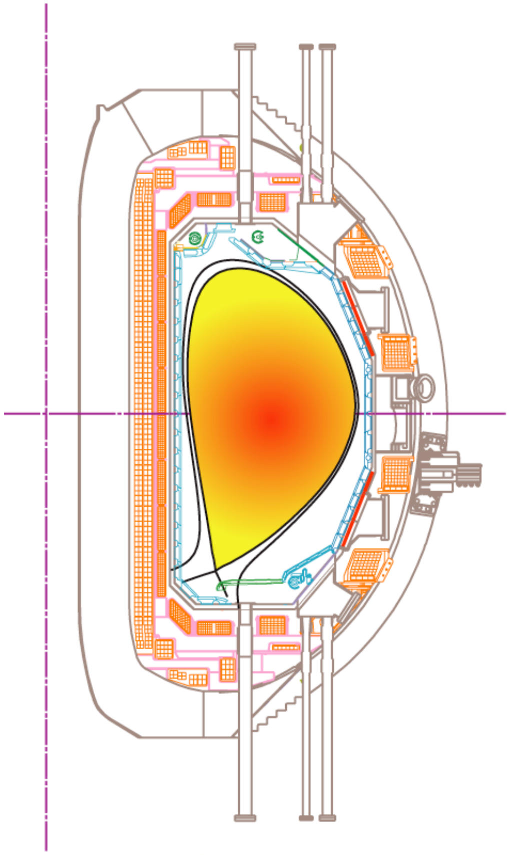
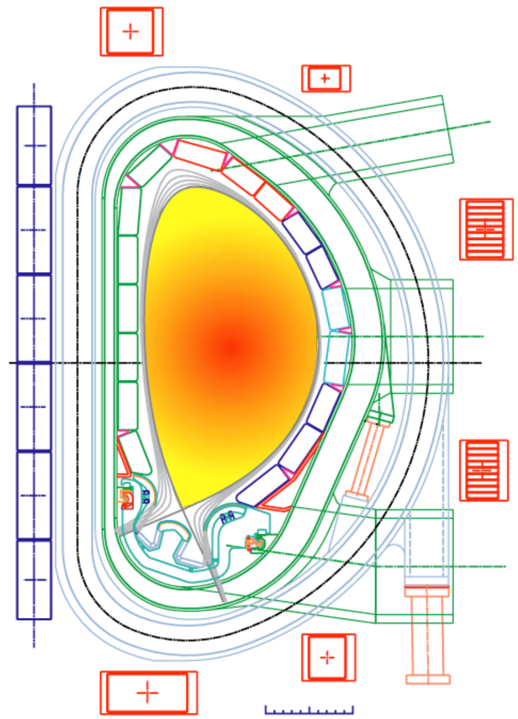
Plans for MHD control in DIII-D (2009-2013)

By
E.J. Strait



DIII–D



ITER

US-Japan Workshop on
MHD Control, Magnetic Islands,
and Rotation

Austin, Texas
November 23-25, 2008

MHD stability research in DIII-D addresses key issues of physics understanding and mode control

- Sawtooth physics
- Fast ion-driven modes
- Neoclassical Tearing Mode stabilization
- Resistive Wall Mode control
- ELM control
- Error Field Correction
- Disruption Mitigation

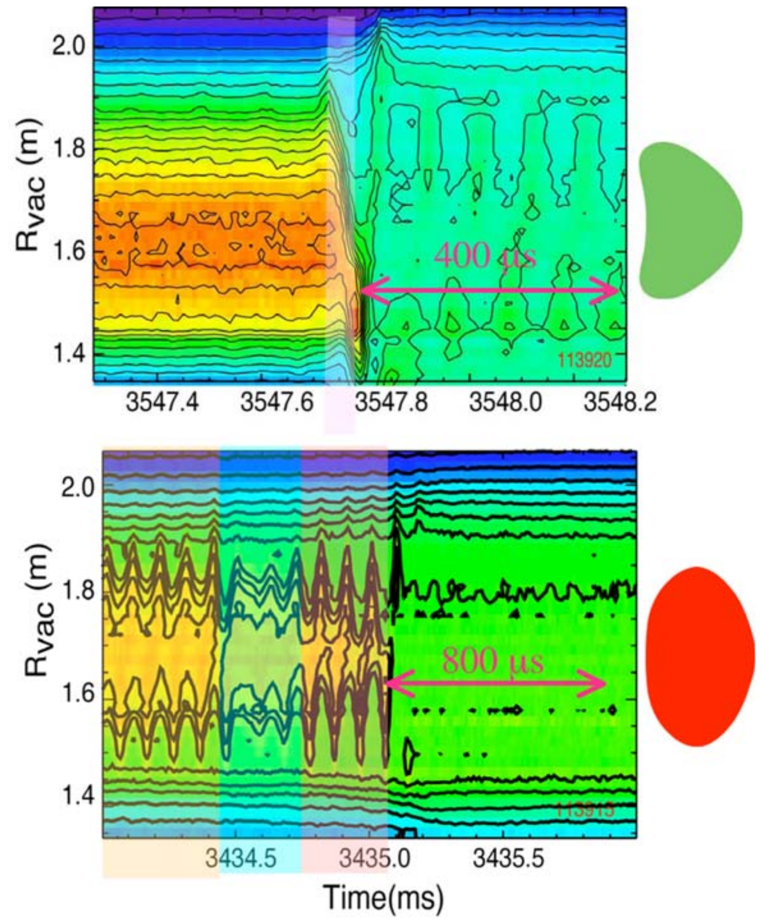
Planned Facility Upgrades are Aimed at Critical Issues for ITER

Tool	Applications
Inner wall RMP coils	ELM control
NBI vertical steering	Steady-state advanced scenarios
EC system expansion to 12 MW	NTM control, low-torque heating, T_e/T_i ~1
FW antenna upgrades	Stability and confinement at low torque Coupling to ITER H–mode edge
RWM amplifier upgrade	RWM plus error field control Simultaneous stabilization of n=1, 2, 3
TF coil connector upgrade	Error field control RWM control
Additional F-coil choppers	Improved shape control for ITER startup
High-throughput pellet injector upgrade	ELM pacemaking Core fueling
High-throughput gas injection, inverse jet custom pellets, liquid jet	Disruption mitigation
Axisymmetric divertor coils	Divertor heat load reduction
Closed loop water/air cooling	Hot wall operation against T retention

