimerdes, H., Rhodes, T.L., Shafer, M.W., Snyder, P.B., Turnbull, A.D., West, W.P., "Optimizing Stability, Transport, and Divertor Operation Through Plasma Shaping for Steady-State Scenario Development," Phys. Plasmas **16**, 056116 (2009); General Atomics Report GA-A26331 (2009).

Holcomb, C.T., Ferron, J.R., Luce, T.C., Politzer, P.A., DeBoo, J.C., Petrie, T.W., Petty, C.C., La Haye, R.J., White, A.E., Turco, F., Doyle, E.J., Rhodes, T.L., Zeng, L., "Dependence of Bootstrap Current, Stability, and Transport on the Safety Factor Profile in DIII-D Steady-state Scenario Discharges," Bull. Am. Phys. Soc. **54**, 58 (2009).

Holland, C., Tynan, G.R., Rhodes, T.L., Peebles, W.A., Schmitz, L., Hillesheim, J.C., Wang, G., Zeng, L., Doyle, E.J., McKee, G.R., Yan, Z., Shafer, M.W., White, A.E., Candy, J., Waltz, R.E., Kinsey, J.E., Staebler, G.M., DeBoo, J.C., Prater, R., Burrell, K.H., Petty, C.C., Makowski, M.A., "Experimental Tests of Elongation Scaling in Gyrokinetic Turbulence Simulations," Bull. Am. Phys. Soc. **54**, 269 (2009).

Holland, C., White, A.E., McKee, G.R., Shafer, M.W., Candy, J., Waltz, R.E., Schmitz, L., Tynan, G.R., "Implementation and Application of Two Synthetic Diagnostics for Validating Simulations of Core Tokamak Turbulence," Phys. Plasmas **16**, 052301 (2009); General Atomics Report GA-A26183 (2008).

Hollmann, E.M., James, A.N., Parks, P.B., Evans, T.E., Humphreys, D.A., Jackson, G.L., Jernigan, T.C., La Haye, R.J., Strait, E.J., West, W.P., Wu, W., Yu, J.H., "Low-Z Shell Pellet Experiments on DIII-D," Proc. 16th Int. Conf. on Atomic Processes in Plasmas, Monterey, California, March 22–23, 2009; General Atomics Report GA-A26402 (2009).

Hollmann, E.M., James, A.N., Yu, J.H., Commaux, N., Jernigan, T.C., Evans, T.E., Humphreys, D.A., Jackson, G.L., Parks, P.B., Strait, E.J., Wu, W., "Shell Pellet Experiments on DIII-D," Bull. Am. Phys. Soc. **54**, 274 (2009).

Hollmann, E.M., Pablant, N.A., Rudakov, D.L., Boedo, J.A., Brooks, N.H., Jernigan, T.C., Pigarov, A.Yu., "Experiments to Measure Hydrogen Release From Graphite Walls During Disruptions in DIII-D," J. Nucl. Mater. **390–391**, 597 (2009); General Atomics Report GA-A26109 (2008).

Hong, R.M., Chiu, H.K., Scoville, J.T., "Development for Extending the Beam Pulse Length of the DIII-D Neutral Beam System," Proc. 23rd IEEE/NPSS Symp. on Fusion Engineering, May 31–June 5, 2009, San Diego, California; General Atomics Report GA-A26418 (2009).

Hudson, B., Leonard, A.W., Evans, T.E., Osborne, T.H., Petty, C.C., Snyder, P.B., "H-Mode Pedestal Structure and Transport in Hybrid Plasmas During Magnetic Perturbation in the DIII-D Tokamak," Bull. Am. Phys. Soc. **54**, 271 (2009).

Humphreys, D.A., Casper, T.A., Eidietis, N.W., Ferrara, M., Gates, D.A., Hutchinson, I.H., Jackson, G.L., Kolemen, E., Leuer, J.A., Lister, J.B., Lodestro, L.L., Meyer, W.H., Pearlstein, L.D., Sartori, F., Walker, M.L., Welander, A.S., Wolfe, S.M., "Experimental Vertical Stability Studies for ITER Performance and Design Guidance," Nucl. Fusion **49** 115003 (2009); General Atomics Report GA-A26391 (2009).

Humphreys, D.A., Eidietis, N.W., Evans, T.E., Parks, P.B., Strait, E.J., Wesley, J.C., Commaux, N., Jernigan, T.C., Hollmann, E.M., James, A.N., Yu, J.H., "3D Field Effects on Disruption-Generated Runaway Electrons in DIII-D," Bull. Am. Phys. Soc. **54**, 164 (2009).

Hurd, L., Brooks, N.H., Unterberg, E.A., Schmitz, O., “Evaluation and Implementation of Helium Line Ratio Technique for Measurement of Edge Density and Temperature on DIII-D,” Bull. Am. Phys. Soc. **54**, 160 (2009).

Hyatt, A.W., Eidietis, N.W., Flanagan, S.M., Humphreys, D.A., Wesley, J.C., Walker, M.D., IDDB Multi-institutional Team, “Fast Disruptions and Halo Currents in the International Disruption Database,” Bull. Am. Phys. Soc. **54**, 164 (2009).

Hyatt, A.W., Ferron, J.R., Humphreys, D.A., Chamberlain, F.R., Johnson, R.D., Penaflor, B.G., Piglowski, D.A., Scoville, J.T., Walker, M.L., “Physics Operations With the DIII-D Plasma Control System,” Proc. 23rd IEEE/NPSS Symp. on Fusion Engineering, San Diego, California, May 31–June 5, 2009; General Atomics Report GA-A26466 (2009).

In, Y., Chu, M.S., Jackson, G.L., Kim, J.S., La Haye, R.J., Liu, Y.Q., Marrelli, L., Okabayashi, M., Reimerdes, H., Strait, E.J., “Requirements for Active Resistive Wall Mod (RWM) Feedback Control,” Plasma Phys. Control. Fusion **52**, 104004 (2009); General Atomics Report GA-A26615 (2009).

In, Y., Kim, J.S., Chu, M.S., Garofalo, A.M., Jackson, G.L., La Haye, R.J., Schaffer, M.J., Strait, E.J., Lanctot, M.J., Reimerdes, H., Liu, Y.Q., Marrelli, L., Martin, P., Okabayashi, M., “Active Feedback Control of the Current-driven Resistive Wall Mode (RWM) in DIII-D,” Bull. Am. Phys. Soc. **54**, 162 (2009).

Izzo, V.A., Hollmann, E.M., James, A.N., Whyte, D.G., Olynyk, G., Lao, L.L., “Studies of Runaway Electron Confinement in MHD Disruption Simulations,” Bull. Am. Phys. Soc. **54**, 59 (2009).

Jackson, G.L., Casper, T.A., Luce, T.C., Humphreys, D.A., Ferron, J.R., Hyatt, A.W., Leuer, J.A., Petrie, T.W., Turco, F., West, W.P., “Simulating ITER Plasma Startup and Rampdown Scenarios in the DIII-D Tokamak,” Nucl. Fusion **49** 115027 (2009); General Atomics Report GA-A26351 (2009).

Jackson, G.L., Humphreys, D.A., Hyatt, A.W., Leuer, J.A., Luce, T.C., Politzer, P.A., Yu, J.H., Casper, T.A., Budny, R.V., “Understanding and Predicting the Dynamics of Tokamak Discharges During Startup,” Bull. Am. Phys. Soc. **54**, 255 (2009).

Jackson, G.L., Politzer, P.A., Casper, T.A., Doyle, E.J., Ferron, J.R., Humphreys, D.A., Hyatt, A.W., Leuer, J.A., Luce, T.C., Petrie, T.W., Rudakov, D.L., Yu, J.H., Walker, M.L., “Experiments Simulating ITER Rampdown and Startup Scenarios in the DIII-D Tokamak,” Proc. 36th EPS Conf. on Controlled Fusion and Plasma Physics, Sofia, Bulgaria, June 29–July 3, 2009; General Atomics Report GA-A26479 (2009).

James, A.N., Hollmann, E.M., Yu, J.H., Tynan, G.R., Commaux, N., Jernigan, T.C., Eidietis, N.W., Evans, T.E., La Haye, R.J., Strait, E.J., Wesley, J.C., Lasnier, C.J., Austin, M.E., “Recent Investigations of Runaway Electron (RE) Generation and Transport in DIII-D,” Bull. Am. Phys. Soc. **54**, 164 (2009).

Jernigan, T.C., Baylor, L.R., Combs, S.K., Commaux, N., Meitner, S.J., Hollmann, E.M., Yu, J.H., Humphreys, D.A., Van Zeeland, M.A., Wesley, J.C., “Large, Shattered Pellets for Disruption Mitigation in DIII-D,” Bull. Am. Phys. Soc. **54**, 164 (2009).

Kessler, J., Volpe, F., Evans, T.E., Ali, H., Punjabi, A., “Magnetic Transport Barriers in the DIII-D Tokamak,” Bull. Am. Phys. Soc. **54**, 160 (2009).

King, J.D., Makowski, M.A., Allen, S.L., Holcomb, C.T., Geer, R., Ellis, R., Morse, E.C., “A Fast MSE Measurement of MHD Magnetic Fluctuations on DIII-D,” Bull. Am. Phys. Soc. **54**, 168 (2009).

La Haye, R.J., “Islands in the Stream: The Effect of Plasma Flow on Tearing Stability,” Bull. Am. Phys. Soc. **54**, 95 (2009).

La Haye, R.J., Buttery, R.J., DIII-D Team, "The Stabilizing Effect of Flow Shear on *m*/*n*=3/2 Magnetic Island Width in DIII-D," Phys. Plasmas **16**, 022107 (2009); General Atomics Report GA-A26086 (2008).

La Haye, R.J., Isayama, A., Maraschek, M., "Prospects for Stabilization of Neoclassical Tearing Modes by Electron Cyclotron Current Drive in ITER," Nucl. Fusion **49**, 045005 (2009); General Atomics Report GA-A26339 (2009).

Lanctot, M.J., Reimerdes, H., Hanson, J.M., Navratil, G.A., Garofalo, A.M., Chu, M.S., Jackson, G.L., La Haye, R.J., Schaffer, M.J., Strait, E.J., Liu, Y.Q., Okabayashi, M., Solomon, W.M., "Global Structure of a Stable, Driven Kink Mode: DIII-D Measurements and Model Validation," Bull. Am. Phys. Soc. **54**, 58 (2009).

Lao, L.L., Prater, R., La Haye, R.J., Chu, M.S., Hyatt, A.W., Luce, T.C., Osborne, T.H., Strait, E.J., Abla, G., Chan, V.S., Collier, A., Turnbull, A.D., Izzo, V.A., Guo, W., Pan, C., Ren, Q., Srinivasan, R., Park, J.M., "Tearing-Mode Excitation by Counter ECCD for Validation of Resistive MHD Models in DIII-D," Bull. Am. Phys. Soc. **54**, 163 (2009).

Lasnier, C.J., Makowski, M.A., Boedo, J.A., Brooks, N.H., Leonard, A.W., West, W.P., Watkins, J.G., "Scaling of Type-I ELM Divertor Energy, Heat Flux, and Profile Width in DIII-D," Bull. Am. Phys. Soc. **54**, 257 (2009)

Lasnier, C.J., Makowski, M.A., Boedo, J.A., Brooks, N.H., Leonard, A.W., Watkins, J.G., West, W.P., "Scaling of Divertor Heat Flux Profile Widths in DIII-D," Proc. 36th EPS Conf. on Controlled Fusion and Plasma Physics, Sofia, Bulgaria, June 29–July 3, 2009; General Atomics Report GA-A26483 (2009).

Leonard, A.W., Groebner, R.J., Porter, G.D., "Neutral Fueling From Recycling and Contributions to Pedestal Density Profiles in DIII-D," Bull. Am. Phys. Soc. **54**, 273 (2009).

Leonard, A.W., Groth, M., Porter, G.D., Rensink, M.E., "Pedestal Fueling Through Interpretive Analysis of Measured Main Chamber and Divertor Target Flux in DIII-D," J. Nucl. Mater. **390–391**, 470 (2009); General Atomics Report GA-A26113 (2008).

Leuer, J.A., Eidietis, N.W., Ferron, J.R., Humphreys, D.A., Hyatt, A.W., Jackson, G.L., Johnson, R.D., Penaflor, B.G., Piglowski, D.A., Walker, M.L., Welander, A.S., Yoon, S.W., Hahn, S.H., Oh, Y.K., Xiao, B.J., Wang, H.Z., Yuan, Q.P., Mueller, D., "Plasma Startup Design and Experience in Fully Superconducting Tokamaks," Proc. 23rd IEEE/NPSS Symp. on Fusion Engineering, May 31–June 5, 2009, San Diego, California; General Atomics Report GA-A26428 (2009).

Leuer, J.A., Eidietis, N.W., Humphreys, D.A., Hyatt, A.W., Jackson, G.L., Lohr, J., Politzer, P.A., Prater, R., Taylor, P.T., Walker, M.L., Cunningham, G., Gates, D., Mueller, D., Oh, Y.-K., Yoon, S.-W., Hahn, S.-H., Yu, J.H., "Solenoid-free Startup of DIII-D," Bull. Am. Phys. Soc. **54**, 59 (2009).

Lohr, J., Cengher, M., DeBoo, J.C., Gorelov, I.A., Moeller, C.P., Neilson, J., Young, D., Ponce, D., "Performance of the Six Gyrotron System on the DIII-D Tokamak," Proc. 34th Int. Conf. on Infrared, Millimeter, and Terahertz Waves, Busan, Korea, September 21–25, 2009; General Atomics Report GA-A26504 (2009).

Lohr, J., Cengher, M., Doane, J.L., Gorelov, Y.A., Moeller, C.P., Ponce, D., Prater, R., "Operation of the Complete DIII-D Gyrotron System," Bull. Am. Phys. Soc. **54**, 166 (2009).

Lohr, J., Cengher, M., Gorelov, I.A., Parks, P.B., Ponce, D., Young, D., Johnson, P., Thompson, K., "Diagnostic Tests, Unusual Experiments and Performance on the DIII-D Gyrotron System," Proc. the 7th Int. Workshop on Strong Microwaves — Sources and Applications, Nizhny Novgorod, Russia, July 7–August 2, 2008; General Atomics Report GA-A26374 (2009).

Luce, T.C., "Realizing Steady State Tokamak Operation for Fusion Energy," Bull. Am. Phys. Soc. **54**, 19 (2009).

Makowski, M.A., Lasnier, C.J., Leonard, A.W., Boedo, J.A., "Characterization and Scaling of Heat Flux Transport in the DIII-D SOL," Bull. Am. Phys. Soc. **54**, 272 (2009).

McDaniel, W.L., Huynh, P., Anastasi, D.D., Tooker, J.F., Hoyt, D.M., "Multiple High Voltage Modulators Operating Independently From a Single Common 100 kV DC Power Supply," Proc. 23rd IEEE/NPSS Symp. on Fusion Engineering, San Diego, California, May 31–June 5, 2009; General Atomics Report GA-A26447 (2009).

McGuire, S., Petty, C.C., Thomas, D.M., Hudson, B., "Optimization of Optical Filters for the LIBEAM Diagnostic," Bull. Am. Phys. Soc. **54**, 161 (2009).

McKee, G.R., Fonck, R.J., Schlossberg, D.J., Shafer, M.W., Yan, Z., Evans, T.E., Moyer, R.A., "Density Fluctuation Enhancement During RMP ELM-Suppressed Discharges," Bull. Am. Phys. Soc. **54**, 269 (2009).

McKee, G.R., Gohil, P., Schlossberg, D.J., Boedo, J.A., Burrell, K.H., deGrassie, J.S., Groebner, R.J., Moyer, R.A., Petty, C.C., Rhodes, T.L., Schmitz, L., Shafer, M.W., Solomon, W.M., Umansky, M., Wang, G., White, A.E., Xu, X., "Dependence of the L- to H-mode Power Threshold on Toroidal Rotation and the Link to Edge Turbulence Dynamics," Nucl. Fusion **49** 115016 (2009); General Atomics Report GA-A26362 (2009).

