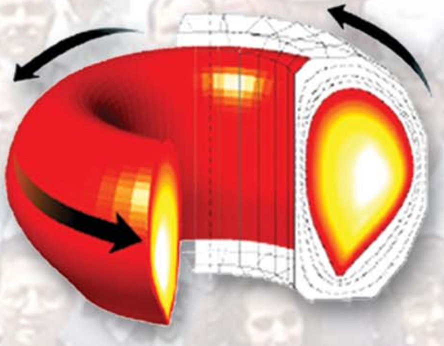
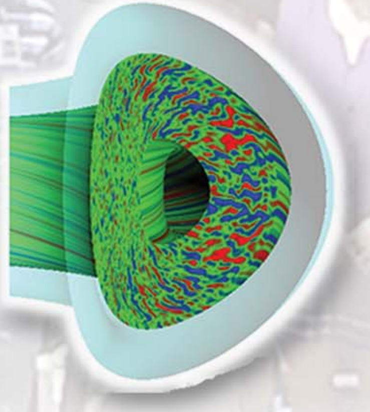
# Stability and Disruption Physics

by
E.J. Strait

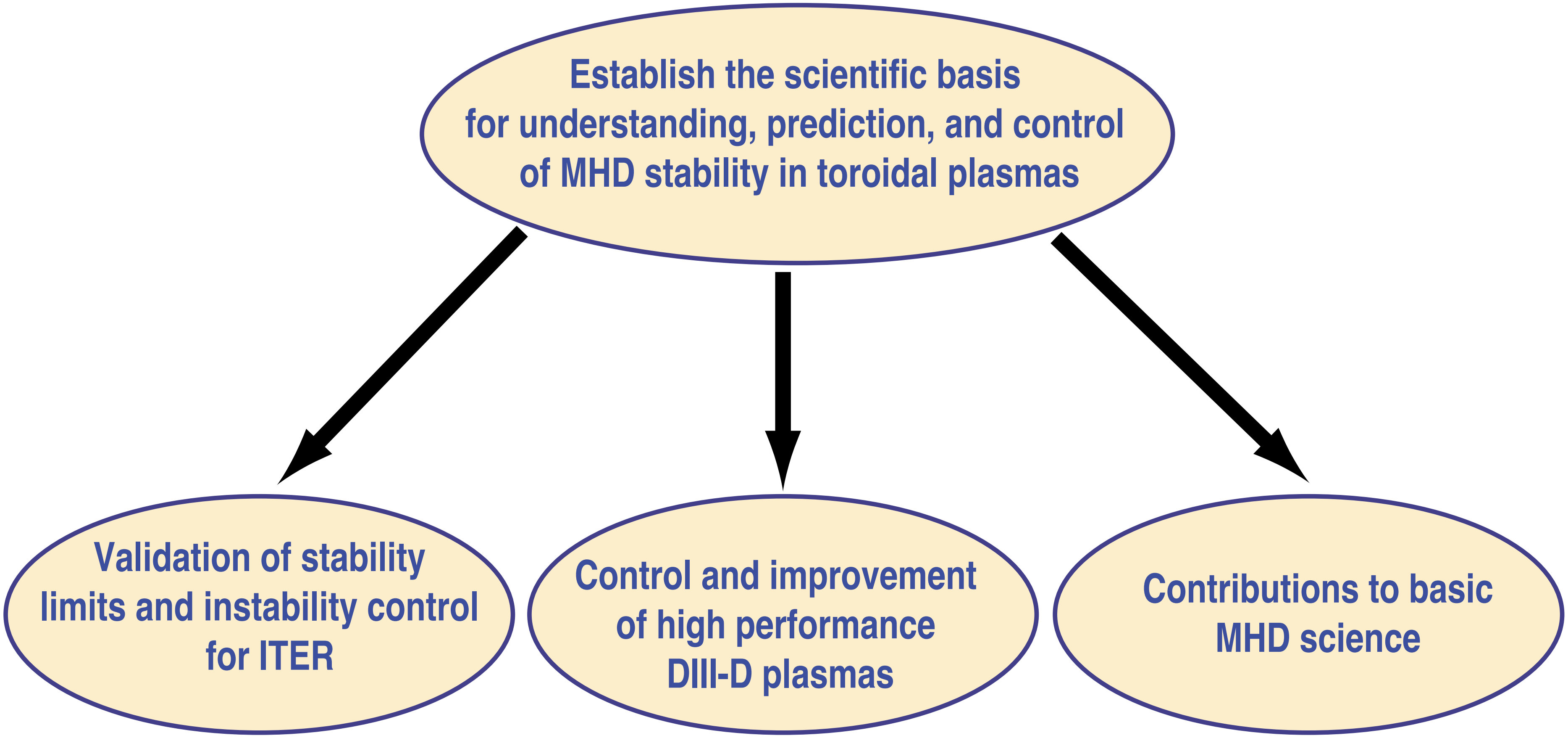


Presented to
DIII–D Program
Advisory Committee



January 31– February 2, 2006

# Long-Term Goals For MHD Stability Research in DIII–D



Establish the scientific basis for understanding, prediction, and control of MHD stability in toroidal plasmas

Validation of stability limits and instability control for ITER

Control and improvement of high performance DIII-D plasmas

Contributions to basic MHD science

# Physics Goals 2006–2007 are Closely Aligned with ITER's Needs

## Active control of instabilities

- Validate models for gas jet mitigation of disruptions (MDC-1, ITER design)
- Demonstrate feedback control of resistive wall modes at low plasma rotation (MDC-2, ITER design)
- Advance the understanding of edge pedestal stability and the physics of ELM control (ITER design issue)
- Validate modified Rutherford equation for neoclassical tearing mode control with localized current drive (MDC-8)

## MHD stability physics

- Establish physics of neoclassical tearing mode threshold and seeding at low plasma rotation (MDC-3)
- Benchmark models of fast ion interaction with Alfvén modes (MDC-9, 10)
- Advance the physics understanding of the sawtooth instability and means of controlling its severity (MDC-5)
- Advance the understanding of plasma response to error fields (MDC-6)

## Develop model-based, multivariable plasma control

# New Actuators Enable Experiments in New Regimes

- **Counter beam line**
  - Rotation control for RWM physics, NTM control with modulated ECCD, error field physics
  - Variable fast ion distribution for Alfvén mode stability

- **5–6 gyrotrons**
  - NTM stabilization
  - q-profile control

- **High-throughput gas jet**
  - Unique capability for disruption mitigation physics

- **High-bandwidth amplifiers for I-coils (6 amplifiers added in 2006)**
  - RWM control
  - MHD spectroscopy
  - Possible NTM control