Sawtooth Experiments Will Study Linkage with Transport as well as Stability Issues

- **Research objectives for 2009-2013**
  - Examine role of shape and fast ions in sawtooth crash dynamics
  - Modify sawteeth to reduce NTM seeding
- **Verify models of sawtooth stability**
  - NIMROD (3-D effects)
  - Porcelli model
- **Control tools**
  - 12 MW ECH
  - Fast Waves
  - Shape flexibility
- **Key diagnostics**
  - ECE, ECE imaging, CER
  - MSE
  - BES, scattering, reflectometry

ECE color map of sawtooth crash



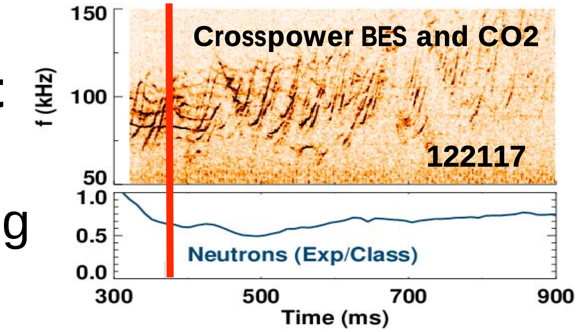
Alpha Physics Will Introduce New Scientific Challenges in ITER

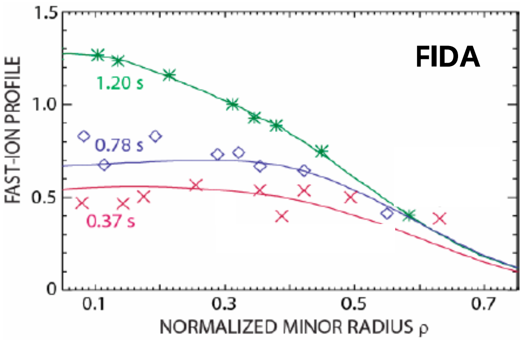
2008	2009	2010	2011	2012	2013

Physics: linear stability — Fast ion transport — Instability control

Fast ion distribution: ECH, FW, co/ctr NBI — Off-axis NBI

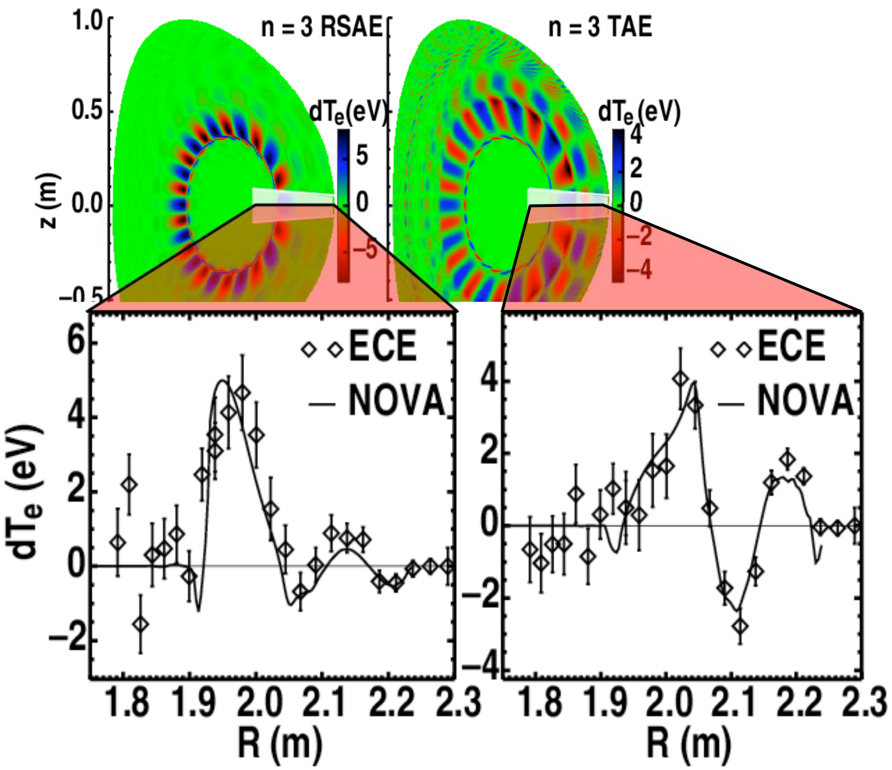
- **Near-term DIII-D goal: validate models for fast ion-driven instabilities**
  - Rigorous tests of sawtooth models
  - Multi-field measurements of Alfven eigenmode structure
  - Detailed comparison to ideal and kinetic theory
- **5-year goal: understand and control fast ion transport**
  - Measurements of fast ion profile
  - Comparison to orbit codes, effects of mode mixing
  - ECH stabilization physics
- **Key hardware elements**
  - NPAs for phase space resolved confined fast ions
  - Poloidal scintillator probe array for fast ion loss
  - Heating and current drive upgrades: 12 MW ECH, 6 MW FW, off-axis NBI