McLean, A.G., Davis, J.W., Stangeby, P.C., Allen, S.L., Boedo, J.A., Bray, B.D., Brezinsek, S., Brooks, N.H., Fenstermacher, M.E., Groth, M., Haasz, A.A., Hollmann, E.M., Isler, R.C., Lasnier, C.J., Mu, Y., Petrie, T.W., Rudakov, D.L., Watkins, J.G., West, W.P., Whyte, D.G., Wong, C.P.C., "Characterization of Chemical Sputtering Using the Mark II DiMES Porous Plug Injector in Attached and Semi-detached Plasmas of DIII-D," J. Nucl. Mater. **390–391**, 160 (2009); General Atomics Report GA-A26122 (2008).

Meyerson, D.F., Austin, M.E., Gentle, K.W., Luce, T.C., Petty, C.C., "SVD Techniques Applied to Modulated ECH Data on DIII-D," Bull. Am. Phys. Soc. **54**, 352 (2009).

Miles, C.J., Hill, D.N., Lasnier, C.J., Makowski, M.A., Garofalo, A.M., "Multi-Parameter Scaling of Divertor Heat Flux Profile Width," Bull. Am. Phys. Soc. **54**, 161 (2009).

Mordijck, S., Evans, T.E., Owen, L.W., Moyer, R.A., "Increased Particle Transport Due to Resonant Magnetic Perturbations Modeled With a Quasi-Vacuum Field Line Tracing Code and a 2D Fluid Code," Nucl. Fusion **50**, 035006 (2009); General Atomics Report GA-A26414 (2009).

Mordijck, S., Moyer, R.A., Evans, T.E., Bonnin, X., Canik, J., Coster, D.P., Groth, M., Maingi, R., Osborne, T.H., Owen, L.W., Petrie, T.W., Reiter, D., Watkins, J.G., Unterberg, E.A., "Fluid Modeling of an ELMing H-mode and an RMP H-mode," J. Nucl. Mater. **390–391**, 299 (2009); General Atonics Report GA-A26107 (2008).

Mordijck, S., Moyer, R.A., Unterberg, E.A., Evans, T.E., "Correlation Between Density Pump-out and Free Streaming Particle Transport in Low Collisionality Resonant Magnetic Perturbation H-modes," Bull. Am. Phys. Soc. **54**, 58 (2009).

Mu, Y., McLean, A.G., Elder, J.D., Stangeby, P.C., Bray, B.D., Brooks, N.H., Davis, J.W., Fenstermacher, M.E., Groth, M., Lasnier, C.J., Rudakov, D.L., Watkins, J.G., West, W.P., Wong, C.P.C., "3-D DIVIMP Modeling Analysis of Methane Injection Into DIII-D Using the DiMES Porous Plug Injector," J. Nucl. Mater. **390–391**, 220 (2009); General Atomics Report GA-A26127 (2008).

Murakami, M., Park, J.M., Kinsey, J.E., Lao, L.L., Luce, T.C., Osborne, T.H., Staebler, G.M., St John, H.E., Snyder, P.B., Doyle, E.J., Budny, R.V., McCune, D., "Predictions of ITER Steady State Scenario Using Scaled Experimental Edge Profiles in DIII-D," Bull. Am. Phys. Soc. **54**, 165 (2009).

Murakami, M., Park, J.M., Petty, C.C., Luce, T.C., Heidbrink, W.W., Osborne, T.H., Prater, R., Wade, M.R., Anderson, P.M., Austin, M.E., Brooks, N.H., Budny, R.V., Challis, C.D., DeBoo, J.C., deGrassie, J.S., Ferron, J.R., Gohil, P., Hobirk, J., Holcomb, C.T., Hollmann, E.M., Hong, R.-M., Hyatt, A.W., Lohr, J., Lanctot, M.J., Makowski, M.A., McCune, D.C., Politzer, P.A., Scoville, J.T., St John, H.E., Suzuki, T., Taylor, T.S., West, W.P., Unterberg, E.A., Van Zeeland, M.A., Yu, J.H., "Off-Axis Neutral Beam Current Drive for Advanced Scenario Development in DIII-D," Nucl. Fusion **49**, 065031 (2009); General Atomics Report GA-26343 (2009).

Murphy, C.J., Scoville, J.T., Smith, J.P., "Analysis of DIII-D Upgraded Neutral Beamline Bending Magnet Thermal Shields," Proc. 23rd IEEE/NPSS Symp. on Fusion Engineering, San Diego, California, May 31–June 5, 2009; General Atomics Report GA-A26435 (2009).

Muscatello, C.M., Heidbrink, W.W., Kolesnichenko, Ya.I., Lutsenko, V.V., Yakovenko, Yu.V., Lazarus, E.A., Van Zeeland, M.A., Yu, J.H., "Fast Ion Transport during Sawteeth in the DIII-D Tokamak," Bull. Am. Phys. Soc. **54**, 160 (2009).

Nagy, A., DePasquale, S., Fredd, E., Greenough, N.L., Hosea, J.C., Nazikian, R., Wilson, J.R., Baity, F.W., Commaux, N., Goulding, R.H., Hanson, G.R., Horton, A.R., Murakami, M., Rasmussen, D.A., Ryan, P.M., Chamberlain, F., Petty, C.C., Pinsker, R.I., Porkolab, M., "Local Gas Puff Effects on Fast Wave Antenna Loading in H-mode," Bull. Am. Phys. Soc. **54**, 167 (2009).

Nazikian, R., Fu, G.Y., Gorelenkov, N.N., Kramer, G.J., Austin, M.E., Berk, H.L., Heidbrink, W.W., McKee, G.R., Shafer, M.W., Strait, E.J., Van Zeeland, M.A., "Global Geodesic Acoustic Modes Driven by Energetic Particles in the DIII-D Tokamak," Bull. Am. Phys. Soc. **54**, 167 (2009).

Neff, A., Garofalo, A.M., Luce, T.C., "Confinement Trends in DIII-D High Performance Plasmas," Bull. Am. Phys. Soc. **54**, 161 (2009).

Okabayashi, M., Bogatu, I.N., Chance, M.S., Chu, M.S., Garofalo, A.M., In, Y., Jackson, G.L., La Haye, R.J., Lanctot, M.J., Manickam, J., Marrelli, L., Martin, P., Navratil, G.A., Reimerdes, H., Strait, E.J., Takahashi, H., Welander, A.S., Bolzonella, T., Budny, R.V., Kim, J.S., Hatcher, R., Liu, Y.Q., Luce, T.C., "Comprehensive Control of Resistive Wall Modes in DIII-D Advanced Tokamak Plasmas," Nucl. Fusion **49** 125003 (2009); General Atomics Report GA-A26365 (2009).

Okabayashi, M., In, Y., Jackson, G.L., Bolzonella, T., Garofalo, A.M., Kim, J.S., La Haye, R.J., Lanctot, M.J., Marrelli, L., Martin, P., Reimerdes, H., Schaffer, M.J., Strait, E.J., "Exploring Robustness of Magnetic Feedback Stabilization on Current-Driven Resistive Wall Mode Stabilization," Proc. 36th EPS Conf. on Controlled Fusion and Plasma Physics, Sofia, Bulgaria, June 29–July 3, 2009; General Atomics Report GA-A26482 (2009).

Okabayashi, M., In, Y., Kim, J.S., Jackson, G.L., Garofalo, A.M., La Haye, R.J., Strait, E.J., Bolzonella, T., Marrelli, L., Martin, P., Lanctot, M.J., Reimerdes, H., "Physics Issues at the Initial Phase of Robust RWM Feedback," Bull. Am. Phys. Soc. **54**, 162 (2009).

Olstad, R.A., Callis, R.W., Doane, J.L., Grunloh, H.J., Kajiwara, K., Kasugai, A., Moeller, C.P., Murphy, C.J., Oda, Y., Sakamoto, K., Takahashi, K., "Design and High Power Testinng of ITER ECH and CD Transmission Line Components," Proc. 34th Int. Conf. on Infrared, Millimeter, and Terahertz Waves, Busan, Korea, September 21–25, 2009; General Atomics Report GA-A26505 (2009).

Orlov, D.M., Moyer, R.A., Evans, T.E., Mordijck, S., Osborne, T.H., Fenstermacher, M.E., Snyder, P.B., Unterberg, E.A., "Numerical Analysis of the Effects of Normalized Plasma Pressure on RMP ELM Suppression in DIII-D," Nucl. Fusion **49**, 034006 (2009); General Atomics Report GA-A26451 (2009).

Orlov, D.M., Moyer, R.A., Evans, T.E., Osborne, T.H., Snyder, P.B., Unterberg, E.A., Fenstermacher, M.E., "Modeling of Plasma Pressure Effects on ELM Suppression With RMP in DIII-D," Bull. Am. Phys. Soc. **54**, 163 (2009).

Osborne, T.H., Beurskens, M.N.A., Frassnetti, L., Groebner, R.J., Horton, L.D., Leonard, A.W., Lomas, P., Nunes, I., Saarelma, S., Snyder, P.B., Balboa, I., Flanagan, J., Giroud C., Giovannozzi, R.E., Kempenaars, M.A.H., Kohen, N., Loarte, A., Lonnroth, J., de la Luna, E., Maddison G., Maggi, C., McDonald, D.C., McKee, G.R., Pasqualotto, R., Saibene, G., Sartori, R., Solano, E.R., Suttrop, W., Wolfrum, E., Walsh, M., Yan, Z., Zabeo, L., Zarzoso, D., JET-EFDA Team, DIII-D Team, ITER ITPA H-mode Study Group, "Scaling of H-mode Pedestal and ELM Characteristics With Gyroradius in the JET and DIII-D Tokamaks," Proc. 12th Int. Workshop on H-mode Physics and Transport Barriers, Princeton, New Jersey, September 30–October 2, 2009; General Atomics Report GA-A26568 (2009).

Osborne, T.H., Groebner, R.J., Leonard, A.W., Snyder, P.B., Beurskens, M.N.A., Horton, L.D., Lomas, P., Saarelma, S., Frassnetti, L., Nunes, I., "Scaling of H-mode Pedestal and ELM Characteristics With Gyroradius," Bull. Am. Phys. Soc. **54**, 60 (2009).

Ou, Y., Schuster, E., Ferron, J.R., Luce, T.C., Walker, M.L., Humphreys, D.A., Casper, T.A., Meyer, W.H., "Development of a Robust Current Profile Feedback Controller in DIII-D," Bull. Am. Phys. Soc. **54**, 274 (2009).

Owen, L.W., Stacey, W.M., Groebner, R.J., Callen, J.D., Bonnin, X., "Analysis of Particle Transport in DIII-D H-mode Plasma With a Generalized Pinch-Diffusion Model," Bull. Am. Phys. Soc. **54**, 270 (2009).

Pablant, N.A., Burrell, K.H., Groebner, R.J., Kaplan, D.H., Holcomb, C.T., Hartog, D. Den, Summers, H.P., "Measurements of the Internal Magnetic Field and n=3 Level Populations of Injected Deuterium Using the B-Stark Motional Stark Effect Diagnostic on DIII-D," Bull. Am. Phys. Soc. **54**, 168 (2009).

Pace, D.C., Heidbrink, W.W., Lin, Z., Zhang, W., McKee, G.R., Murakami, M., Park, J.M., Petty, C.C., Van Zeeland, M.A., "Transport of Energetic Ions Due to Interaction With Microturbulence in DIII-D," Bull. Am. Phys. Soc. **54**, 269 (2009).

Park, J.M., Murakami, M., Luce, T.C., Politzer, P.A., Lao, L.L., Snyder, P.B., St John, H.E., Staebler, G.M., Doyle, E.J., "Scaled Experiment of ITER Operational Scenarios on DIII-D and Extrapolation to ITER," Bull. Am. Phys. Soc. **54**, 165 (2009).

Park, J.M., Murakami, M., Petty, C.C., Heidbrink, W.W., Osborne, T.H., Holcomb, C.T., Van Zeeland, M.A., Prater, R., Luce, T.C., Wade, M.R., Austin, M.E., Brooks, N.H., Budny, R.V., Challis, C.D., DeBoo, J.C., deGrassie, J.S., Ferron, J.R., Gohil, P., Hobirk, J., Hollmann, E.M., Hong, R.-M., Hyatt, A.W., Lohr, J., Lanctot, M.J., Makowski, M.A., McCune, D.C., Politzer, P.A., St John, H.E., Suzuki, T., West, W.P., Unterberg, E.A., Yu, J.H., "Validation of On- and Off-Axis Neutral Beam Current Drive Against Experiment in DIII-D," Phys. Plasmas **16**, 092508 (2009); General Atomics Report GA-A26376 (2009).

Parks, P.B., Lu, T., Samulyak, R., "Charging and *E*x*B* Rotation of Ablation Clouds Surrounding Refueling Pellets," Phys. Plasmas **16**, 060705 (2009); General Atomics Report GA-A26206 (2008).

Penaflor, B.G., Ferron, J.R., Walker, M.L., Humphreys, D.A., Leuer, J.A., Piglowski, D.A., Johnson, R.D., Xiao, B.J., Hahn, S.H., Gates, D.A., "Extending the Capabilities of the DIII-D Plasma Control System for Worldwide Fusion Research Collaborations," Fusion Engin. Design **390–391**, 242 (2009); General Atomics Report GA-A26193 (2008).

Petrie, T.W., Brooks, N.H., Evans, T.E., Ferron, J.R., Hyatt, A.W., Luce, T.C., Politzer, P.A., Petty, C.C., Schaffer, M.J., Fenstermacher, M.E., Lasnier, C.J., Porter, G.D., Watkins, J.G., Mordijck, S., "Initial Results from Radiating Divertor Experiments with RMP ELM Suppression," Bull. Am. Phys. Soc. **54**, 272 (2009).

Petrie, T.W., Porter, G.D., Brooks, N.H., Fenstermacher, M.E., Ferron, J.R., Groth, M., Hyatt, A.W., La Haye, R.J., Lasnier, C.J., Leonard, A.W., Luce, T.C., Politzer, P.A., Rensink, M.E., Schaffer, M.J., Wade, M.R., Watkins, J.G., "The Behavior of Injected Impurities Under Radiating Divertor Conditions With Puff-and-Pump Type Particle Control," Proc. 36th EPS Conf. on Controlled Fusion and Plasma Physics, Sofia, Bulgaria, June 29–July 3, 2009; General Atomics Report GA-A26459 (2009).

Petrie, T.W., Portr, G.D., Brooks, N.H., Fenstermacher, M.E., Ferron, J.R., Groth, M., Hyatt, A.W., La Haye, R.J., Lasnier, C.J., Leonard, A.W., Luce, T.C., Politzer, P.A., Rensink, M.E., Schaffer, M.J., Wade, M.R., Watkins, J.G., West, W.P., "Impurity Behavior Under Puff-and-Pump Radiating Divertor Conditions," Nucl. Fusion **49** 065013 (2009); General Atomics Report GA-A26338 (2009).

Petty, C.C., DeBoo, J.C., Evans, T.E., Ferron, J.R., Kinsey, J.E., La Haye, R.J., Luce, T.C., Osborne, T.H., Politzer, P.A., Reimerdes, H., Allen, S.L., Fenstermacher, M.E., Holcomb, C.T., Murakami, M., Doyle, E.J., Moyer, R.A., "Development of Hybrid Scenario on DIII-D for Burning Plasma Devices," Bull. Am. Phys. Soc. **54**, 166 (2009).

Piglowski, D.A., Humphreys, D.A., Walker, M.L., Ferron, J.R., Penaflor, B.G., Johnson, R.D., Sammuli, B.S., Xiao, B., Hahn, S.H., Mastrovito, D., "Accumulated Experiences From Implementations of the DIII-D Plasma Control System Worldwide," Proc. 23rd IEEE/NPSS Symp. on Fusion Engineering, San Diego, California, May 31–June 5, 2009; General Atomics Report GA-A26471 (2009).

