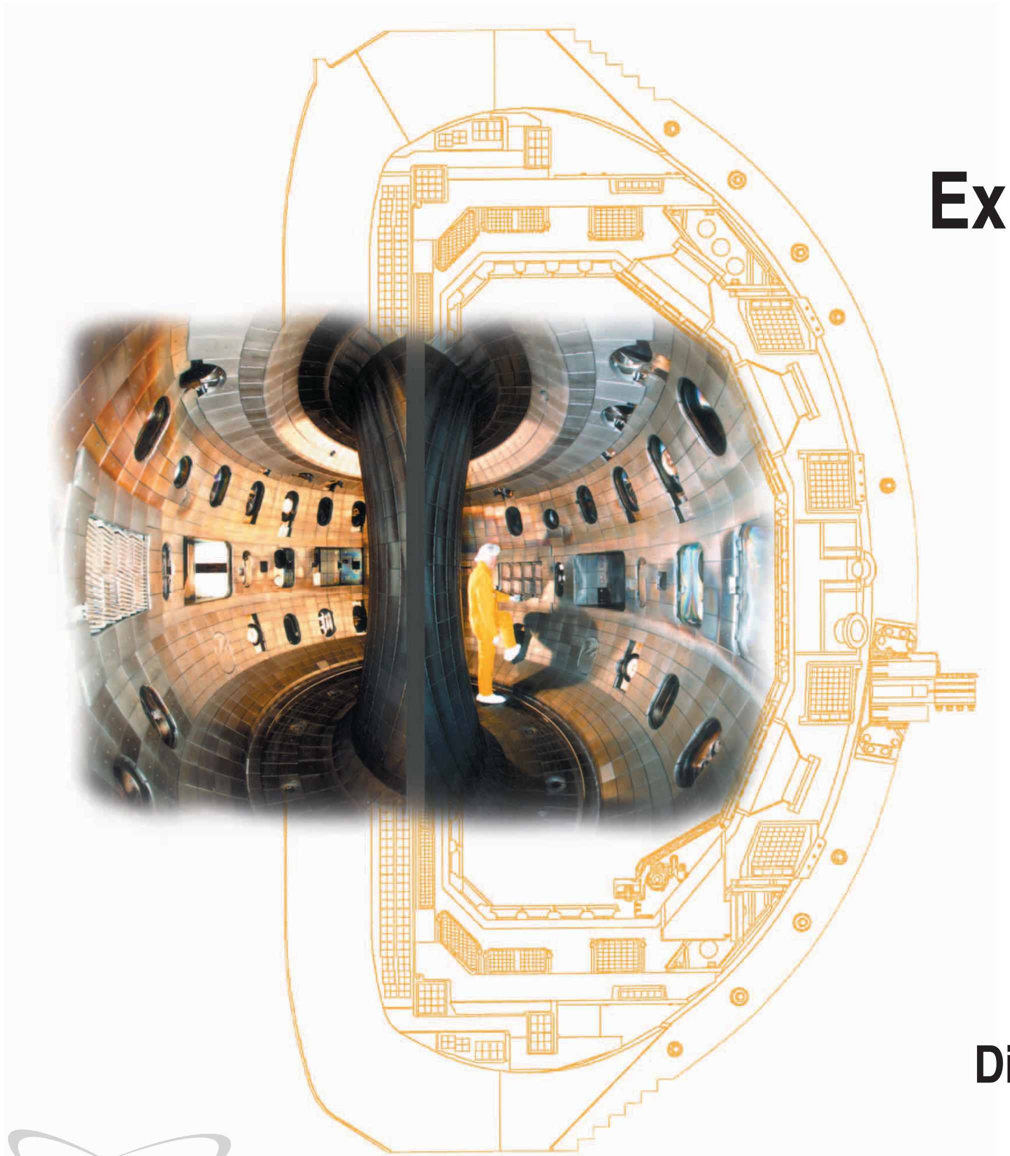


Overview of the 2002 DIII–D Experimental Campaign

S. L. Allen
and the
DIII-D Team

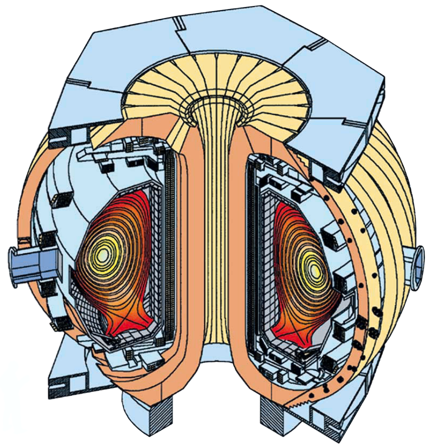
Presented at
the American Physical Society
Division of Plasma Physics Meeting

DIII–D
NATIONAL FUSION FACILITY
SAN DIEGO, CALIFORNIA

DIII–D National Program is a Multi-Institution Collaborative Effort

Flexibility

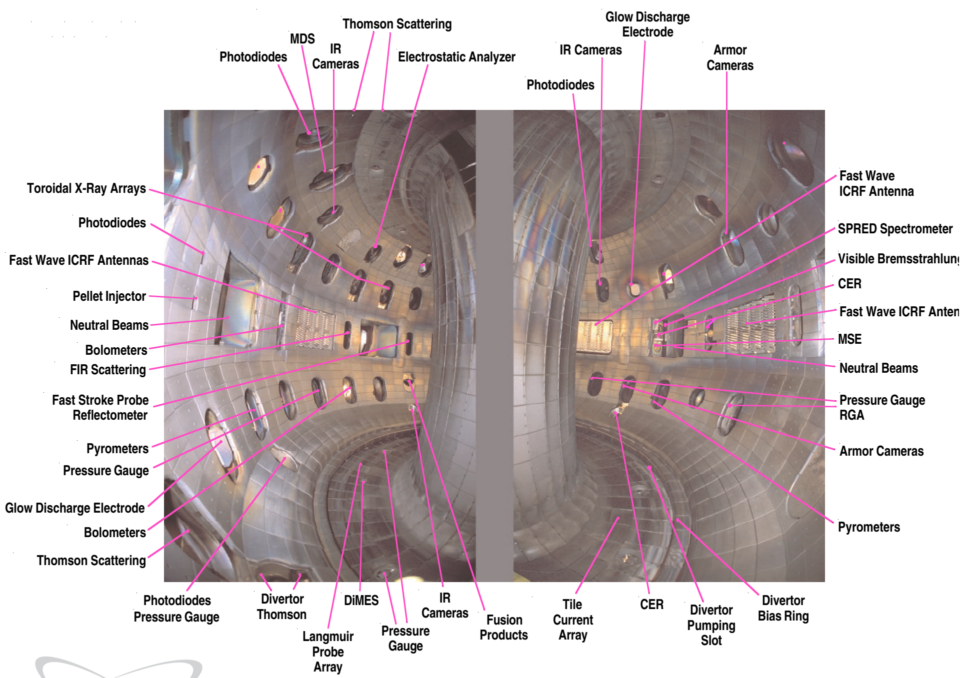
Flexibile shape capability with 18 independent poloidal coils



Control

Internal profile control with high power microwave

Large Diagnostic Set



International Research Team
Collaborations with 60 institutions – 300 users

NATIONAL LABS	UNIVERSITIES	INTERNATIONAL LABS
ANL	Alaska	ASIPP (China)
INEL	Alberta (Canada)	Cadarache (France)
LANL	Cal Tech	CCFM (Canada)
LLNL	Chalmers U. (Sweden)	Culham (England)
ORNL	Columbia U.	FOM (Netherlands)
PNL	Georgia Tech	Frascati (Italy)
PPPL	Hampton U.	Ioffe (Russia)
SNLL	Helsinki U. (Finland)	IPP (Germany)
	Johns Hopkins U.	JAERI (Japan)
	Lehigh	JET (EC)
	MIT	KAIST (Korea)
	Moscow State U. (Russia)	KBSI (Korea)
	RPI	Keldysh Inst. (Russia)
	U. Maryland	KFA (Germany)
	U. Texas	Kurchatov (Russia)
	U. Toronto (Canada)	Lausanne (Switzerland)
	U. Wales (Wales)	NIFS (Japan)
	U. Washington	Troitsk (Russia)
	U. Wisconsin	SWIP (China)
	UC Berkeley	Southwestern Inst. (China)
	UC Irvine	Tsukuba U. (Japan)
	UCLA	
	UCSD	

INDUSTRY COLLABS
CompX
CPI (Varian)
GA
Gycom
Orincon
Creare
FAR Tech
Gycom
HiTech Metallurgical
IR&T
Surmet
Thermacore
TSI Research

DIII–D NATIONAL FUSION FACILITY SAN DIEGO

212-00/rs

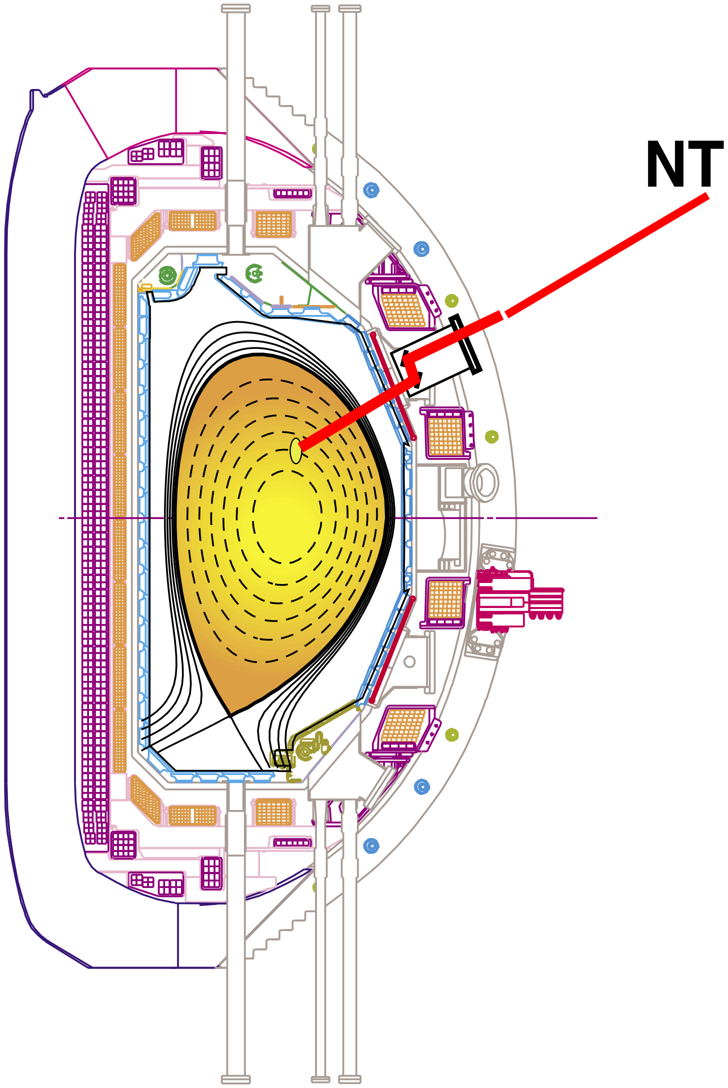
The goal of the DIII-D program is to advance the tokamak concept

1. Advanced Tokamak: Steady-state high β, high τ_E, high bootstrap fraction plasma

- The MHD - stable operating space has been expanded with plasma control

NATIONAL FUSION FACILITY
SAN DIEGO

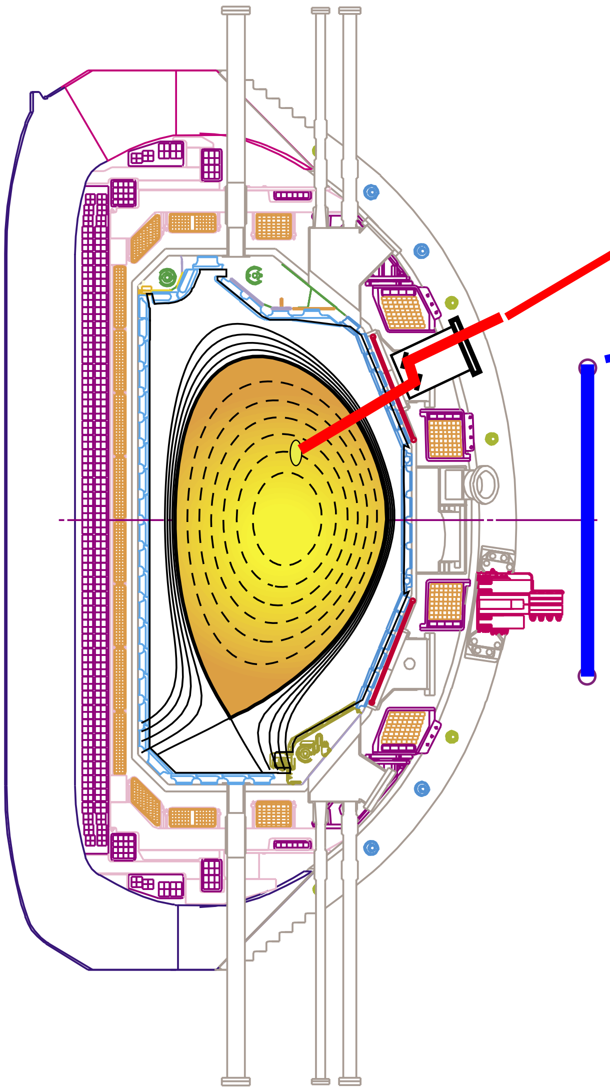
DIII-D uses many feedback and control systems