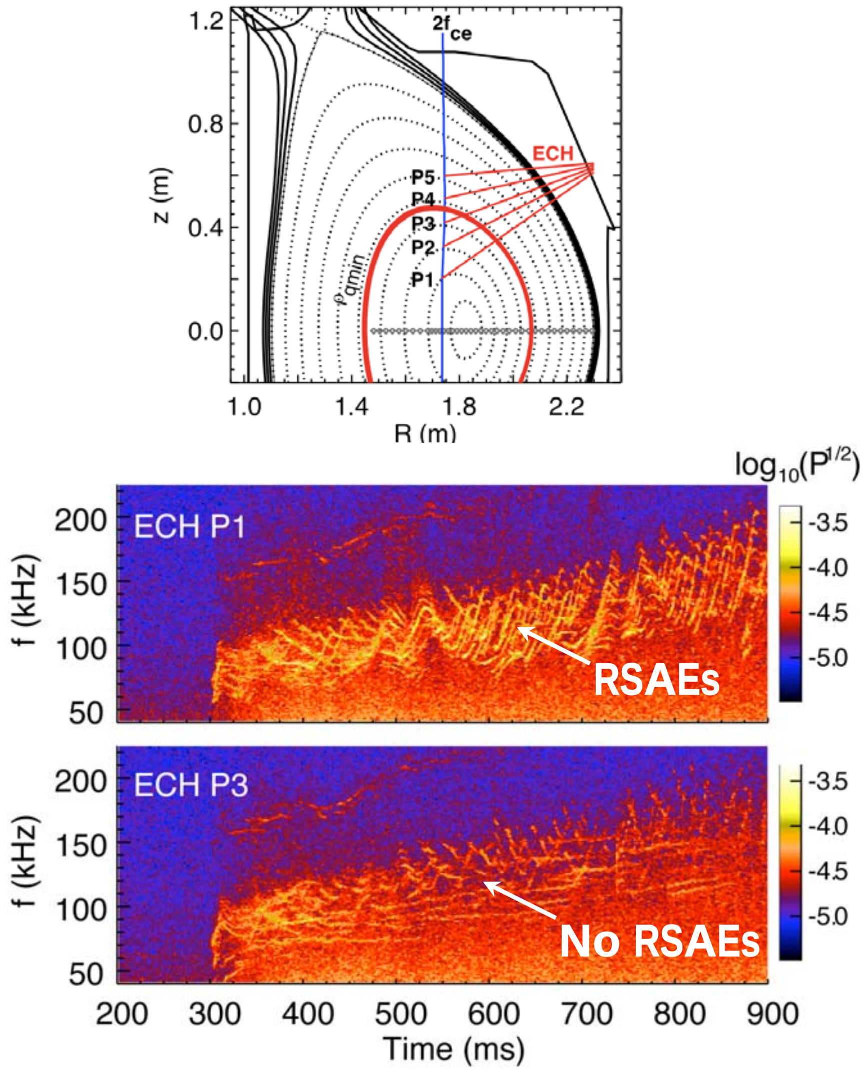
DIII-D has the Diagnostic Set to Validate AE Stability Models for Future Burning Plasma Experiments

- **Research objectives for 2009-2013**
  - Make multi-field measurements to further explore mode structure
  - Assess high order (low velocity) resonances
- **New diagnostics**
  - Mode polarization, linear BES, high frequency CER, ECE imaging, polarimetry
- **Test multi-field codes (two fluid, gyrokinetic) being developed**
  - GTC, NOVA-2F
- **Collaborations**
  - UT, UCI, PPPL (NSTX), Frascati, SciDAC, JET



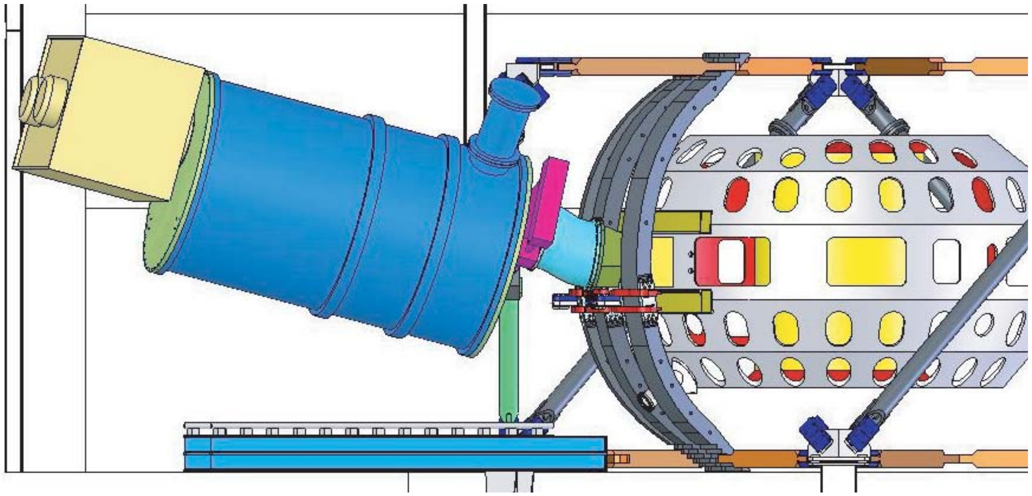
DIII-D Will Continue to Develop the Tools for Controlling AEs and Fast Ion Transport

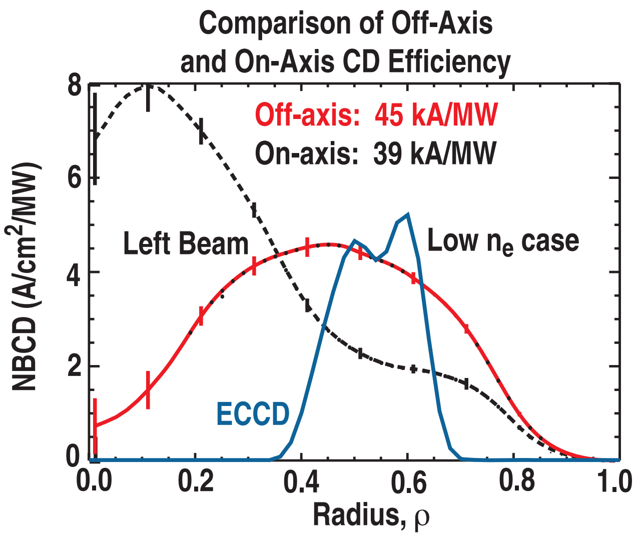
- **Research objectives for 2009-2013**
  - Assess effect of ECH on a range of fast ion instabilities (TAEs, EAEs) at different radii
  - Investigate effect of ECH stabilization on fast ion loss
  - Determine mechanism for stabilization and extrapolate to ITER
- **Key tools**
  - 12 MW ECH
  - 6 MW FW power with multiple frequencies (60, 90 MHz)
    - Can effect AE stability by accelerating beam ions
  - Counter NBI & off-axis NBI
    - Alters mode drive and damping



Off-axis NBCD Enables Near-Term Scenario Development

- **High q_{min} scenario development at high β is limited at present by overdrive of the central current by the NBI required for heating**
- **Off-axis NBCD is as efficient as off-axis ECCD and would allow the existing ECCD to be used for tailoring the current profile**
- **Plan is for 2 beamlines to be modified for off-axis operation, retaining the capability for the present on-axis aiming**