Pinsker, R.I., Choi, M., Porkolab, M., Heidbrink, W.W., Zhu, Y., Baity, F.W., Hosea, J.C., "Synergy in Two-Frequency Fast Wave Cyclotron Harmonic Absorption in DIII-D," Bull. Am. Phys. Soc. **54**, 58 (2009).

Pinsker, R.I., Heidbrink, W.W., Porkolab, M., Baity, F.W., Choi, M., Hosea, J.C., Zhu, Y., "Snyergy in Two-Frequency Fast Wave Cyclotron Harmonic Absorption in DIII-D," Proc. 18th Top. Conf. on Radio Frequency Power in Plasmas, Gent, Belgium, June 24–26, 2009; General Atomics Report GA-A26474 (2009).

Politzer, P.A., Jackson, G.L., Humphreys, D.A., Luce, T.C., Hyatt, A.W., "Simulation of the ITER Rampdown Scenario on DIII-D," Bull. Am. Phys. Soc. **54**, 304 (2009).

Prater, R., Cengher, M., Gorelov, Y.A., Ponce, D., "Applications of Electron Cyclotron Waves in the DIII-D Tokamak," Proc. 18th Top. Conf. on Radio Frequency Power in Plasmas, Gent, Belgium, June 24–26, 2009; General Atomics Report GA-A26465 (2009).

Prater, R., deGrassie, J.S., Gohil, P., Osborne, T.H., Petty, C.C., Doyle, E.J., Hudson, B., Murakami, M., "Confinement and Pedestal Characteristics in H-mode With ECH Heating," Bull. Am. Phys. Soc. **54**, 185 (2009).

Reimerdes, H., Garofalo, A.M., Strait, E.J., Buttery, R.J., Chu, M.S., In, Y., Jackson, G.L., La Haye, R.J., Lanctot, M.J., Liu, Y.Q., Okabayashi, M., Park, J.-K., Schaffer, M.J., Solomon, W.M., "Effect of Resonant and Non-Resonant Magnetic Braking on Error Field Tolerance in High Beta Plasmas," Nucl. Fusion **49** 115001 (2009); General Atomics Report GA-A26382 (2009).

Reimerdes, H., Lanctot, M.J., Hanson, J.M., Garofalo, A.M., Chu, M.S., Jackson, G.L., La Haye, R.J., Schaffer, M.J., Strait, E.J., Schmitz, O., Liu, Y.Q., Okabayashi, M., Solomon, W.M., "Measurement and Modeling of the Plasma Response to Externally Applied Non-axisymmetric Magnetic Fields," Bull. Am. Phys. Soc. **54**, 162 (2009).

Ren, Q., Lao, L.L., Chu, M.S., St John, H.E., Abla, G., Collier, A., Prater, R., Park, J.M., Li, G., Guo, W., Pan, C., Srinivasan, R., Worrall, M., "Progress in the Development of an Integrated Modeling Tool to Support DIII-D and EAST," Bull. Am. Phys. Soc. **54**, 24 (2009).

Rhodes, T.L., Peebles, W.A., Schmitz, L., Hillesheim, J.C., Wang, G., Zeng, L., Doyle, E.J., Holland, C., McKee, G.R., White, A.E., DeBoo, J.C., Burrell, K.H., Petty, C.C., "Turbulence and Transport Dependence on Plasma Shape in DIII-D," Bull. Am. Phys. Soc. **54**, 268 (2009).

Rost, J.C., Porkolab, M., Dorris, J.R., Burrell, K.H., "Study of the Variation of Turbulence With Poloidal Angle on DIII-D Using Phase Contrast Imaging," Bull. Am. Phys. Soc. **54**, 270 (2009).

Rudakov, D.L., Boedo, J.A., Yu, J.H., Brooks, N.H., Fenstermacher, M.E., Groth, M., Hollmann, E.M., Lasnier, C.J., McLean, A.G., Moyer, R.A., Stangeby, P.C., Tynan, G.R., Wampler, W.R., Watkins, J.G., West, W.P., Wong, C.P.C., Zeng, L., Bastasz, R.J., Buchenauer, D., Whaley, J., "ELM-Induced Plasma Wall Interactions in DIII-D," J. Nucl. Mater. **390–391**, 785 (2009); General Atomics Report GA-A26117 (2008).

Rudakov, D.L., Leuer, J.A., Moyer, R.A., Pitts, R.A., Leonard, A.W., Jackson, G.L., Lasnier, C.J., Stangeby, P.C., Watkins, J.G., Zeng, L., "SOL Width Studies for ITER Ramp-up," Bull. Am. Phys. Soc. **54**, 185 (2009).

Rudakov, D.L., Litnovsky, A., West, W.P., Yu, J.H., Boedo, J.A., Bray, B.D., Brezinsek, S., Brooks, N.H., Fenstermacher, M.E., Groth, M., Hollmann, E.M., Huber, A., Hyatt, A.W., Krasheninnikov, S.I., Lasnier, C.J., Moyer, R.A., Pigarov, A.Yu., Philipps, V., Pospieszczyk, A., Smirnov, R.D., Sharpe, J.P., Solomon, W.M., Watkins, J.G., Wong, C.P.C., "Dust Studies in DIII-D and TEXTOR," Nucl. Fusion **49**, 085022 (2009); General Atomics Report GA-A26386 (2009).

Rudakov, D.L., Wong, C.P.C., Litnovsky, A., Wampler, W.R., Boedo, J.A., Brooks, N.H., Fenstermacher, M.E., Groth, M., Hollmann, E.M., Jacob, W., Krasheninnikov, S.I., Krieger, K., Lasnier, C.J., Leonard, A.W., McLean, A.G., Marot, M., Moyer, R.A., Petrie, T.W., Philipps, V., Smirnov, R.D., Stangeby, P.C., Watkins, J.G., West, W.P., Yu, J.H., "Overview of the Recent DiMES and MiMES Experiments in DIII-D," Proc. 12th Int. Workshop on Plasma Facing Materials and Components For Fusion Applications, Jülich, Germany, May 11–14, 2009; General Atomics Report GA-A26426 (2009).

Sammuli, B.S., Walker, M.L., Humphreys, D.A., Ferron, J.R., Johnson, R.D., Penaflor, B.G., Piglowski, D.A., Hahn, S.H., Hong, J., Xiao, B., Yuan, Q., "Approaches to Tokamak Off-Normal Event Detection and Response at DIII-D, KSTAR, and EAST," Proc. 7th IAEA Technical Committee Meeting on Control Data Acquisition and Remote Participation for Fusion Research, Aix-en-Provence, France, June 15–19, 2009 in Fusion Engin. Design **85**, 456 (2010); General Atomics Report GA-A26467 (2009).

Schaffer, M.J., Evans, T.E., Fenstermacher, M.E., Moyer, R.A., DIII-D Team, "ELM Suppression by Resonant Magnetic Perturbations at DIII-D," Proc. 23rd IEEE/NPSS Symp. on Fusion Engineering, San Diego, California, May 31–June 5, 2009; General Atomics Report GA-A26461 (2009).

Schmitz, L., Wang, G., Hillesheim, J.C., Peebles, W.A., Rhodes, T.L., Doyle, E.J., Zeng, L., Holland, C., White, A.E., McKee, G.R., DeBoo, J.C., deGrassie, J.S., Burrell, K.H., Petty, C.C., "Measurements of the Wavenumber Spectrum of Multi-scale Turbulence in the Core of DIII-D H-mode Plasmas," Bull. Am. Phys. Soc. **54**, 270 (2009).

Schmitz, L., White, A.E., Wang, G., DeBoo, J.C., deGrassie, J.S., McKee, G.R., Hillesheim, J.C., Peebles, W.A., Rhodes, T.L., Carter, T.A., Doyle, E.J., Zeng, L., Burrell, K.H., Petty, C.C., Kinsey, J.E., Solomon, W.M., Staebler, G.M., DIII-D Team, "Observation of Reduced Core Electron Temperature Fluctuations and Intermediate Wavenumber Density Fluctuations in H-Mode Plasmas," Nucl. Fusion **49**, 095004 (2009); General Atomics Report GA-A26356 (2009).

Schmitz, O., Evans, T.E., Fenstermacher, M.E., Unterberg, E.A., Austin, M.E., Bray, B.D., Brooks, N.H., Frerichs, H., Groth, M., Jakubowski, M.W., Lasnier, C.J., Lehnen, M., Leonard, A.W., Mordijck, S.A., Moyer, R.A., Osborne, T.H., Reiter, D., Samm, U., Schaffer, M.J., Unterberg, B., West, W.P., DIII-D Team, TEXTOR Team, "Resonant Pedestal Pressure Reduction Induced by a Thermal Transport Enhancement Due to Stochastic Magnetic Boundary Layers in High-Temperature Plasmas," Phys. Rev. Lett. **103**, 165005 (2009); General Atomics Report GA-A26396 (2009).

Schmitz, O., Frerichs, H., Austin, M.E., Bray, B.D., Evans, T.E., Osborne, T.H., Reimerdes, H., Fenstermacher, M.E., Lasnier, C.J., Jakubowski, M.W., Mordijck, S., Moyer, R.A., Unterberg, E.A., "Observations of Thermal Transport Enhancement in Stochastic Boundary Experiments at DIII-D and TEXTOR," Bull. Am. Phys. Soc. **54**, 58 (2009).

Scoville, J.T., DIII-D Team, "Recent Results and Planned Upgrades for the DIII-D Tokamak," Proc. 23rd IEEE/NPSS Symp. on Fusion Engineering, San Diego, California, May 31–June 5, 2009; General Atomics Report GA-A26450 (2009).

Shafer, M.W., McKee, G.R., Austin, M.E., Burrell, K.H., Fonck, R.J., Schlossberg, D.J., "Localized Turbulence Suppression and Increased Flow Shear Near the q=2 Surface During Internal Transport Barrier Formation," Phys. Rev. Lett. **103**, 075004 (2009); General Atomics Report GA-A26203 (2009).

Shafer, M.W., McKee, G.R., Fonck, R.J., Schlossberg, D.J., Yan, Z., Holland, C., White, A.E., "2D Core Turbulence Properties on DIII-D," Bull. Am. Phys. Soc. **54**, 268 (2009).

Snyder, P.B., Aiba, N., Beurskens, M., Groebner, R.J., Horton, L.D., Hubbard, A.E., Hughes, J.W., Huysmans, G.T.A., Kamada, Y., Kirk, A., Konz, C., Leonard, A.W., Lonnroth, J., Maggi, C.F., Maingi, R., Osborne, T.H., Oyama, N., Pankin, A., Saarelma, S., Saibene, G., Terry, J.L., Urano, H., Wilson, H.R., "Pedestal Stability Comparison and ITER Pedestal Predictions," Nucl. Fusion **49** 085035 (2009); General Atomics Report GA-A26364 (2009).

Snyder, P.B., Groebner, R.J., Leonard, A.W., Osborne, T.H., Wilson, H.R., "Further Development of a Predictive Pedestal Model," Bull. Am. Phys. Soc. **54**, 270 (2009).

Snyder, P.B., Groebner, R.J., Leonard, A.W., Osborne, T.H., Wilson, H.R., "Development and Validation of a Predictive Model for Pedestal Height," Phys. Plasmas **16**, 056118 (2009); General Atomics Report GA-A26341 (2009).

Solomon, W.M., "Generation and Sustainment of Rotation in Tokamaks," Bull. Am. Phys. Soc. **54**, 269 (2009).

Solomon, W.M., Burrell, K.H., Garofalo, A.M., Cole, A.J., Budny, R.V., deGrassie, J.S., Heidbrink, W.W., Jackson, G.L., Lanctot, M.J., Nazikian, R., Reimerdes, H., Strait, E.J., VanZeeland, M.A, DIII-D Rotation Physics Task Force, "Advances in Understanding the Generation and Evolution of the Toroidal Rotation Profile on DIII-D," Nucl. Fusion **49**, 085005 (2009); General Atomics Report GA-A26342 (2009).

Stacey, W.M., Groebner, R.J., "Evaluation of Particle Pinch and Diffusion Coefficients in the Edge Pedestal of DIII-D H-mode Discharges," Bull. Am. Phys. Soc. **54**, 274 (2009).

Stacey, W.M., Petrie, T.W., "An Interpretation of "Puff & Pump" Radiative Divertor Experiments in DIII-D," Bull. Am. Phys. Soc. **54**, 351 (2009).

Stangeby, P.C., "Some Divertor Scaling Considerations," Bull. Am. Phys. Soc. **54**, 273 (2009).

Stemprok, R., Jackson, G.L., Cary, W.P., Campbell, G.L., Nagy, A., "Operation of a Versatile Multi-Power Supply System Driving Non-Axisymmetric Coil Sets on the DIII-D Tokamak," Proc. 23rd IEEE/NPSS Symp. on Fusion Engineering, San Diego, California, May 31–June 5, 2009; General Atomics Report GA-A26432 (2009).

Strait, E.J., DIII-D Team, "DIII-D Research in Support of ITER," Nucl. Fusion **49** 104008 (2009); General Atomics Report GA-A26347 (2009).

Tooker, J.F., Huynh, P., Street, R.W., "Solid-State High Voltage Modulator and Its Application to RF Source High Voltage Power Supplies," Fusion Engin. Design **84**. 1857 (2009); General Atomics Report GA-A26129 (2008).

Tooker, J.F., Huynh, P., Street, R.W., "Solid-State High-Voltage Crowbar Utilizing Series-Connected Thyristors," Proc. 17th IEEE Int. Pulsed Power Conf., Washington, DC, June 29–July 2, 2009; General Atomics Report GA-A26497 (2009).

Turco, F., Luce, T.C., Brennan, D.P., Turnbull, A.D., Ferron, J.R., Petty, C.C., Politzer, P.A., LoDestro, L.L., Pearlstein, L.D., Jayakumar, R.J., Casper, T.A., Holcomb, C.T., Murakami, M., "Modeling Steady-State DIII-D Plasmas for Tearing Stability Studies," Bull. Am. Phys. Soc. **54**, 165 (2009).

Turco, F., Luce, T.C., Ferron, J.R., Petty, C.C., Politzer, P.A., Turnbull, A.D., Brennan, D.P., Murakami, M., Lodestro, L.L., Pearlstein, L.D., Casper, T.A., Jayakumar, R.J., Holcomb, C.T., "Measurement and Modeling of Tearing Mode Stability for Steady-State Plasmas in DIII-D," Proc. 36th EPS Conf. on Controlled Fusion and Plasma Physics, Sofia, Bulgaria, June 29–July 3, 2009; General Atomics Report GA-A26472 (2009).

Turnbull, A.D., "A New View of Internal Kink Modes and Their Relation to the Sawtooth Instability," Bull. Am. Phys. Soc. **54**, 94 (2009).

Unterberg, E.A., "Particle Exhaust and Scrape-off Layer Conditions During RMPs in Deuterium and Helium Discharges on DIII-D," Bull. Am. Phys. Soc. **54**, 272 (2009).

Unterberg, E.A., Brooks, N.H., Evans, T.E., Fenstermacher, M.E., Hillis, D.L., Maingi, R., Mordijck, S., Moyer, R.A., Osborne, T.H., Petrie, T.W., Watkins, J.G., "Experimental Comparison of Recycling and Pumping Changes During Resonant Magnetic Perturbation Experiments at Low and High Collisionality in DIII-D," J. Nucl. Mater. **390–391**, 486 (2009); General Atomics Report GA-A26120 (2008).

Unterberg, E.A., Canik, J.M., Evans, T.E., Maingi, R., Schmitz, O., Brooks, N.H., Fenstermacher, M.E., Moyer, R.A., Watkins, J.G., "Particle Exhaust and Scrape-Off Layer Conditions in ELM Suppressed Resonant Magnetic Perturbation Discharges on DIII-D," Proc. 36th EPS Conf. on Controlled Fusion and Plasma Physics, Sofia, Bulgaria, June 29–July 3, 2009; General Atomics Report GA-A26473 (2009).