# New Diagnostics and Control Systems will Lead to New Physics Understanding

- **Soft x-ray/XUV array**
  - MHD mode structure
  - Toroidal asymmetry of disruptions

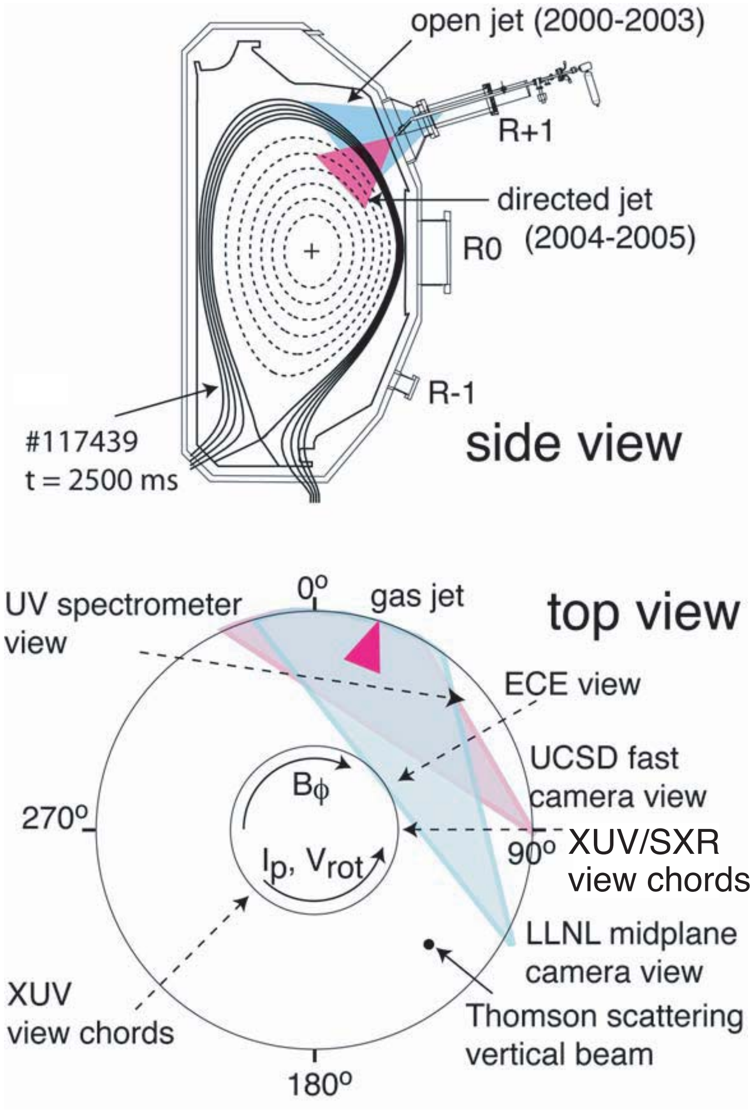
- **Fast ion profile from $D_\alpha$ spectroscopy**
  - Equilibrium pressure profile
  - MHD-induced fast ion transport

- **Plasma control system enhancements**
  - 10 μs cycle time for RWM control
  - Modulation of gyrotrons in phase with NTM
  - Real-time CER analysis
  - Feedback control of plasma rotation

# DIII–D Experiments will Contribute to Validated Models of Disruption Physics and Disruption Mitigation for ITER

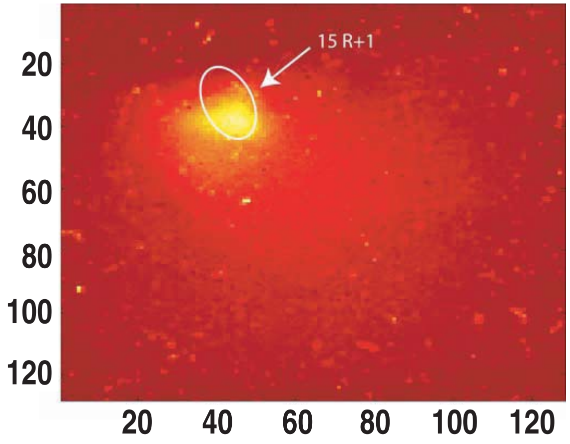
- **DIII-D pioneered the use of high-pressure impurity gas injection to mitigate effects of disruptions**
  - – Reduce localized heat flux
  - – Reduce halo current forces
  - – Suppress runaway electrons
- **New high-flow gas valve in 2006**
  - – 10x throughput of previous valves
  - – Will reach Rosenbluth density for runaway avalanche suppression in ~1 ms
- **GA is hosting new ITPA disruption database**
  - – ITER urgent research item
  - – Data from 4 tokamaks, so far

DIII–D Elevation 120°

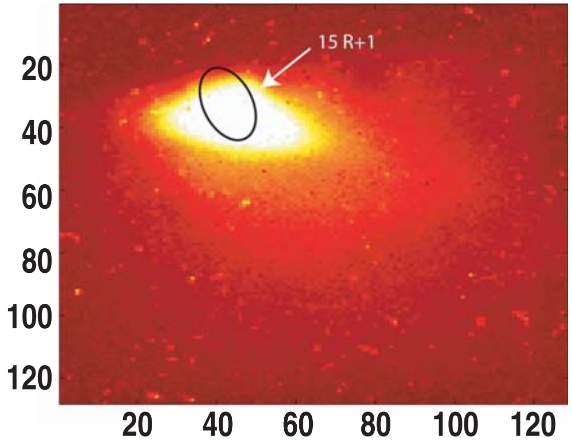


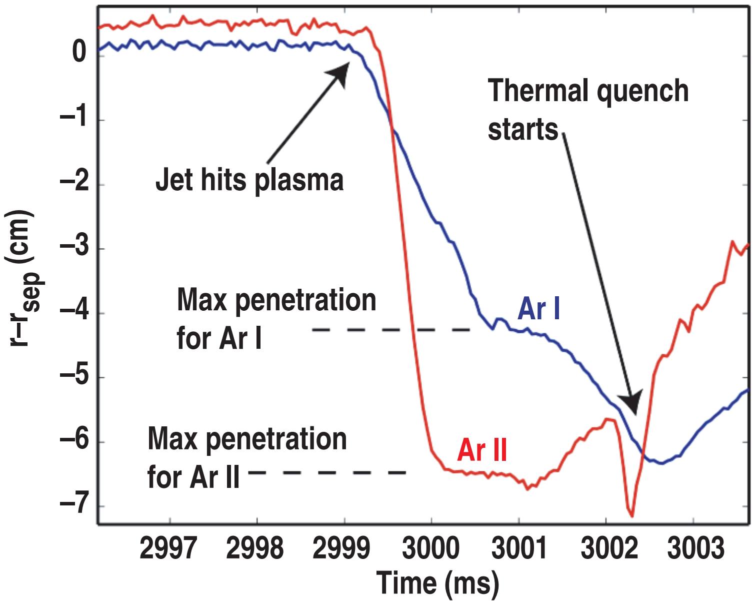
# Physics of Impurity Penetration is a Key Remaining Issue

