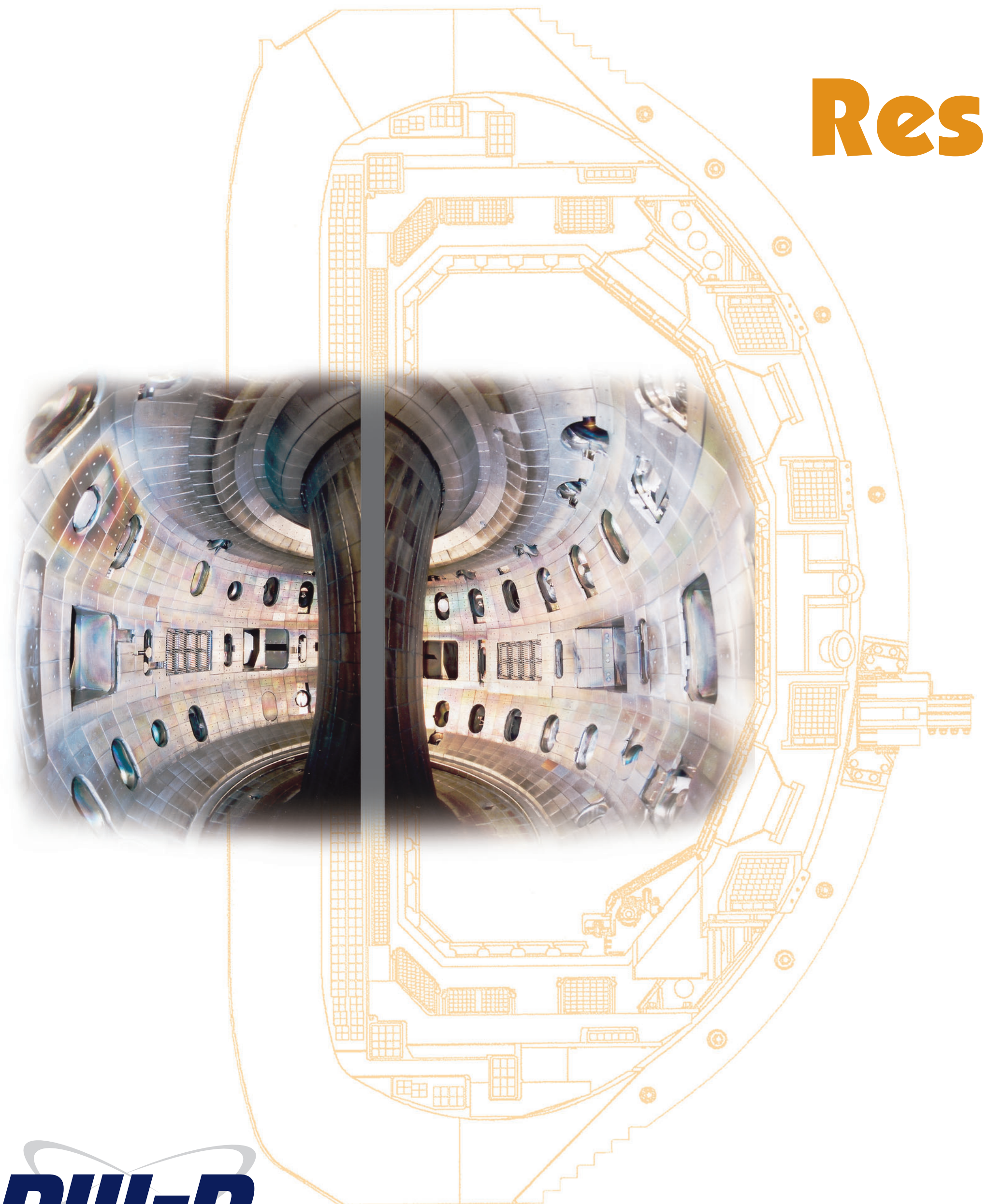
MHD Stability Research in DIII–D



by
E.J. Strait
and the DIII–D Stability Group

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November 11-15, 2002

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GOALS FOR MHD STABILITY RESEARCH IN DIII–D

- Establish the scientific basis for understanding and predicting limits to macroscopic stability of toroidal plasmas

- Apply this understanding toward the control and improvement of MHD stability in toroidal plasmas

- Key physics areas
  - Resistive wall mode stability, including stabilization by plasma rotation and feedback control
  - Edge-driven instabilities in plasmas with a large edge pressure gradient and associated bootstrap current
  - Neoclassical tearing modes, including threshold mechanisms and means of active stabilization
  - Non-ideal plasma instabilities such as sawteeth, resistive interchange modes, and fast ion driven instabilities
  - Disruption dynamics and methods of disruption mitigation

DIII–D STABILITY STUDIES WILL MAKE USE OF NEW TOOLS

- Resistive wall modes
  – Internal control coils
- Neoclassical tearing modes
  – 8 gyrotrons with steerable launchers
- Edge pedestal stability
  – Li beam polarimetry measurements of edge current profile
- Fast ion-driven instabilities
  – Fast ion profile diagnostic
- Disruption physics
  – Fast multi-channel bolometry
- Validation of theoretical models
  – Nonlinear MHD codes

DIII–D STABILITY PROGRAM

2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008

Stability Theory & Modeling

- Nonlinear Initial Value Codes (NIMROD) →
- Nonlinear Edge Modeling (BOUT) →
- Gyrokinetic Edge Modeling →
- RWM Feedback Models with Rotation (VALEN) →

New Diagnostics

- Improved core j(r)
- Edge j(r) (Li beam)
- Real-time q-profile
- 3-D equilibrium and island physics
- Fast ion profile

New Control Tools

- 6 gyrotrons
- FW (<3 MW)
- 8 gyrotrons
- FW (6 MW)
- 9 MW ECH long-pulse
- High frequency control amplifiers
- Counter NBI
- Edge ergodization
- Internal (12) control coils
- Disruption predictor

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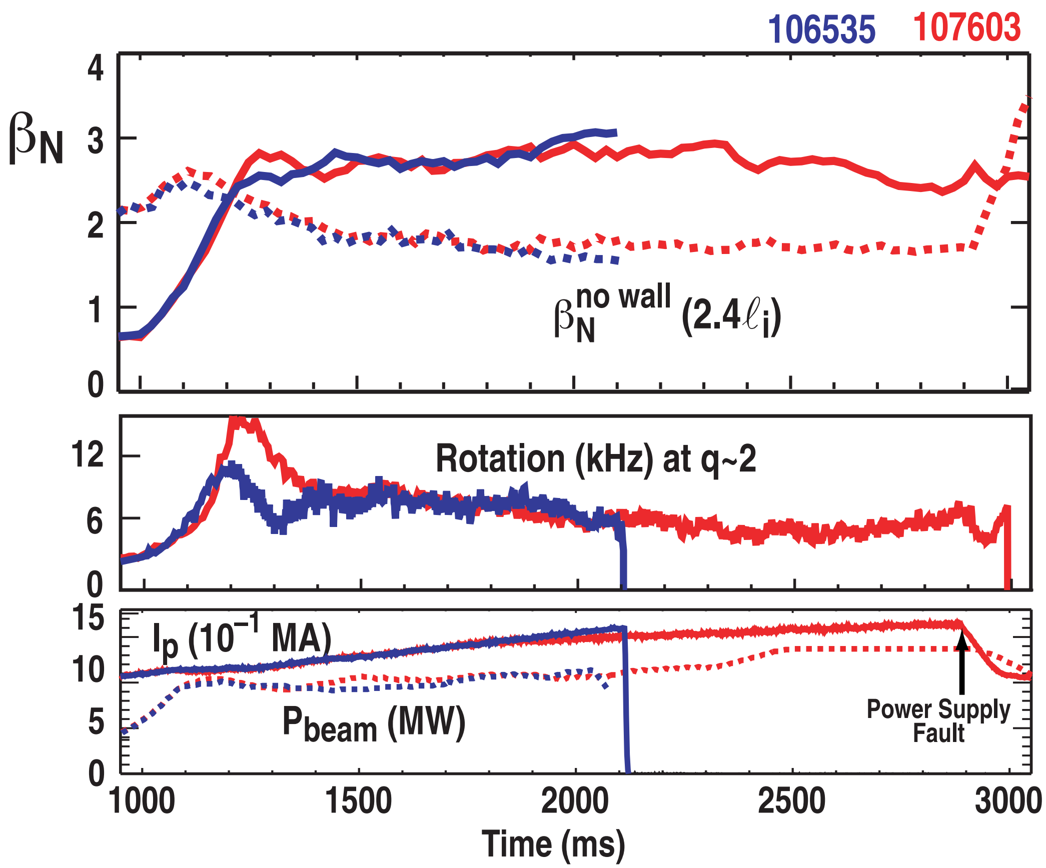
REDUCED ERROR FIELDS ⇒ SUSTAINED ROTATION ⇒ STABILIZATION OF THE RWM ⇒ RELIABLE OPERATION ABOVE THE NO-WALL LIMIT