Unterberg, E.A., Evans, T.E., Maingi, R., Brooks, N.H., Fenstermacher, M.E., Mordijck, S., Moyer, R.A., "Demonstration of Particle Exhaust Control During ELM Suppression by Resonant Magnetic Perturbation in DIII-D," Nucl. Fusion **49**, 092001 (2009); General Atomics Report GA-A26377 (2009).

Van Zeeland, M.A., Heidbrink, W.W., Nazikian, R., Austin, M.E., Berk, H.L., Gorelenkov, N.N., Holcomb, C.T., Hyatt, A.W., Kramer, G.J., Lohr, J., McKee, G.R., Petty, C.C., Prater, R., Solomon, W.M., Spong, D.A., "Measurements, Modeling, and Electron Cyclotron Heating Modification of Alfvenic Eigenmode Activity in DIII-D," Nucl. Fusion **49**, 065003 (2009); General Atomics Report GA-A26344 (2009).

Van Zeeland, M.A., Heidbrink, W.W., Yu, J.H., "Fast Ion D_α Imaging in the DIII-D Tokamak," Plasma Phys. Control. Fusion **51**, 055001 (2009); General Atomics Report GA-A26623 (2008).

Van Zeeland, M.A., Yu, J.H., Brooks, N.H., Burrell, K.H., Groebner, R.J., Hyatt, A.W., Luce, T.C., Wade, M.R., Heidbrink, W.W., Solomon, W.M., "Active and Passive Spectroscopic Imaging in the DIII-D Tokamak," Bull. Am. Phys. Soc. **54**, 167 (2009).

Van Zeeland, M.A., Yu, J.H., Heidbrink, W.W., Brooks, N.H., Burrell, K.H., Chu, M.S., Hyatt, A.W., Nazikian, R., Pablant, N.A., Pace, D.C., Solomon, W.M., Wade, M.R., "Visible Imaging of Injected Neutrals, the Fast Ion Profile, and Internal MHD in the DIII-D Tokamak," Proc. 11th IAEA Technical Meeting on Energetic Particles in Magnetic Confinement Systems, Kyiv, Ukraine, September 21–23, 2009; General Atomics Report GA-A26554 (2009).

Volpe, F.A.G., Austin, M.E., La Haye, R.J., Lohr, J., Prater, R., Strait, E.J., Welander, A.S., "Advanced Techniques for Neoclassical Tearing Mode Control in DIII-D," Phys. Plasmas **16**, 102502 (2009); General Atomics Report GA-A26357 (2009).

Wade, M.R., "Physics and Engineering Issues Associated With Edge Localized Mode Control in ITER," Fusion Engin. Design **84**, 178 (2009); General Atomics Report GA-A26319 (2008).

Wade, M.R., "Physics and Engineering Issues Associated with Edge Localized Mode Control in ITER," presented at the 25th Symp. on Fusion Technology, Rostock, Germany, September 15–19, 2008, in Fusion Engin. Design **84**, 178 (2009); General Atomics Report GA-A26319 (2008). DEC 2008

Walker, M.L., Sammuli, B.S., Humphreys, D.A., Ferron, J.R., Johnson, R.D., Penaflor, B.G., Piglowski, D.A., Strait, E.J., "Development of Off-Normal and Fault Event Detection and Response Techniques for ITER and DEMO," Bull. Am. Phys. Soc. **54**, 164 (2009).

Wang, G., Peebles, W.A., Rhodes, T.L., Hillesheim, J.C., Doyle, E.J., Schmitz, L., Zeng, L., White, A.E., McKee, G.R., Petty, C.C., Burrell, K.H., Solomon, W.M., "Core Turbulence and Flow Dynamics Across L-H Transition on DIII-D," Bull. Am. Phys. Soc. **54**, 268 (2009).

Watkins, J.G., Evans, T.E., Joseph, I., Lasnier, C.J., Moyer, R.A., Rudakov, D.L., Schmitz, O., Jakubowski, M., Fenstermacher, M.E., "Particle, Heat, and Sheath Power Transmission Factor Profiles During ELM Suppression Experiments on DIII-D," J. Nucl. Mater. **390–391**, 839 (2009); General Atomics Report GA-A26123 (2008).

Watkins, J.G., Lasnier, C.J., Leonard, A.W., Evans, T.E., Pitts, R.A., Stangeby, P.C., Boedo, J.A., Moyer, R.A., Rudakov, D.L., "Characteristics of the Secondary Divertor on DIII-D," Bull. Am. Phys. Soc. **54**, 273 (2009).

West, W.P., Groth, M., Hyatt, A.W., Brooks, N.H., Jackson, G.L., Wade, M.R., Greenfield, C.M., "Plasma Impurity Content, Gas Fueling, and Exhaust on DIII-D Over Extended Periods Between Boronizations," J. Nucl. Mater. **390–391**, 461 (2009); General Atomics Report GA-A26115 (2008).

White, A.E., "Simultaneous Measurement of Electron Temperature and Density Fluctuations in the Core of DIII-D Plasmas," Bull. Am. Phys. Soc. **54**, 105 (2009).

Wingen, A., Evans, T.E., Spatschek, K.H., "Footprint Structures Due to Resonant Magnetic Perturbations in DIII-D," Phys. Plasmas **16**, 042504 (2009); General Atomics Report GA-A26100 (2008).

Wingen, A., Evans, T.E., Spatschek, K.H., "High Resolution Numerical Studies of Separatrix Splitting Due to Non-Axisymmetric Perturbation in DIII-D," Nucl. Fusion **49** 055027 (2009); General Atomics Report GA-A26188 (2008).

Wong, C.P.C., "Innovative Tokamak DEMO First Wall and Divertor Material Concepts," J. Nucl. Mater. **390–391**, 1026 (2009); General Atomics Report GA-A26104 (2008).

Wong, C.P.C., Chen, B., Hassanein, A., "Low-Z Loaded Tungsten Surface for DEMO First Wall and Divertor," Proc. 14th Int. Conf. on Fusion Reactor Materials, Sapporo, Japan, September 7–12, 2009; General Atomics Report GA-A26527 (2009).

Xie, F., Schuster, E., Humphreys, D.A., Walker, M.L., In, Y., "Model-based Adaptive Control of Resistive Wall Modes in DIII-D," Bull. Am. Phys. Soc. **54**, 274 (2009).

Yan, Z., McKee, G.R., Shafer, M.W., Groebner, R.J., Snyder, P.B., Burrell, K.H., Osborne, T.H., Leonard, A.W., Rhodes, T.L., Zeng, L., “Pedestal Density Fluctuations During Quiescent and ELMing H-mode Plasmas,” Bull. Am. Phys. Soc. **54**, 60 (2009).

Yip, H.H., Mauzey, P.S., Anderson, P.M., “DIII-D Water-Cooling System Upgrades Through Modeling and Power Saving Projects,” Proc. 23rd IEEE/NPSS Symp. on Fusion Engineering, San Diego, California, May 31–June 5, 2009; General Atomics Report GA-A26457 (2009).

Yu, J.H., James, A.N., Hollmann, E.M., Boedo, J.A., Commaux, N., Jernigan, T.C., Evans, T.E., Humphreys, D.A., Strait, E.J., Van Zeeland, M.A., Wesley, J.C., “Fast Imaging of Runaway Electron Beams in DIII-D,” Bull. Am. Phys. Soc. **54**, 165 (2009).

Yu, J.H., Rudakov, D.L., Pigarov, A.Yu., Smirnov, R.D., Brooks, N.H., Muller, S.H., West, W.P., “Fast Camera Imaging of Dust in the DIII-D Tokamak,” J. Nucl. Mater. **390–391**, 216 (2009); General Atonics Report GA-A26112 (2008).

Yu, J.H., Van Zeeland, M.A., Chu, M.S., Izzo, V.A., La Haye, R.J., “Fast Imaging of Transients and Coherent MHD Modes in DIII-D,” Phys. Plasmas **16**, 056114 (2009); General Atomics Report GA-A26337 (2008).

Zeng, L., Doyle, E.J., Rhodes, T.L., Peebles, W.A., Petty, C.C., DeBoo, J.C., Solomon, W.M., Tala, T., “High Resolution Density Profile Measurement for Electron Transport Studies in DIII-D,” Bull. Am. Phys. Soc. **54**, 270 (2009).

Zhang, W.L., “Energetic Particle Transport by Microturbulence,” Bull. Am. Phys. Soc. **54**, 344 (2009).

12.5. PUBLICATIONS FOR FY08

Abrams, T., Pinsker, R.I., Baity, F.W., Yoon, J.-S., "Applications of an Ultra-high-speed Digitizer in ICRF Experiments on DIII-D," Bull. Am. Phys. Soc. **53**, 131 (2008).

Austin, M.E., Gentle, K.W., Holcomb, C.T., McKee, G.R., Shafer, M.W., Petty, C.C., Rhodes, T.L., "Transport Changes Near *q*=1 Surfaces in DIII-D," Bull. Am. Phys. Soc. **53**, 251 (2008).

Baylor, L.R., Jernigan, T.C., Commaux, N., Combs, S.K., Evans, T.E., Parks, P.B., Fenstermacher, M.E., Moyer, R.A., Yu, J.H., "ELMs Triggered From Deuterium Pellets Injected into DIII-D," Bull. Am. Phys. Soc. **53**, 143 (2008).

Baylor, L.R., Jernigan, T.C., Commaux, N., Combs, S.K., Foust, C.R., Parks, P.B., Evans, T.E., Fenstermacher, M.E., Moyer, R.A., Osborne, T.H., Yu, J.H., "ELMs Triggered From Deuterium Pellets Injected Into DIII-D and Extrapolation to ITER," Proc. 35th EPS Conf. on Controlled Fusion and Plasma Physics, Crete, Greece, June 9–13, 2008, ; General Atomics Report GA-A26143 (2008).

Bogatu, I.N., Galkin, S.A., Kim, J.S., "Disruption Mitigation with Hyper-Velocity High-Density C60-Fullerene Plasma Jets," Bull. Am. Phys. Soc. **53**, 140 (2008).

Boivin, R.L., "Role of Fusion Product Measurements in Physics Understanding of a Burning Plasma," presented at the Intl. Wkshp. on Burning Plasma Diagnostics, September 24–28, 2007, Varenna, Italy, in AIP Conf. Proc. **988**, 259 (2008); General Atomics Report GA-A25955 (2007).

Bray, B.D., West, W.P., Rudakov, D.L., "Dust Production by Impulsive ELM Heating During Plasma Discharges at DIII-D," Bull. Am. Phys. Soc. **53**, 141 (2008).

Brooks. N.H., Colchin, R.J., Fehling, D.T., Hillis, D.L., Mu, Y., Unterberg, E.A., "Filterscopes — Spectral Line Monitors for Long-Pulse Plasma Devices," Rev. Sci. Instrum. **79**, 10F330 (2008); General Atomics Report GA-A26090 (2008).

Burrell, K.H., "Edge Pedestal Control in Quiescent H-Mode Discharges in DIII-D Using Co Plus Counter Neutral Beam Injection," Bull. Am. Phys. Soc. **53**, 159 (2008).

Burrell, K.H., Osborne, T.H., Snyder, P.B., West, W.P., Chu, M.S., Fenstermacher, M.E., Gohil, P., Solomon, W.M., "Edge Pedestal Control in Quiescent H-mode Discharges in DIII-D Using Co- Plus Counter-Neutral Beam Injection," Proc. 22nd IAEA Fusion Energy Conf., Geneva, Switzerland, October 13–18, 2008; General Atomics Report GA-A26244 (2008).

Buttery, R.J., deGrassie, J.S., Jackson, G.L., La Haye, R.J., Strait, E.J., Maraschek, M., Reimerdes, H., DIII-D Team, "Influence of Rotation and Error Field on Tearing Stability in Low Torque ITER-like Plasmas in DIII-D," Bull. Am. Phys. Soc. **53**, 200 (2008).

Casper, T.A., Meyer, W.H., Humphreys, D.A., Hyatt, A.W., Jackson, G.L., Luce, T.C., "Experimental and Model Validation of ITER Operational Scenarios," Bull. Am. Phys. Soc. **53**, 202 (2008).

Cengher, M., Lohr, J., Gorelov, I.A., Grosnickle, W.H., Ponce, D., Johnson, P., "Measurements of the ECH Power and of the Transmission Line Losses on DIII-D," Proc. 15th Joint Workshop on Electron Cyclotron Emission and Electron Cyclotron Resonance Heating, Yosemite Park, California, March 10–13, 2008; General Atomics Report GA-A26250 (2008).

Cengher, M., Lohr, J., Gorelov, I.A., Ponce, D., "Progress on Measurements of the ECH Power on DIII-D," Bull. Am. Phys. Soc. **53**, 258 (2008).

Chiu, H.K., Noraky, S., Hong, R.-M., "A Network-Based Telemetry Upgrade for the DIII-D Neutral Beam Power Diagnostics," 17th ANS Topical Mtg. on the Technology of Fusion Energy, November 13-16, 2006, Albuquerque, New Mexico, in Fusion Sci. Technol. **52**(4), 1051 (2007); General Atomics Report GA-A25638 (2006).

Commaux, N., Baylor, L.R., Jernigan, T.C., Pegourie, B., Geraud, A., Parks, P.B., "Influence of the ∇B-drift on the Pellet Particle Deposition in DIII-D and Comparison with Tore Supra," Bull. Am. Phys. Soc. **53**, 143 (2008).

DeBoo, J.C., Staebler, G.M., Rhodes, T.L., Schmitz, L., White, A.E., Doyle, E.J., Peebles, W.A., Holland, C., "Modulation of TEM Turbulence in DIII-D L-mode Discharges," Bull. Am. Phys. Soc. **53**, 201 (2008).

deGrassie, J.S., Groebner, R.J., Burrell, K.H., Solomon, W.M., "Intrinsic Rotation in H-mode Pedestal in DIII-D," Proc. 22nd IAEA Fusion Energy Conf., Geneva, Switzerland, October 13–18, 2008; General Atomics Report GA-A26240 (2008).

deGrassie, J.S., Groebner, R.J., Burrell, K.H., Waltz, R.E., Solomon, W.M., "Boundary Intrinsic Velocity in DIII-D H-modes," Bull. Am. Phys. Soc. **53**, 200 (2008).

DIII-D Research Team, "DIII-D Year 2008 Experiment Plan," General Atomics Report GA-A26134 (2008).

Doane, J.L., "Design of Circular Corrugated Waveguides to Transmit Millimeter Waves at ITER," Special Issue Fusion Sci. Technol. **53**(1), 159 (2008); General Atomics Report GA-A25567 (2007).

Dorris, J.R., Rost, J.C., Porkolab, M., Burrell, K.H., "Localized Measurement of Short Wavelength Plasma Fluctuations Using the DIII-D Phase Contrast Imaging Diagnostic," Bull. Am. Phys. Soc. **53**, 253 (2008).

Doyle, E.J., "Demonstration of ITER Operational Scenarios on DIII-D," Bull. Am. Phys. Soc. **53**, 140 (2008).

Doyle, E.J., Budny, R.V., DeBoo, J.C., Ferron, J.R., Jackson, G.L., Luce, T.C., Murakami, M., Osborne, T.H., Park, J.M., Politzer, P.A., Reimerdes, H., Casper, T.A., Challis, C.D., Groebner, R.J., Holcomb, C.T., Hyatt, A.W., La Haye, R.J., McKee, G.R., Petrie, T.W., Petty, C.C., Rhodes, T.L., Shafer, M.W., Snyder, P.B., Strait, E.J., Wade, M.R., Wang, G., West, W.P., Zeng, L., "Demonstration of ITER Operational Scenarios on DIII-D," Proc. 22nd IAEA Fusion Energy Conf., Geneva, Switzerland, October 13–18, 2008; General Atomics Report GA-A26270 (2008).