t = 2999.3 ms



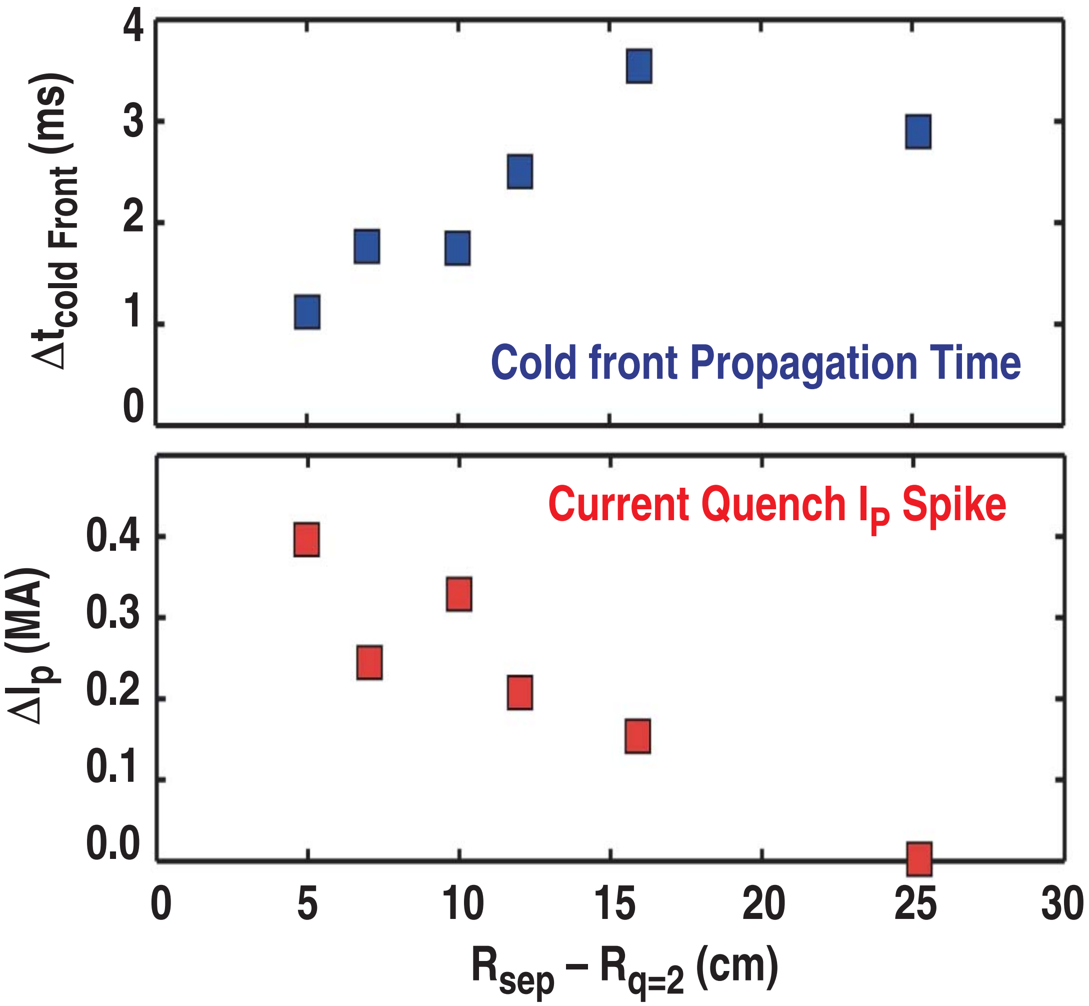
t = 3000.2 ms





- **Fast camera Ar I images confirm neutral gas penetrates only a few cm**
  - Similar observations at low plasma pressure
- **Neutral stopping may be due to magnetic pressure**
  - Via J×B force at ionized boundary

# q-Scan Verifies Importance of Low-Order MHD in Thermal Quench



- Time for thermal quench onset (cold front propagation time) increases with depth of q=2 surface
- Amplitude of $I_P$ spike decreases, consistent with smaller (2/1) reconnection volume
- New diagnostics (second XUV array) will investigate n=1 asymmetry of thermal quench

# DIII–D Experiments Will Demonstrate Feedback Stabilization of Resistive Wall Mode

- **Recent experiments have shown RWM feedback control**
  - At low rotation: transiently, with large n=1 error field
  - At marginal rotation: sustained

- **New capabilities will allow sustained feedback stabilization with rotation below the critical value**
  - Rotation control by near-balanced neutral beam injection
  - Additional high-speed amplifiers
  - Faster cycle time for digital control system

**Research thrust on RWM control will be discussed by A. Garofalo**

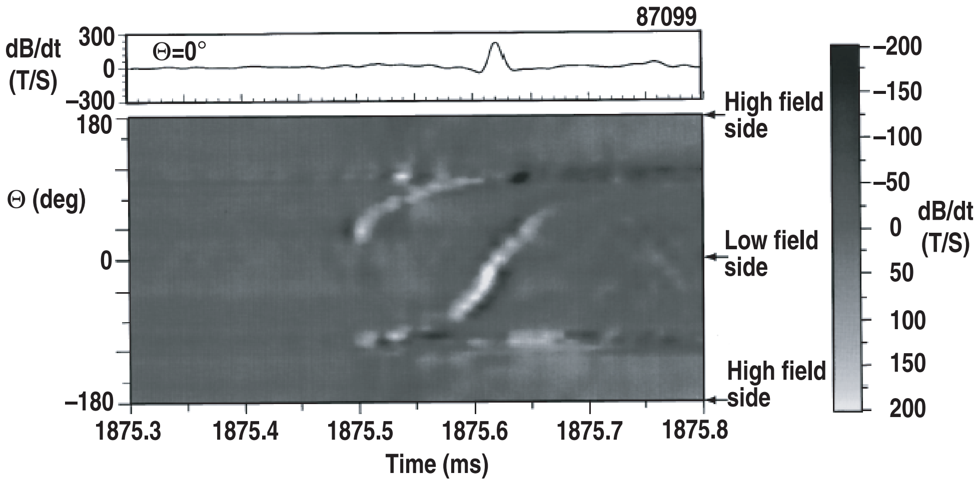
# Control of Edge Stability is An Urgent Need for ITER