Neoclassical Tearing Mode Control is Required in ITER's Baseline Scenario

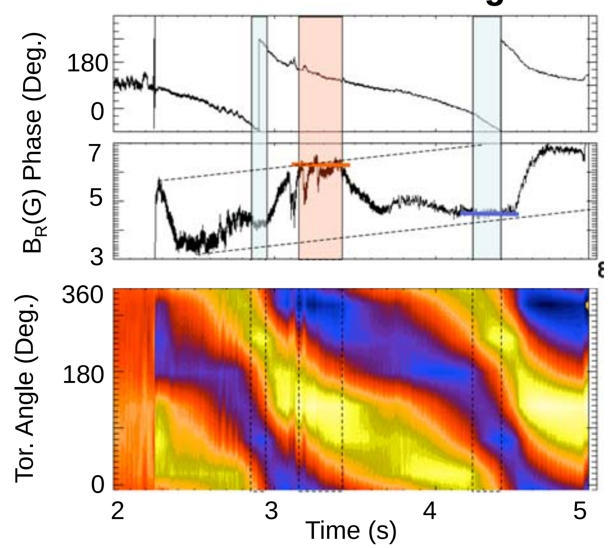
2008	2009	2010	2011	2012	2013

Validate stabilization models — Apply in ITER-relevant plasmas

Multi-mode control — Real-time mirror steering

- **Near-term DIII-D goal: validate the physics basis and power requirements for 2/1 mode stabilization by ECCD**
  - Dependence on current drive width, alignment, modulation, …
- **5-year goal: develop control techniques for routine stabilization of high-performance plasmas in DIII-D and ITER**
  - Simultaneous control of multiple islands (e.g. 3/2 and 2/1)
  - Robust control by island detection at the current drive location
  - "Unlocking" of locked islands in low-torque plasmas
    - Magnetic perturbations and ECCD
- **Key hardware elements**
  - Increased gyrotron power
  - Real-time mirror steering
  - Oblique ECE detection

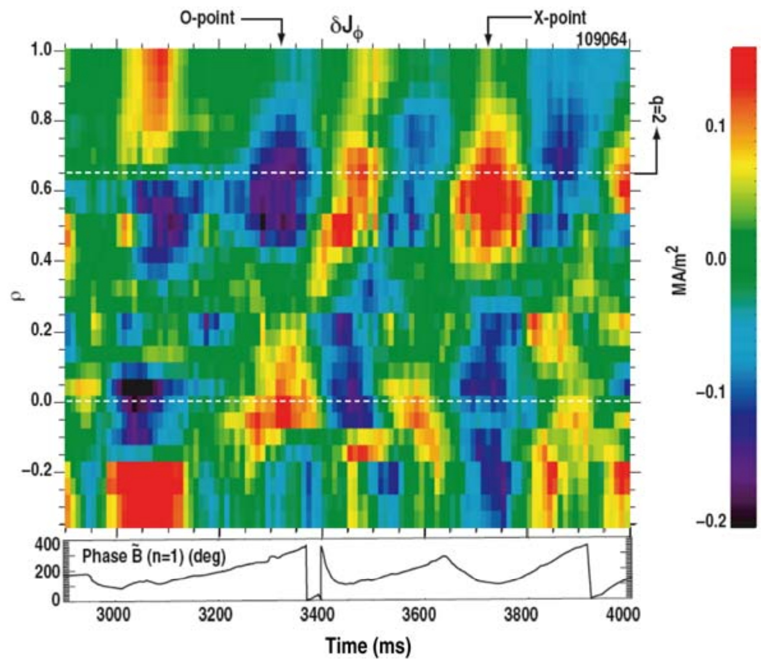
I–Coil Rotates Island During ECCD



DIII-D has the Tools to Advance Our Understanding of NTM Onset and Suppression

- **Research objectives for 2009-2013**
  - Assess mechanisms determining NTM seeding, onset threshold
  - Evaluate ECCD modulation for improved suppression
- **Control tools of NTM studies**
  - 12 MW ECH
  - Co/counter NBI
  - RMP coils
  - Multi-variable PCS
- **Key diagnostics**
  - ECE, ECE imaging, MSE
  - BES, high frequency CER
- **Collaborations**
  - AUG, JET, JT-60U, NSTX

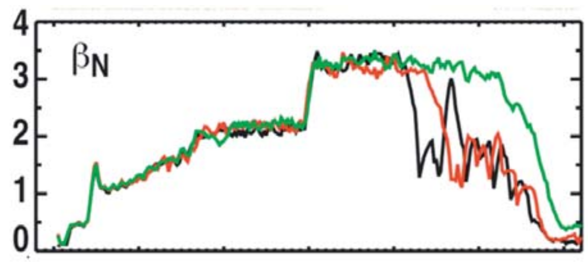
Helical perturbations in J_ϕ, measured by MSE, for a slowly rotating 2/1 mode

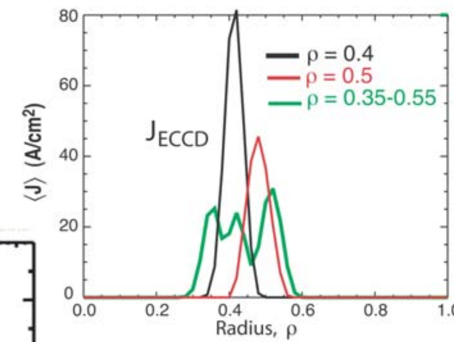


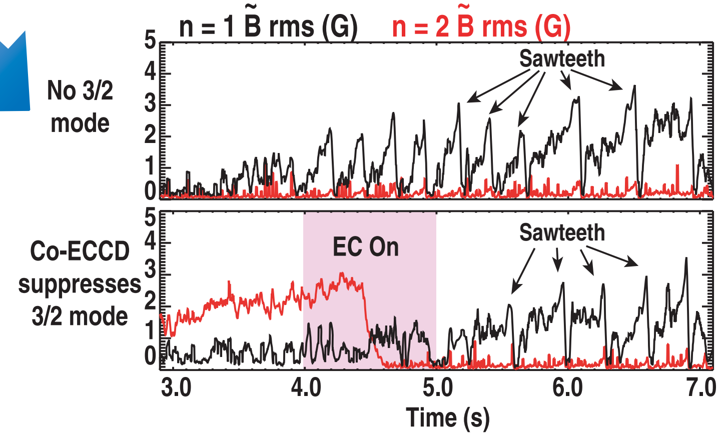
Understanding of Resistive MHD is Needed for Scenario Design, Extrapolation, and Control