- $\beta_N \lesssim 2\ \beta_N^{no\ wall} \sim \beta_N^{ideal\ wall}$
- Recent breakthrough: understanding of resonant field amplification
  - By weakly damped RWM
- Feedback control allows "adaptive" reduction of magnetic field asymmetry

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RESISTIVE WALL MODE PHYSICS

- Interaction with plasma rotation
  - Validate models of rotational stabilization
  - Critical rotation frequency, rotational drag by RWM
    - ★ New tools for rotation control: rf heating, counter-NBI
  - Develop adaptive magnetic symmetrization for general use

- Feedback control
  - Quantitative validation of feedback models
    - ★ Incorporate effects of rotation in the models
  - Develop multi-sensor RWM detection
  - Test internal coils for improved feedback control

⇒ Apply one or both approaches to improve the performance of "Advanced Tokamak" discharges

- Demonstrate sustained operation at $\beta_N \geq 5$ high f_{BS}

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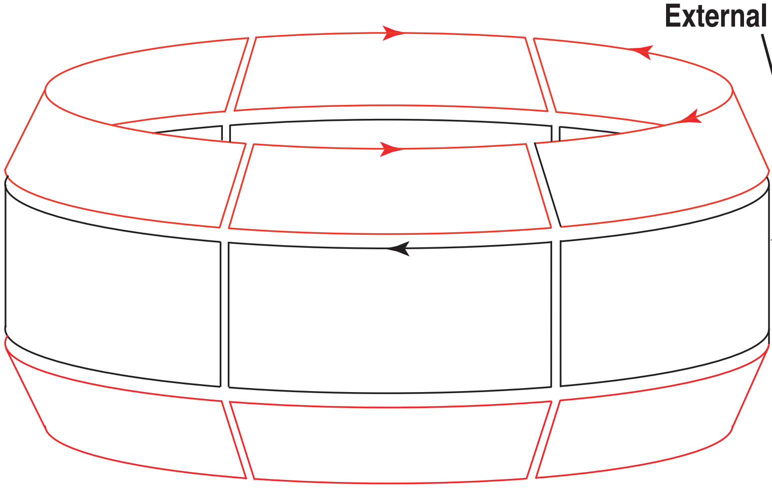
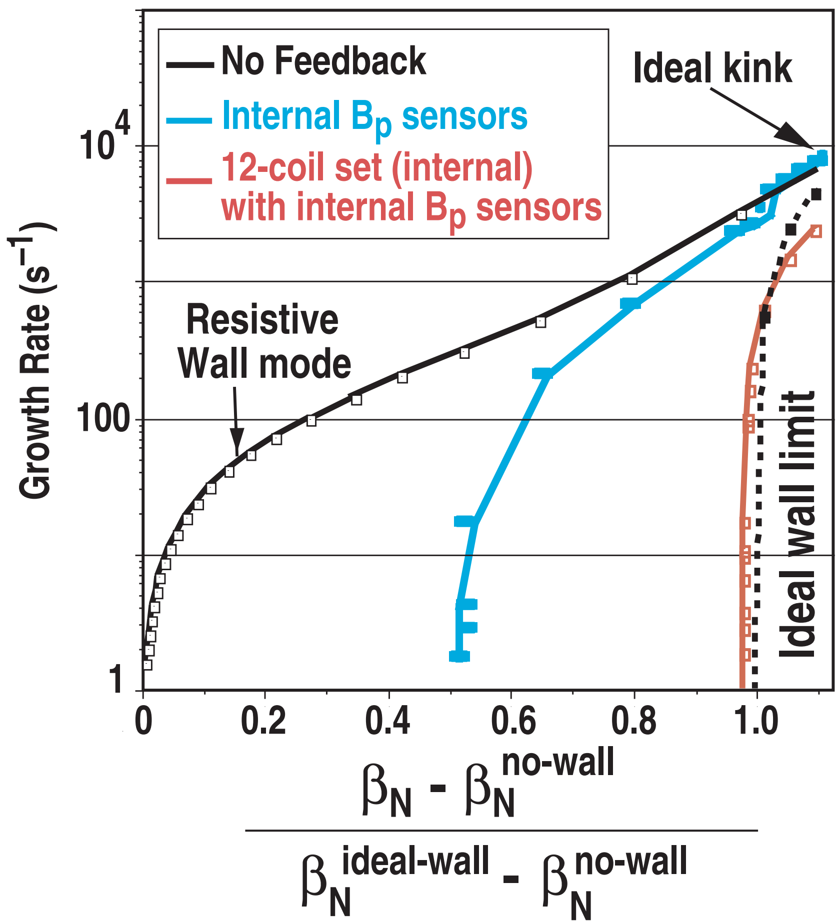
INTERNAL CONTROL COILS WILL BE AN EFFECTIVE TOOL FOR PURSUING ACTIVE AND PASSIVE STABILIZATION OF THE RWM

- Better matching to poloidal error field spectrum
- Active feedback stabilization is calculated to open high beta wall-stabilized regime to plasmas without rotation

Internal Coils



VALEN Modeling (No Rotation)



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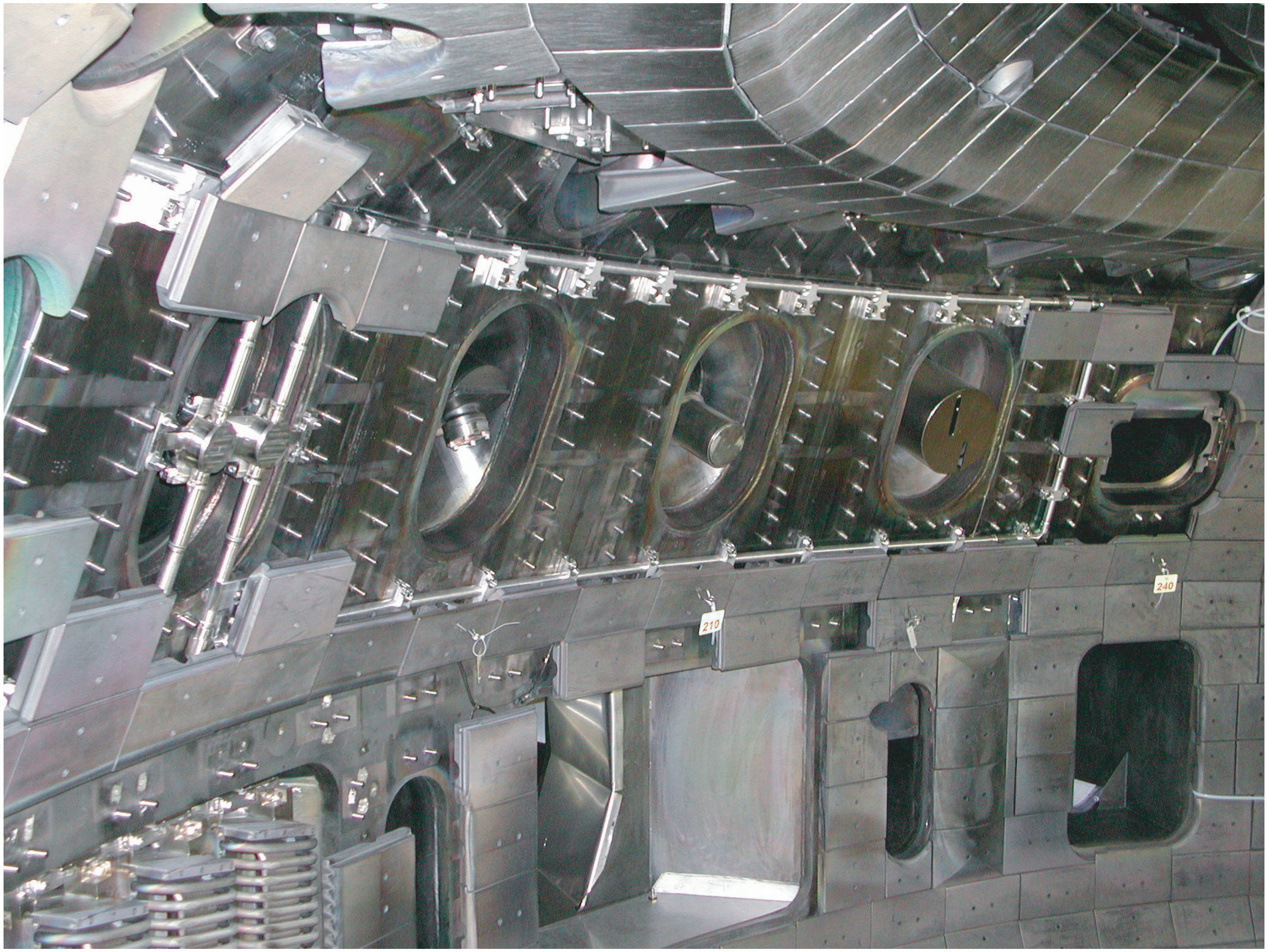
TWO PROTOTYPE RWM CONTROL COILS INSTALLED IN DIII–D