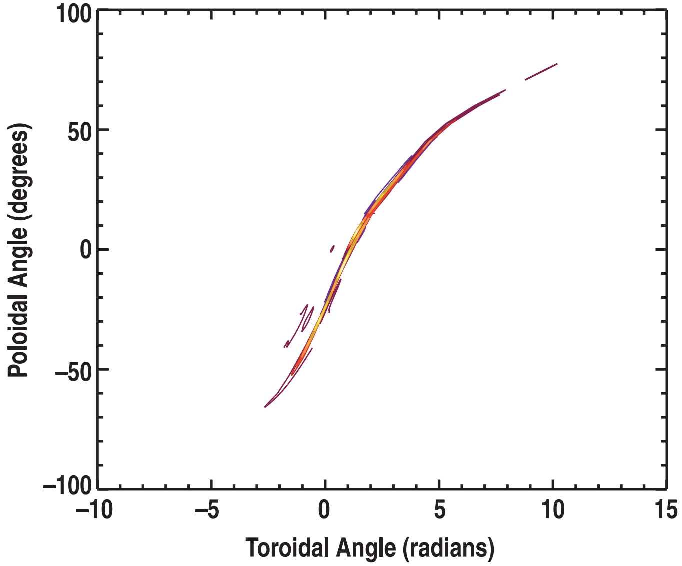
- **Resonant magnetic perturbations have reduced or eliminated ELMs in recent DIII-D experiments**
  - Enhanced transport may keep the edge pressure gradient below the stability limit

- **A major goal of future experiments is sufficient understanding of the physics of ELM suppression to allow extrapolation to ITER**

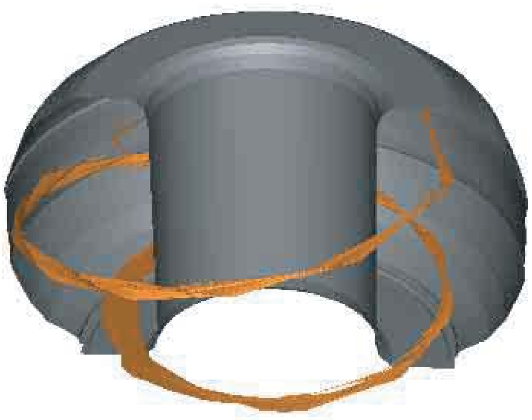
**Research thrust on ELM control will be discussed by M. Fenstermacher**

# Nonlinear Models Allow Study of ELM Physics





- **Filament structure predicted by nonlinear BOUT code simulation**
  - Consistent with observations from fast magnetics and other diagnostics



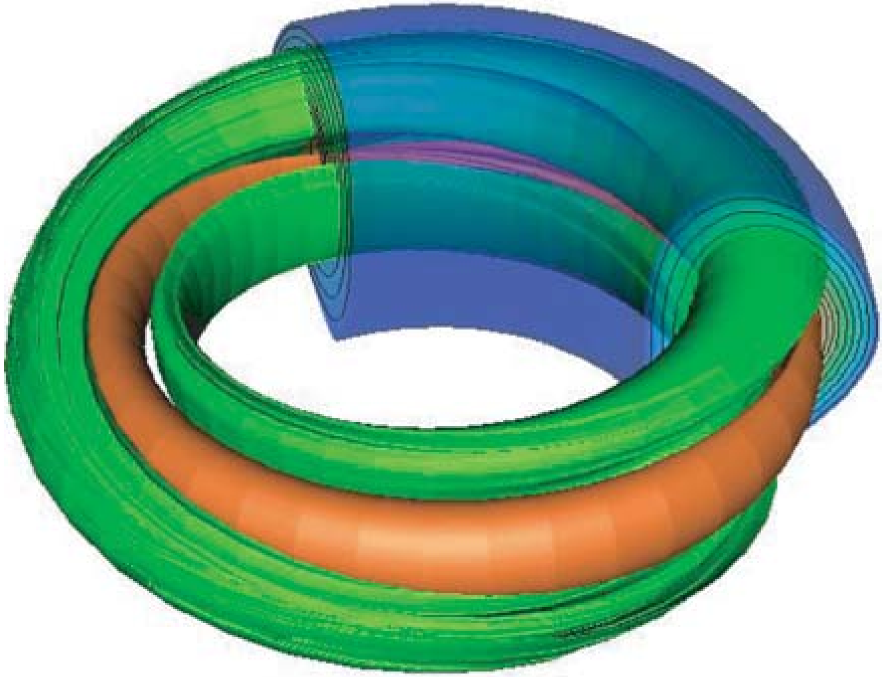
# Neoclassical Tearing Modes May Degrade Fusion Performance of ITER Plasmas

- **Recent experiments have demonstrated NTM stabilization up to the ideal MHD no-wall limit**
- **Goal of upcoming experiments is to validate key features of NTM stabilization by localized current drive:**
  - Benefits of synchronous modulation of the current drive
  - Dependence on the width of the current drive layer

**Research thrust on NTM control will be discussed by R. La Haye**

# Experiment and Modeling will Investigate the Role of Rotation in NTM Stability

- **NIMROD code models the seeding of a 3/2 island by a sawtooth crash**
  - Model includes sheared rotation