NTM: Magnetics —> ECCD

DIII-D
NATIONAL FUSION FACILITY
SAN DIEGO

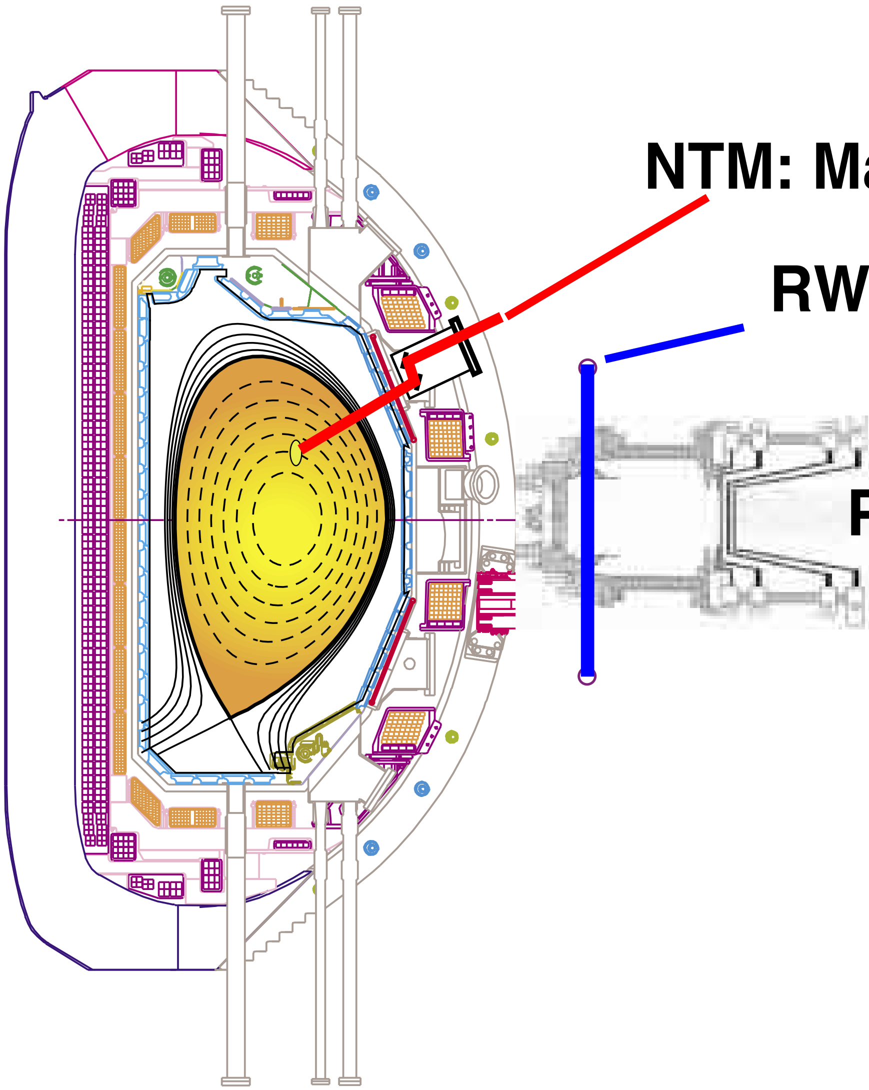
DIII-D uses many feedback and control systems