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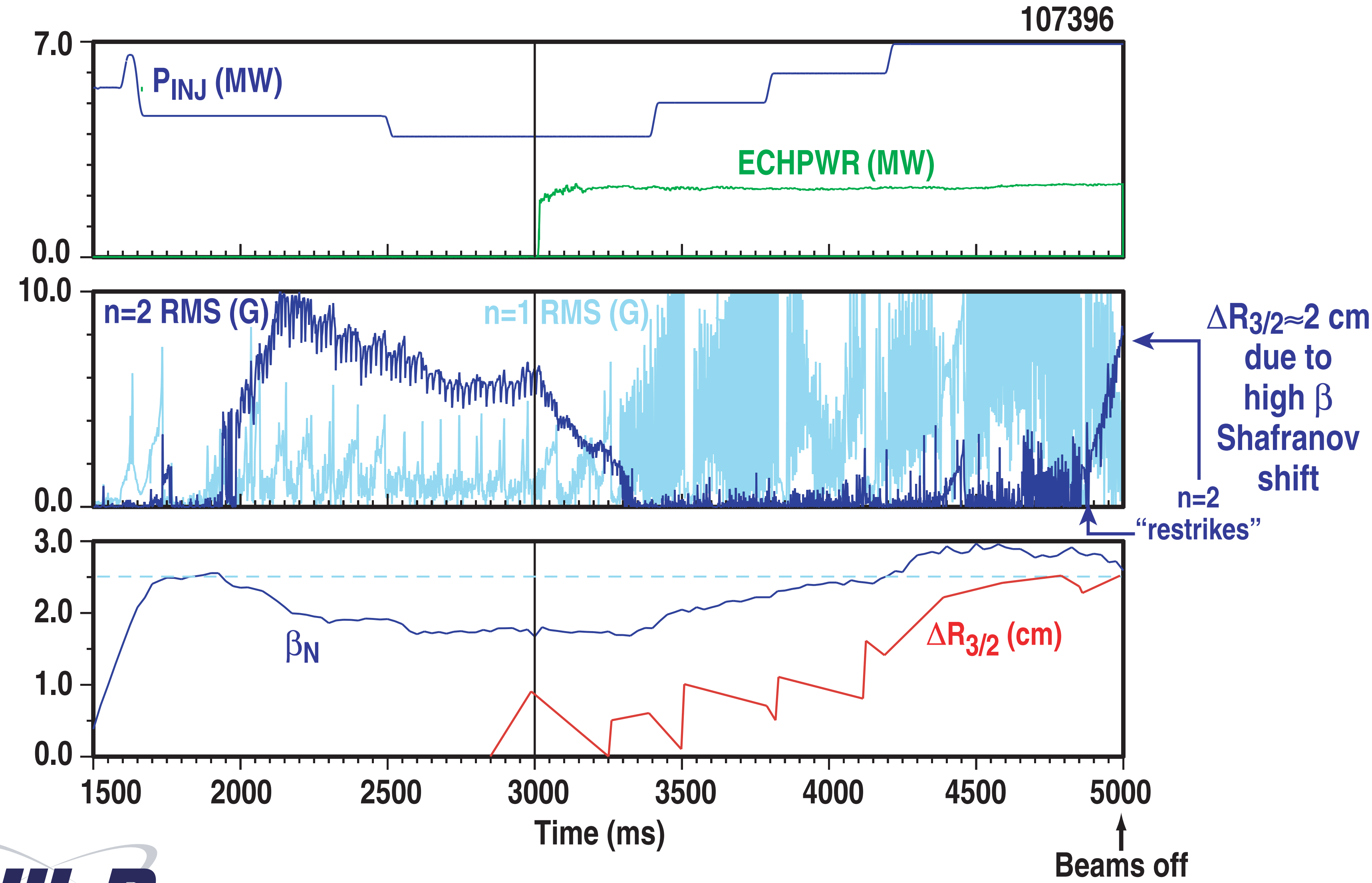
ECCD SUPPRESSION OF m/n = 3/2 NTM ALLOWS β_N INCREASE

- β_N raised 60% (20% above onset level)
  - ★ mode restrikes as q = 3/2 moves radially by 2 cm off ECCD



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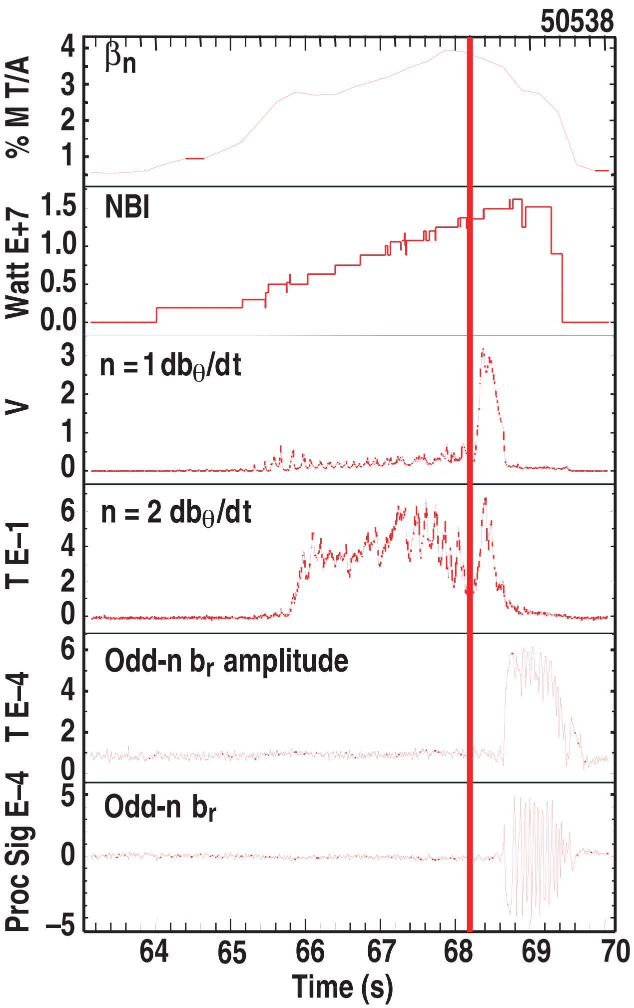
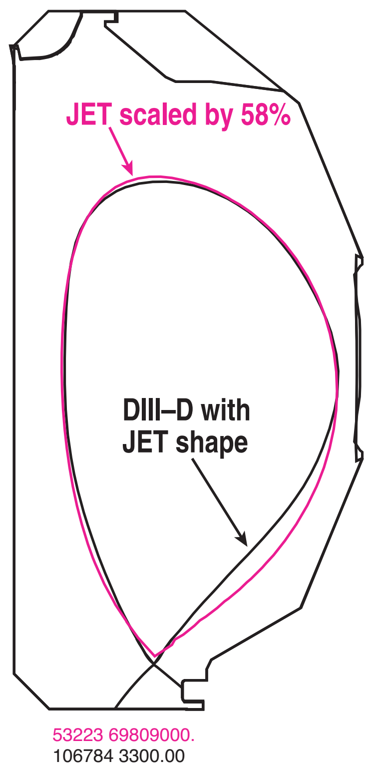
JET/DIII–D NONDIMENSIONAL MATCH OF (2, 1) NTM CRITICAL β_N