- **Ideal MHD calculations have been the cornerstone of scenario development of DIII–D**
- **Resistive MHD limits the range of current profiles available for steady-state operation**
- **Physics basis for extrapolation of the favorable effects of resistive MHD in the hybrid scenario does not exist**
- **Feedback control of access to advanced scenarios needs to incorporate a roadmap of resistive MHD stability**

ECCD distribution alters resistive mode stability







3/2 mode affects current profile beyond local flattening

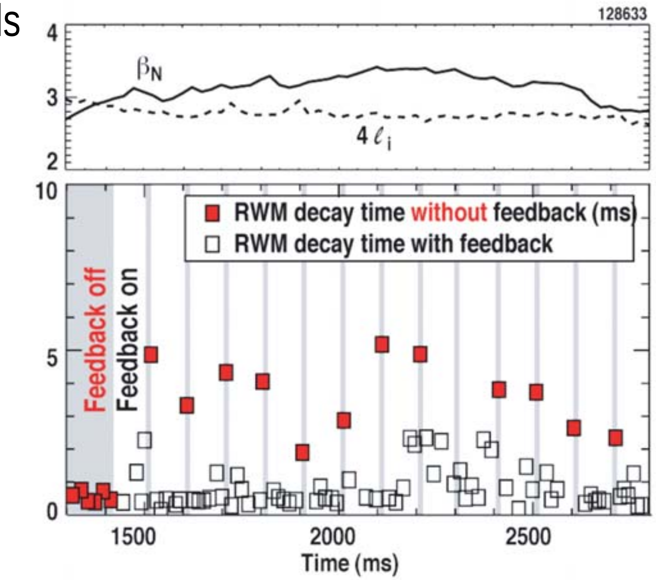
Resistive Wall Mode Control Will Allow Stable Operation of High-β Advanced Scenarios in ITER

2008	2009	2010	2011	2012	2013

Feedback at low rotation · Multi-mode feedback · Simulate ITER's RWM control
Internal vs. external coils · Validate feedback models

- **Near-term goal: provide input to ITER's choice of coils for RWM stabilization**
  - Feedback control of n=1 RWM in low-torque plasmas
  - Direct comparison of internal vs. external control coils
  - Validate control models for ITER coil design

- **5-year goal: establish the basis for optimized control of RWMs in ITER**
  - Validate models of rotational stabilization, including kinetic effects
  - Simulate ITER's control system (bandwidth, etc.)
  - Role of n>1 modes at high beta
  - Optimal controllers for operation near the ideal-wall stability limit

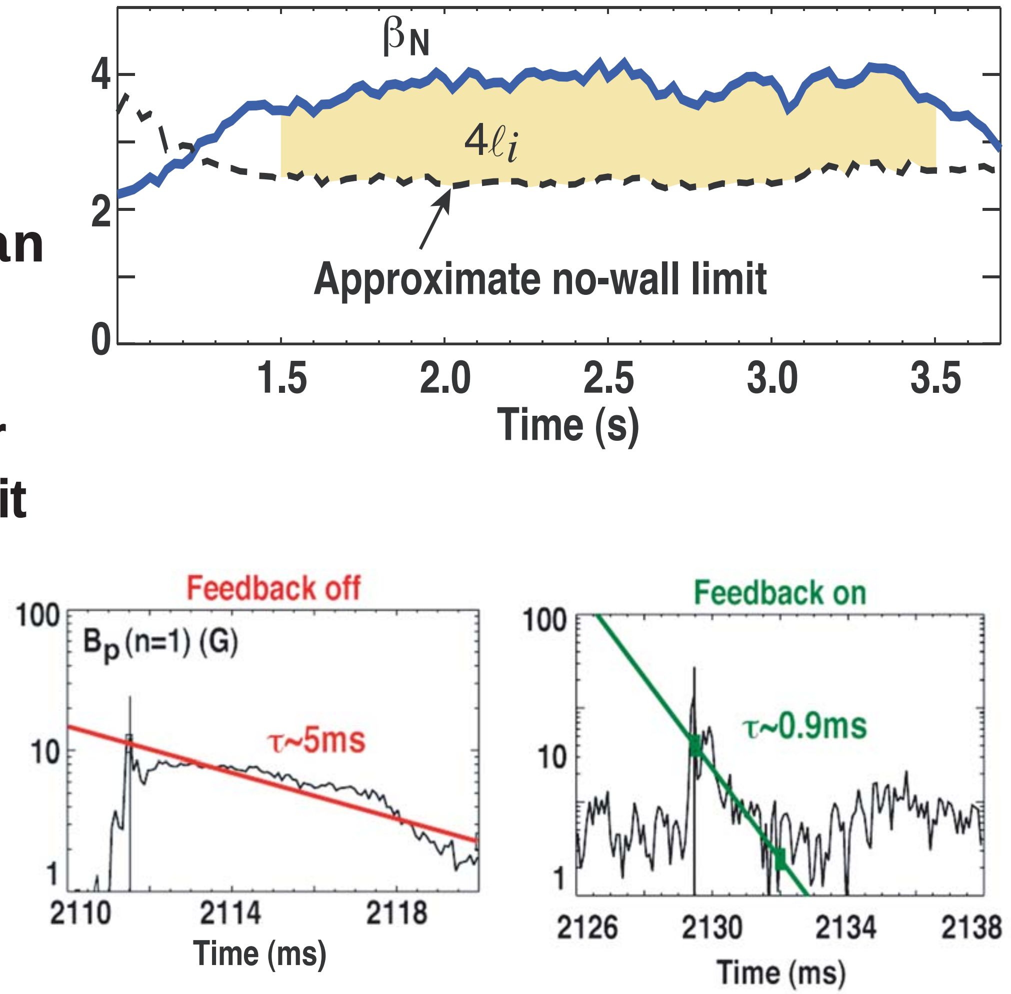


Feedback Stabilizes ELM-Driven RWMs

- **Key hardware elements**
  - Additional amplifiers for the I-coil ⇒ simultaneous control of n=1, 2, 3
  - Multiple toroidal locations for profile diagnostics (ECE)
  - Reduction of known error field sources

Understanding of RWM Stabilization is Essential for Steady-state Operation Above the No-wall Limit