NTM: Magnetics —> ECCD

RWM: Sensors —> Active Coils

DIII-D uses many feedback and control systems



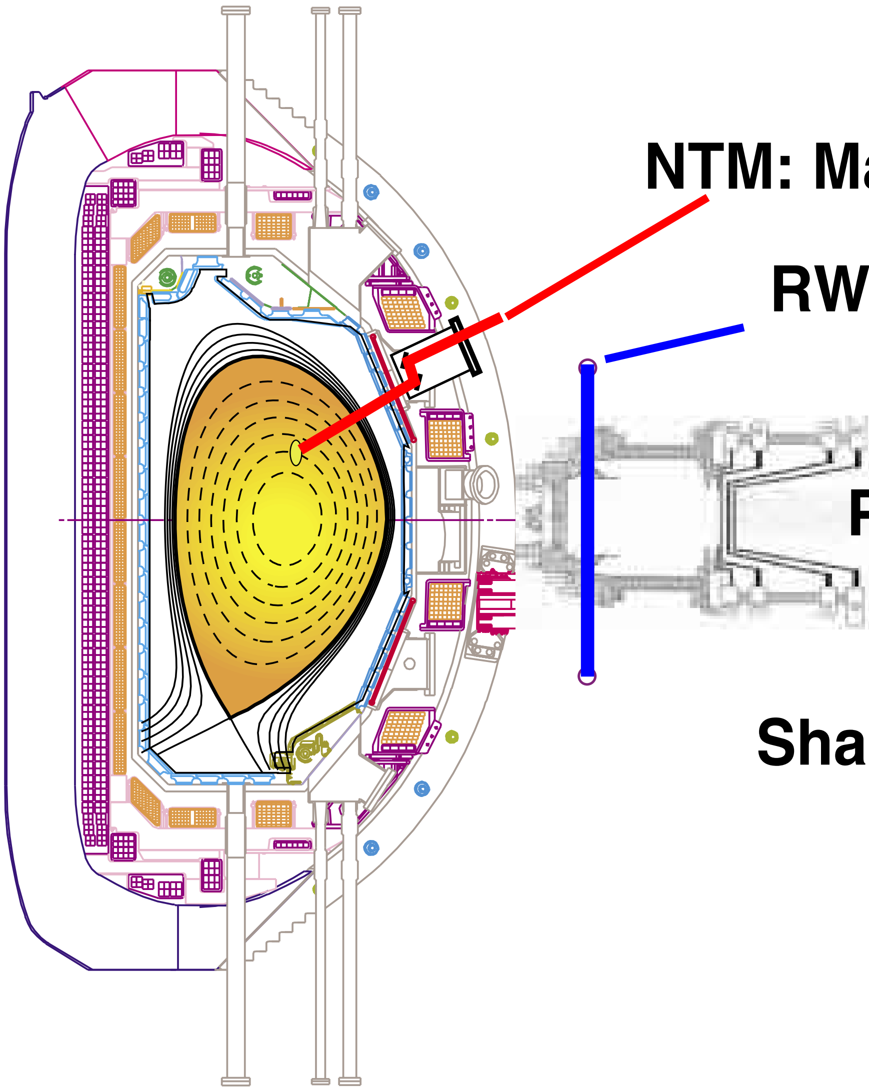
NTM: Magnetics —> ECCD

RWM: Sensors —> Active Coils

Plasma Beta: EFIT —> NBI power

DIII-D NATIONAL FUSION FACILITY SAN DIEGO

DIII-D uses many feedback and control systems



NTM: Magnetics —> ECCD

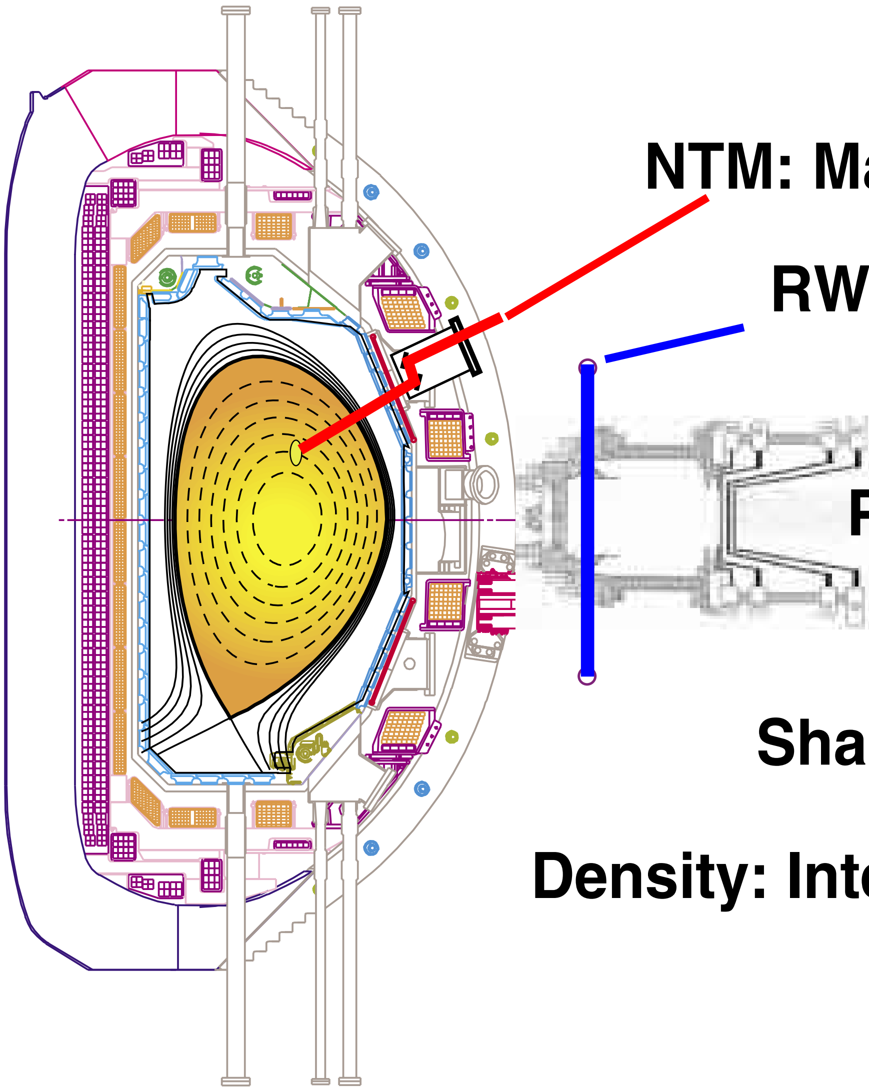
RWM: Sensors —> Active Coils

Plasma Beta: EFIT —> NBI power

Shape: EFIT —> PF coils

DIII-D NATIONAL FUSION FACILITY SAN DIEGO

DIII-D uses many feedback and control systems



NTM: Magnetics —> ECCD

RWM: Sensors —> Active Coils

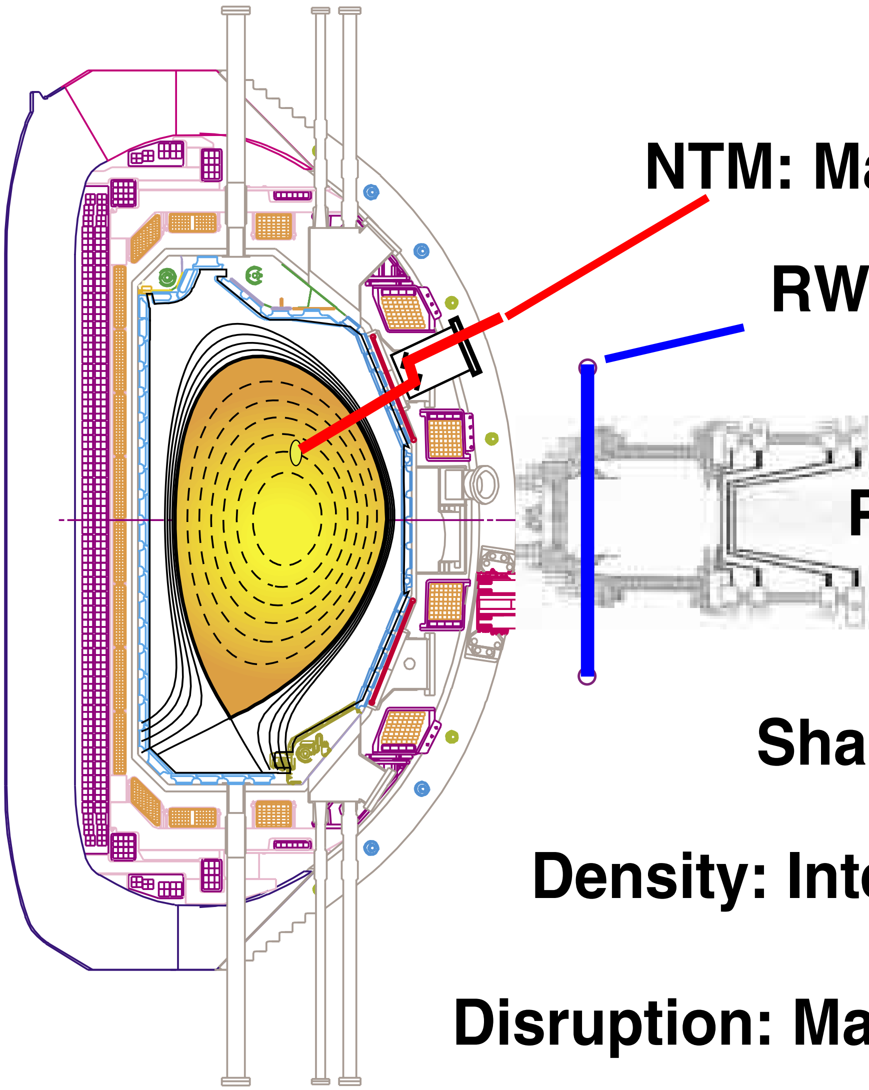
Plasma Beta: EFIT —> NBI power

Shape: EFIT —> PF coils

Density: Interferometer —> Cryopump

DIII-D NATIONAL FUSION FACILITY SAN DIEGO

DIII-D uses many feedback and control systems



NTM: Magnetics —> ECCD

RWM: Sensors —> Active Coils

Plasma Beta: EFIT —> NBI power

Shape: EFIT —> PF coils

Density: Interferometer —> Cryopump

Disruption: Magnetics —> Gas Jet

DIII-D NATIONAL FUSION FACILITY SAN DIEGO

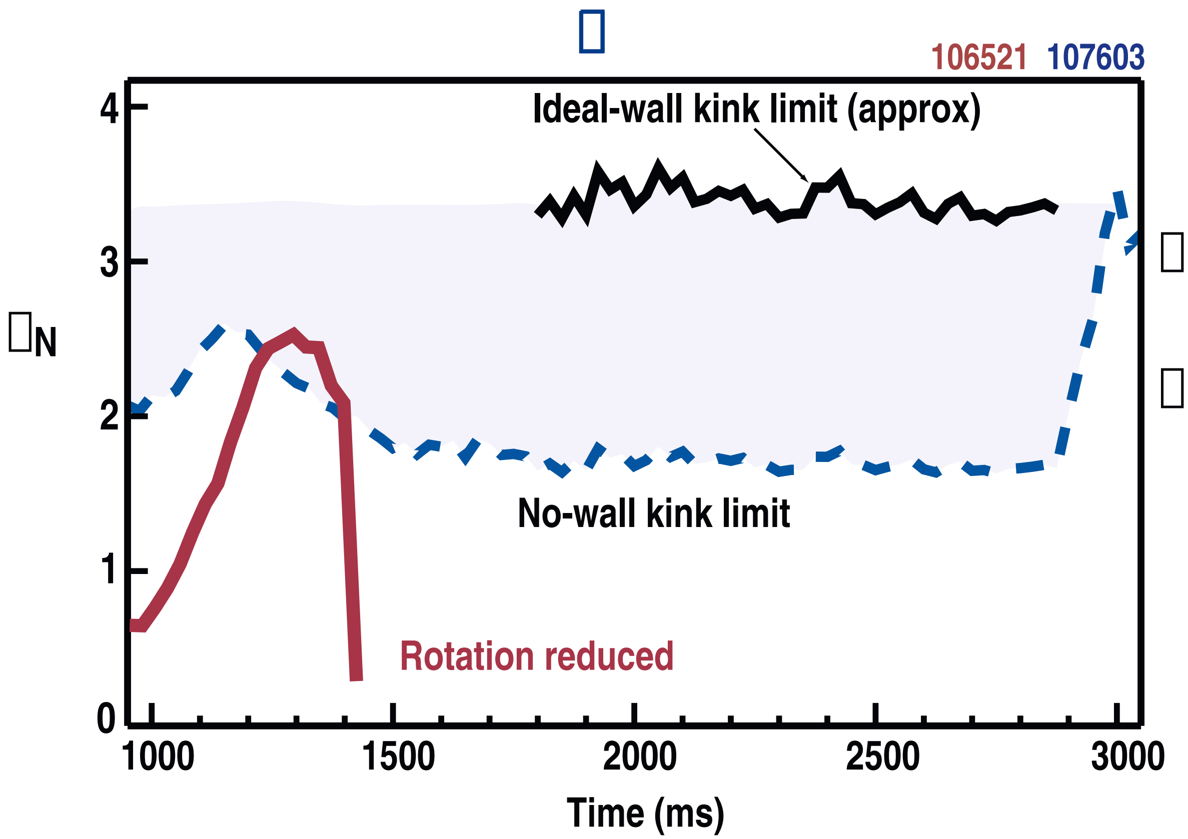
The goal of the DIII-D program is to advance the tokamak concept

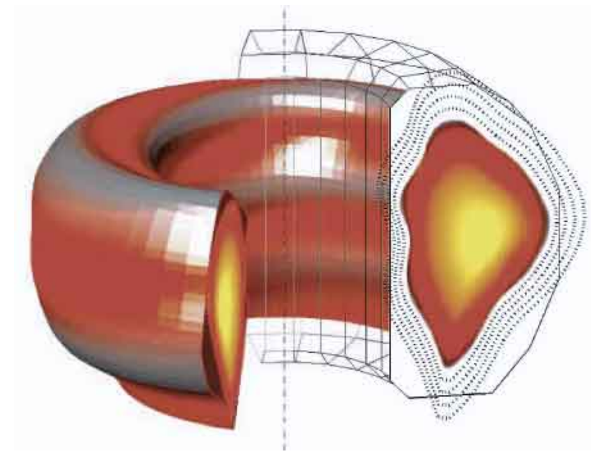
1. Advanced Tokamak: Steady-state high , high $_E$, high bootstrap fraction plasma

- The MHD - stable operating space has been expanded with plasma control
  - — Rotational stabilization of Resistive Wall Modes yielding
    - —> $_N$ ≅ $_N$ (ideal wall) ≅ 2 $_N$ (no wall)

External Kink Instability limits high-β operation
Sustainment of plasma rotation stabilizes mode

- Rotation slowing is a consequence of "resonant error field amplification" at β above the no-wall limit [A. Boozer, Phys. Rev. Lett. 86 (2001)]



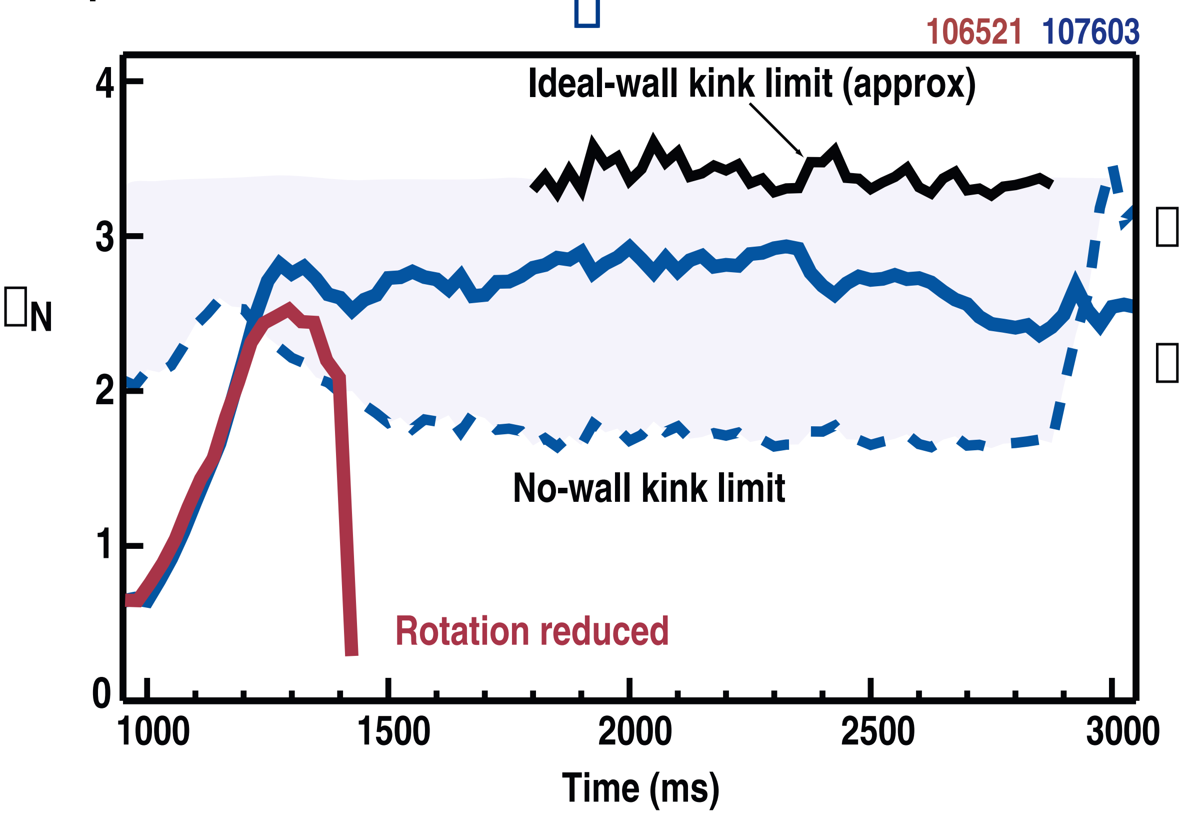


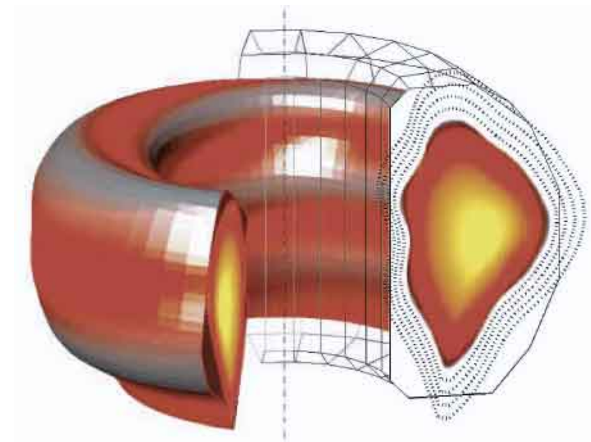
Unstable (x10)

DIII-D NATIONAL FUSION FACILITY SAN DIEGO

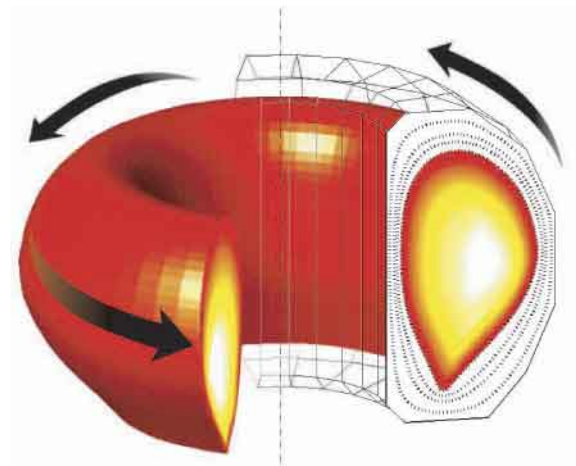
External Kink Instability limits high-β operation
Sustainment of plasma rotation stabilizes mode

- Rotation slowing is a consequence of “resonant error field amplification" at β above the no-wall limit [A. Boozer, Phys. Rev. Lett. 86 (2001)]
- Reduction of the non-axisymmetric (error) fields enables operation above the no-wall limit





Unstable (x10)



Stable with Rotation

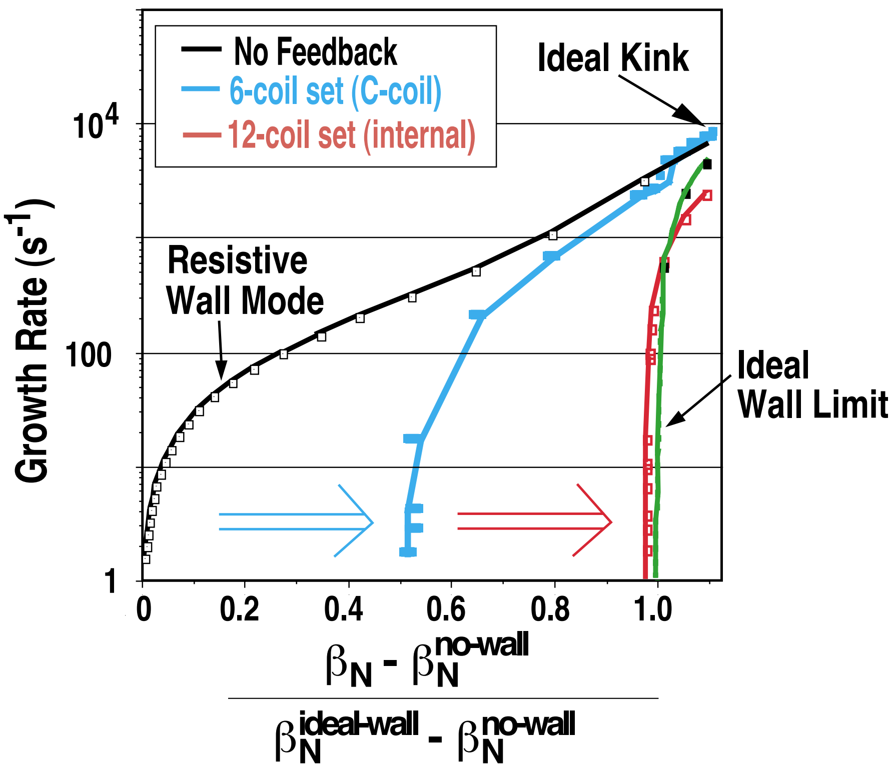
DIII-D
NATIONAL FUSION FACILITY
SAN DIEGO