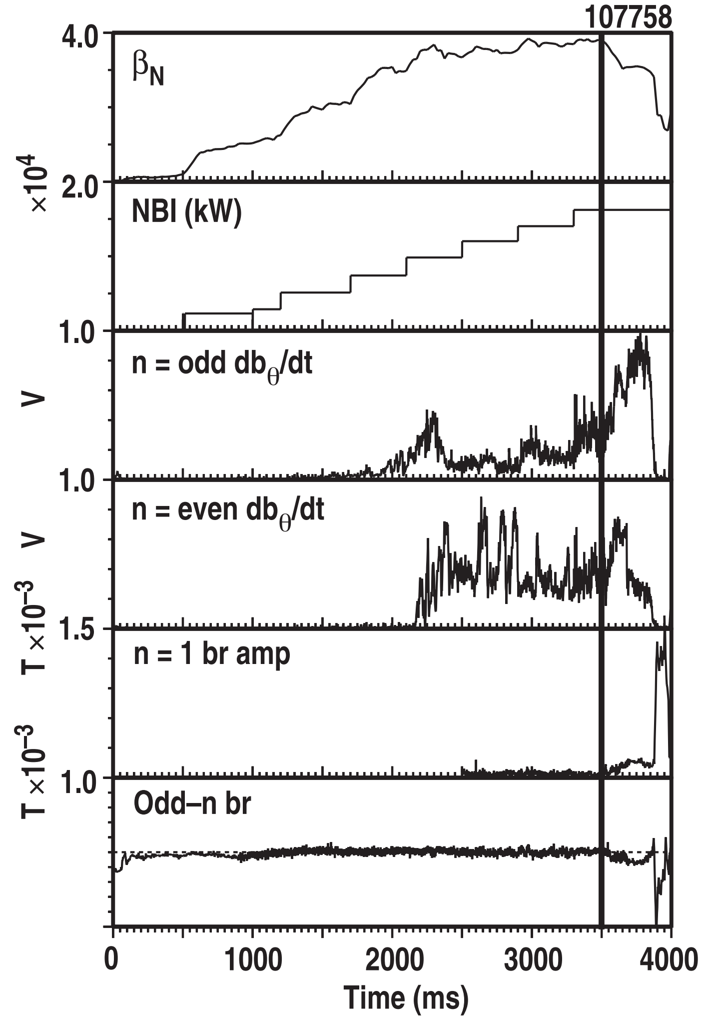
- JET, 0.95 MA, 0.97 T, 2.6×10^{19} m^{-3}
  - ★ $\beta_{N,crit} = 3.8$



- Same β, ρ^* and ν^* (and $\nu_i/\varepsilon\omega^* \propto \nu^*/\rho^*$)



- DIII–D, 1.06 MA, 1.88 T, 6.7×10^{19} m^{-3}
  - ★ $\beta_{N,crit} = 3.8$ also



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NEOCLASSICAL TEARING MODE PHYSICS

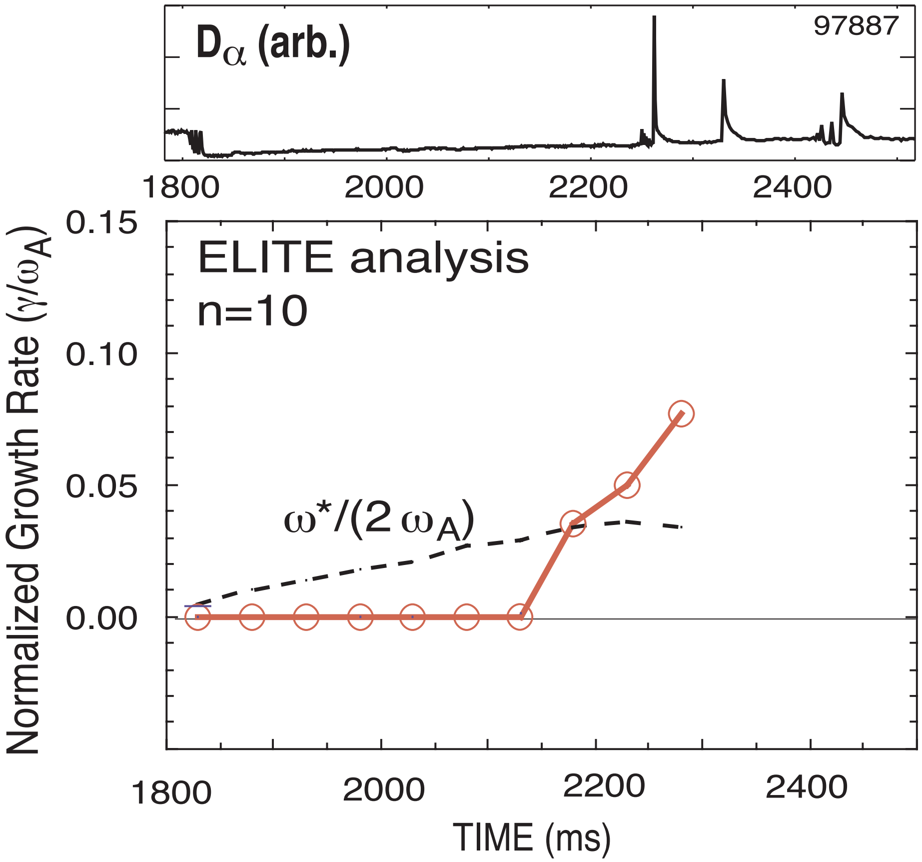
- **Understanding of NTM onset physics**
  - Seeding by RWM, other stationary perturbations
    - ★ Internal control coils
  - Possible “classical” destabilization near ideal stability boundary
  - Validation of models for NTM damping
  - Threshold scaling with plasma size (ρ_i/a)
    - ★ Comparison with JET, C–Mod
  - Damping rate measurements by active MHD spectroscopy (C–Mod antennas, DIII–D control coils)

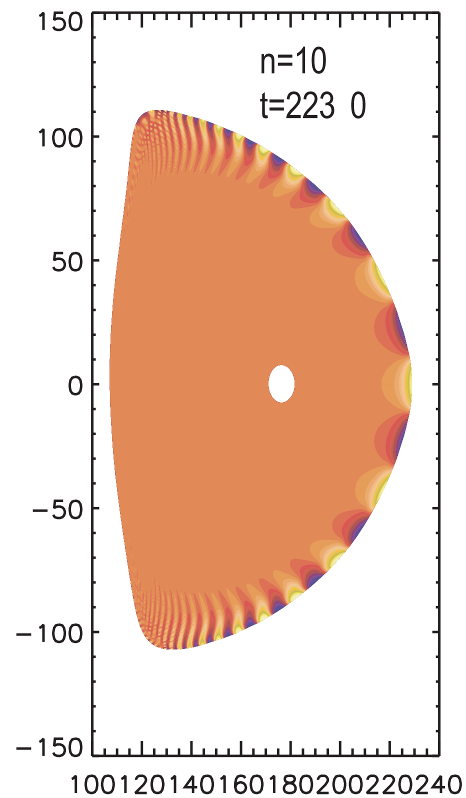
- **Active stabilization of NTM**
  - Improved real-time control methods
    - ★ Real-time q profile, mirror steering
  - Multi-mode stabilization by ECCD
  - Current profile control
    - ★ ECCD, benign NTMs
  - Non-resonant magnetic perturbations
    - ★ Internal control coils allow poloidal mode selection

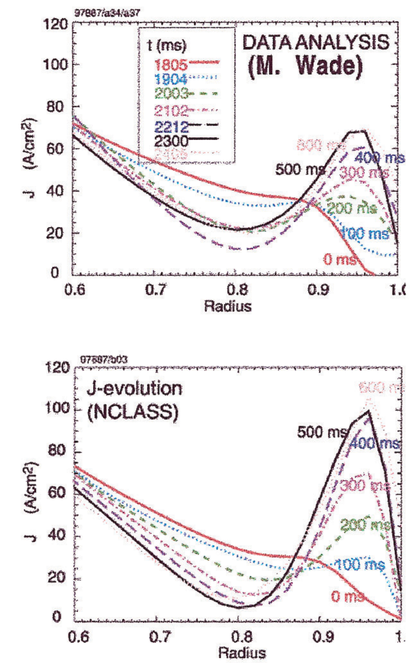
- **Improved analysis and modeling capabilities (PEST-III, MARS, NIMROD)**