- **Present understanding indicates rotational stabilization will be sufficient for scenario development in this five-year plan**
- **The focus of the physics studies is to provide the physics basis for operating near the ideal wall limit in DIII–D and beyond:**
  - Stability at low rotation
  - Development of feedback methods and requirements
  - Understanding stability for n > 1



Control of Edge-Localized Modes is Critical to the Lifetime of ITER's Divertor

2008	2009	2010	2011	2012	2013

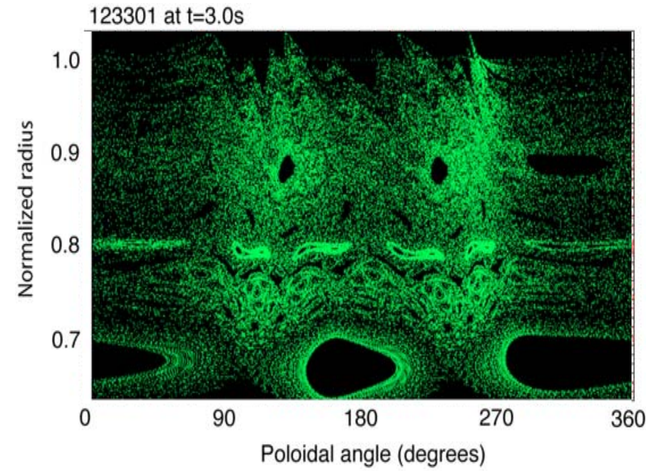
RMP physics basis

Pellet pacing

Extend QH mode regime

Inner Wall coils

- **Near-term DIII-D goal: provide input on choice of RMP coils for ITER**
  - Dependence on mode spectrum
  - Braking of plasma rotation
- **5-year goal: establish the physics basis for optimized ELM control in ITER**
  - RMP control: optimization of RMP spectrum, physics of particle transport
  - Pellet pacing: optimization of pellet size and rate
  - ELM-free QH mode: extension to low torque plasmas
  - Small-ELM regimes: extension to ITER-like parameters
  - Dependence on plasma rotation
- **Key hardware elements**
  - Inner wall RMP coils (48)
  - Low field side "pellet dropper"
  - Diagnostic improvements: edge current density, edge gas puff imaging, fast IR cameras



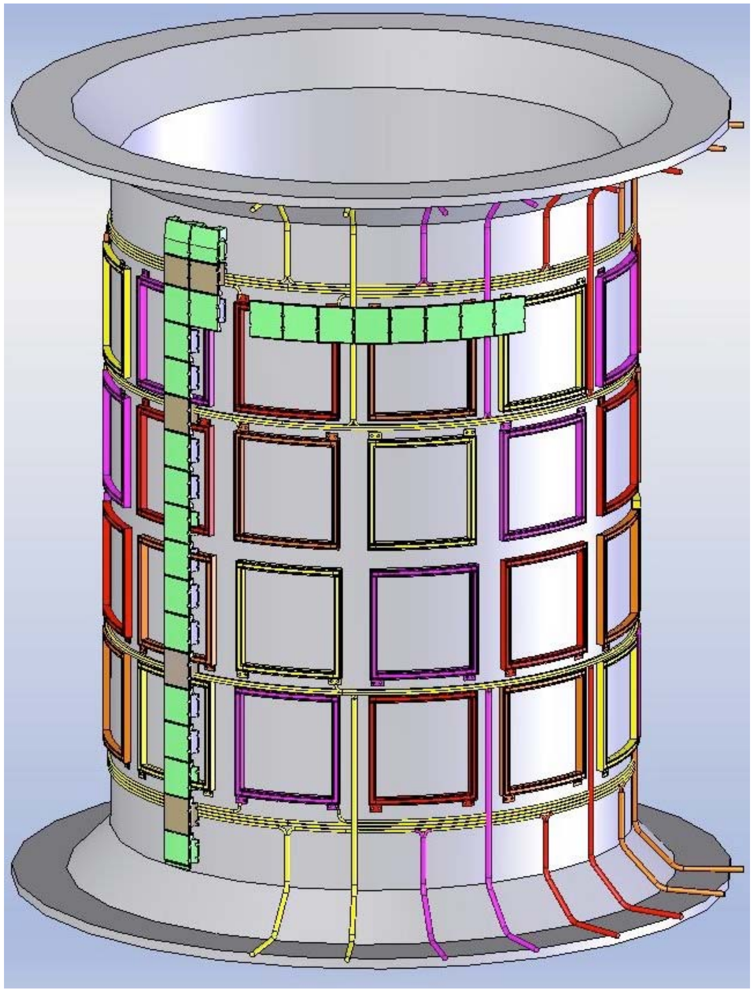
Edge Stability Studies Will Focus on ELMs, Building Upon Previous Theory/Experiment Collaborations

- **Research objectives for 2009-2013**
  - Develop improved understanding of ELM crash
  - Assess tools for ELM suppression
- **Need to model nonlinear evolution and saturation of peeling-ballooning modes**
  - BOUT, NIMROD
- **Control tools**
  - RMP coils (internal, inner wall)
  - Co/counter NBI (QH-mode)
- **New diagnostics**
  - IR + visible TV periscopes
  - BES upgrade
  - Gas puff imaging