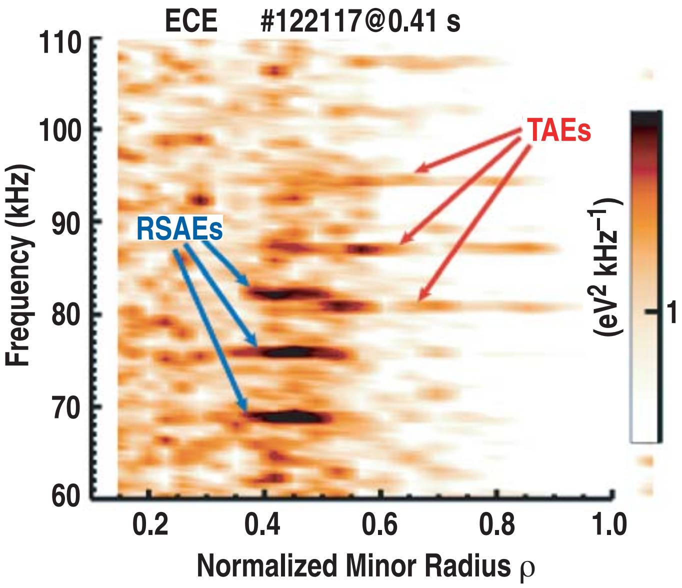


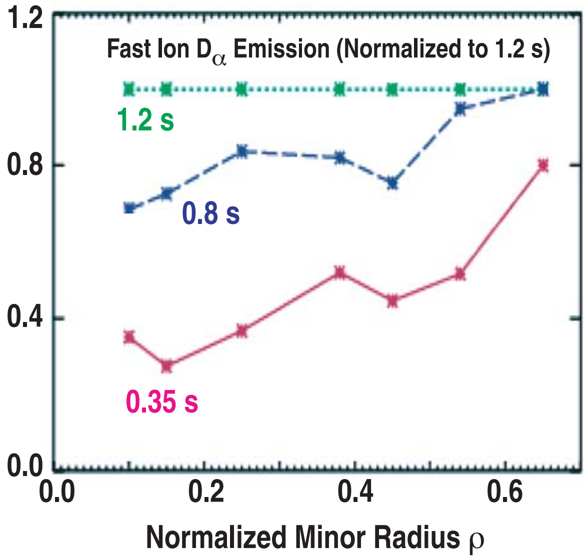
- **Counter NBI allows control of rotation**
  - Lower β threshold with weaker rotational shear?
  - Locking of 3/2 modes at low rotation?
  - Possibility of feedback stabilization with I-coils

# New Diagnostics Provide Insight into Alfvén Instabilities

- **Core fluctuation diagnostics show radial and poloidal mode structure**
  - ECE, BES, FIR scattering, $CO_2$ interferometers, ...

- **Fast-ion $D_\alpha$ measurements indicate strong reduction in the central fast-ion density during strong Alfvén activity**

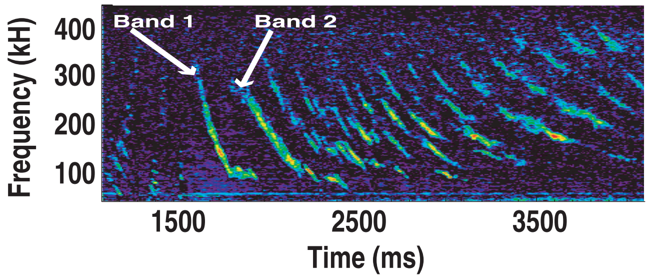


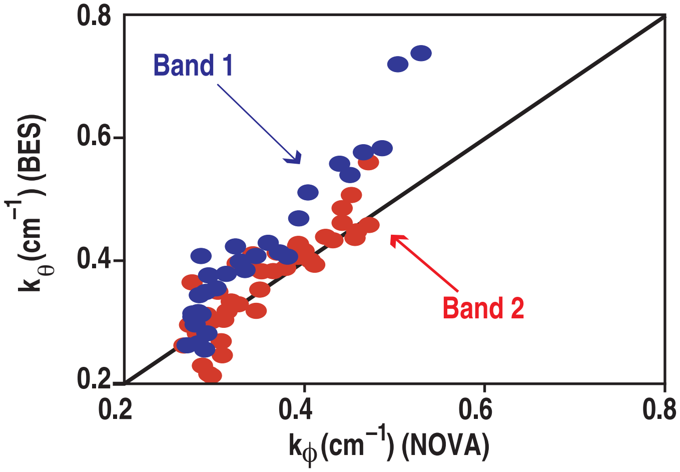


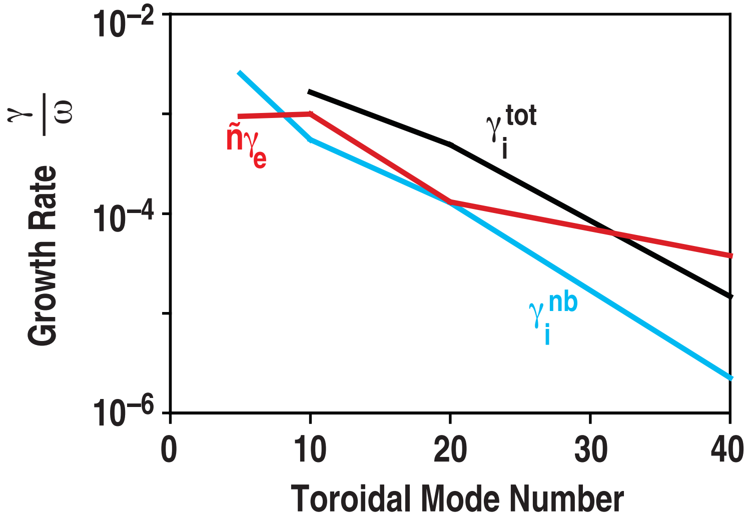
- **Future experiments will use new diagnostics to document the eigenfunction and fast ion redistribution, and benchmark code predictions**

# Data and Modeling Suggest A Key Role for Thermal Ion Drive

- **BES data and NOVA modeling indicate short wavelengths for core-localized Alfven modes**
- **NOVA-K model predicts short wavelength modes have a strong driving term from the tail of the thermal ion distribution**
  - Possible implications for ITER advanced scenarios with weak magnetic shear





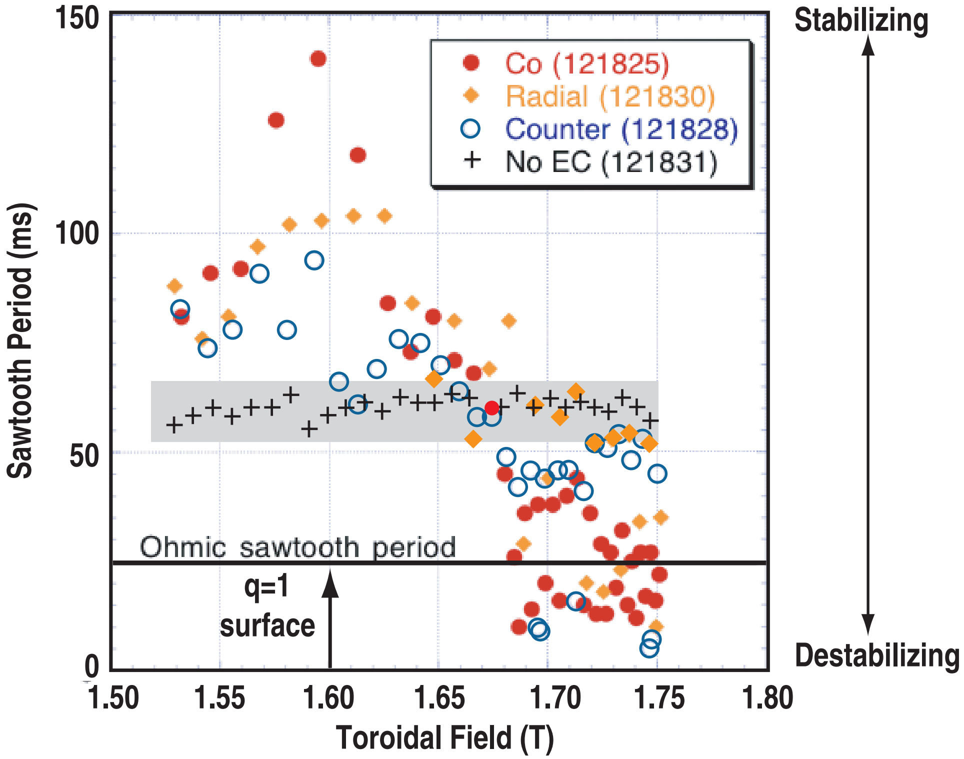


- **Future experiments will investigate drive, damping, and fast ion transport**
  - Attempt to separate beam ion and thermal ion drive