Eidietis, N.W., Hahn, S.H., Oh, Y.K., Humphreys, D.A., Hyatt, A.W., Leuer, J.A., Walker, M.L., "Real-Time Plasma Control During KSTAR First Plasma," Bull. Am. Phys. Soc. **53**, 258 (2008).

Elder, J.D., Stangeby, P.C., Allen, S.L., Fenstermacher, M.E., Groth, M., Boedo, J.A., Rudakov, D.L., Bray, B.D., Brooks, N.H., Leonard, A.W., West, W.P., Watkins, J.G., Unterberg, E.A., "OEDGE Modeling of SOL Flow Experiments on DIII-D," Bull. Am. Phys. Soc. **53**, 257 (2008).

Evans, T.E., Brooks, N.H., Schaffer, M.J., Unterberg, E.A., Fenstermacher, M.E., Lasnier, C.J., Frerichs, H., Schmitz, O., Unterberg, B., Jakubowski, M.W., Mordijck, S., Moyer, R.A., Watkins, J.G., "Spectral Effects on Plasma Performance in ITER Similar DIII-D RMP H-modes," Bull. Am. Phys. Soc. **53**, 142 (2008)

Evans, T.E., Fenstermacher, M.E., Jakubowski, M., Moyer, R.A., Osborne, T.H., Schaffer, M.J., Schmitz, O., Watkins, J.G., Zeng, L., Baylor, L.R., Boedo, J.A., Burrell, K.H., deGrassie, J.S., Gohil, P., Joseph, I., Lasnier, C.J., Leonard, A.W., Mordijck, S., Petty, C.C., Pinsker, R.I., Rhodes, T.L., Rost, J.C., Snyder, P.B., Unterberg, E.A., West, W.P., "Operating Characteristics in DIII-D ELM-Suppressed RMP H-modes With ITER Similar Shapes," Proc. 22nd IAEA Fusion Energy Conf., Geneva, Switzerland, October 13–18, 2008; General Atomics Report GA-A26245 (2008).

Evans, T.E., Fenstermacher, M.E., Moyer, R.A., Osborne, T.H., Watkins, J.G., Gohil, P., Joseph, I., Schaffer, M.J., Baylor, L.R., Bécoulet, M., Boedo, J.A., Burrell, K.H., Finken, K.H., Jernigan, T.C., Jakubowski, M., Lasnier, C.J., Lehnen, M., Leonard, A.W., Lonnroth, J., Nardon, E., Parail, V., Schmitz, O., Unterberg, B., West, W.P., "RMP ELM Suppression in DIII-D Plasmas with ITER Similar Shapes and Collisionalities," Nucl. Fusion **48**, 024002 (2008); General Atomics Report GA-A25786 (2007).

Fenstermacher, M.E., Evans, T.E., Osborne, T.H., Schaffer, M.J., deGrassie, J.S., Groebner, R.J., Leonard, A.W., Snyder, P.B., Moyer, R.A., "Comparison of ELM Control Using One vs Two Rows of RMP Coils in DIII-D," Bull. Am. Phys. Soc. **53**, 83 (2008).

Ferron, J.R., Basiuk, V., Casper, T.A., DeBoo, J.C., Doyle, E.J., Gao, Q., Garofalo, A.M., Greenfield, C.M., Holcomb, C.T., Luce, T.C., Murakami, M., Ou, Y., Petty, C.C., Politzer, P.A., Reimerdes, H., Schuster, E., Schneider, M., Wang, A., "Development in DIII-D of High Beta Discharges Appropriate for Steady-State Tokamak Operation WIth Burning Plasmas," Proc. 22nd IAEA Fusion Energy Conf., Geneva, Switzerland, October 13–18, 2008; General Atomics Report GA-A26257 (2008).

Ferron, J.R., DeBoo, J.C., Luce, T.C., Petrie, T.W., Petty, C.C., Politzer, P.A., Reimerdes, H., Schneider, M., Casper, T.A., Holcomb, C.T., Park, J.M., Murakami, M., Ou, Y., Schuster, E., Doyle, E.J., "Studies in DIII-D of High Beta Discharge Scenarios Appropriate for Steady-State Tokamak Operation with Burning Plasmas," Bull. Am. Phys. Soc. **53**, 201 (2008).

Fitzpatrick, B.W.N., Davis, J.W., Haasz, A.A., Stangeby, P.C., Allen, S.L., Ellis, R., West, W.P., "Assessment of Collateral Effects to Tokamak Systems During Planned Air Baking of DIII-D to Simulate ITER Tritium Removal," Bull. Am. Phys. Soc. **53**, 257 (2008).

Frerichs, H.G., Schmitz, O., Harting, D., Reiter, D., Unterberg, B., Feng, Y., Evans, T.E., Fenstermacher, M.E., Joseph, I., Moyer, R.A., "3D Numerical Analysis of Magnetic Topology and Edge Transport for RMP Limiter Scenarios at TEXTOR-DED and DIII-D," Proc. 35th EPS Conf. on Controlled Fusion and Plasma Physics, Crete, Greece, June 9–13, 2008; General Atomics Report GA-A26141 (2008).

Friis, Z.W., Stacey, W.M., Groebner, R.J., Rognlien, T.D., "Implementation of GTNEUT for Analysis of the Effect of Neutral Particles on Edge Phenomena in DIII-D," Bull. Am. Phys. Soc. **53**, 257 (2008).

Garofalo, A.M., "Plasma Rotation Driven by Static Nonresonant Magnetic Fields," Bull. Am. Phys. Soc. **53**, 21 (2008).

Garofalo, A.M., Burrell, K.H., DeBoo, J.C., deGrassie, J.S., Jackson, G.L., Lanctot, M.J., Reimerdes, H., Schaffer, M.J., Solomon, W.M., Strait, E.J., DIII-D Team, "Observation of Plasma Rotation Driven by Static Non-Axisymmetric Magnetic Fields in a Tokamak," Phys. Rev. Lett. **101**, 195005 (2008); General Atomics Report GA-A26105 (2008).

Gohil, P., "H-mode Power Threshold, Pedestal and ELM Characteristics and Transport in Hydrogen Plasmas in DIII-D," Bull. Am. Phys. Soc. **53**, 83 (2008).

Gohil, P., deGrassie, J.S., McKee, G.R., Petty, C.C., Schlossberg, D.J., "H-mode Power Threshold for EC and NBI Heated Discharges in DIII-D and Their Dependence on the Input Torque," Proc. 35th EPS Conf. on Controlled Fusion and Plasma Physics, Crete, Greece, June 9–13, 2008; General Atomics Report GA-A26135 (2008).

Gohil, P., Groebner, R.J., McKee, G.R., deGrassie, J.S., Jernigan, T.C., Leonard, A.W., Osborne, T.H., Schlossberg, D.J., Scoville, J.T., Snyder, P.B., Strait, E.J., "The H-Mode Power Threshold, Pedestal Width and Plasma Transport in Hydrogen Plasmas in DIII-D," Proc. 22nd IAEA Fusion Energy Conf., Geneva, Switzerland, October 13–18, 2008; General Atomics Report GA-A26312 (2008).

Gohil, P., Groebner, R.J., McKee, G.R., deGrassie, J.S., Jernigan, T.C., Leonard, A.W., Osborne, T.H., Schlossberg, D.J., Schmitz, L., Scoville, J.T., Snyder, P.B., Strait, E.J., Wang, G., Zeng, L., "The H-mode Power Threshold, Pedestal Width and Plasma Transport in Hydrogen Plasmas in DIII-D," Proc. 22nd IAEA Fusion Energy Conf., Geneva, Switzerland, October 13–18, 2008; General Atomics Report GA-A26271 (2008).

Gorelov, I.A., Lohr, J., Cengher, M., Ponce, D., "ECH System on the DIII-D Tokamak," Proc. 15th Joint Workshop on Electron Cyclotron Emission and Electron Cyclotron Resonance Heating, Yosemite Park, California, March 10–13, 2008; General Atomics Report GA-A26251 (2008).

Gorelov, I.A., Lohr, J., Ponce, D., Cengher, M., "Extension of Gyrotron Pulse Length on the DIII-D ECH System," Bull. Am. Phys. Soc. **53**, 257 (2008).

Greenfield, C.M., DIII-D National Team, "Overview of Recent DIII-D Results in Support of ITER," Bull. Am. Phys. Soc. **53**, 200 (2008).

Greenfield, C.M., Murakami, M., Garofalo, A.M., Ferron, J.R., Luce, T.C., Wade, M.R., Doyle, E.J., Casper, T.A., Jayakumar, R.J., Kessel, C.E., Kinsey, J.E., La Haye, R.J., Lohr, J., Mahdavi, M.A., Makowski, M.A., Okabayashi, M., Park, J.M., Petty, C.C., Petrie, T.W., Pinsker, R.I., Prater, R., Politzer, P.A., Reimerdes, H., Scoville, J.T., St. John, H.E., Strait, E.J., Taylor, T.S., Van Zeeland, M.A., and the DIII-D Team, "Progress Toward High Performance Steady-State Operation in DIII-D," submitted to Nucl. Fusion; General Atomics Report GA-A25717 (2007).

Groebner, R.J., Leonard, A.W., Snyder, P.B., Osborne, T.H., Maggi, C.F., Fenstermacher, M.E., Petty, C.C., Owen, L.W., "Progress Towards a Predictive Model for Pedestal Height in DIII-D," Proc. 22nd IAEA Fusion Energy Conf., Geneva, Switzerland, October 13–18, 2008; General Atomics Report GA-A26243 (2008).

Groebner, R.J., Snyder, P.B., Leonard, A.W., Osborne, T.H., "Test of a Pedestal Height Model in DIII-D," Bull. Am. Phys. Soc. **53**, 144 (2008).

Groth, M., Boedo, J.A., Brooks, N.H., Isler, R.C., Leonard, A.W., Porter, G.D., Watkins, J.G., West, W.P., Bray, B.D., Fenstermacher, M.E., Groebner, R.J., Moyer, R.A., Rudakov, D.L., Yu, J.H., Zeng, L., "Effect of Cross-Field Drifts and Core Rotation on Particle Flows in the Main Scrape-Off layer of DIII-D L-mode Plasmas," Proc. 22nd IAEA Fusion Energy Conf., Geneva, Switzerland, October 13–18, 2008; General Atomics Report GA-A26263 (2008).

Heidbrink, W.W., Petty, C.C., Van Zeeland, M.A., Murakami, M., Park, J.M., Yu, J.H., "Beam-Ion Confinement for Different Injection Angles," Bull. Am. Phys. Soc. **53**, 146 (2008).

Hill, D.N., Bonoli, P., Doyle, E.J., Ferron, J.R., Fredrickson, E.D., Garofalo, A.M., Gates, D.A., Gerhardt, S., Hutchinson, I., Mikkelson, D., Prater, R., Scott, S.D., Soukhanovskii, V.A., West, W.P., Whyte, D.G., Wolfe, S., "Summary Report on the National Tokamak Planning Workshop," General Atomics Report GA-A26095 (2008).

Hillesheim, J.C., Peebles, W.A., Rhodes, T.L., Schmitz, L., Carter, T.A., Gourdain, P.A., Wang, G., "Sawtooth Crash Modifications to Intermediate-k Turbulence and Flows on DIII-D," Bull. Am. Phys. Soc. **53**, 252 (2008).

Holcomb, C.T., "Optimizing Stability, Transport, and Divertor Operation Through Plasma Shaping for Steady-state Scenario Development in DIII-D," Bull. Am. Phys. Soc. **53**, 47 (2008)

Holcomb, C.T., Makowski, M.A., Allen, S.L., Meyer, W.H., Van Zeeland, M.A., "Overview of Equilibrium Reconstruction on DIII-D Using New Measurements From an Expanded Motional Stark Effect Diagnostic," Rev. Sci. Instrum. **79**, 10F518 (2008); General Atomics Report GA-A26096 (2008).

Holland, C., Candy, J., Waltz, R.E., White, A.E., McKee, G.R., Shafer, M.W., Schmitz, L., Tynan, G.R., “Validating Simulations of Core Tokamak Turbulence Current Status and Future Directions,” J. Phys. Conf. Series **125**, 012043 (2008); General Atomics Report GA-A26148 (2008).

Holland, C., Waltz, R.E., Candy, J., McKee, G.R., Shafer, M.W., White, A.E., Schmitz, L., Tynan, G.R., “Validation of Gyrokinetic Transport Simulations Using DIII-D Core Turbulence Measurements,” Proc. 22nd IAEA Fusion Energy Conf., Geneva, Switzerland, October 13–18, 2008; General Atomics Report GA-A26237 (2008).

Hollmann, E.M., James, A.N., Yu, J.H., Jernigan, T.C., Evans, T.E., Humphreys, D.A., Parks, P.B., Strait, E.J., Van Zeeland, M.A., Wesley, J.C., West, W.P., Wu, W., “Impurity Assimilation During Massive Gas Injection for Disruption Mitigation in DIII-D,” Bull. Am. Phys. Soc. **53**, 85 (2008)

Hollmann, E.M., Jernigan, T.C., Parks, P.B., Boedo, J.A., Evans, T.E., Groth, M., Humphreys, D.A., James, A., Lanctot, M.J., Nishijima, D., Rudakov, D.L., Scott, H.A., Strait, E.J., Van Zeeland, M.A., Wesley, J.C., West, W.P., Wu, W., Yu, J.H., “Measurements of Injected Impurity Assimilation During Massive Gas Injection Experiments in DIII-D,” Nucl. Fusion **48**, 115007 (2008); General Atomics Report GA-A26005 (2008).

Hollmann, E.M., Jernigan, T.C., Wesley, J.C., Boedo, J.A., Evans, T.E., Humphreys, D.A., James, A., Moyer, R.A., Parks, P.B., Rudakov, D.L., Strait, E.J., Van Zeeland, M.A., West, W.P., Wu, W., Yu, J.H., “Measurements of Injected Impurity Assimilation During Fast Shutdown Initiated by Multiple Gas Valves in DIII-D,” Proc. 35th EPS Conf. on Controlled Fusion and Plasma Physics, Crete, Greece, June 9–13, 2008; General Atomics Report GA-A26124 (2008).

Hudson, B., Petty, C.C., Burrell, K.H., Lao, L.L., Snyder, P.B., THomas, D.M., Allen, S.L., Holcomb, C.T., Makowski, M.A., “Determination of Edge Current in the DIII-D Tokamak,” Bull. Am. Phys. Soc. **53**, 255 (2008).

Humphreys, D.A., Casper, T.A., Eidietis, N., Ferrara, M., Gates, D.A., Hutchinson, I.H., Jackson, G.L., Kolemen, E., Leuer, J.A., Lister, J.B., Lodestro, L.L., Meyer, W.H., Pearlstein, L.D., Sartori, F., Walker, M.L., Welander, A.S., Wolfe, S.M., “Experimental Vertical Stability Studies for ITER Performance and Design Guidance,” Proc. 22nd IAEA Fusion Energy Conf., Geneva, Switzerland, October 13–18, 2008; General Atomics Report GA-A26255 (2008).

Humphreys, D.A., Eidietis, N.W., Jackson, G.L., Leuer, J.A., Walker, M.L., Welander, A.S., Casper, T.A., Lodestro, L.L., Meyer, W.H., Pearlstein, L.D., Ferrara, M., Hutchinson, I.H., Wolfe, S.M., Gates, D.A., Kolemen, E., Lister, J.B., Sartori, F., Treutterer, W., “ITER Vertical Stability Guidance from Multi-machine Experiments,” Bull. Am. Phys. Soc. **53**, 84 (2008).