ELM mode structure calculated by ELITE showing filaments

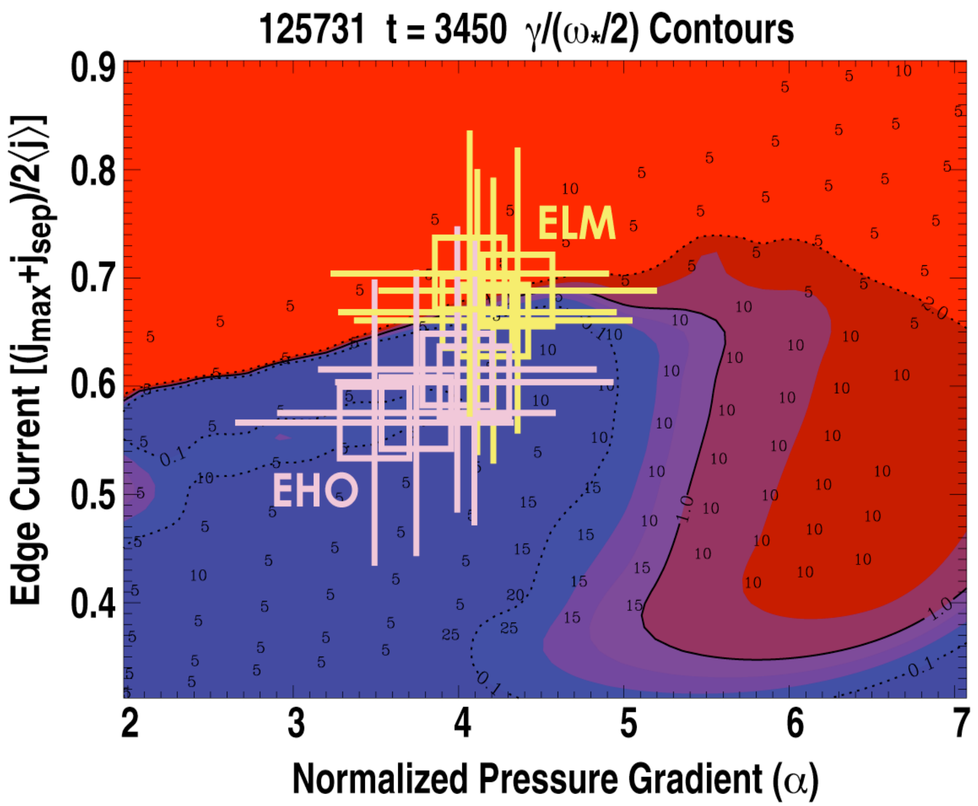
The Proposed HFS Coil Provides Important New Physics Research Opportunities

- **HFS coil — physics opportunities (short list):**
  - Resonant and non-resonant flow damping variations with applied spectrum
  - Single/multi-row HFS coils versus single/multi-row LFS coils
  - ELM suppression at low q_{95} with high n spectrum
  - Physics of pedestal transport
  - ELM suppression in AT and Hybrid plasmas
- **HFS coil designed to increase RMP physics understanding**
  - Not intended as a reactor prototype



QH-Mode Offers an Alternative Path to ELM Stabilization

- **Agreement of QH operating point with peeling ballooning theory suggest QH-mode possible in ITER**
- **Peeling-ballooning stability boundary independent of rotation direction**
  - New result: QH-mode with co-injection
- **Diagnostic improvements for physics understanding and ITER predictions**
  - Main ion T_i and v_ϕ measurement for MHD modeling
  - Routine edge current density measurement
  - Improved poloidal magnetics for EHO analysis



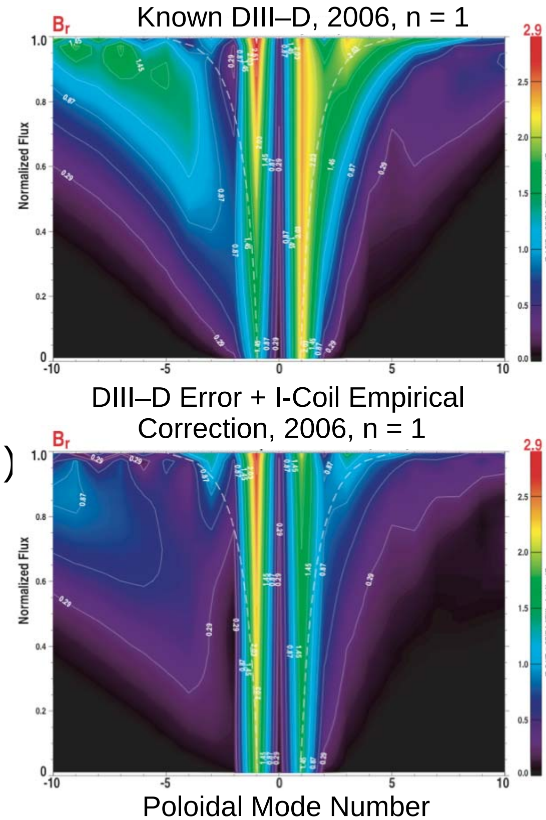
Error Field Control is Critical to ITER's Performance at Low Rotation and High Beta

2008	2009	2010	2011	2012	2013

Error field physics at low torque — Multi-mode error correction

Validate models of plasma response — Optimize error field control

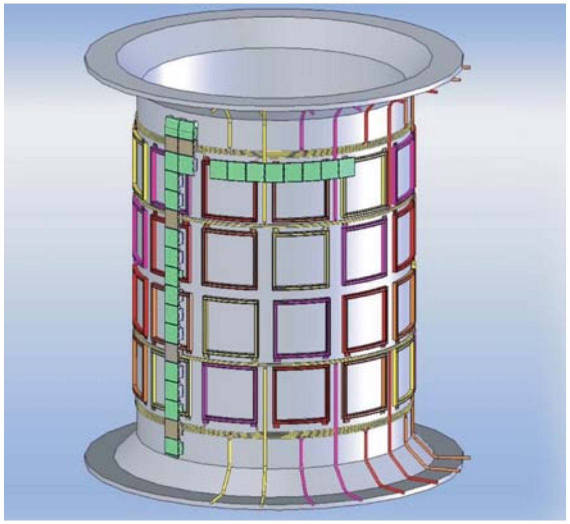
- **Recent breakthrough: semi-quantitative agreement of experimental results with ideal perturbed MHD equilibrium theory**
  - Shows importance of global plasma response to the error field
- **Near-term DIII-D goal: improved error correction for low-torque experiments in DIII-D**
  - Qualitative or quantitative guidance by theory
- **5-year goal: physics basis for error field control in ITER**
  - Validate models of plasma response to error fields
    - Dependence on rotation, β, spatial mode spectrum
  - Optimize error field control techniques (possibly feedback-based)
- **Key hardware elements**
  - Additional amplifiers for the I-coil ⇒ control of n=1, 2, 3
  - Multiple toroidal locations for profile diagnostics (ECE)
  - Reduction of known error field: 30˚ TF feed



Need to Understand How to Reduce Error Field Effects Using Realistic, Imperfect Coils

- **Research objectives for 2009-2013**
  - Improve understanding of plasma response to error field
- **3-D equilibria codes are critical**
  - EFIT3D
  - IPEC
- **Control tools**
  - Redesigned B-coil current feed at 30°
  - I-coil, C-coil
  - Inner wall coil
  - Co/counter NBI
- **New diagnostics**
  - 3-D magnetics
  - ECE at multiple toroidal locations
  - SXR at multiple toroidal locations