# DIII–D Has A Unique Opportunity to Study Giant Sawteeth

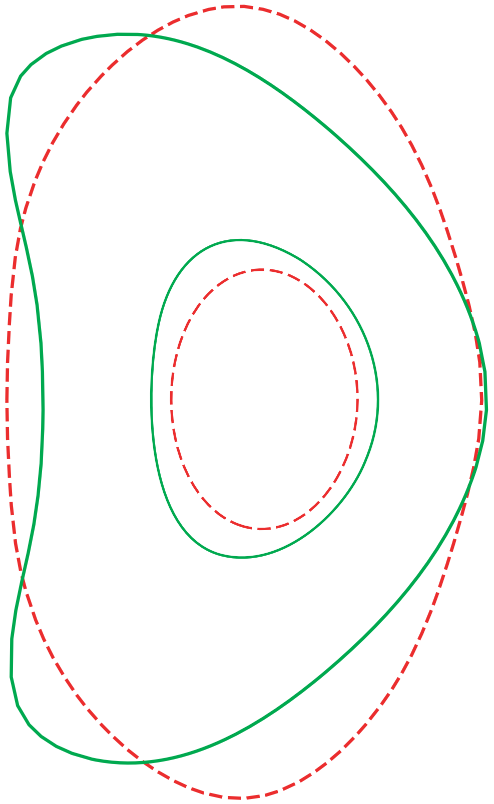
- **Giant sawteeth with stabilization by fast $\alpha$'s are a possible risk to ITER's performance**
  - Validated models for stabilization and destabilization will improve confidence in predictions for ITER
- **DIII-D has a unique set of tools to study physics of giant sawteeth**
  - Fast-wave heating to stabilize sawteeth
  - Fast ion profile measurements
  - Core fluctuation diagnostics
  - ECCD for sawtooth control
- **Experiments will benchmark models for fast ion stabilization of sawteeth**
  - Possible role of AE-driven fast ion transport as sawtooth trigger
- **ECCD near the q=1 surface is a possible approach to reducing the sawtooth period**
  - Demonstrated in L-mode discharges

**Sawtooth Period in $B_T$ Ramps**

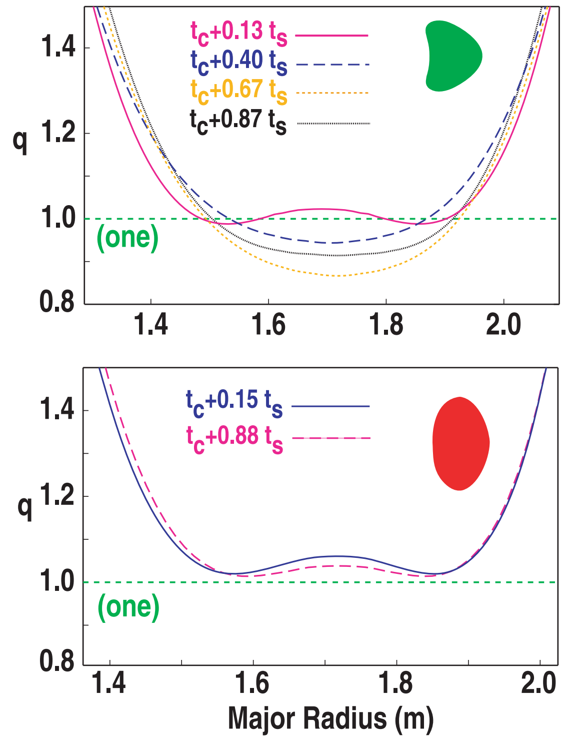


# Basic MHD Physics: Sawtooth Experiment Challenges Our Understanding of Stability and Transport in the Core

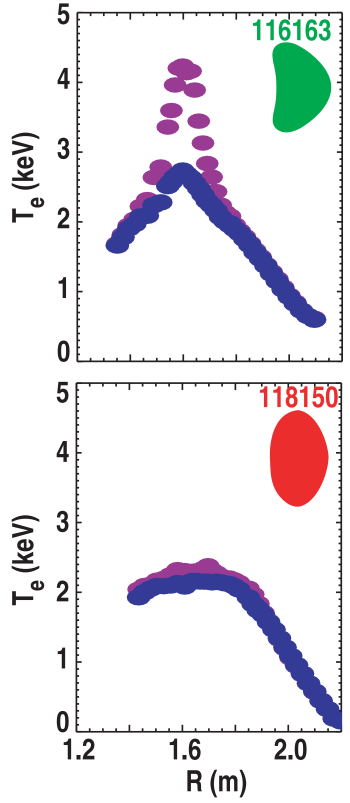
- **Strong shaping increases the central elongation and triangularity**



- **q-profile evolution during a sawtooth cycle is significantly different**
  - Internal kink versus interchange modes

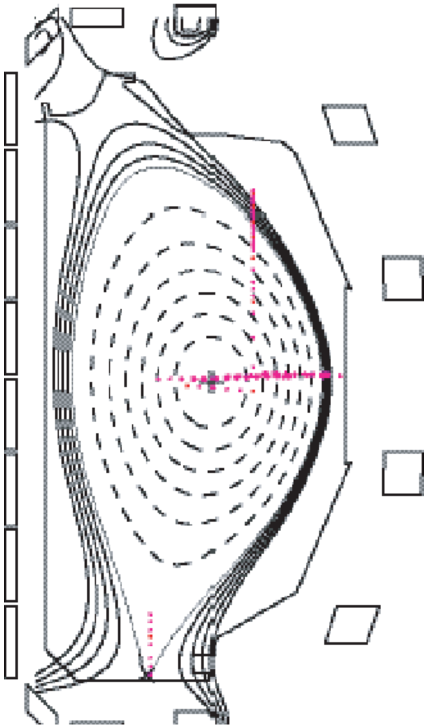


- **Central $\chi_e$ is significantly different (response to central ECH)**
  - Leads to different q-profile evolution