⇒ Apply these approaches to improve the performance of “Advanced Tokamak” discharges

INTERMEDIATE n PEELING-BALLOONING MODES ARE A SOLID CANDIDATE FOR ELMs: CASE STUDY IN DIII–D







- DIII–D shot analyzed using experimental reconstruction of equilibria
- n=10 growth rate attains significant value just before ELM observed
- Edge current remains an important uncertainty ⇒ Li beam diagnostic

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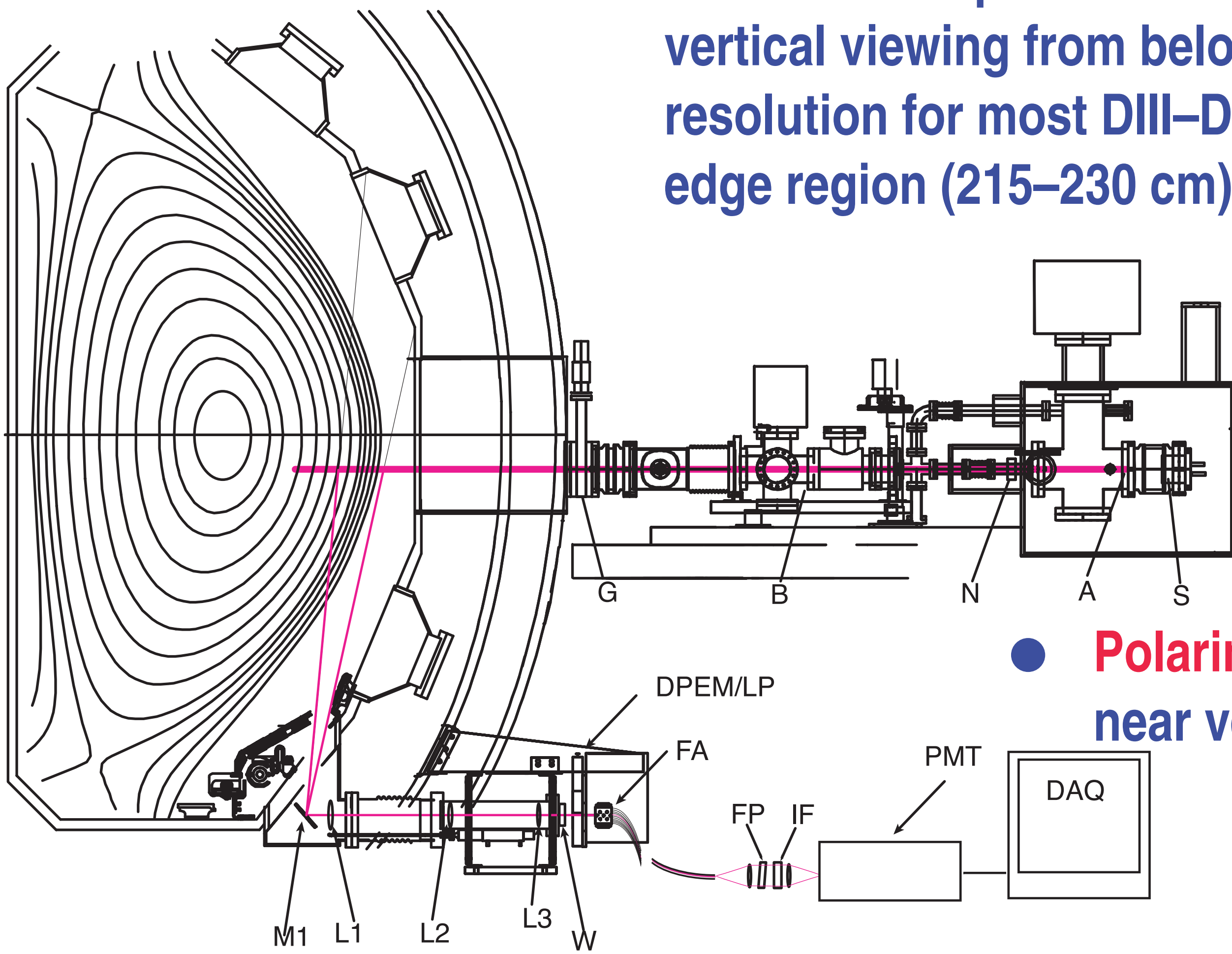
EDGE PEDESTAL STABILITY PHYSICS

- Validation of the role of edge current density
  – Li beam polarimetry diagnostic
- Mode coupling and ELM depth
- Physics of H–mode discharges with small ELMs or no ELMs
  – Type II ELMs
  – Quiescent H–mode
    ★ DIII–D edge harmonic oscillation
    ★ C–Mod quasi-coherent mode
  – Active edge control
    ★ Ergodic layer, shaping, impurity injection
- Linear and nonlinear edge modeling (ELITE, BOUT, gyrokinetic modeling)

⇒ Develop regimes of tolerable ELMs that can be extrapolated to larger devices

LITHIUM BEAM POLARIMETRY WILL PROVIDE HIGH RESOLUTION MEASUREMENTS OF EDGE J(r)

- **LiBEAM:** Neutral lithium beam is injected just below the midplane. This geometry along with vertical viewing from below gives best radial resolution for most DIII–D shapes. Good view of edge region (215–230 cm)



- **Polarimeter:** View from below, near vertical viewchord fan

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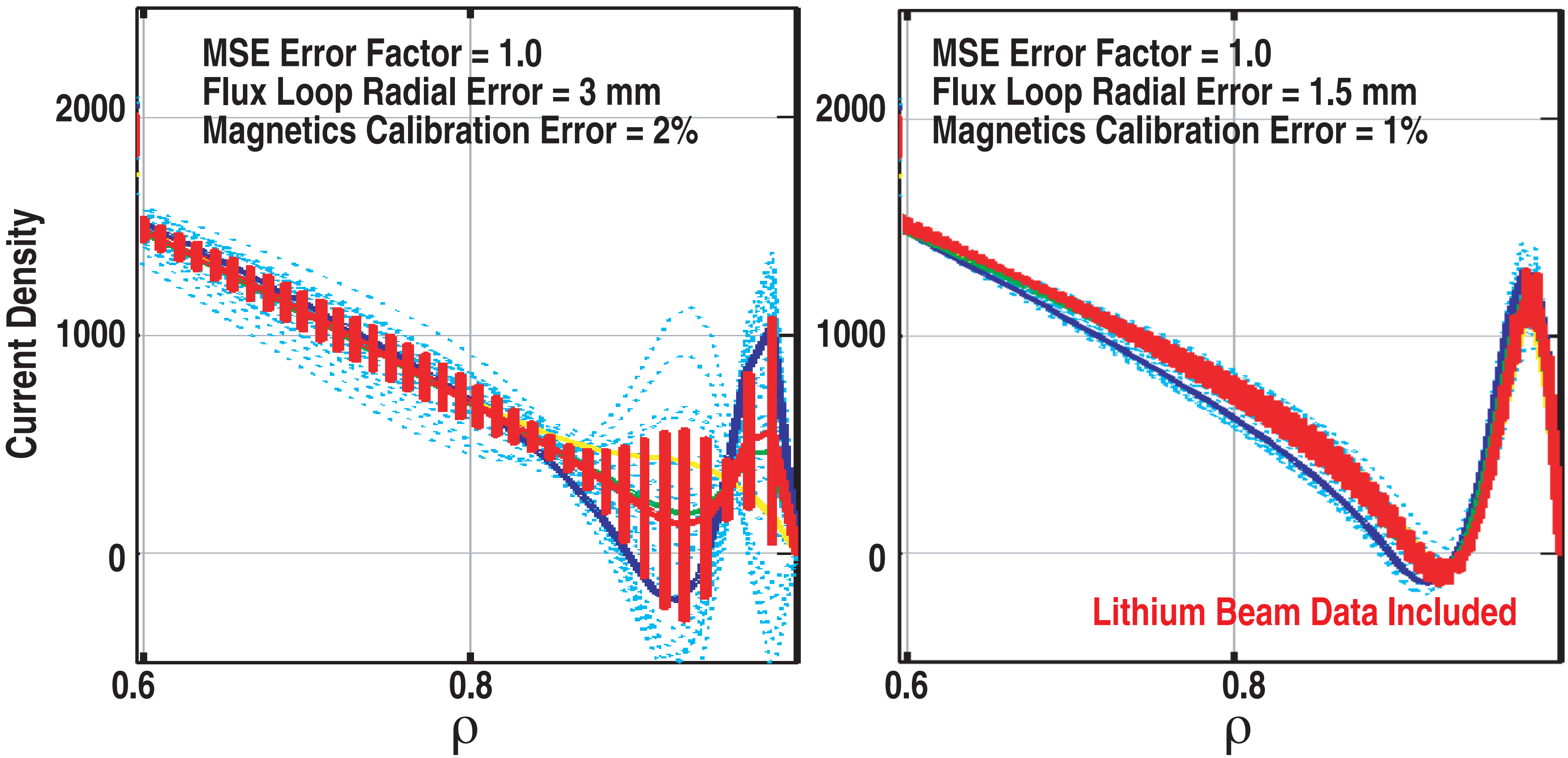
EXPECTED REDUCTION IN UNDERTAINTY IN j_{edge} FROM INCLUSION OF Li BEAM DATA AND REDUCTION IN MAGNETIC DIAGNOSTIC ERROR