INTERNAL CONTROL COILS WILL BE AN EFFECTIVE TOOL FOR PURSUING BOTH ACTIVE AND PASSIVE STABILIZATION OF THE RWM

- Off-midplane coils allow better matching to poloidal spectrum of error field or RWM
- Feedback stabilization is calculated to open high beta wall-stabilized regime to plasma without rotation (may be important for burning plasma)

12-coil internal set available for experiments 2003

(VALEN 3-D)



The goal of the DIII-D program is to advance the tokamak concept

1. Advanced Tokamak: Steady-state high β, high τ_E, high bootstrap fraction plasma

- **The MHD - stable operating space has been expanded with plasma control**
  - — Rotational stabilization of Resistive Wall Modes yielding
    - —> $\beta_N \cong \beta_N$ (ideal wall) $\cong 2\,\beta_N$ (no wall)
  - — Stabilization of (3,2) Neoclassical Tearing Mode with ECCD
    - —> Increase β by 60% in sawtoothing plasmas

Steerable ECCD has stabilized Neoclassical Tearing Modes

1 MW Class GYROTRON

2002

Experiments with 5 gyrotrons

2003

Experiments with up to 6 gyrotrons

DIII-D NATIONAL FUSION FACILITY SAN DIEGO

Steerable ECCD has stabilized Neoclassical Tearing Modes

1 MW Class GYROTRON

PPPL Steerable
Waveguides
(Between Shots)
Launch EC
2 in 2002
3 in 2003

2002

Experiments
with
5 gyrotrons

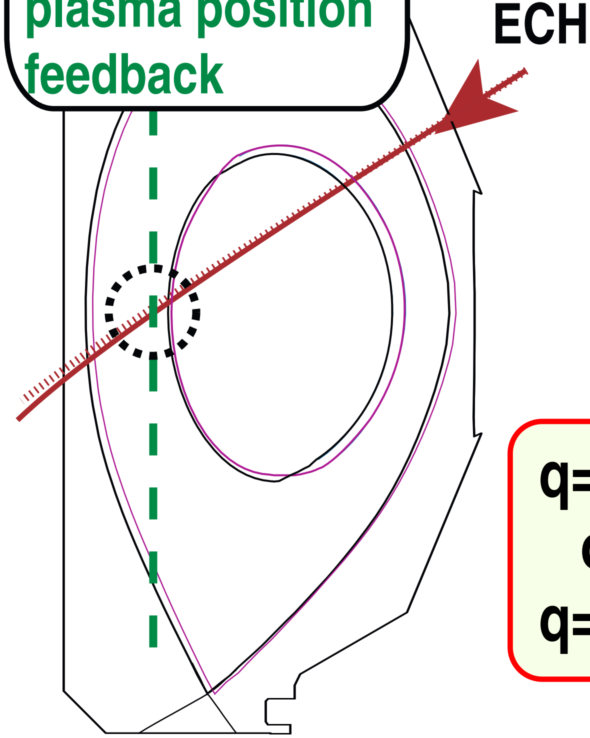
2003

Experiments
with up to
6 gyrotrons

DIII-D
NATIONAL FUSION FACILITY
SAN DIEGO

Steerable ECCD has stabilized Neoclassical Tearing Modes

ECH Resonance varied during shot by B_T or plasma position feedback



q=3/2
or
q=2/1

PPPL Steerable Waveguides (Between Shots) Launch EC
2 in 2002
3 in 2003

2002
Experiments with 5 gyrotrons

2003
Experiments with up to 6 gyrotrons

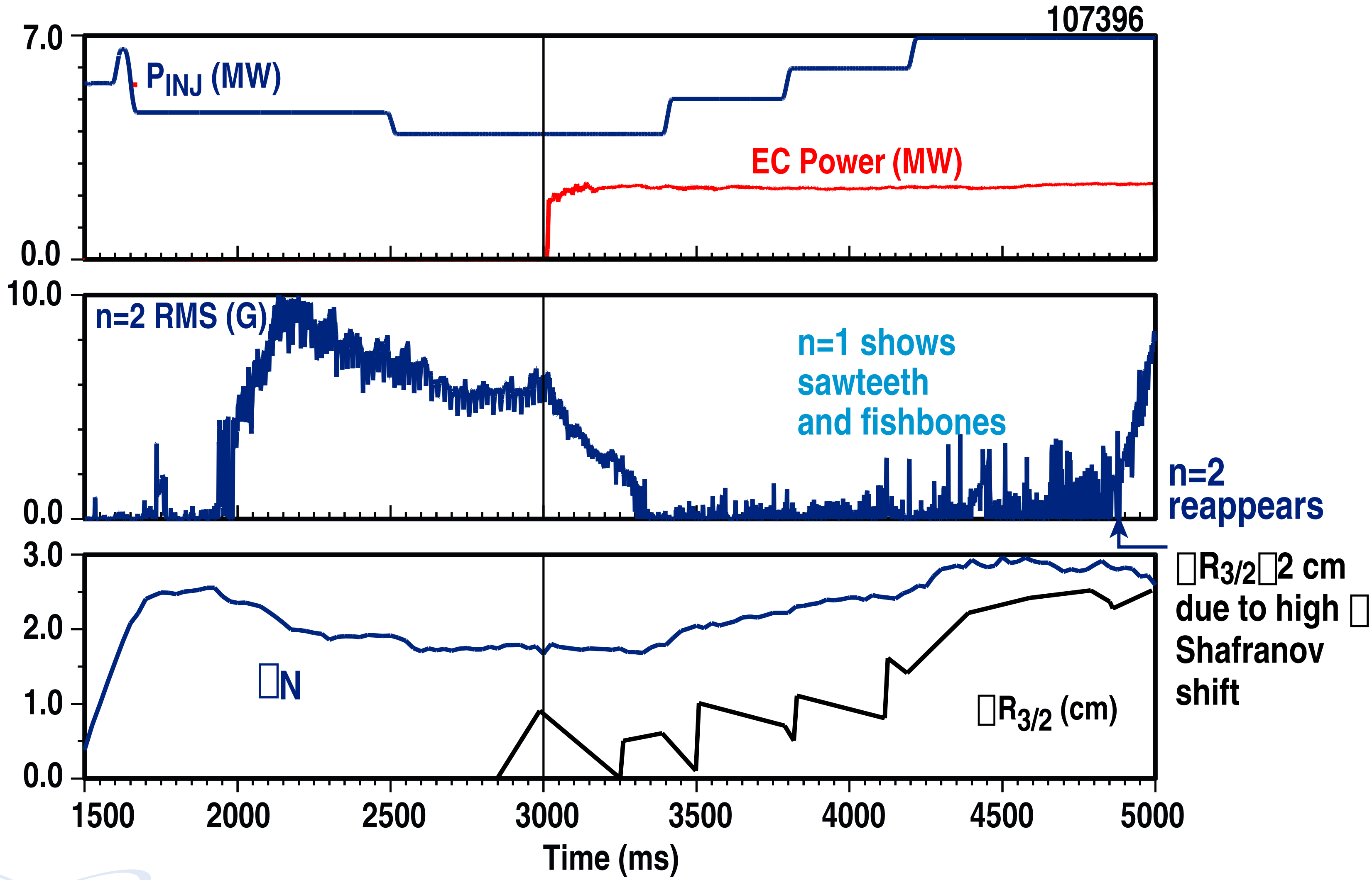
1 MW Class GYROTRON

DIII-D NATIONAL FUSION FACILITY SAN DIEGO

βN RAISED 60% AFTER ECCD SUPPRESSION OF m/n = 3/2 NTM

Location of ECCD optimized in real time to minimize NTM amplitude

- Location held fixed when amplitude is zero
- Mode restrikes as q = 3/2 moves radially by 2 cm off ECCD location

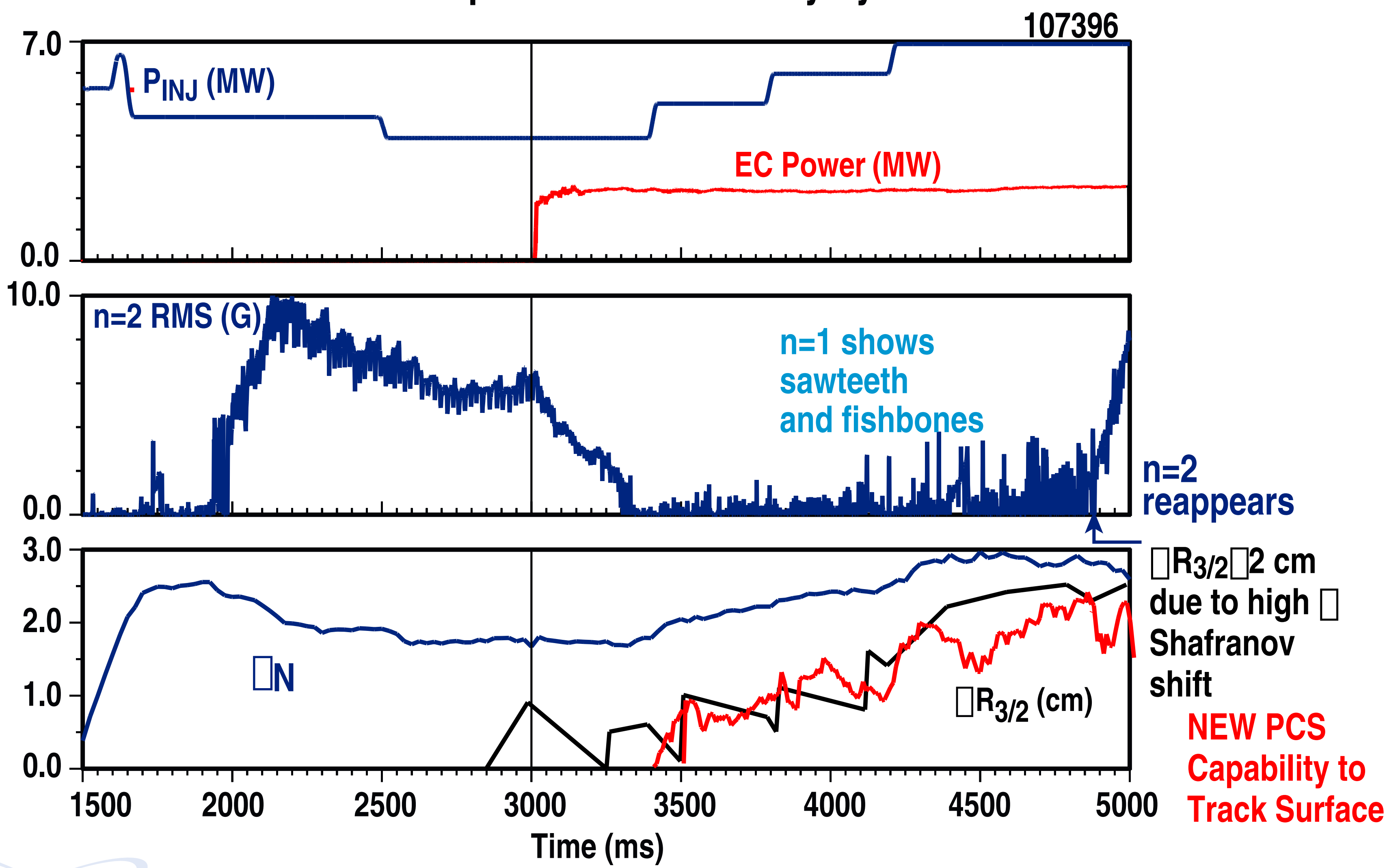


255–02/KHB/wj

β_N RAISED 60% AFTER ECCD SUPPRESSION OF m/n = 3/2 NTM

Location of ECCD optimized in real time to minimize NTM amplitude

- Location held fixed when amplitude is zero
- Mode restrikes as q = 3/2 moves radially by 2 cm off ECCD location