Humphreys, D.A., Ferron, J.R., Hyatt, A.W., La Haye, R.J., Leuer, J.A., Penaflor, B.G., Walker, M.L., Welander, A.S., In, Y., “DIII-D Integrated Plasma Control Solutions for ITER and Next-Generation Tokamaks,” Proc. 6th IAEA Tech. Mtg. on Control, Data Acquisition, and Remote Participation for Fusion Research, June 4–8, 2007, Inuyama, Japan, in Fusion Engin. Design **83**(2–3), 193 (2008); General Atomics Report GA-A25808 (2007).

Hyatt, A.W., Humphreys, D.A., Johnson, R.D., Walker, M.L., Ferron, J.R., Scoville, J.T., Wade, M.R., “Enhancing Physics Operations and Increasing Physics Productivity at DIII-D,” Bull. Am. Phys. Soc. **53**, 145 (2008).

In, Y., Kim, J., Kim, J.S., Garofalo, A.M., Jackson, G.L., La Haye, R.J., Strait, E.J., Okabayashi, M., Reimerdes, H., “Influences of Multiple Low-n Modes on n=1 Resistive Wall Moder (RWM) Identification and Feedback Control,” Phys. Plasmas **15**, 102506 (2008); General Atomics Report GA-A26058 (2008).

In, Y., Kim, J.S., Bogatu, I.N., Jackson, G.L., La Haye, R.J., Schaffer, M.J., Strait, E.J., Garofalo, A.M., Lanctot, M.J., Reimerdes, H., Okabayashi, M., Marrelli, L., Martin, P., "Feedback Stabilization of Current-Driven Resistive-Wall Modes (RWMs) near q_{95}~4 in DIII-D," Bull. Am. Phys. Soc. **53**, 202 (2008).

Izzo, V.A., Joseph, I., Moyer, R.A., Evans, T.E., Fenstermacher, M.E., Osborne, T.H., Lao, L.L., Snyder, P.B., "RMP Enhanced Transport and Rotation Screening in DIII-D Simulations," Proc. 22nd IAEA Fusion Energy Conf., Geneva, Switzerland, October 13–18, 2008; General Atomics Report GA-A26236 (2008).

Izzo, V.A., Whyte, D.G.,, Granetz, R.S., Parks, P.B., Hollmann, E.M., Lao, L.L., Wesley, J.C., "MHD Simulations of Massive Gas Injection Into Alcator C-Mod and DIII-D Plasmas," Phys. Plasmas **15**, 056109 (2008); General Atomics Report GA-A25976 (2008).

Jackson, G.L., Austin, M.E., deGrassie, J.S., Hyatt, A.W., Lohr, J., Luce, T.C., Prater, R., West, W.P., "Plasma Initiation and Startup Studies in the DIII-D Tokamak With Second Harmonic Electron Cyclotron Assist," Proc. 15th Joint Workshop on Electron Cyclotron Emission and Electron Cyclotron Resonance Heating, Yosemite National Park, California, March 10–13, 2008, ; General Atomics Report GA-A26067 (2008).

Jackson, G.L., Casper, T.A., Luce, T.C., Humphreys, D.A., Ferron, J.R., Hyatt, A.W., Petrie, T.W., West, W.P., "Simulating the ITER Plasma Startup Scenario in the DIII-D Tokamak," Proc. 22nd IAEA Fusion Energy Conf., Geneva, Switzerland, October 13–18, 2008; General Atomics Report GA-A26259 (2008).

Jackson, G.L., Hyatt, A.W., Ferron, J.R., Luce, T.C., Humphreys, D.A., Petrie, T.W., Casper, T.A., "Experimental Investigation of ITER Startup and Rampdown Scenarios in the DIII-D Tokamak," Bull. Am. Phys. Soc. **53**, 144 (2008).

Jacobs, A.M., Finn, J.M., Lao, L.L., Strait, E.J., "The Impact of Correlations on MHD Equilibrium Reconstruction," Bull. Am. Phys. Soc. **53**, 132 (2008).

James, A.N., Hollmann, E.M., Yu, J.H., Evans, T.E., Jackson, G.L., Parks, P.B., "Impurity Pellet Injector for Disruption Mitigation Studies in DIII-D," Bull. Am. Phys. Soc. **53**, 141 (2008)

Jayakumar, R.J., Austin, M.E., Greenfield, C.M., Hawkes, N.C., Kinsey, J.E., Lao, L.L., Parks, P.B., Solano, E.R., Taylor, T.S., "Formation, Sustainment, and Characteristics of Current Hole Plasmas in DIII-D Discharges," Nucl. Fusion **48**, 015004 (2008); General Atomics Report GA-A25131 (2007).

Joseph, I., Evans, T.E., Moyer, R.A., Fenstermacher, M.E., Groth, M., Kasilov, S.V., Lasnier, C.J., Porter, G.D., Runov, A.M., Schaffer, M.J., Schneider, R., Watkins, J.G., "Calculation of the Thermal Footprint of Resonant Magnetic Perturbations in DIII-D," Nucl. Fusion **48**, 045009 (2008); General Atomics Report GA-A25869 (2007).

La Haye, R.J., "Stabilization of Neoclassical Tearing Modes in Tokamaks by Electric Cyclotron Current Drive," Proc. 15th Joint Workshop on Electron Cyclotron Emission and Electron Cyclotron Resonance Heating, Yosemite National Park, March 10–13, 2008; General Atomics Report GA-A26060 (2008).

La Haye, R.J., Buttery, R.J., "The Stabilizing Effect of Flow Shear on m/n=3/2 Magnetic Island Width in DIII-D," Bull. Am. Phys. Soc. **53**, 145 (2008).

La Haye, R.J., DIII-D Team, Isayama, A., JT-60 Team, Maraschek, M., ASDEX Upgrade Team, MHD Topical Group, "Prospects for Stabilization of Neoclassical Tearing Modes by Electron Cyclotron Current Drive in ITER," Proc. 22nd IAEA Fusion Energy Conf., Geneva, Switzerland, October 13–18, 2008; General Atomics Report GA-A26231 (2008).

La Haye, R.J., Ferron, J.R., Humphreys, D.A., Luce, T.C., Petty, C.C., Prater, R., Strait, E.J., Welander, A.S., "Requirements for Alignment of Electron Cyclotron Current Drive for Neoclassical Tearing Mode Stabilization in ITER," Nucl. Fusion **48**, 054004 (2008); General Atomics Report GA-A25848 (2007).

La Haye, R.J., Politzer, P.A., Brennan, D.P., "Beta Limit Due to m/n=2/1 Tearing Mode Onset in the DIII-D Hybrid Scenario," Nucl. Fusion **48**, 015005 (2008); General Atomics Report GA-A25707 (2007).

Lanctot, M.J., Bogatu, I.N., Garofalo, A.M., In, Y., Jackson, G.L., La Haye, R.J., Navratil, G.A., Okabayashi, M., Reimerdes, H., Solomon, W.M., Strait, E.J., Turnbull, A.D., "Internal Mode Structure of Resonant Field Amplification in DIII-D," Proc. 35th EPS Conf. on Controlled Fusion and Plasma Physics, Crete, Greece, June 9–13, 2008; General Atomics Report GA-A26143 (2008).

Lanctot, M.J., Navratil, G.A., Reimerdes, H., Bogatu, I.N., In, Y., Chu, M.S., Garofalo, A.M., Jackson, G.L., La Haye, R.J., Strait, E.J., Turnbull, A.D., Liu, Okabayashi, M., Solomon, W.M., "Internal Mode Structure of Resonant Field Amplification in DIII-D," Bull. Am. Phys. Soc. **53**, 251 (2008).

Lasnier, C.J., Fenstermacher, M.E., Groth, M., Evans, T.E., Groebner, R.J., Leonard, A.W., Osborne, T.H., "Comparison of ELMs in Hydrogen and Deuterium Discharges in DIII-D," Bull. Am. Phys. Soc. **53**, 140 (2008).

Leonard, A.W., Groth, M., Porter, G.D., Rensink, M.E., "Pedestal Fueling from Recycling in DIII-D," Bull. Am. Phys. Soc. **53**, 144 (2008).

Leuer, J.A., Humphreys, D.A., Hyatt, A.W., Walker, M.L., Yoon, S.W., Hahn, S.H., Oh, Y.K., Eidietis, N.W., "Unique Scenario Development Issues for KSTAR First Plasma," Bull. Am. Phys. Soc. **53**, 259 (2008).

Logan, N., Strait, E.J., Reimerdes, H., "Measurement of the Electromagnetic Torque on a Rotating Plasma for DIII-D," Bull. Am. Phys. Soc. **53**, 132 (2008).

Lohr, J., Cengher, M., Gorelov, I.A., Ponce, D., "Operation of a Six Gyrotron System on the DIII-D Tokamak," Bull. Am. Phys. Soc. **53**, 257 (2008).

Luce, T.C., Doyle, E.J., DeBoo, J.C., Jackson, G.L., Casper, T.A., Ferron, J.R., Politzer, P.A., Wade, M.R., Groebner, R.J., Holcomb, C.T., Humphreys, D.A., Hyatt, A.W., Lazarus, E.A., Leuer, J.A., Murakami, M., Petrie, T.W., Petty, C.C., West, W.P., "Simulation of ITER Operational and Startup Scenarios in the DIII-D Tokamak." Proc. 35th EPS Conf. on Controlled Fusion and Plasma Physics, Crete, Greece, June 9–13, 2008; General Atomics Report GA-A26138 (2008).

Makowski, M.A., Groth, M., Umansky, M., Xu, X., "Edge Turbulence Analysis of DIII-D Single Null L-Mode Discharges with BOUT," Bull. Am. Phys. Soc. **53**, 256 (2008).

McKee, G.R., Gohil, P., Schlossberg, D.J., Boedo, J.A., Burrell, K.H., deGrassie, J.S., Groebner, R.J., Makowski, M.A., Moyer, R.A., Petty, C.C., Rhodes, T.L., Schmitz, L., Shafer, M.W., Solomon, W.M., Umansky, M., Wang, G., White, A.E., Xu, X., "Dependence of the L- to H-mode Power Threshold on Toroidal Rotation and the Link to Edge Turbulence Dynamics," Proc. 22nd IAEA Fusion Energy Conf., Geneva, Switzerland, October 13–18, 2008; General Atomics Report GA-A26256 (2008).

McKee, G.R., Schlossberg, D.J., Shafer, M.W., Holland, C., "Long-Wavelength Turbulence Scaling Properties in DIII-D," Bull. Am. Phys. Soc. **53**, 252 (2008)

McLean, A.G., Cohen, B.I., Hill, D.N., Hooper, E.B., Hudson, B., Jayakumar, R.J., Lodestro, L.L., King, J.D., Moller, J.M., Romero-Talamas, C.A., Stewart, T.L., Wood, R.D., Morse, E.C., Johnson III, J.A., Mezonlin, E.D., Titus, J., Sovinec, C.R., "Final Results from the SSPX Spheromak Program," Bull. Am. Phys. Soc. **53**, 266 (2008).

Mordijck, S., Moyer, R.A., Stacey, W.M., Evans, T.E., "Comparisons of ELMing and RMP H-mode Transport Results from a 2D Fluid Code Theoretical Models," Bull. Am. Phys. Soc. **53**, 142 (2008).

Moyer, R.A., Izzo, V.A., Mordijck, S., Boedo, J.A., Rudakov, D.L., Evans, T.E., Brooks, N.H., Gohil, P., Unterberg, E.A., Fenstermacher, M.E., Frerichs, H., Schmitz, O., Unterberg, B., Jakubowski, M.W., Watkins, J.G., McKee, G.R., Rhodes, T.L., Schmitz, L., Zeng, L., Chang, C.S., Park, G., "Particle Transport in RMP H-modes," Bull. Am. Phys. Soc. **53**, 200 (2008).

Murakami, M., Park, J.M., Luce, T.C., Petty, C.C., Prater, R., Taylor, T.S., Wade, M.R., "Advanced Scenario Development Using Off-Axis Neutral Beam Current Drive in DIII-D," Bull. Am. Phys. Soc. **53**, 250 (2008).

Murakami, M., Park, J.M., Luce, T.C., Wade, M.R., and the DIII-D Team, "Prospects for Off-Axis Neutral Beam Current Drive in the DIII-D Tokamak," Fusion Sci. Technol. **54**(4), 994 (2008); General Atomics Report GA-A25933 (2007).

Murakami, M., Park, J.M., Petty, C.C., Luce, T.C., Heidbrink, W.W., Osborne, T.H., Wade, M.R., Austin, M.E., Brooks, N.H., Budny, R.V., Challis, C.D., DeBoo, J.C., deGrassie, J.S., Ferron, J.R., Gohil, P., Hobirk, J., Holcomb, C.T., Hollmann, E.M., Hong, R.-M., Hyatt, A.W., Lohr, J., Lanctot, M.J., Makowski, M.A., McCune, D.C., Politzer, P.A., Prater, R., St John, H.E., Suzuki, T., West, W.P., Unterberg, E.A., Van Zeeland, M.A., Yu, J.H., "Off-Axis Neutral Beam Current Drive for Advanced Scenario Development in DIII-D," Proc. 22nd IAEA Fusion Energy Conf., Geneva, Switzerland, October 13–18, 2008; General Atomics Report GA-A26265 (2008).

Muscatello, C.M., Heidbrink, W.W., Liu, D., Ruskov, E., Burrell, K.H., Taussig, D.A., Van Zeeland, M.A., "New Fast Ion D_α (FIDA) Capabilities," Bull. Am. Phys. Soc. **53**, 146 (2008).

Nazikian, R., Fu, G.Y., Austin, M.E., Berk, H.L., Budny, R.V., Gorelenkov, N.N., Heidbrink, W.W., Holcomb, C.T., Kramer, G.J., McKee, G.R., Makowski, M.A., Solomon, W.M., Shafer, M.W., Strait, E.J., Van Zeeland, M.A., "Intense Geodesic Acoustic-Like Modes Driven by Suprathermal Ions in a Tokamak Plasma," Phys. Rev. Lett. **101**, 185001 (2008); General Atomics Report GA-A26145 (2008).

Nazikian, R., Gorelenkov, N.N., Kramer, G.J., Austin, M.E., Berk, H.L., Heidbrink, W.W., McKee, G.R., Shafer, M.W., Strait, E.J., Van Zeeland, M.A., "Recent Advances in Alfven Eigenmode Research on DIII-D," Bull. Am. Phys. Soc. **53**, 203 (2008).

Okabayashi, M., Bogatu, I.N., Bolzonella, T., Chance, M.S., Chu, M.S., Garofalo, A.M., Hatcher, R., In, Y., Jackson, G.L., La Haye, R.J., Lanctot, M.J., Liu, Y.Q., Luce, T.C., Marrelli, L., Martin, P., Navratil, G.A., Reimerdes, H., Strait, E.J., Takahashi, H., Welander, A.S., "Comprehensive Control of Resistive Wall Modes in DIII-D Advanced Tokamak Plasmas," Proc. 22nd IAEA Fusion Energy Conf., Geneva, Switzerland, October 13–18, 2008; General Atomics Report GA-A26254 (2008).

Okabayashi, M., Chance, M.S., Takahashi, H., Lanctot, M.J., Reimerdes, H., In, Y., Chu, M.S., Garofalo, A.M., Jackson, G.L., La Haye, R.J., Strait, E.J., Welander, A.S., Buttery, R.J., "Resistive Wall Modes With ECCD-NTM Suppressed High Beta Plasmas in DIII-D," Bull. Am. Phys. Soc. **53**, 251 (2008).

Osborne, T.H., Burrell, K.H., Chu, M.S., Snyder, P.B., West, W.P., "Edge MHD Stability of Co-injected QH-mode Discharges in DIII-D," Bull. Am. Phys. Soc. **53**, 143 (2008).

Ou, Y., Schuster, E., Ferron, J.R., Luce, T.C., Walker, M.L., Humphreys, D.A., Casper, T.A., Meyer, W.H., "Control of Current Profile Evolution During the Ramp-Up Phase at DIII-D," Bull. Am. Phys. Soc. **53**, 144 (2008).