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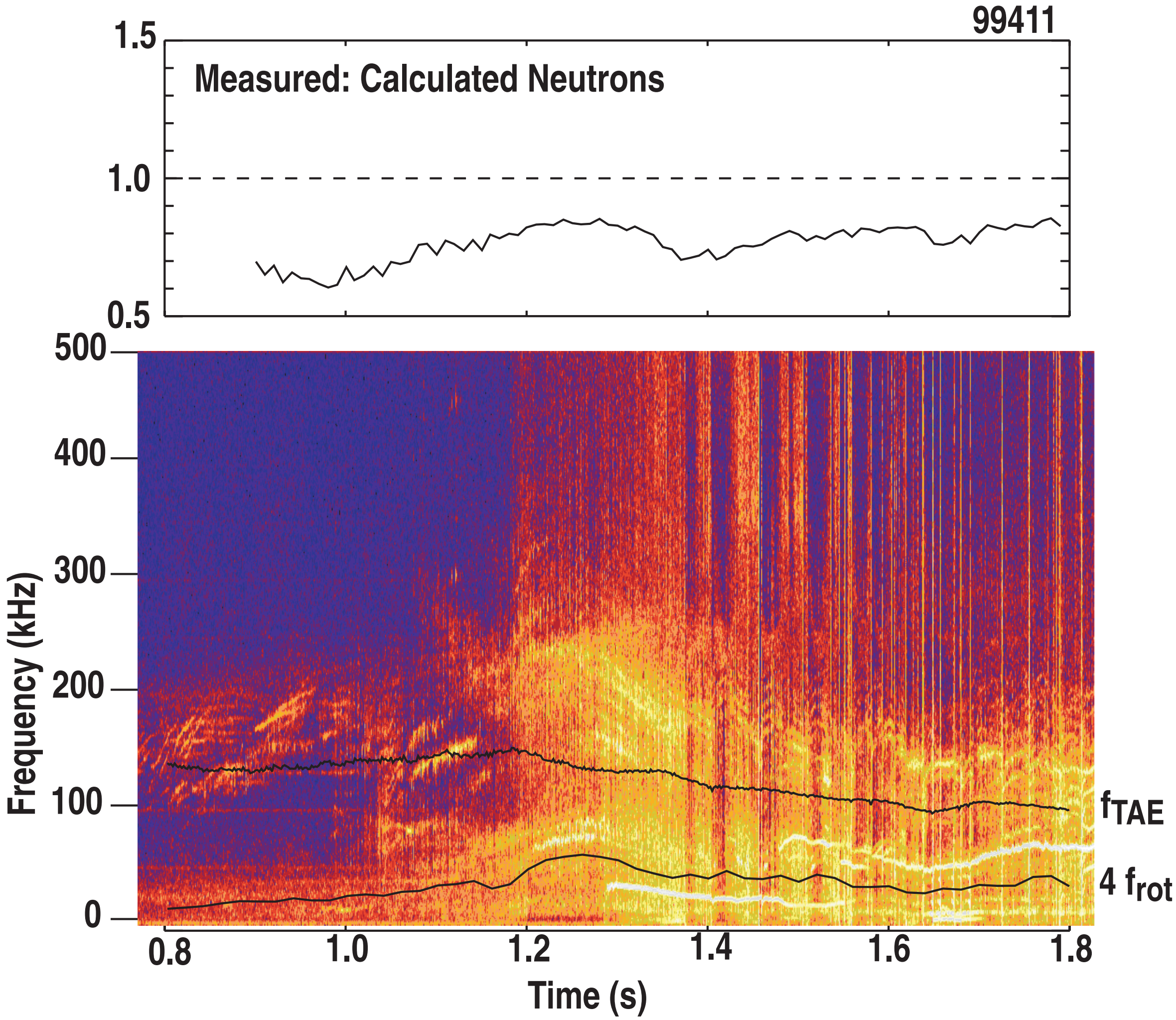
ALFVEN MODE ACTIVITY CORRELATES WITH LOSS OF FAST IONS

- Measured neutron rate compared to TRANSP calculation



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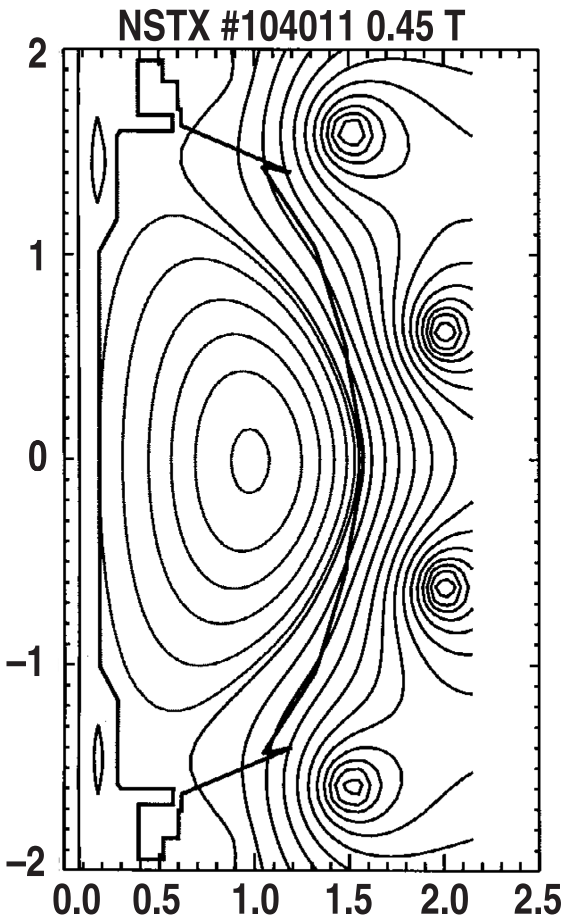
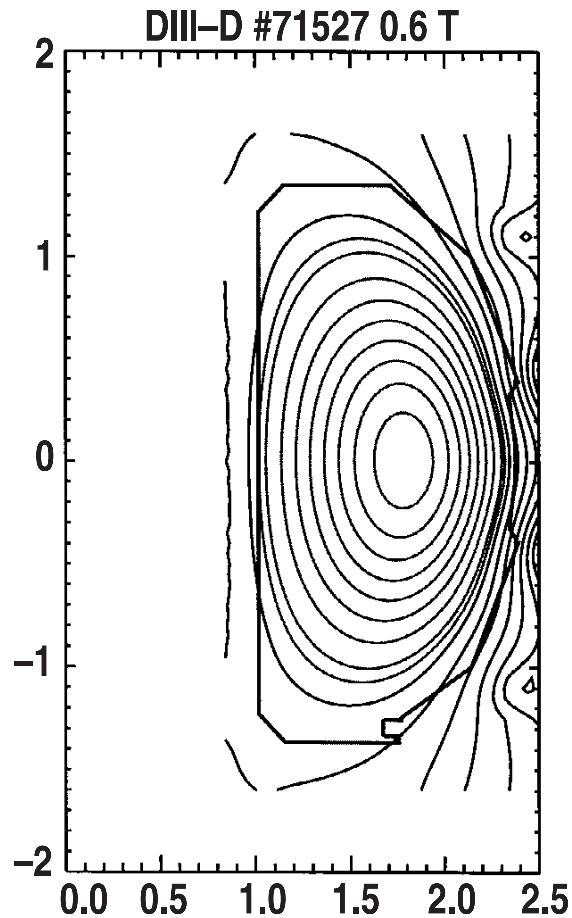
NSTX/DIII–D COMPARISON ISOLATES TOROIDICITY EFFECTS ON ALFVEN EIGNMODES