DIII–D NATIONAL FUSION FACILITY SAN DIEGO

The goal of the DIII-D program is to advance the tokamak concept

1. Advanced Tokamak: Steady-state high □, high $□_E$, high bootstrap fraction plasma

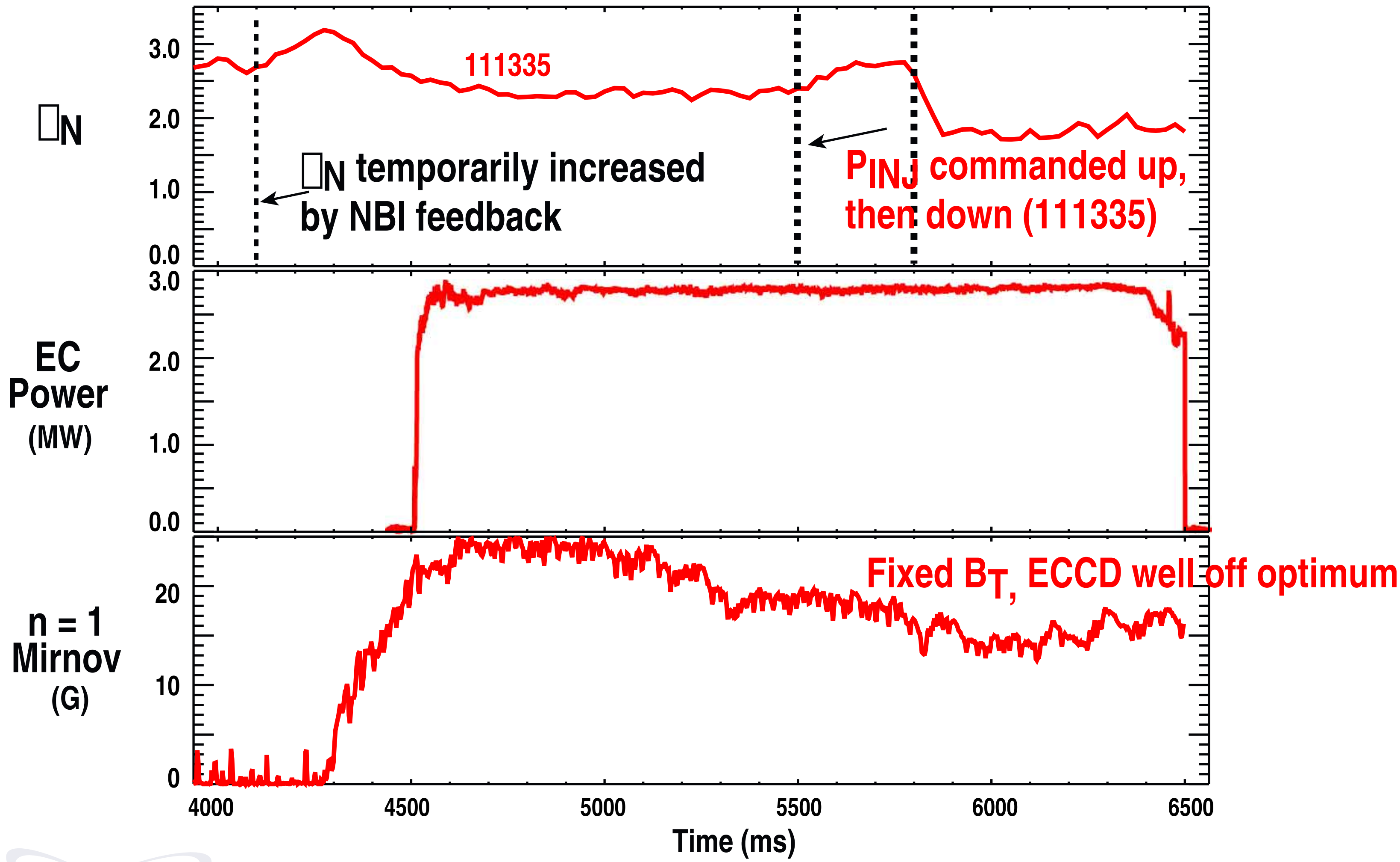
- The MHD - stable operating space has been expanded with plasma control
  - — Rotational stabilization of Resistive Wall Modes yielding
    - —> $□_N$ ≅ $□_N$ (ideal wall) ≅ 2 $□_N$ (no wall)
  - — Stabilization of (3,2) Neoclassical Tearing Mode with ECCD
    - —> Increase □ by 60% in sawtoothing plasmas
  - — First stabilization of (2,1) NTM with ECCD

□ □ □

DIII-D NATIONAL FUSION FACILITY SAN DIEGO

DEMONSTRATED COMPLETE SUPPRESSION OF THE m/n = 2/1 TEARING MODE BY RADIALLY LOCALIZED ECCD

- β_N is feedback controlled to temporarily rise to excite the mode
- Location of ECCD optimized (#111367) by toroidal field PCS "Search and Suppress"



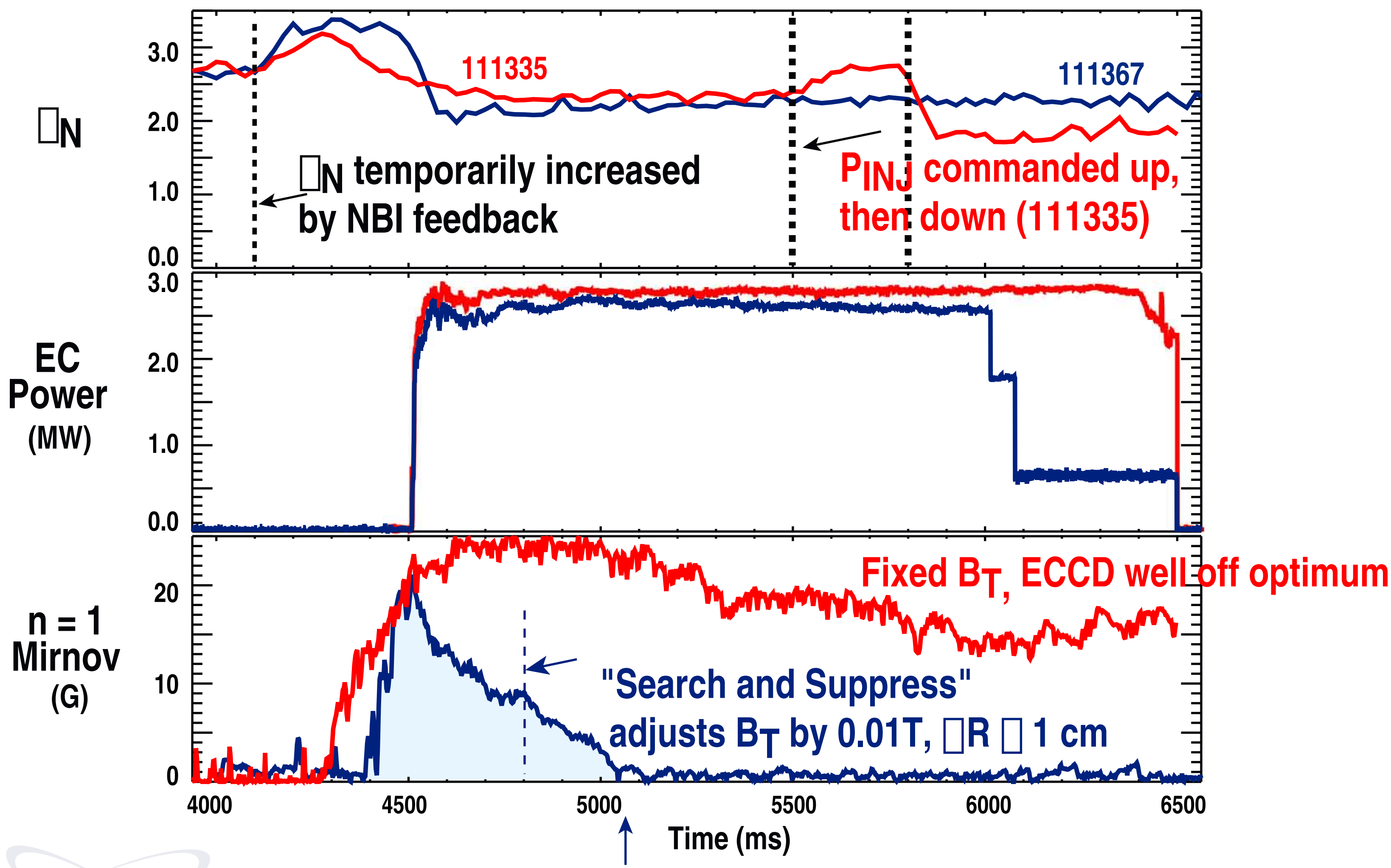
DIII-D NATIONAL FUSION FACILITY SAN DIEGO

244-02/KB/amw

DEMONSTRATED COMPLETE SUPPRESSION OF THE m/n = 2/1 TEARING MODE BY RADIALLY LOCALIZED ECCD

β_N is feedback controlled to temporarily rise to excite the mode

Location of ECCD optimized (#111367) by toroidal field PCS "Search and Suppress"



m/n = 2/1 MODE ELIMINATED

DIII–D NATIONAL FUSION FACILITY SAN DIEGO

244-02/KB/amw

The goal of the DIII-D program is to advance the tokamak concept

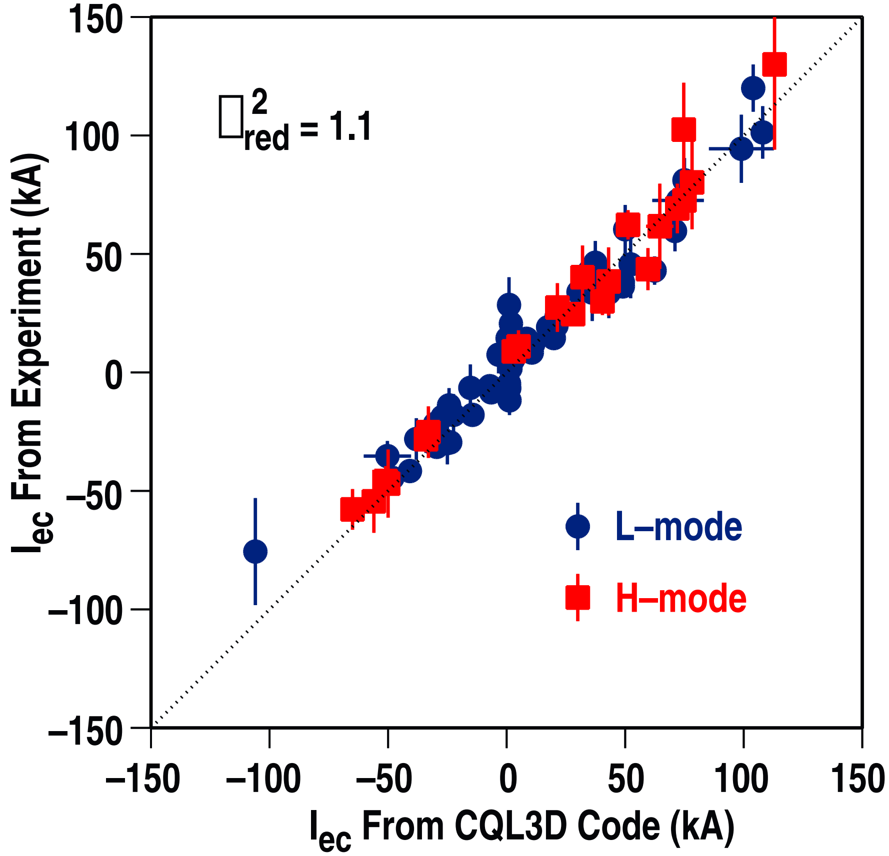
1. Advanced Tokamak: Steady-state high □, high $\square_E$, high bootstrap fraction plasma

- **The MHD - stable operating space has been expanded with plasma control**
  - — Rotational stabilization of Resistive Wall Modes yielding
    - —> $\square_N \cong \square_N$ (ideal wall) $\cong 2\,\square_N$ (no wall)
  - — Stabilization of (3,2) Neoclassical Tearing Mode with ECCD
    - —> Increase □ by 60% in sawtoothing plasmas
  - — First stabilization of (2,1) NTM with ECCD
- **First integrated *A T* discharges with current profile control by ECCD**
  - — Modeling of current evolution and predictions of capabilities