Pablant, N.A., Burrell, K.H., Groebner, R.J., Kaplan, D.H., Holcomb, C.T., "Measurements of the Internal Magnetic Field on DIII-D Using Intensity and Spacing of the Motional Stark Multiplet," Rev. Sci. Instrum. **79**, 10F517 (2008); General Atomics Report GA-A26110 (2008).

Pablant, N.A., Burrell, K.H., Gu, M.F., Holcomb, C.T., "Measurements of the Internal Magnetic Field on DIII-D Using Intensity and Spacing of the Motional Stark Multiplet," Bull. Am. Phys. Soc. **53**, 255 (2008).

Pan, C., Lao, L.L., Chu, M.S., St John, H.E., Prater, R., Li, G.Q., Ren, Q., Guo, W., Park, J.M., Stacey, W.M., "Development of an IMFIT Particle Transport Module and Modeling of Tokamak Particle Transport," Bull. Am. Phys. Soc. **53**, 255 (2008).

Park, J.M., "Validation of On- and Off-Axis Neutral Beam Current Drive Against Experiment in DIII-D," Bull. Am. Phys. Soc. **53**, 317 (2008).

Peebles, W.A., Rhodes, T.L., White, A.E., Wang, G., Hillesheim, J.C., Schmitz, L., Zeng, L., Doyle, E.J., McKee, G.R.,l Shafer, M.W., DeBoo, J.C., Van Zeeland, M.A., "Multi-Scale, Multi-Field Turbulence Response During Electron Cyclotron Heating," Bull. Am. Phys. Soc. **53**, 252 (2008).

Penaflor, B.G., Ferron, J.R., Walker, M.L., Humphreys, D.A., Leuer, J.A., Piglowski, D.A., Johnson, R.D., Xiao, B.J., Hahn, S.H., Gates, D.A., "Worldwide Collaborative Efforts in Plasma Control Software Development," Proc. 6th IAEA Tech. Mtg. on Control, Data Acquisition, and Remote Participation for Fusion Research, June 4–8, 2007, Inuyama, Japan in Fusion Engin. Design **83**(2–3) 176 (2008); General Atomics Report GA-A25809 (2007).

Petrie, T.W., Brooks, N.H., Fenstermacher, M.E., Groth, M., Hyatt, A.W., Isler, R.C., Lasnier, C.J., Leonard, A.W., Porter, G.D., Schaffer, M.J., Watkins, J.G., Wade, M.R., West, W.P., "Comparison of Radiating Divertor Behavior in Single-Null and Double-Null Plasmas in DIII-D," Nucl. Fusion **48**, 045010 (2008); General Atomics Report GA-A25781 (2007).

Petrie, T.W., Brooks, N.H., Fenstermacher, M.E., Groth, M., Hyatt, A.W., Lasnier, C.J., Leonard, A.W., Porter, G.D., Schaffer, M.J., Wade, M.R., Watkins, J.G., West, W.P., "Sensitivity of Injected Impurity Behavior to Magnetic Balance in Double-null Plasmas in DIII-D," Proc. 18th Int. Conf. on Plasma Surface Interactions and Controlled Fusion Devices, Toledo, Spain, May 26–30, 2008 in J. Nucl. Mater. **390–391**, 242 (2009); General Atomics Report GA-A26106 (2008).

Petrie, T.W., Brooks, N.H., Ferron, J.R., Hyatt, A.W., Leonard, A.W., Luce, T.C., Wade, M.R., West, W.P., Fenstermacher, M.E., Groth, M., Lasnier, C.J., Porter, G.D., Watkins, J.G., "Impact of Divertor Magnetic Balance and Particle Drifts on Radiating Divertor Behavior in DIII-D," Bull. Am. Phys. Soc. **53**, 201 (2008).

Petrie, T.W., Porter, G.D., Brooks, N.H., Fenstermacher, M.E., Ferron, J.R., Groth, M., Hyatt, A.W., La Haye, R.J., Lasnier, C.J., Leonard, A.W., Politzer, P.A., Rensink, M.E., Schaffer, M.J., Wade, M.R.,, Watkins, J.G., West, W.P., "The Effect of Magnetic Balance and Particle Drifts on Radiating Divertor Behavior in DIII-D," Proc. 22nd IAEA Fusion Energy Conf., Geneva, Switzerland, October 13–18, 2008; General Atomics Report GA-A26235 (2008).

Petty, C.C., Austin, M.E., Lohr, J., Luce, T.C., Makowski, M.A., Prater, R., Harvey, R.W., Smirnov, A.P., "Effect of Particle Transport on the Measured Electron Cyclotron Current Drive Profile," Proc. 17th Topical Conf. on High Temperature Plasma Diagnostics, Albuquerque, New Mexico, May 11–15, 2008; General Atomics Report GA-A26068 (2008).

Petty, C.C., deGrassie, J.S., Hyatt, A.W., Leonard, A.W., Politzer, P.A., Prater, R., Van Zeeland, M.A., Heidbrink, W.W., Murakami, M., Park, J.M., Solomon, W.M., "Validation of Neutral Beam Physics on DIII-D," Bull. Am. Phys. Soc. **53**, 146 (2008).

Petty, C.C., West, W.P., DeBoo, J.C., Doyle, E.J., Evans, T.E., Fenstermacher, M.E., Groth, M., Ferron, J.R., McKee, G.R., Politzer, P.A., Schmitz, L., Allen, S.L., Austin, M.E., Brooks, N.H., Casper, T.A., Chu, M.S., Greenfield, C.M., Holcomb, C.T., Hyatt, A.W., Jackson, G.L., Kinsey, J.E., La Haye, R.J., Luce, T.C., Makowski, M.A., Moyer, R.A., Murakami, M., Osborne, T.H., Rhodes, T.L., Wade, M.R., Wang, G., "Advances in the Physics Basis of the Hybrid Scenario on DIII-D," Proc. 22nd IAEA Fusion Energy Conf., Geneva, Switzerland, October 13–18, 2008; General Atomics Report GA-A26254 (2008).

Pinsker, R.I., Choi, M., Porkolab, M., Heidbrink, W.W., Zhu, Y.B., Baity, F.W., Hosea, J.C., "Synergy in Two-Frequency Fast Wave Cyclotron Harmonic Absorption in DIII-D," Bull. Am. Phys. Soc. **53**, 256 (2008).

Pinsker, R.I., Evans, T.E., Baity, F.W., Ryan, P.M., Hosea, J.C., "Experiments on Minimizing ELM-Induced Fast Wave Antenna Breakdown in DIII-D," Proc. 35th EPS Conf. on Controlled Fusion and Plasma Physics, Crete, Greece, June 9–13, 2008; General Atomics Report GA-A26125 (2008).

Pinsker, R.I., Porkolab, M., Heidbrink, W.W., Luo, Y., Petty, C.C., Prater, R., Choi, M., Baity, F.W., Hosea, J.C., Harvey, R.W., Smirnov, A.P., Jaeger, E.F., Murakami, M., "Experimental Study of Fast Wave Absorption Mechanisms in DIII-D in the Presence of Energetic Ions," Proc. 22nd IAEA Fusion Energy Conf., Geneva, Switzerland, October 13–18, 2008; General Atomics Report GA-A26241 (2008).

Politzer, P.A., "Demonstration of ITER Operational Scenarios on DIII-D," Bull. Am. Phys. Soc. **53**, 84 (2008).

Politzer, P.A., Petty, C.C., Jayakumar, R.J., Luce, T.C., Wade, M.R., DeBoo, J.C., Ferron, J.R., Gohil, P., Holcomb, C.T., Hyatt, A.W., Kinsey, J., La Haye, R.J., Makowski, M.A., Petrie, T.W., "Influence of Toroidal Rotation on Transport and Stability in Hybrid Scenario Plasmas in DIII-D," Nucl. Fusion **48**, 075001 (2008); General Atomics Report GA-A25755 (2007).

Ponce, D.M., Bray, B.D., Deterly, T.M., Hsieh, C.-L., Liu, C., "Upgraded Thomson Scattering Diagnostic on DIII-D," Bull. Am. Phys. Soc. **53**, 256 (2008)

Prater, R., Lee, X., Flanagan, S.M., Groebner, R.J., Lao, L.L., Peng, Q., Schissel, D.P., St John, H.E., Wade, M.R., "Automated and Between-Shot Analysis of DIII-D Discharges," Bull. Am. Phys. Soc. **53**, 255 (2008).

Project Staff, "The DIII-D National Fusion Program Five-Year Plan 2009–2013," General Atonics Report GA-A25889 (2008).

Qian, J.P., Lao, L.L., Ren, Q.L., Volpe, F., Rinderknecht, H., Wan, B.N., "Equilibrium Reconstruction of Plasma Profiles Based on Soft X-ray Imaging in DIII-D," Nucl. Fusion **49**, 025003 (2009); General Atomics Report GA-A26149 (2008).

Reimerdes, H., Berkery, J.W., Lanctot, M.J., Chu, M.S., Garofalo, A.M., Jackson, G.L., La Haye, R.J., Strait, E.J., Welander, A.S., In, Y., Liu, Y.Q., Okabayashi, M., Solomon, W.M., "Wall-Stabilization and Its Limits in High Beta DIII-D Plasmas," Bull. Am. Phys. Soc. **53**, 202 (2008)

Reimerdes, H., Garofalo, A.M., Strait, E.J., Buttery, R.J., Chu, M.S., In, Y., Jackson, G.L., La Haye, R.J., Lanctot, M.J., Liu, Y.Q., Park, J.-K., Okabayashi, M., Schaffer, M.J., Solomon, W.M., "Effect of Resonant and Nonresonant Magnetic Braking on Error Field Tolerance in High Beta Plasmas," Proc. 22nd IAEA Fusion Energy Conf., Geneva, Switzerland, October 13–18, 2008; General Atomics Report GA-A26247 (2008).

Rhodes, T.L., Peebles, W.A., Schmitz, L., White, A.E., Hillesheim, J.C., Wang, G., Zeng, L., Doyle, E.J., McKee, G.R., Shafer, M.W., "Multi-Scale Fluctuation Behavior During Balanced NBI H-Mode in the DIII-D Tokamak," Bull. Am. Phys. Soc. **53**, 252 (2008)

Rost, J.C., Porkolab, M., Dorris, J.R., Burrell, K.H., "Phase Contrast Imaging Measurements of Turbulence in ELMing Plasmas," Bull. Am. Phys. Soc. **53**, 252 (2008).

Rudakov, D.L., Litnovsky, A., West, W.P., Yu, J.H., Boedo, J.A., Bray, B.D., Brezinsek, S., Brooks, N.H., Fenstermacher, M.E., Groth, M., Hollmann, E.M., Huber, A., Hyatt, A.W., Krasheninnikov, S.I., Lasnier, C.J., Moyer, R.A., Pigarov, A.Yu., Philipps, V., Pospieszczyk, A., Smirnov, R.D., Sharpe, J.P., Solomon, W.M., Watkins, J.G., Wong, C.P.C., "Dust Studies in DIII-D and TEXTOR," Proc. 22nd IAEA Fusion Energy Conf., Geneva, Switzerland, October 13–18, 2008; General Atomics Report GA-A26258 (2008).

Rudakov, D.L., West, W.P., Groth, M., Yu, J.H., Boedo, J.A., Bray, B.D., Brooks, N.H., Fenstermacher, M.E., Hollmann, E.M., Hyatt, A.W., Krasheninnikov, S.I., Lasnier, C.J., Moyer, R.A., Pigarov, A.Yu., Smirnov, R.D., Solomon, W.M., Wong, C.P.C., "Dust Studies in DIII-D," AIP Conf. Proceedings **1041**, 55 (2008); General Atomics Report GA-A26088 (2008).

Rudakov, D.L., Yu, J.H., Boedo, J.A., Hollmann, E.M., Krasheninnikov, S.I., Moyer, R.A., Muller, S.H., Pigarov, A.Yu., Rosenberg, M., Smirnov, R.D., West, W.P., Boivin, R.L., Bray, B.D., Brooks, N.H., Hyatt, A.W., Wong, C.P.C., Ratynskaia, S., Roquemore, A.L., Skinner, C.H., Solomon, W.M., Fenstermacher, M.E., Groth, M., Lasnier, C.J., McLean, A.G., Stangeby, P.C., "Dust Measurements in Tokamaks," Rev. Sci. Instrum. **79**, 10F303 (2008); General Atomics Report GA-A26108 (2008).

Schaffer, M.J., Evans, T.E., Garofalo, A.M., Fenstermacher, M.E., Becoulet, M., Nardon, E., Hawryluk, R.J., Menard, J.E., Park, J.-K., Sabbagh, S.A., Aldan, M.P., "ELM Control Coils for ITER," Bull. Am. Phys. Soc. **53**, 143 (2008).

Schaffer, M.J., Menard, J.E., Aldan, M.P., Bialek, J.M., Evans, T.E., Moyer, R.A., "Study of Nonaxisymmetric ELM Control Coils for ITER," Nucl. Fusion **48**, 024004 (2008); General Atomics Report GA-A25795 (2007).

Schlossberg, D.J., McKee, G.R., Shafer, W.M., Burrell, K.H., Gohil, P., Groebner, R.J., Solomon, W.M., Wang, G., "Dependence of the Low to High Confinement Mode Transition Power Threshold on Injected Torque," Phys. Plasmas **16**, 080701 (2009); General Atomics Report GA-A25929 (2007).

Schmitz, L., "Reduction of TEM/ETG-Scale Density Fluctuations in the Core and Edge of H-mode DIII-D Plasmas," Bull. Am. Phys. Soc. **53**, 232 (2008).

Schmitz, L., White, A.E., Wang, G., DeBoo, J.C., McKee, G.R., deGrassie, J.S., Hillesheim, J.C., Peebles, W.A., Rhodes, T.L., Petty, C.C., Zeng, L., Doyle, E.J., Carter, T.A., Burrell, K.H., Solomon, W.M., Kinsey, J.E., Staebler, G.M., DIII-D Team, "First Observations of Reduced Core Electron Temperature Fluctuations and Intermediate Wavenumber Density Fluctuations in H- and QH-mode Plasmas," Proc. 22nd IAEA Fusion Energy Conf., Geneva, Switzerland, October 13–18, 2008; General Atomics Report GA-A26253 (2008).

Schmitz, O., Bray, B.D., Brooks, N.H., Evans, T.E., Leonard, A.W., Osborne, T.H., West, W.P., Fenstermacher, M.E., Groth, M., Lasnier, C.J., Frerichs, H., Lehnen, M., Unterberg, B., Jakubowski, M.W., Moyer, R.A., Watkins, J.G., "Resonant Character of Edge Plasma Parameters in Stochastic Boundary Experiments at DIII-D and TEXTOR," Bull. Am. Phys. Soc. **53**, 141 (2008).

Schmitz, O., Evans, T.E., Fenstermacher, M.E., Frerichs, H., Jakubowski, M., Schaffer, M.J., Wingen, A., West, W.P., Brooks, N.H., Groth, M., Joseph, I., Lasnier, C.J., Moyer, R.A., Stoschus, H., Unterberg, B., Watkins, J.G., Burrell, K.H., deGrassie, J.S., Finken, K.H., Gohil, P., Feng, Y., Lehnen, M., Mordijck, S., Nicolai, A., Osborne, T.H., Reiter, D., Samm, U., Spatschek, K.H., Unterberg, E.A., Wolf, R., DIII-D and TEXTOR Team, "Three Dimensional Transport Analysis for ELM Control Experiments in ITER Similar Shape Plasmas at Low Collisionality in DIII-D," Proc. 35th EPS Conf. on Controlled Fusion and Plasma Physics, Crete, Greece, June 9–13, 2008; General Atomics Report GA-A26136 (2008).

Sears, S., Petty, C.C., Forest, C.B., Rice, B.W., "Testing Magnetic Diffusion in the DIII-D Tokamak," Bull. Am. Phys. Soc. **53**, 146 (2008).