# Plasma Equilibrium Has a Significant 3-D Response to Error Fields

- **I-coil applies n=1 field rotating at 5 Hz, $\delta B_r \sim 10^{-3} B_t$**
  - $\Delta Z$ of plasma boundary (from Thomson scattering) responds with ~2 cm amplitude



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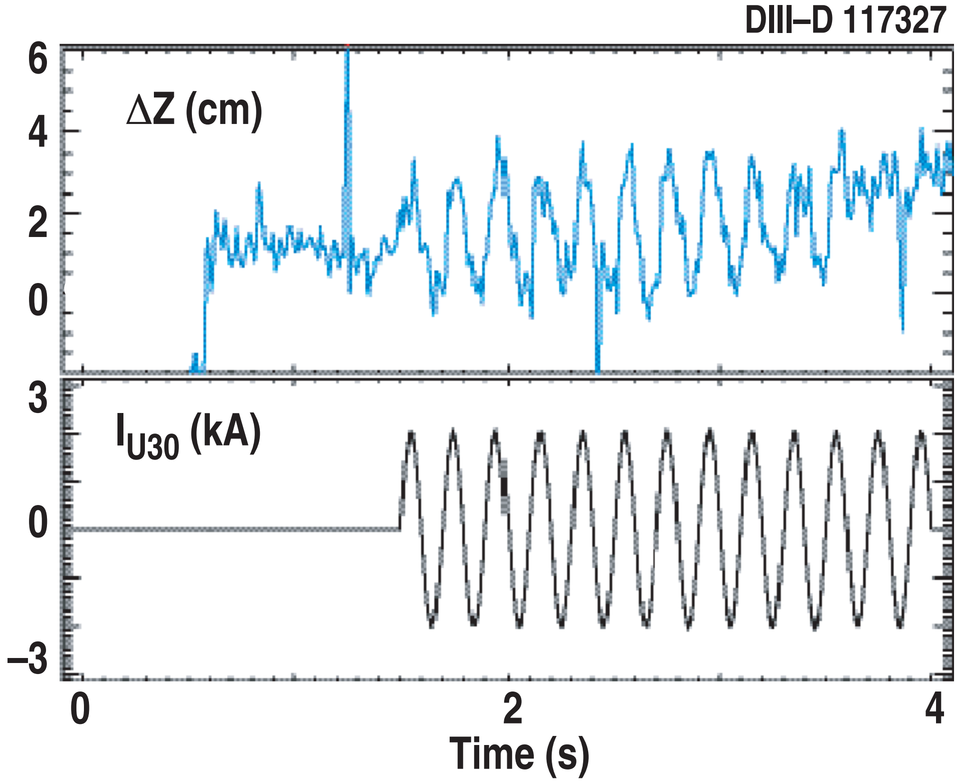
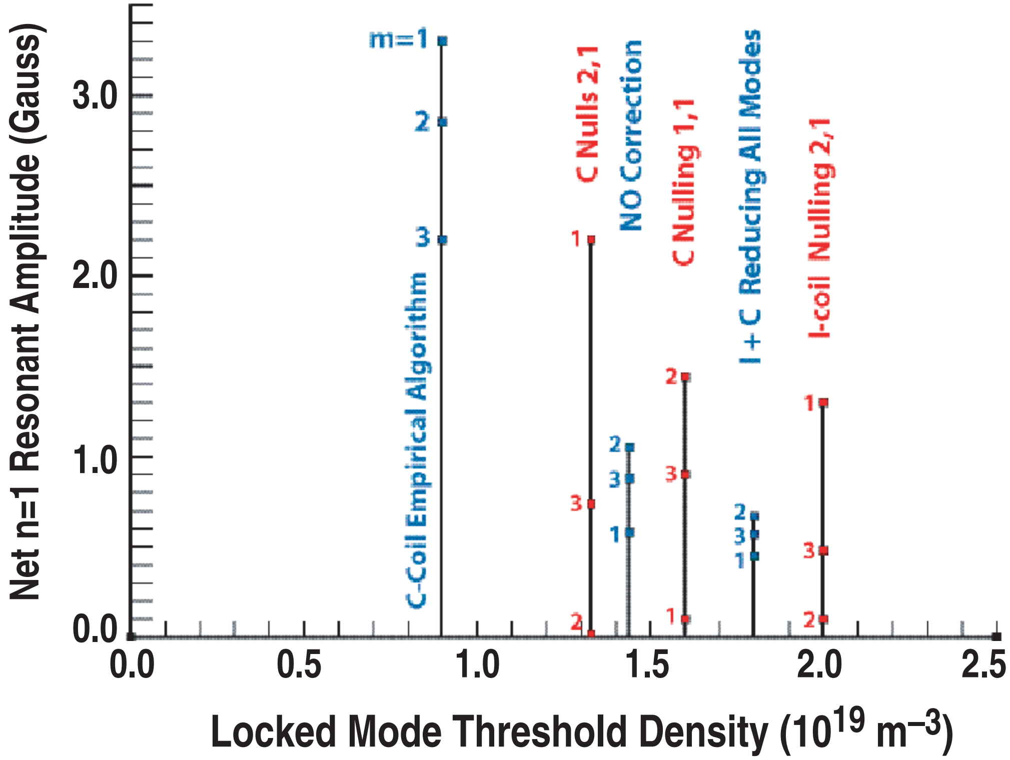


- **3-D equilibrium modeling will improve understanding of error field effects**

# Locked Mode Avoidance Does NOT Depend Just on Resonant Mode Amplitude

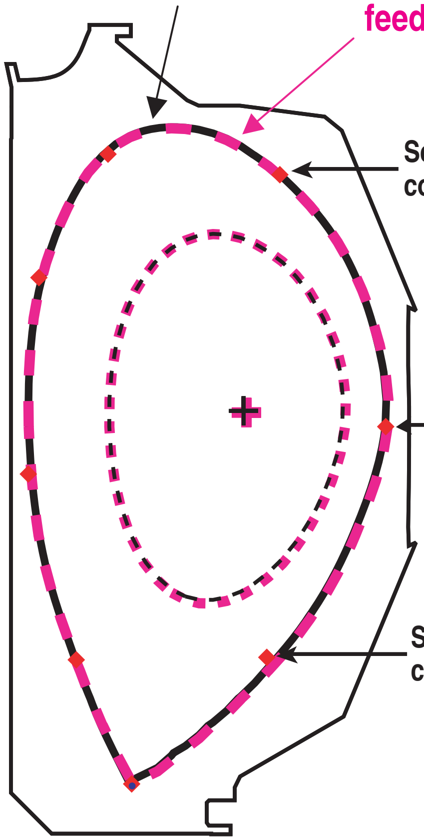


- **Empirical C-algorithm performs best, even though all low rational B-components are large**
- **No correction at all is better than most of the theory-based corrections**
- **Evidence suggests non-resonant error fields may be important**
- **Empirical correction algorithm must be re-optimized after the recent modifications to DIII–D**
  - Plasma also may be more vulnerable to error fields at low rotation (balanced NBI)