□ □ □

VALIDATED ECCD THEORY ALLOWS USE OF DETAILED COMPUTER MODELS TO DEVELOP EXPERIMENTS

- Excellent agreement of ECCD theory and experiment

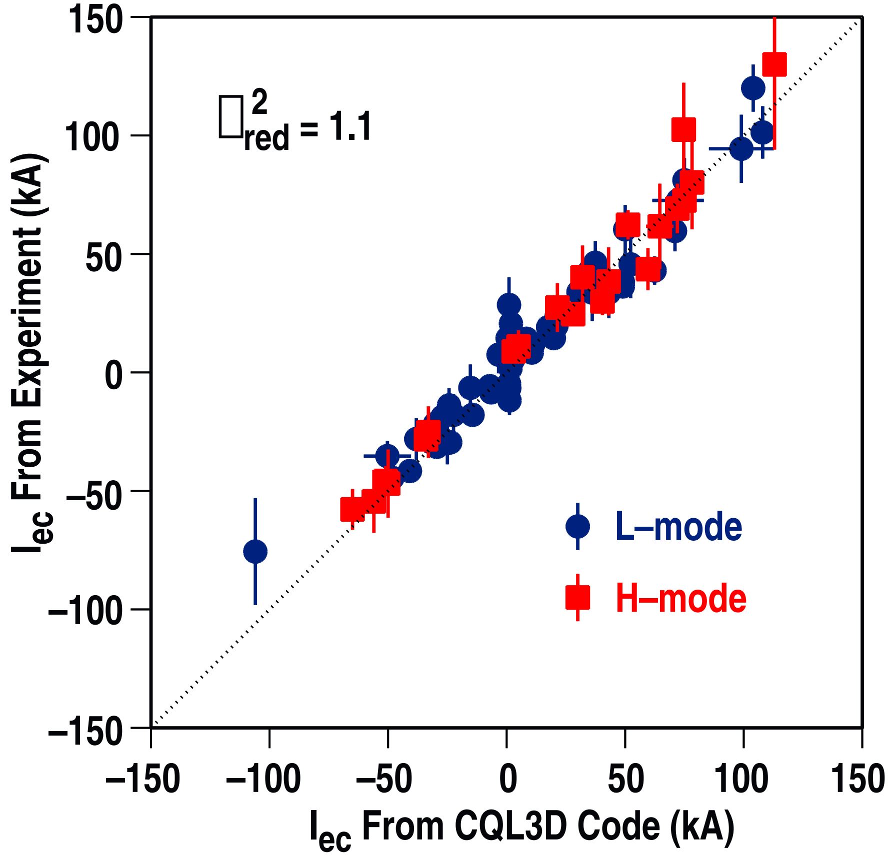


DIII–D
NATIONAL FUSION FACILITY
SAN DIEGO

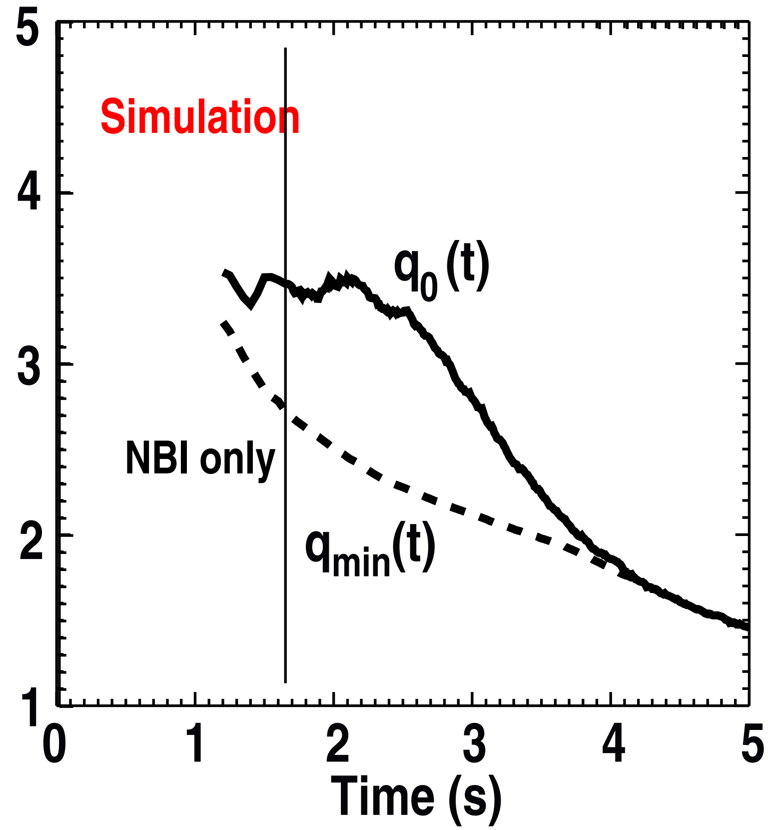
258–02/KHB/wjj

VALIDATED ECCD THEORY ALLOWS USE OF DETAILED COMPUTER MODELS TO DEVELOP EXPERIMENTS

- Excellent agreement of ECCD theory and experiment



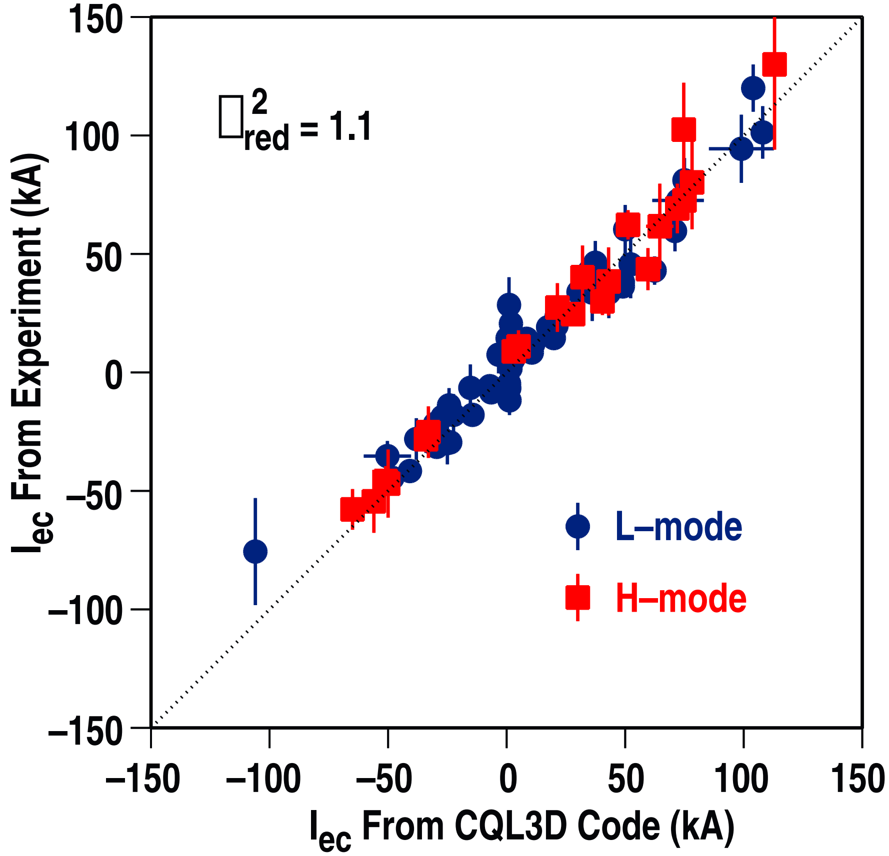
- Prediction of enhanced negative central shear in AT plasma with



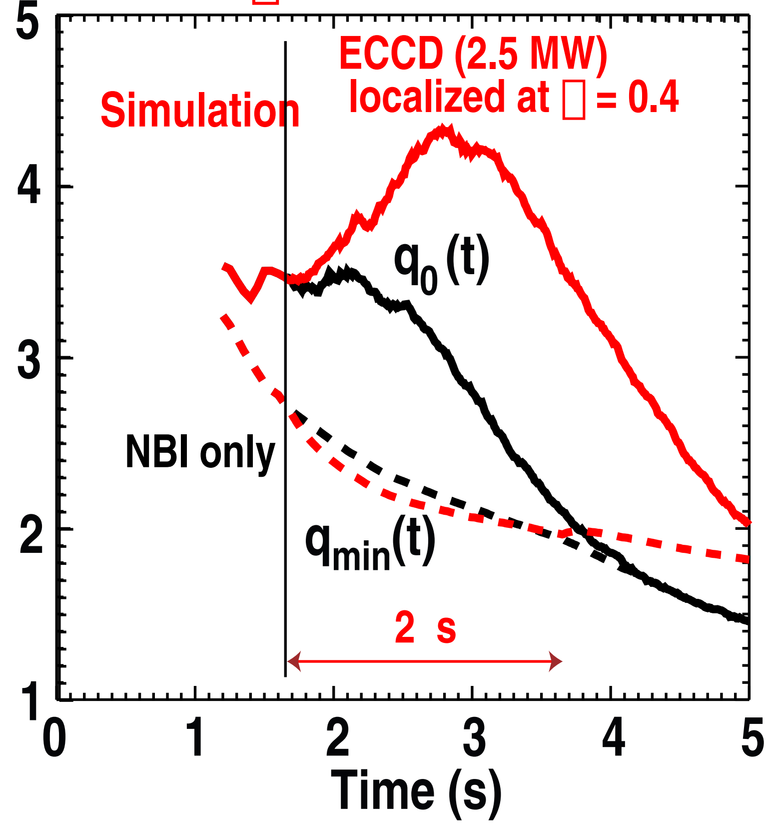
DIII–D
NATIONAL FUSION FACILITY
SAN DIEGO

VALIDATED ECCD THEORY ALLOWS USE OF DETAILED COMPUTER MODELS TO DEVELOP EXPERIMENTS

- Excellent agreement of ECCD theory and experiment



- Prediction of enhanced negative central shear in AT plasma with ECCD at ρ = 0.4

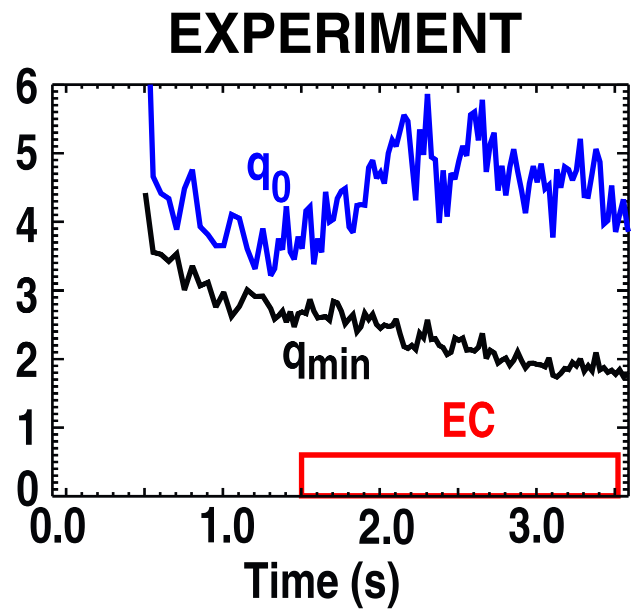


DIII–D NATIONAL FUSION FACILITY SAN DIEGO

258–02/KHB/wjj

ECCD PRODUCES CURRENT PROFILE MODIFICATION IN ADVANCED TOKAMAK PLASMA

- $\beta_N H_{89} \gtrsim 7$ for full 2.0 s ECCD pulse
- β_N at or slightly above β_N (no-wall)
- Total non-inductive current fraction ≳90%
- q profile modified during high β, AT phase of shot



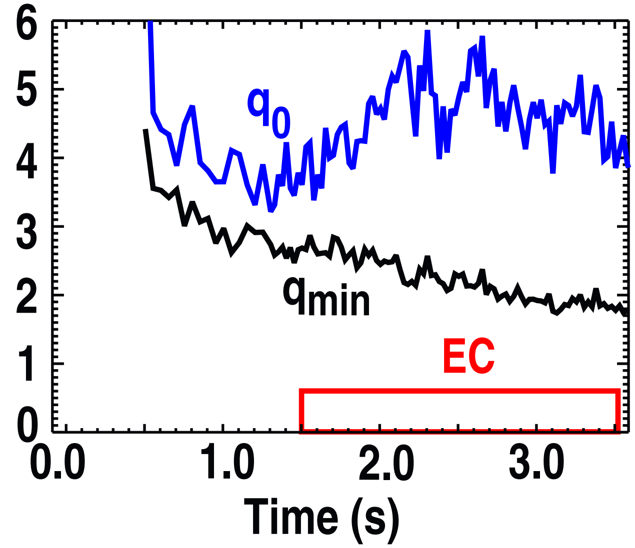
DIII–D NATIONAL FUSION FACILITY SAN DIEGO

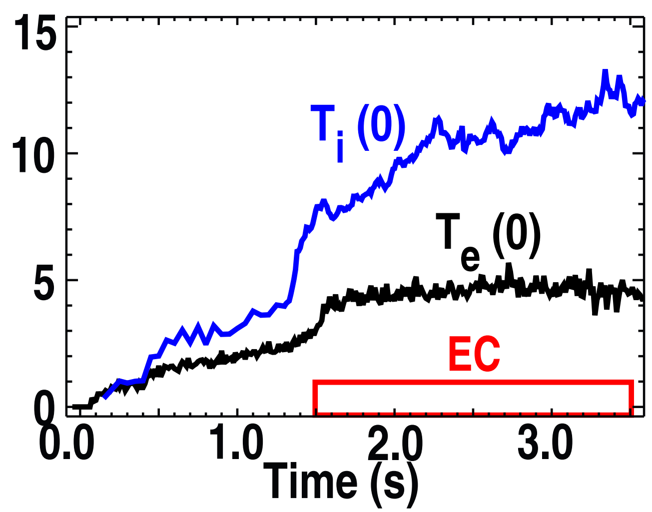
255–02/KHB/wj

ECCD PRODUCES CURRENT PROFILE MODIFICATION IN ADVANCED TOKAMAK PLASMA

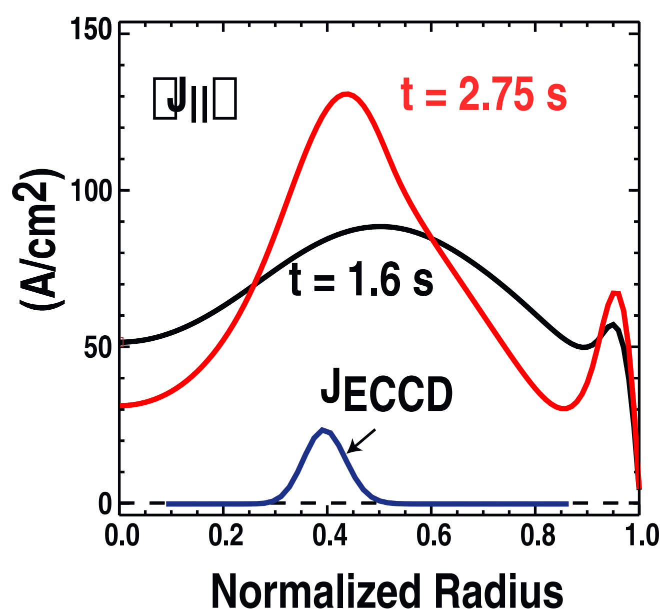
- $\beta_N H_{89} \gtrsim 7$ for full 2.0 s ECCD pulse
- β_N at or slightly above β_N (no-wall)
- Total non-inductive current fraction ≳90%
- q profile modified during high β, AT phase of shot