- NSTX and DIII–D can match shape, toroidal field, and neutral beam energy
  $\Rightarrow$ Can match all Alfven mode parameters (V_f/V_A, for example)
- Goal: compare stability thresholds and mode structure with modeling predictions
  - Most unstable mode number
  - Multiple unstable modes
  - Kinetic effects
- Critical physics for next-step device

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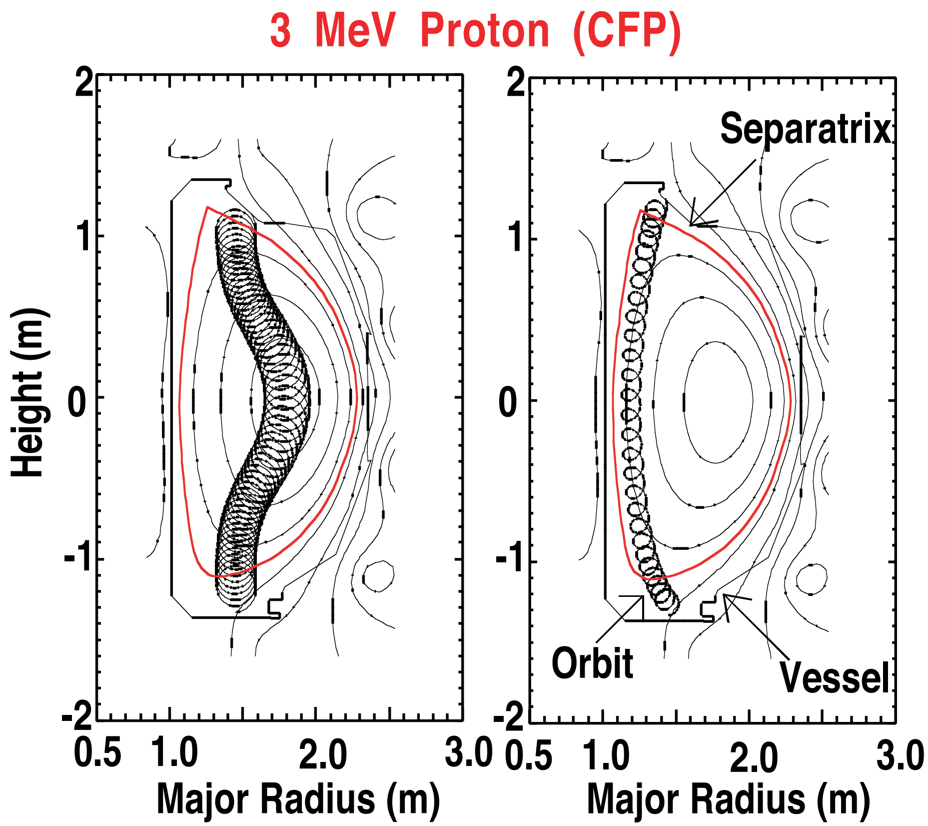
FAST ION PHYSICS

- Validation of models for Alfvén eigenmodes and energetic particle modes
  - Linear stability
  - Nonlinear saturation
  - Fast ion transport
  - Transition to “energetic particle mode”

⇒ Develop physics basis for extrapolation to a burning plasma

- Key need is fast ion profile measurement. Will select from:
  - Fast neutral particle analyzers
  - Neutron collimator
  - 3 MeV proton camera
  - Collective scattering



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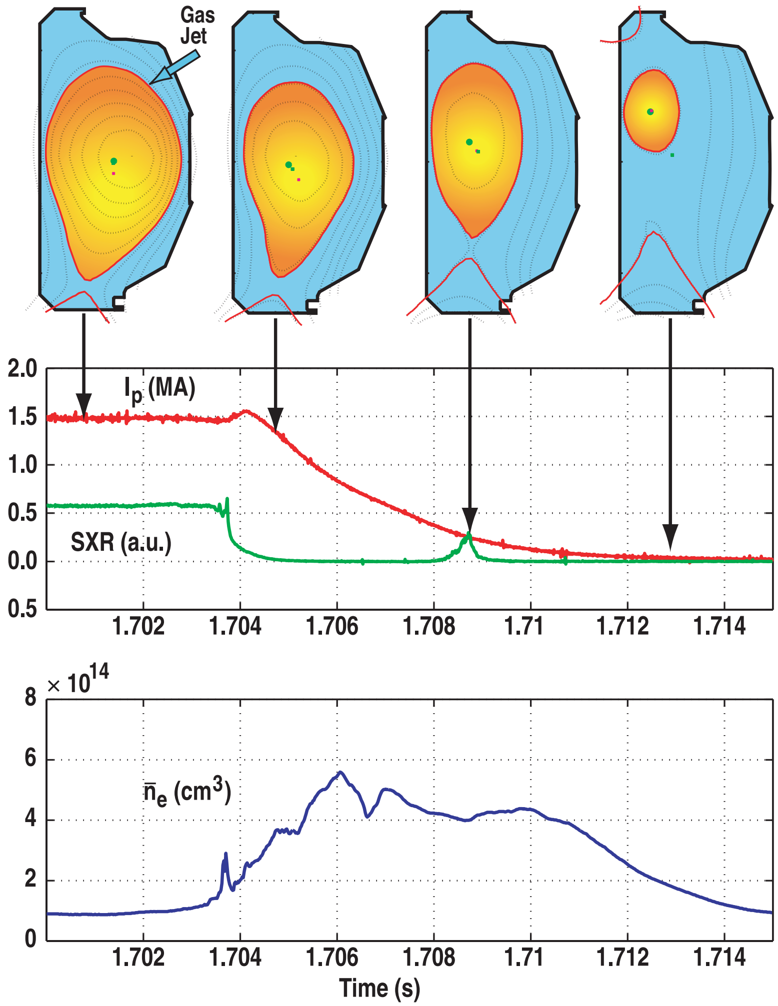
CONTROLLED PLASMA TERMINATION WITH HIGH PRESSURE NOBLE GAS INJECTION



- Rapid uncontrolled plasma termination (disruption) is source of concern for large tokamaks (ITER)
  - Thermal stress
  - Mechanical stress
  - Fast electrons (runaways)
- Simple high pressure gas Jet pre-emptively terminates plasma
  - Mitigates disruption concern
    - ★ Low thermal loads – 99% radiation
    - ★ Low mechanical stress – reduced “halo” currents
    - ★ No fast electrons

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DISRUPTION MITIGATION PHYSICS