# Model-based Multivariable Control is Ready to Implement and Test in Multiple Plasma Shapes

- **Precise shape control is needed for double-null pumping**
- **The advanced shape control algorithm set has three basic features:**
  - A pre-computed, model-based shaping coil current trajectory for each coil
    - Allows the system gain to be greatly reduced
    - Accounts for nonlinear response at x-point
  - Machine hardware limitations are directly incorporated to closely match the desired shape given those limitations
    - Coil current limits, e.g. 0 < F1A < 4500 Amps
    - Constraint on net current of inner PF coil stack
  - The controller takes into account every coil's effect on each control point and x-point (Multiple Input, Multiple Output)

# 2005 Experiments Demonstrated Model-Based Multivariable Control with RPF Current Regulation



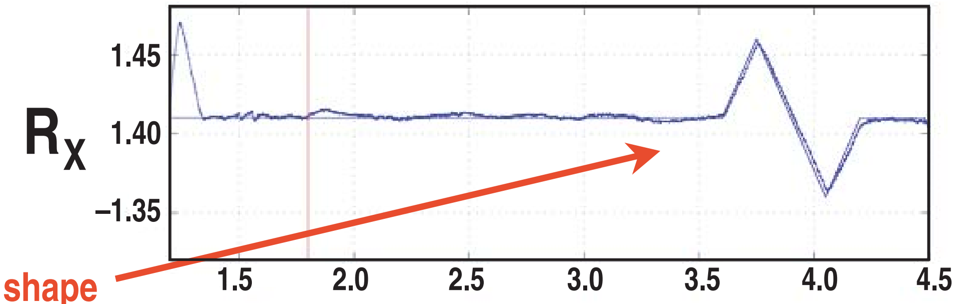
Shape with standard isoflux control just before Advanced Control starts at 2 s

Shape with only feedforward trajectory

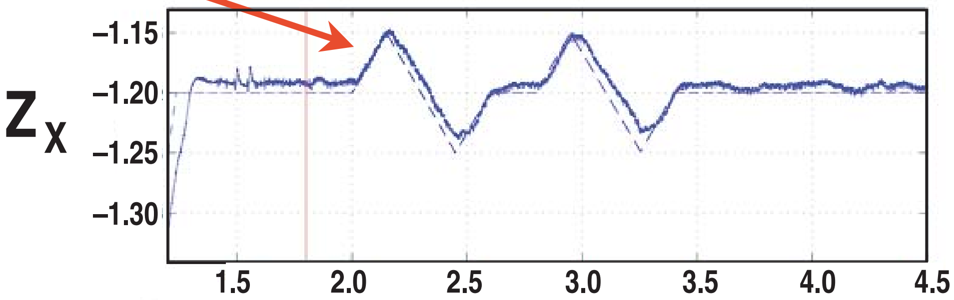
Segment 2 control point

Segment 1 control point

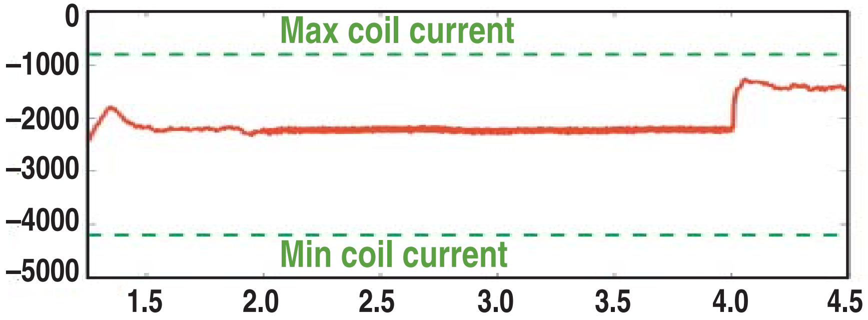
Segment 7 control point



Good shape control



Regulated Coil Currents Avoid Limits



# DIII–D Stability Experiments Address Critical Issues for ITER, Advanced Scenarios, and Basic MHD Physics

- **Plasma control for reliable and precise operation**
  - Measure error field and re-optimize correction
  - Develop feedback control of rotation
  - Incorporate multivariable control into routine experimental use
- **Stability physics in 2006**
  - Disruption mitigation: impurity penetration, runaway avalanche suppression ✓
  - Benchmark models of fast-ion transport by Alfvén eigenmodes ✓
  - Effects of low rotation on NTM stability: seeding and locking ✓
- **Experiments in 2007 and beyond**
  - Validate physics of giant sawteeth and sawtooth control ✓
  - Sawtooth physics: transport and stability vs. magnetic curvature
  - Reverse Shear Alfvén Eigenmodes: stability, thermal ion drive ✓
  - Validate prediction of 2nd regime access everywhere with $q_{min}>2$
  - Plasma response to error fields at low rotation ✓
  - Localized ECCD to modify sawtooth stability ✓
  - Disruption physics: energy loss and time scale, size scaling with JET ✓
  - NTM threshold: marginal $\beta_p$ for 2/1 mode with beta ramp down ✓

**✓ = ITPA experiments**

# The DIII–D Stability Program Addresses Key Issues for ITER

**Scientific goals are closely related to the capability to predict and control MHD stability in a burning plasma**

- **Physics of disruption mitigation**
  - Key issue for protection of ITER first wall
- **RWM stability with rotation and feedback**
  - Stability limit of ITER advanced scenarios
- **Edge pedestal stability and ELM control**
  - Key issue for ITER first wall and divertor
- **Physics of NTM onset and stabilization**
  - Stability of ITER baseline scenario
- **Stability of Alfven eigenmodes and effect on fast ion transport**
  - Key issue for fusion gain in ITER
- **Physics of sawtooth instability and control of sawteeth**
  - Key issue for fusion gain in ITER
- **Plasma response to error fields**
  - Stability of burning plasma in ITER with little or no torque
- **Advanced plasma control**
  - Crucial to sustainment of ITER baseline and advanced scenarios

# Summary

- **The DIII–D stability program will use new diagnostic instruments, control actuators, and modeling tools to develop the scientific basis needed for**
  - Detailed extrapolation to ITER and future fusion devices
  - Control and sustainment of high performance tokamak plasmas
  - Understanding of fundamental MHD physics

- **New tools for active control will be an essential element of the DIII–D Advanced Tokamak program during the next five years, leading to**
  - Reliable operation of high performance plasmas
  - New operating regimes beyond present stability limits