EXPERIMENT





EFIT equilibrium analysis using MSE



DIII-D
ExENATIONAL FUSION FACILITY
SAN DIEGO

255–02/KHB/wj

The goal of the DIII-D program is to advance the tokamak concept

1. Advanced Tokamak: Steady-state high β, high τ_E, high bootstrap fraction plasma

- **The MHD - stable operating space has been expanded with plasma control**
  - — Rotational stabilization of Resistive Wall Modes yielding
    - —> $\beta_N \cong \beta_N$ (ideal wall) $\cong$ 2 β_N (no wall)
  - — Stabilization of (3,2) Neoclassical Tearing Mode with ECCD
    - —> Increase β by 60% in sawtoothing plasmas
  - — First stabilization of (2,1) NTM with ECCD

- **First integrated *AT* discharges with current profile control by ECCD**
  - — Modeling of current evolution and predictions of capabilities

2. Key burning plasma issues - ELMs, integrated operation, disruptions

- QH-mode plasmas with ITB small ELMs, some impurity issues

We have expanded the operational regime of the Quiescent H–Mode to higher density

- Requires neutral beam injection counter to I_p direction plus divertor cryopumping

- QH–mode seen to date for

  $3.4 \le q_{95} \le 5.8$

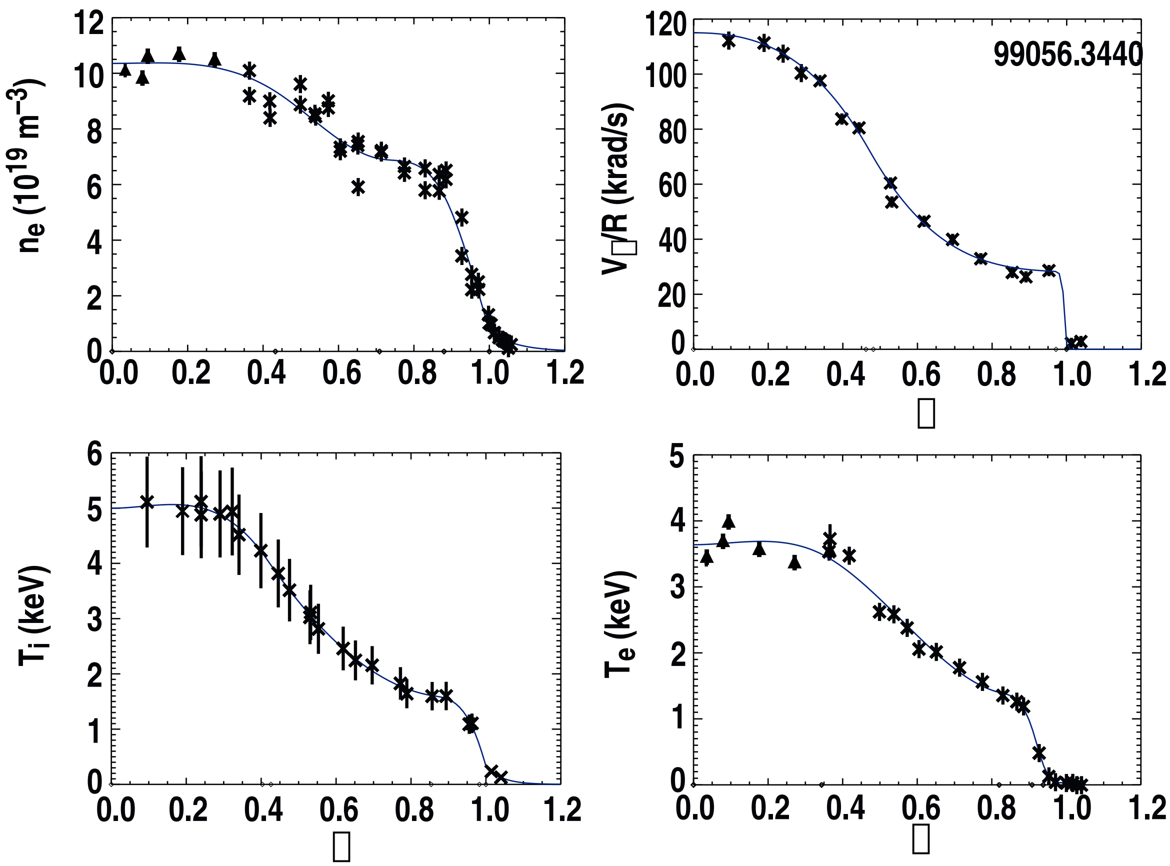
  $1.0 \le I_p$ (MA) ≤ 2.0

  $1.8 \le B_T$ (T) ≤ 2.1

  $1.0 \le n_e^{ped}$ (10^{19} m^{-3}) ≤ 6.5

- QH–mode recently seen in ASDEX–U

High Density QH–Mode



DIII–D NATIONAL FUSION FACILITY SAN DIEGO

255-02/KB/JY

The goal of the DIII-D program is to advance the tokamak concept

1. Advanced Tokamak: Steady-state high β, high τ_E, high bootstrap fraction plasma

- The MHD - stable operating space has been expanded with plasma control
  - — Rotational stabilization of Resistive Wall Modes yielding
    - —> $\beta_N \cong \beta_N$ (ideal wall) $\cong 2\ \beta_N$ (no wall)
  - — Stabilization of (3,2) Neoclassical Tearing Mode with ECCD
    - —> Increase β by 60% in sawtoothing plasmas
  - — First stabilization of (2,1) NTM with ECCD
- First integrated *AT* discharges with current profile control by ECCD
  - — Modeling of current evolution and predictions of capabilities

2. Key burning plasma issues - ELMs, integrated operation, disruptions

- QH-mode plasmas with ITB small ELMs, some impurity issues
- Pedestal width is set by neutral physics, ELMs depend on n_e or ν^*

The goal of the DIII-D program is to advance the tokamak concept

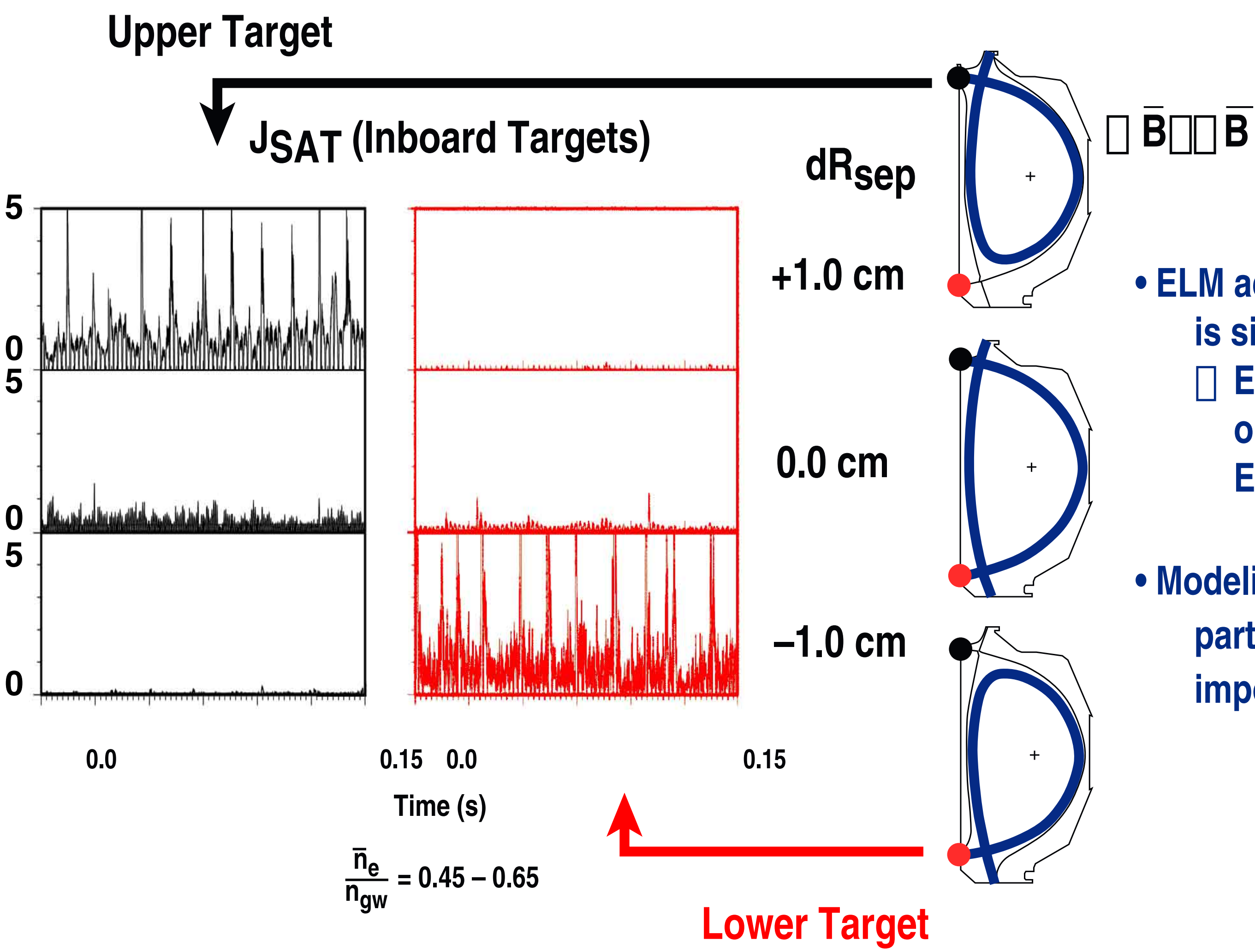
1. Advanced Tokamak: Steady-state high β, high τ_E, high bootstrap fraction plasma

- The MHD - stable operating space has been expanded with plasma control
  - — Rotational stabilization of Resistive Wall Modes yielding
    - —> $\beta_N \cong \beta_N$ (ideal wall) $\cong 2\,\beta_N$ (no wall)
  - — Stabilization of (3,2) Neoclassical Tearing Mode with ECCD
    - —> Increase β by 60% in sawtoothing plasmas
  - — First stabilization of (2,1) NTM with ECCD
- First integrated *AT* discharges with current profile control by ECCD
  - — Modeling of current evolution and predictions of capabilities

2. Key burning plasma issues - ELMs, integrated operation, disruptions

- QH-mode plasmas with ITB small ELMs, some impurity issues
- Pedestal width is set by neutral physics, ELMs depend on n_e or [illegible]
- Balanced double null divertor results in small inner strike point heat loads

The Inboard Divertor Particle And Heat Fluxes Are Low In Symmetric Double-null Plasma



- ELM activity at the inboard target(s) is significantly reduced in DN
  - ELMs are generated on the outboard side (consistent with ELITE analysis)
- Modeling (UEDGE) indicates that particle drifts in the divertor are important