48 inner wall coils



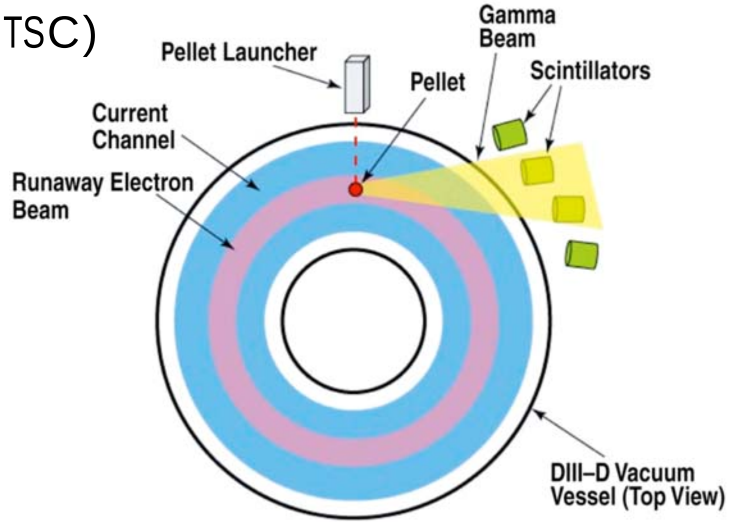
A Broad Physics Program in ITER Requires Predictive Capability for Consequences of Disruptions

2008	2009	2010	2011	2012	2013

ITER disruption loads — Runaway electron physics — Validate 3D models

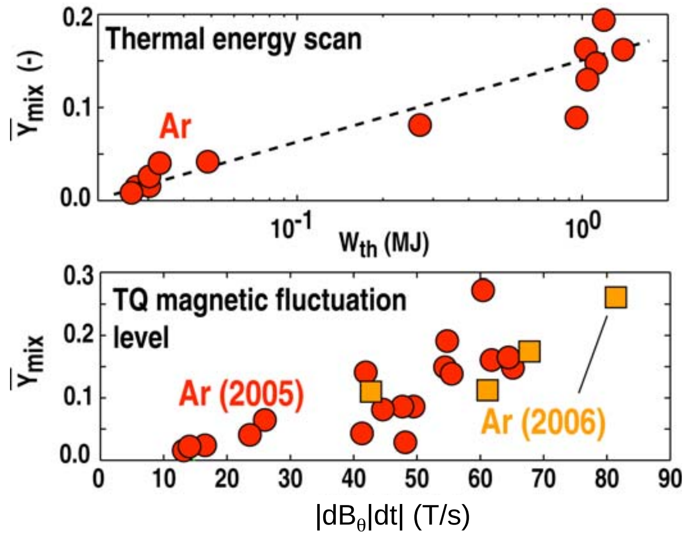
Gas jet mitigation reqmts — Alternate mitigation methods

- **Near-term DIII-D goal: contribute to the specification of ITER disruption loads**
  - Characterize asymmetric thermal and electromagnetic loads in DIII-D
  - Establish the scaling with I_p, q_{95}, …
- **5-year goal: establish the physics basis for prediction of ITER disruption loads**
  - Expand disruption databases: DIII-D and international (ITPA)
  - Validate modeling of disruption dynamics (DINA, TSC)
  - Validate physics of runaway electron generation and deposition
- **Key hardware elements**
  - Halo current diagnostics
  - Diagnostics for horizontal vessel motion
  - Runaway electron diagnostics



A Broad Physics Program in ITER Requires a Reliable Disruption Protection System

- **Near-term DIII-D goal: provide input to specifications of ITER gas jet and pumping systems**
  - Establish physics basis for fast gas jet shutdown
  - Physics of impurity assimilation, role of MHD activity
  - Validation of nonlinear 3D models (NIMROD)
- **5-year goal: develop mitigation of runaway electron avalanche**
  - Validate physics of runaway electron multiplication
  - Shutdown with sufficient density for runaway suppression
  - Develop alternative methods of runaway suppression (e.g., RMP)
  - Validate nonlinear 3D models (NIMROD)
- **Key hardware elements**
  - Runaway electron diagnostics
  - Fast risetime gas delivery (rupture disk)
  - “Custom” impurity pellets, cryogenic liquid jet
  - Fast framing cameras



Argon Assimilation Increases with Plasma Energy and MHD Amplitude

Operation of ITER Without Disruptions Will Require Multiple Levels of Protection

Plasma configuration →	Multivariable shape control	Current, pressure profile control	Rotation profile control
Detect & avoid operational limits →	Radiated power, density, q(r), ...	Real-time beta measurements	Real-time stability code
Actively suppress instabilities →	NTM stabilization (ECCD)	Rotation, error field control	RWM feedback (int./ext. coils)
Off-normal condition: soft shutdown →	Action depends on plasma state	Change heating, fueling	Radiated power (small pellets)
Onset of disruption: fast shutdown →	High-pressure gas jet, liquid jet	Large pellets: High-Z, Low-Z	Magnetic perturbations

These features must become integrated and routine!

Long-term Goal is Disruption-Free Operation in DIII-D and ITER

2008	2009	2010	2011	2012	2013

Stability control methods (NTM, RWM,. . .) Begin integration of stability control

Real-time stability prediction

Integrated stability control
⇒ **avoidance of disruptions and other instabilities**

- **Enable full use of machine capabilities through reliable operation near stability limits**
- **Avoid the need to establish stability limits by trial-and-error**
- **Disruption mitigation only as a last resort**

Possible new elements over next 5 years include:

- **Real-time stability calculations (DCON)**
- **Real-time measurements of MHD damping rates**
- **Optimized coils for control of ELMs and RWMs**
- **Fast steering mirrors for ECCD**
- **Upgraded injectors for gas, pellets**
- **Plasma control computer upgrades**

Stability control in ITER must become as routine and reliable as shape control

DIII-D research in 2009-2013 will address key issues in MHD stability

- Physics understanding for prediction and avoidance of stability limits
- Mode control for suppression of instabilities
- Disruption mitigation to reduce the impact of instabilities

- Long-term goal: integrated stability control
  ➔ reliable, stable operation in DIII-D and ITER