Shafer, M.W., McKee, G.R., Schlossberg, D.J., Austin, M.E., Burrell, K.H., "Local Turbulence Suppression and Shear Flow Dynamics During q_{min}-Triggered Internal Transport Barriers on DIII-D," Bull. Am. Phys. Soc. **53**, 201 (2008).

Sheffield, T.Y., West, W.P., Brooks, N.H., Boivin, R.L., Labombard, B., "Penning Gauge Sensitivity and Spectra for Use in DIII-D," Bull. Am. Phys. Soc. **53**, 132 (2008).

Snyder, P.B., "Development and Validation of a Predictive Model for the Pedestal Height," Bull. Am. Phys. Soc. **53**, 158 (2008).

Snyder, P.B., Aiba, N., Beurskens, M., Groebner, R.J., Horton, L.D., Hubbard, A., Hughes, J., Huysmans, G.T.A., Kamada, Y., Kirk, A., Konz, C., Leonard, A.W., Maggi, C.F., Maingi, R., Osborne, T.H., Oyama, N., Pankin, A., Saarelma, S., Saibene, G., Terry, J., Urano, H., Wilson, H.R., "Pedestal Stability Comparison and ITER Pedestal Prediction," Proc. 22nd IAEA Fusion Energy Conf., Geneva, Switzerland, October 13–18, 2008; General Atomics Report GA-A26260 (2008).

Solomon, W.M., Burrell, K.H., Garofalo, A.M., Cole, A.J., Budny, R.V., deGrassie, J.S., Heidbrink, W.W., Jackson, G.L., Lanctot, M.J., Nazikian, R., Reimerdes, H., Strait, E.J., Van Zeeland, M.A., DIII-D Rotation Physics Task Force, "Developments in Predictive Understanding of Plasma Rotation on DIII-D," Proc. 22nd IAEA Fusion Energy Conf., Geneva, Switzerland, October 13–18, 2008; General Atomics Report GA-A26238 (2008).

Solomon, W.M., Feder, R., Nagy, A., Burrell, K.H., Gohil, P., Groebner, R.J., "Characterization of Cross-Section Correction to Charge Exchange Recombination Spectroscopy Rotation Measurements Using Co + Counter Neutral Beam Views," Rev. Sci. Instrum. **79**, 10F531 (2008); General Atomics Report GA-A26097 (2008).

Stacey, W.M., "A SOL and Divertor Plasma Calculation Model," Bull. Am. Phys. Soc. **53**, 257 (2008).

Strait, E.J., DIII-D Team, "DIII-D Research in Support of ITER," Proc. 22nd IAEA Fusion Energy Conf., Geneva, Switzerland, October 13–18, 2008; General Atomics Report GA-A26264 (2008).

Strait, E.J., DIII-D Team, "DIII-D Research in Support of ITER," Bull. Am. Phys. Soc. **53**, 140 (2008).

Strait, E.J., Garofalo, A.M., Jackson, G.L., La Haye, R.J., Reimerdes, H., Lanctot, M.J., Okabayashi, M., In, Y., "Phase-Space Analysis of Resistive Wall Mode Dynamics," Bull. Am. Phys. Soc. **53**, 332 (2008).

Takahashi, H., Fredrickson, E.D., Schaffer, M.J., Watkins, J.G., "Relationships Between ELM Period and Scrape-Off Layer Current (SOLC) Density at Divertor Tiles in DIII-D," Bull. Am. Phys. Soc. **53**, 256 (2008).

Tooker, J.F., for the DIII-D Team, "Upgrades Completed at the DIII-D Facility During the Long Torus Opening in FY05-06," 17th ANS Topical Mtg. on the Technology of Fusion Energy, November 13-16, 2006, Albuquerque, New Mexico; General Atomics Report GA-A25629 (2006).

Turco, F., Luce, T.C., Ferron, J.R., Petty, C.C., Politzer, P.A., Turnbull, A.D., Brennan, D.P., Casper, T.A., Holcomb, C.T., Murakami, M., "Tearing Mode Stability of Steady-State Scenario Plasmas in DIII-D," Bull. Am. Phys. Soc. **53**, 251 (2008).

Turnbull, A.D., Choi, M., Chu, M.S., Lao, L.L., Gorelenkov. N.N., Kramer G.J., "Stability Modeling of the Internal Kink and Application to Tokamak Sawteeth," Bull. Am. Phys. Soc. **53**, 256 (2008).

Unglaub, W., Pinsker, R.I., Harvey, R.W., "Time-Dependent Modeling of Fast Wave Absorption With Multiple Damping Mechanisms," Bull. Am. Phys. Soc. **53**, 132 (2008).

Unterberg, E.A., Brooks, N.H., Evans, T.E., Fenstermacher, M.E., Maingi, R., Moyer, R.A., "Global Particle Balances and Wall Recycling Changes During the RMP Induced Density Pump-Out in DIII-D H-Mode Plasmas," Bull. Am. Phys. Soc. **53**, 142 (2008).

Van Zeeland, M.A., Boivin, R.L., Carlstrom, T.N., Deterly, T.M., "CO_2 Laser Polarimeter for Faraday Rotation Measurements in the DIII-D Tokamak," Rev. Sci. Instrum. **79**, 10E719 (2008); General Atomics Report GA-A26099 (2008).

Van Zeeland, M.A., Heidbrink, W.W., Nazikian, R., Solomon, W.M., Austin, M.E., Gorelenkov, N.N., Holcomb, C.T., Hyatt, A.W., Kramer, G.J., Lohr, J., Makowski, M.A., McKee, G.R., Petty, C.C., Sharapov, S.E., Rhodes, T.L., "Reversed Shear Alfvén Eigenmode Stabilization by Localized Electron Cyclotron Heating," Plasma Phys. Control. Fusion **50**, 035009 (2008); General Atomics Report GA-A25914 (2007).

Van Zeeland, M.A., Kramer, G.J., "Measurements of Alfvén Eigenmodes in Fusion Plasmas," presented at the Intl. Wkshp. on Burning Plasma Diagnostics, September 24–28, 2007, Varenna, Italy in AIP Conf. Proc. **988**, 103 (Year?); General Atomics Report GA-A25932 (2007).

Van Zeeland, M.A., Yu, J.H., Chu, M.S., Burrell, K.H., La Haye, R.J., Luce, T.C., Nazikian, R., Solomon, W.M., West, W.P., "Tearing Mode Structure in the DIII-D Tokamak Through Spectrally-Filtered Fast Visible Bremsstrahlung Imaging," Nucl. Fusion **48**, 092002 (2008); General Atomics Report GA-A26059 (2008).

Von der Linden, J., Leonard, A.W., Groebner, R.J., Osborne, T.H., Parks, P.B., "Numerical Study of the Pedestal MHD Stability Limit on Upper and Lower Separatrix Triangularities," Bull. Am. Phys. Soc. **53**, 134 (2008).

Walker, M.L., Humphreys, D.A., "On Feedback Stabilization of the Tokamak Plasma Vertical Instability," Automatica **45**(3), 665 (2009); General Atomics Report GA-A25874 (2007).

Walker, M.L., Schuster, E., Mazon, D., Moreau, D., "Open and Emerging Control Problems in Tokamak Plasma Control," Proc. 47th IEEE Conf. on Decision and Control, Cancun, Mexico, December 9–11, 2008; General Atomics Report GA-A26064 (2008).

Wang, G., Peebles, W.A., Rhodes, T.L., Hillesheim, J.C., Doyle, E.J., Schmitz, L., White, A.E., Zeng, L., "Radial Correlation Length of Turbulent Density Fluctuations in DIII-D Plasmas," Bull. Am. Phys. Soc. **53**, 253 (2008).

Watkins, J.G., Evans, T.E., Schaffer, M.J., Murphy, C.J., Jakubowski, M., Schmitz, O., Lasnier, C.J., "Target Plate Particle and Power Flux During ELM Suppression Experiments on DIII-D," Bull. Am. Phys. Soc. **53**, 145 (2008)

Watkins, J.G., Taussig, D.A., Boivin, R.L., Mahdavi, M.A., Nygren, R.E., "High Heat Flux Langmuir Probe Array for the DIII-D Divertor Plates," Rev. Sci. Instrum. **79**, 10F125 (2008); General Atomics Report GA-A26101 (2008).

Wesley, J.C., Hollmann, E.M., Jernigan, T.C., Van Zeeland, M.A., Baylor, L.R., Boedo, J.A., Combs, S.K., Evans, T.E., Groth, M., Humphreys, D.A., Hyatt, A.W., Izzo, V.A., James, A., Moyer, R.A., Parks, P.B., Rudakov, D.L., Strait, E.J., Wu, W., Yu, J.H., "Fast Plasma Shutdowns Obtained With Massive Hydrogenic, Noble and Mixed-Gas Injection in DIII-D," Proc. 22nd IAEA Fusion Energy Conf., Geneva, Switzerland, October 13–18, 2008; General Atomics Report GA-A26239 (2008).

Wesley, J.C., Hyatt, A.W., Strait, E.J., Flanagan, S.M., Schissel, D.P., Devries, P.C., Fredrickson, E.J., Gates, D.A., Granetz, R.S., Gribov, Y., Hender, T.C., Johnson, M.F., Kawano, Y., Lister, J., Martin, R., Menard, J.E., Pautasso, G., Sugihara, M., "Disruption Characterization and Database Activities for ITER," submitted to Nucl. Fusion; General Atomics Report GA-A25723 (2007).

Wesley, J.C., Van Zeeland, M.A., Evans, T.E., Humphreys, D.A., Hyatt, A.W., Parks, P.B., Strait, E.J., Wu, W., Hollmann, E.M., Boedo, J.A., Izzo, V.A., James, A.N., Moyer, R.A., Rudakov, D.L., Yu, J.H., Jernigan, T.C., Baylor, L.R., Combs, S.K., Groth, M., “Fast Plasma Shutdowns by Massive Hydrogen, Noble and Mixed-Gas Injection in DIII-D,” Bull. Am. Phys. Soc. **53**, 141 (2008).

West, W.P., Brooks, N.H., Leonard, A.W., Whyte, D.G., Lipschultz, B.L., Watkins, J.G., Groth, M., Lasnier, C.J., Fenstermacher, M.E., Boedo, J.A., Rudakov, D.L., Unterberg, E.A., “Gas Balance in Ohmic Discharges on DIII-D,” Bull. Am. Phys. Soc. **53**, 140 (2008).

West, W.P., Groth, M., Hyatt, A.W., Jackson, G.L., Wade, M.R., Greenfield, C.M., Politzer, P.A., “The Maintenance of Good Wall Conditions and High Performance Operation on DIII-D Over Extended Periods Without Boronization,” Phys. Plasmas Control. Fusion **51**, 055014 (2009).

White, A.E., Schmitz, L., McKee, G.R., Holland, C., Peebles, W.A., Carter, T.A., Shafer, M.W., Austin, M.E., Burrell, K.H., Candy, J., DeBoo, J.C., Doyle, E.J., Makowski, M.A., Prater, R., Rhodes, T.L., Staebler, G.M., Tynan, G.R., Waltz, R.E., Wang, G., “Measurements of Electron Temperature and Density Fluctuations and Comparison of Gyrokinetic Simulations,” Proc. 15th Joint Workshop on Electron Cyclotron Emission and Electron Cyclotron Resonance Heating, Yosemite National Park, California, March 10–13, 2008; General Atomics Report GA-A26061 (2008).

White, A.E., Schmitz, L., Peebles, W.A., Carter, T.A., Rhodes, T.L., Wang, G., Doyle, E.J., Hillesheim, J.C., Zeng, L., McKee, G.R., Shafer, M.W., DeBoo, J.C., Staebler, G.M., “Ratio of Electron Temperature and Density Fluctuation Amplitudes During ECH in DIII-D Ohmic and L-mode Discharges,” Bull. Am. Phys. Soc. **53**, 200 (2008).

White, A.E., Schmitz, L., Peebles, W.A., Carter, T.A., Rhodes, T.L., Doyle, E.J., Gourdain, P.A., Hillesheim, J.C., Wang, G., Holland, C., Tynan, G.R., Austin, M.E., McKee, G.R., Shafer, M.W., Burrell, K.H., Candy, J., DeBoo, J.C., Prater, R., Staebler, G.M., Waltz, R.E., Makowski, M.A., DIII-D Team, “A Correlation Electron Cyclotron Emission Diagnostic and the Importance of Multi-Field Fluctuation Measurements for Testing Nonlinear Gyrokinetic Turbulence Simulations,” Rev. Sci. Instrum. **79**, 103505 (2008); General Atomics Report GA-A26094 (2008).

Whyte, D.G., Baylor, L.R., Campbell, D.C., Granetz, R.S., Guluga, M., Hawyluk, R.J., Pearce, R., Maruyama, Sugihara, M., Wesley, J.C., Wykes, M., “Studies of Requirement for ITER Disruption Mitigation Systems,” Proc. 22nd IAEA Fusion Energy Conf., Geneva, Switzerland, October 13–18, 2008; General Atomics Report GA-A26081 (2008).

Wong, C.P.C., Salavy, J.-F., Kim, Y., Kirillov, I., Rajendra Kumar, E., Morley, N.B., Tanaka, S., Wu, Y.C., and TBM Teams, “Overview of Liquid Metal TBM Concepts and Programs,” presented at 8th Intl. Symp. on Fusion Nucl. Technology, September 30, 2007 through October 5, 2007, Heidelberg, Germany in Fusion Engin. Design **83**(7–9) 850 (2008); General Atomics Report GA-A25928 (2007).

Wong, S.K., Chan, V.S., Solomon, W.M., “Neoclassical Poloidal and Toroidal Velocities of Impurity Ions,” Bull. Am. Phys. Soc. **53**, 252 (2008).

Wu, W., Parks, P.B., Izzo, V.A., “Modeling of Massive Particle Injection (MPI) in Tokamaks,” Bull. Am. Phys. Soc. **53**, 202 (2008).

Xu, C., Ou, Y., Schuster, E., Humphreys, D.A., Walker, M.L., In, Y., Kim, J.S., “Momentum Diffusivity Estimation Via PDE-Constrained Optimization,” Bull. Am. Phys. Soc. **53**, 332 (2008).

Yang, S., Schuster, E., Humphreys, D.A., Walker, M.L., In, Y., Kim, J.S., “Comparison of RWM Stabilization Strategies in DIII-D,” Bull. Am. Phys. Soc. **53**, 251 (2008).

Yu, J.H., “Fast Imaging of Transients and Coherent MHD Modes in DIII-D,” Bull. Am. Phys. Soc. **53**, 241 (2008).

Yu, J.H., Boedo, J.A., Hollmann, E.M., Moyer, R.A., Rudakov, D.L., Snyder, P.B., "Fast Imaging of ELM Structure and Dynamics in DIII-D," Phys. Plasmas **15**, 032504 (2008); General Atomics Report GA-A25871 (2007).

Yu, J.H., Van Zeeland, M.A., "Spectrally Filtered Fast Imaging of Internal MHD Activity in the DIII-D Tokamak," Rev. Sci. Instrum. **79**, 10F516 (2008); General Atomics Report GA-A26098 (2008).

Zeng, L., Rhodes, T.L., Peebles, W.A., Wang, G., Schmitz, L., Doyle, E.J., Baylor, L.R., Jernigan, T.C., Evans, T.E., "Effect of Resonant Magnetic Perturbations (RMPs) on Local Density Decay During Pellet Injection in DIII-D," Bull. Am. Phys. Soc. **53**, 143 (2008).

Zhu, Y.B., Heidbrink, W.W., West, W.P., Burrell, K.H., "Burst of Fast Ion Loss in DIII-D Quiescent H-mode Plasmas," Bull. Am. Phys. Soc. **53**, 145 (2008).

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P.O. BOX 85608 SAN DIEGO, CA 92186-5608 (858) 455-3000