The goal of the DIII-D program is to advance the tokamak concept

1. Advanced Tokamak: Steady-state high □, high $□_E$, high bootstrap fraction plasma

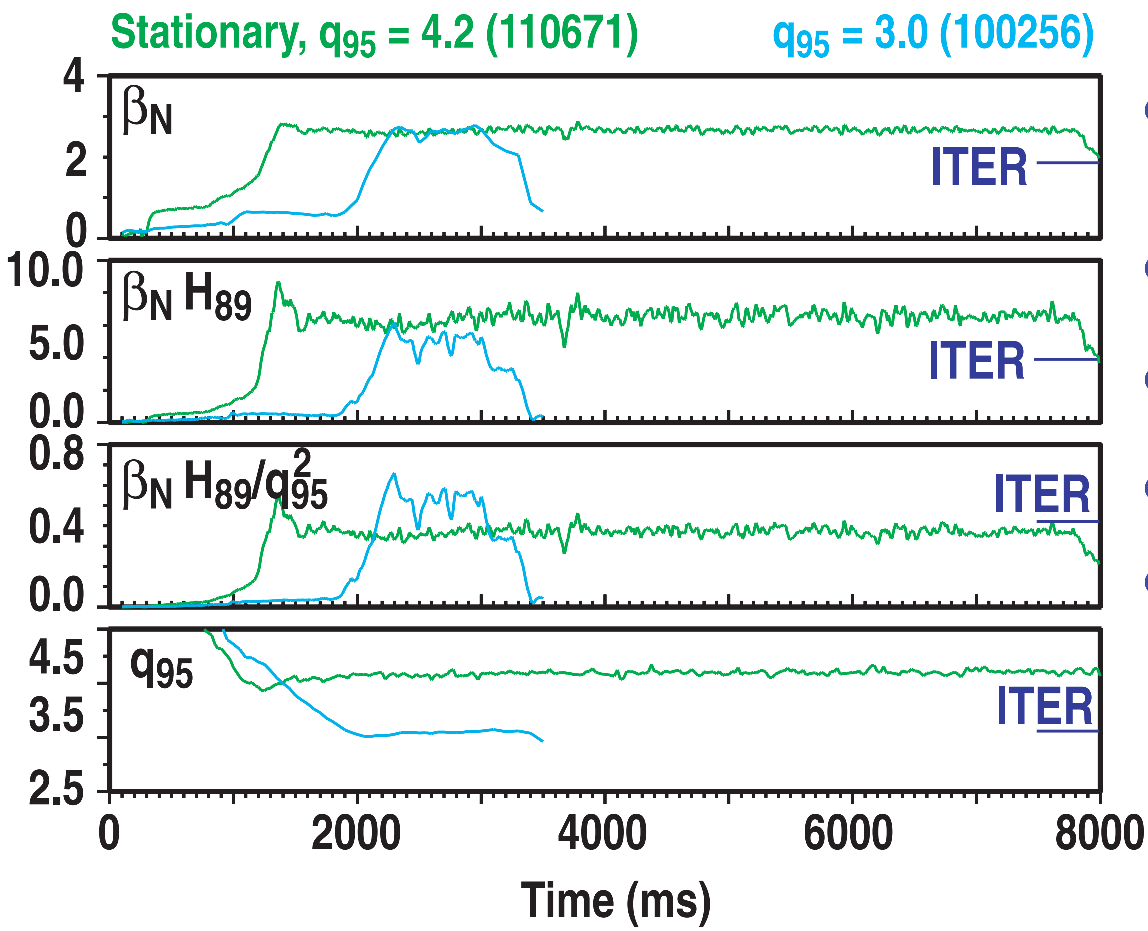
- The MHD - stable operating space has been expanded with plasma control
  - — Rotational stabilization of Resistive Wall Modes yielding
    - —> $□_N$ ≅ $□_N$ (ideal wall) ≅ 2 $□_N$ (no wall)
  - — Stabilization of (3,2) Neoclassical Tearing Mode with ECCD
    - —> Increase □ by 60% in sawtoothing plasmas
  - — First stabilization of (2,1) NTM with ECCD
- First integrated *A T* discharges with current profile control by ECCD
  - — Modeling of current evolution and predictions of capabilities

2. Key burning plasma issues - ELMs, integrated operation, disruptions

- QH-mode pla□sma□s with ITB smal□ELMs, some impurity issues
- Pedestal width is set by neutral physics, ELMs depend on n_e or $□^□$
- Balanced double null divertor results in small inner strike point heat loads
- Demonstrated q_{95} ~ 4 operating scenario for ITER

DIII-D
NATIONAL FUSION FACILITY
SAN DIEGO

STATIONARY PLASMAS WITH $\beta_N H/q_{95}^2 \simeq$ ITER DESIGN VALUE AND $q_{95} > 4$ HAVE BEEN DEMONSTRATED ON DIII–D



- Fusion gain proportional to $\beta_N H_{89}/q_{95}^2$
- $q(0) > 1$
- 3/2 NTM prevents sawteeth
- $\beta_N \simeq \beta_N^{\text{no-wall}}$
- Non-inductive current fraction $\simeq$ 50%

DIII–D NATIONAL FUSION FACILITY SAN DIEGO

255-02/KB/JY

The goal of the DIII-D program is to advance the tokamak concept

1. Advanced Tokamak: Steady-state high β, high τ_E, high bootstrap fraction plasma

- The MHD - stable operating space has been expanded with plasma control
  - — Rotational stabilization of Resistive Wall Modes yielding
    - —> $\beta_N \cong \beta_N$ (ideal wall) $\cong 2\ \beta_N$ (no wall)
  - — Stabilization of (3,2) Neoclassical Tearing Mode with ECCD
    - —> Increase β by 60% in sawtoothing plasmas
  - — First stabilization of (2,1) NTM with ECCD
- First integrated *A T* discharges with current profile control by ECCD
  - — Modeling of current evolution and predictions of capabilities

2. Key burning plasma issues - ELMs, integrated operation, disruptions

- QH-mode plasmas with ITB small ELMs, some impurity issues
- Pedestal width is set by neutral physics, ELMs depend on n_e or ν^*
- Balanced double null divertor results in small inner strike point heat loads
- Demonstrated q_{95} ~ 4 operating scenario for ITER
- Disruption mitigation via a massive gas puff

DIII-D NATIONAL FUSION FACILITY SAN DIEGO

Other DIII-D Presentations Remaining This Week

1. Poster Sessions:
   - Thursday Morning, QP1
   - Thursday Afternoon, RP1
2. Invited Oral Talks
   - Friday Morning:

     Whyte (Disruption Avoidance)

     Candy (Transport)

     McKee (Zonal Flows)

DIII-D NATIONAL FUSION FACILITY SAN DIEGO

The goal of the DIII-D program is to advance the tokamak concept

1. Advanced Tokamak: Steady-state high β, high τ_E, high bootstrap fraction plasma

- The MHD - stable operating space has been expanded with plasma control
  - — Rotational stabilization of Resistive Wall Modes yielding
    - —> $\beta_N \cong \beta_N$ (ideal wall) $\cong 2\,\beta_N$ (no wall)
  - — Stabilization of (3,2) Neoclassical Tearing Mode with ECCD
    - —> Increase β by 60% in sawtoothing plasmas
  - — First stabilization of (2,1) NTM with ECCD
- First integrated *A T* discharges with current profile control by ECCD
  - — Modeling of current evolution and predictions of capabilities

2. Key burning plasma issues - ELMs, integrated operation, disruptions

- QH-mode plasmas with ITB small ELMs, some impurity issues
- Pedestal width is set by neutral physics, ELMs depend on n_e or □□
- Balanced double null divertor results in small inner strike point heat loads
- Demonstrated q_{95} ~ 4 operating scenario for ITER
- Disruption mitigation via a massive gas puff

DIII-D NATIONAL FUSION FACILITY SAN DIEGO

The goal of the DIII-D program is to advance the tokamak concept

1. Advanced Tokamak: Steady-state high β, high τ_E, high bootstrap fraction plasma

- The MHD - stable operating space has been expanded with plasma control
  - — Rotational stabilization of Resistive Wall Modes yielding
    - —> $\beta_N \cong \beta_N$ (ideal wall) $\cong 2\,\beta_N$ (no wall)
  - — Stabilization of (3,2) Neoclassical Tearing Mode with ECCD
    - —> Increase β by 60% in sawtoothing plasmas
  - — First stabilization of (2,1) NTM with ECCD
- First integrated *AT* discharges with current profile control by ECCD
  - — Modeling of current evolution and predictions of capabilities

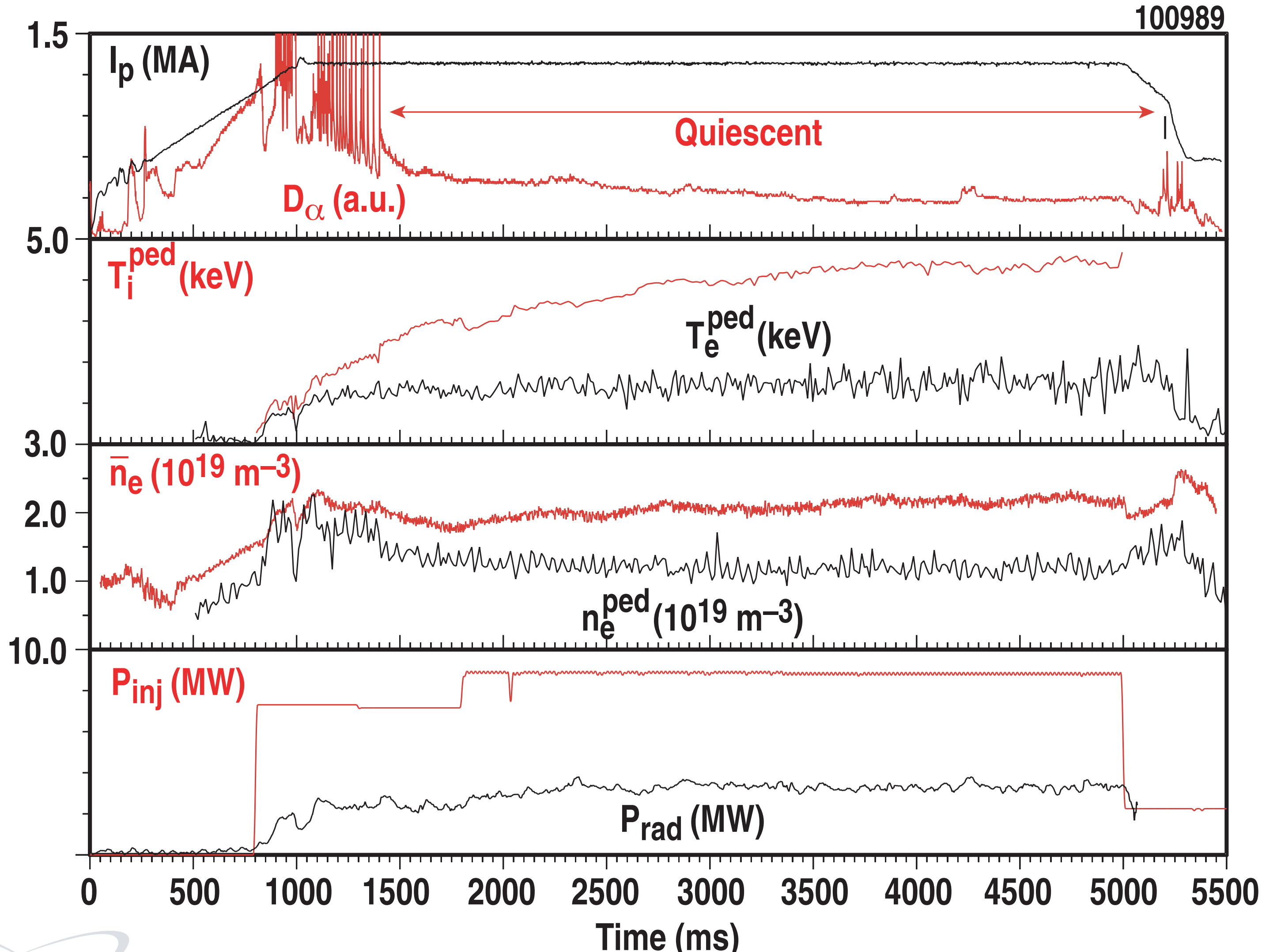
2. Key burning plasma issues - ELMs, integrated operation, disruptions

- QH-mode plasmas with ITB small ELMs, some impurity issues
- Pedestal width is set by neutral physics, ELMs depend on n_e or ν^*
- Balanced double null divertor results in small inner strike point heat loads
- Demonstrated $q_{95} \sim 4$ operating scenario for ITER
- Disruption mitigation via a massive gas puff

DIII-D NATIONAL FUSION FACILITY SAN DIEGO

QUIESCENT H–MODE RUNS ELM–FREE FOR LONG PULSES WITH CONSTANT DENSITY AND RADIATED POWER

- Duration limited by neutral beam pulse length



DIII–D NATIONAL FUSION FACILITY SAN DIEGO

255-02/KB/JY

THE DIII–D RESEARCH PROGRAM WILL MAKE MAJOR CONTRIBUTIONS IN THREE FOCUS AREAS

- **Advanced Tokamak: in-principle steady-state, high performance discharges**
  - Scientific understanding of key elements
    - ★ MHD stabilization
    - ★ Profile optimization
  - Plasma control
  - Integrated self-consistent scenarios

- **Transport: major advance in turbulent transport understanding**
  - Develop state-of-the-art simulations and models
  - Measure turbulence generated flows
  - Measure short wavelength turbulence (electron transport)

- **Mass transport in the boundary**
  - Integrated modeling of the boundary
  - Measure flow of primary ions
  - Measure erosion and redeposition (tritium retention issue)

DIII–D progress over a broad range of science issues will support these accomplishments