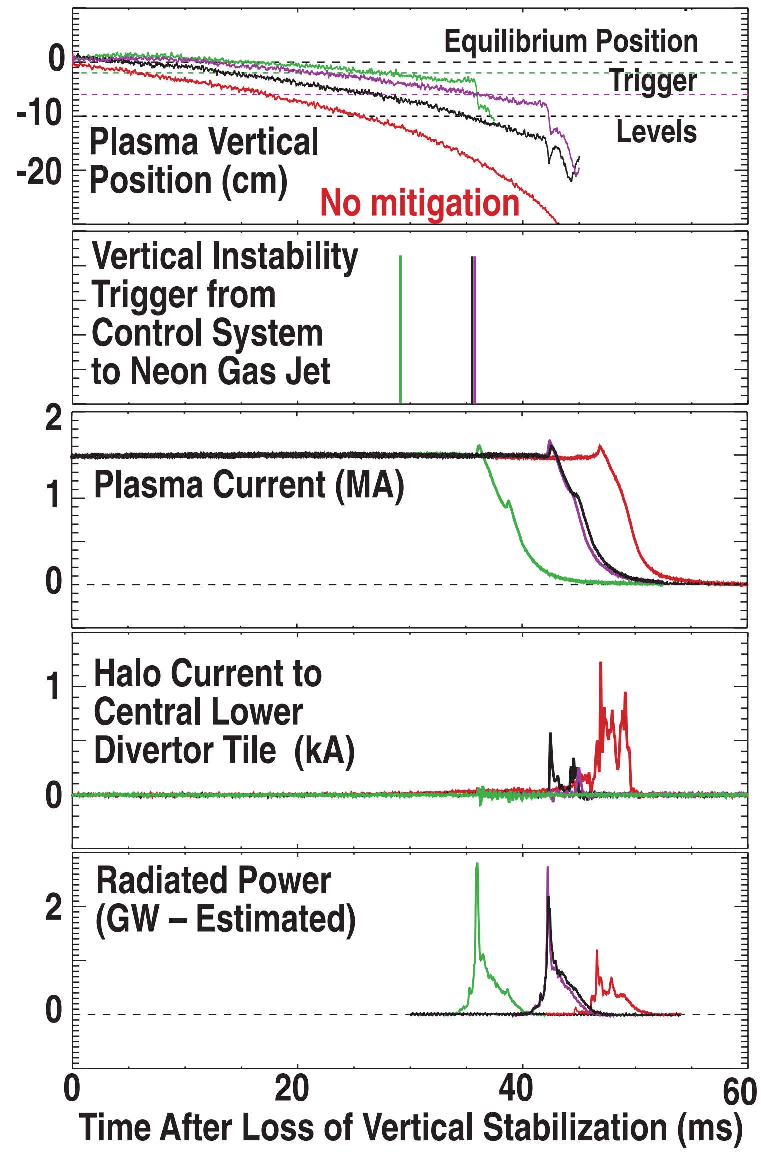
- Validate models for mitigation process
  - Gas jet penetration
    - ★ Fast sequential visible camera (100 μs)
  - Radiative dissipation
    - ★ Fast multi-chord bolometer (DISRAD-II)
  - Physics of runaway electron suppression
    - ★ Collaboration with JET
  - Comparison of low-Z gas jet (DIII–D) and high-Z pellet (C–Mod)

- Develop reliable real-time disruption detection and trigger
  - Vertical instability
  - Mode locking
  - Density limit

⇒ Develop mitigation techniques that can be extrapolated to a burning plasma experiment

REAL-TIME TRIGGERING OF HIGH PRESSURE GAS JET FOR DISRUPTION MITIGATION

- Earlier detection of vertical displacement improves effectiveness
  - Greater radiative dissipation
  - Reduced halo current



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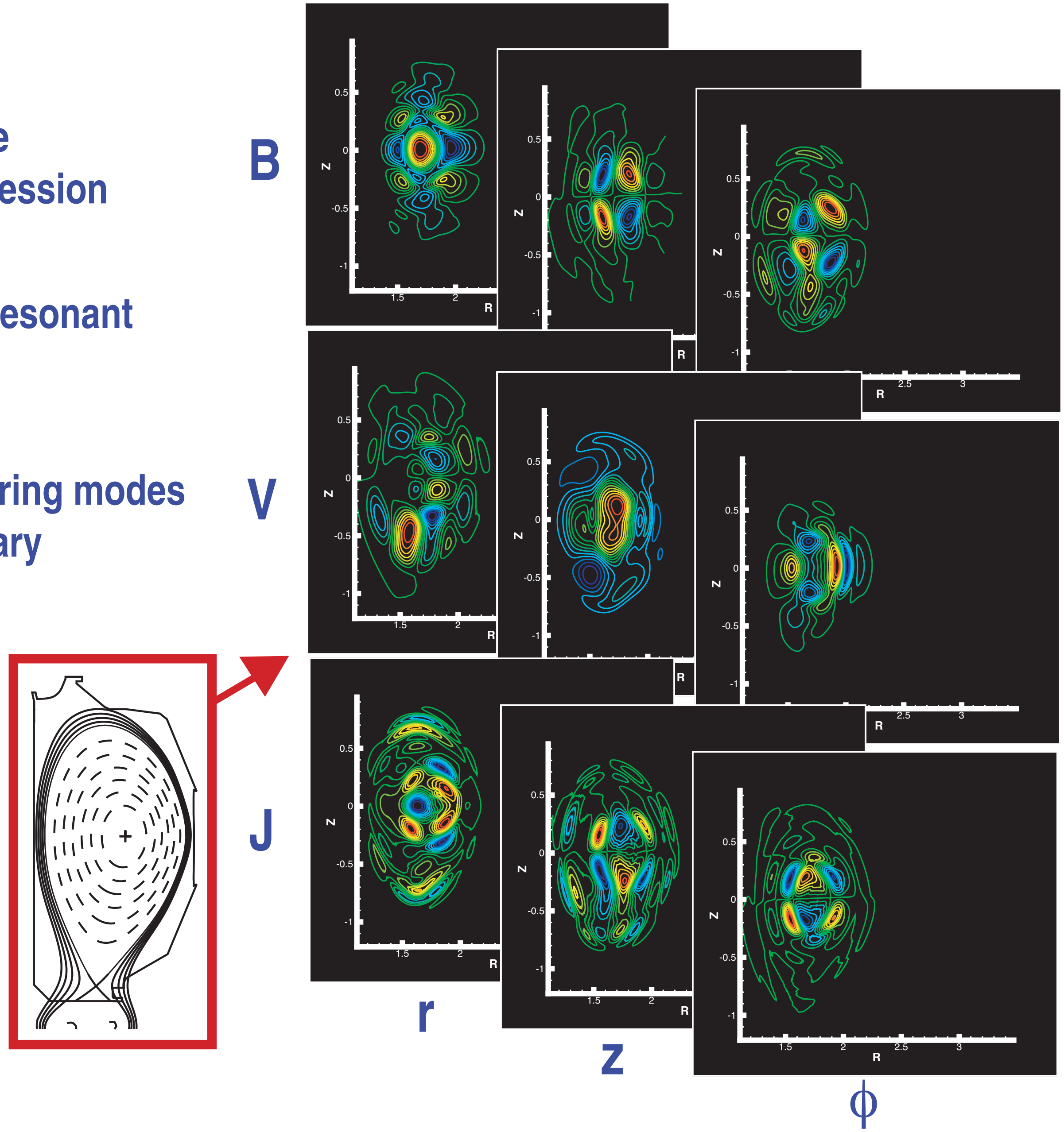
DIII–D EXPERIMENTS AND MODELING WILL EXPLORE PHYSICS BEYOND IDEAL, AXISYMMETRIC MHD

- **Plasma rotation**
  - Key element of RWM stability
  - Tools include rf heating, counter-NBI, non-axisymmetric coils
- **Extended MHD**
  - Dissipative effects — reconnection physics, resistive interchange
  - Neoclassical effects — NTM threshold and saturation
  - Two-fluid effects — edge stability
  - Kinetic effects — fast ion modes, sawtooth stabilization
- **3-D effects**
  - Interaction of finite-amplitude islands
  - Plasma response to non-axisymmetric walls and coils
  - Fast ion transport by MHD modes

⇒ **Validation of more realistic stability models will allow extrapolation to**
  - Burning plasma experiments
  - Non-tokamak (and non-fusion) plasmas

NIMROD MODELING OF DIII–D PLASMAS IS IN PROGRESS

- Neoclassical tearing mode stability, and ECCD suppression
- NTM suppression by nonresonant helical perturbations
- Nonlinear evolution of tearing modes near ideal stability boundary
- Physics of the edge harmonic oscillation in quiescent H–mode plasmas



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THE DIII–D LONG-RANGE PROGRAM ADDRESSES KEY ISSUES OF MHD STABILITY

- Physics of interaction of a rotating plasma with a resistive wall
- Validation of classical and neoclassical tearing mode theory
- Stability properties of transport barriers
- Nonlinear coupling of modes (core, edge)
- Tests of m=1 reconnection and resistive interchange theories
- Interaction of fast ions with MHD modes
- Physics of disruptions and disruption mitigation
- Validation of nonlinear and extended MHD models
- Improved stability through profile control and active stabilization

This program will develop the scientific basis needed for

— Control and sustainment of high performance tokamak plasmas

— Predictive capabilities for other devices