Supported by Office of Science

Macroscopic Plasma Physics (MHD) Research
5 Year Plan: NSTX

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National Tokamak Planning Workshop

September 17-19, 2007

MIT Plasma Science and Fusion Center

Cambridge, MA

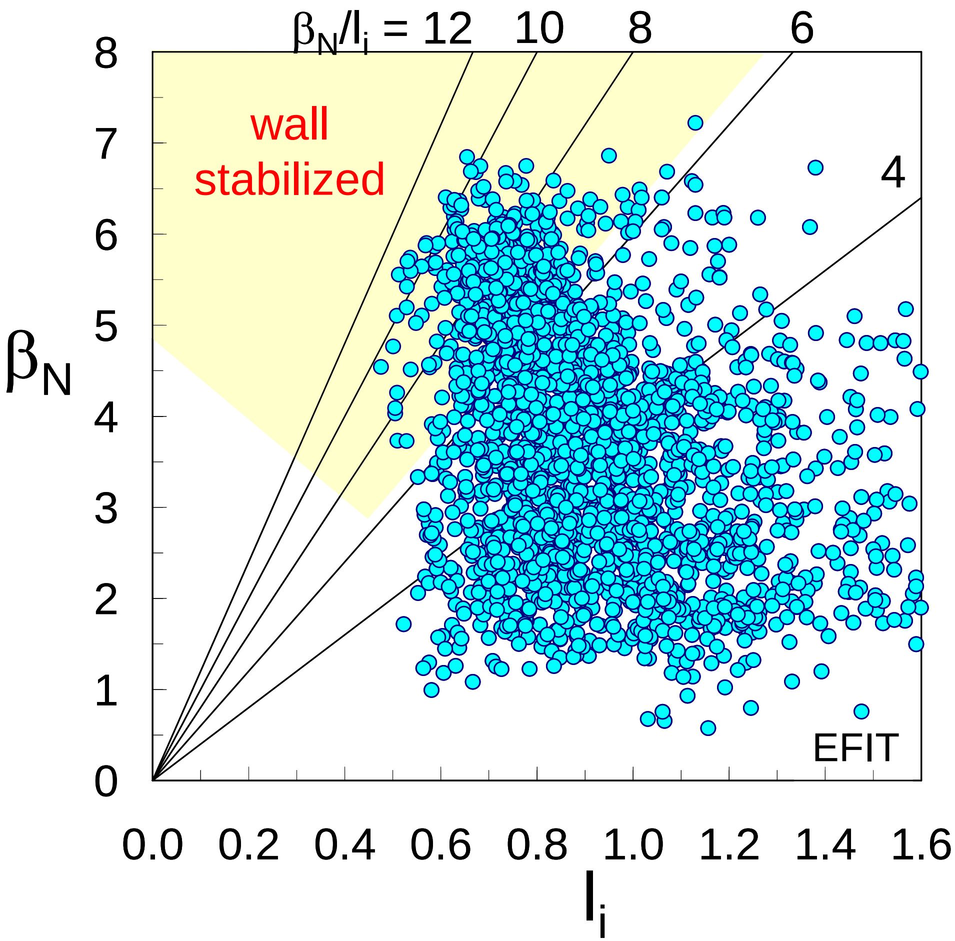
Maintain high β_N wall-stabilized operation by applying first-principles tokamak physics understanding

- Objectives:
  - Advancement of low-*A*, high beta tokamak plasma devices in support of an ST development path to sustained fusion generation
    - Addresses OFES goal: Configuration Optimization
  - Applied stability physics understanding applicable to tokamaks in general, leveraged by unique low-*A*, and high β operational regime
    - Addresses OFES goal: Predictive Capability for Burning Plasmas

Community discussion - input welcomed (email comments to sabbagh@pppl.gov)

Advanced tokamak operation demonstrated in a mega-Ampere class spherical torus

- High β operational space
  - Ultra-high β_t = 39%, near unity in core
  - Broad current and pressure profiles
  - $\beta_N > 7$, $\beta_N/l_i > 11$
  - Wall-stabilized, $\beta_N/\beta_N^{no\text{-}wall} >$ 50% at highest β_N
- Future research moves forward to demonstrate the ***reliable maintenance*** of wall-stabilized state



S.A. Sabbagh, et al., *Nucl. Fusion* **46**, 635 (2006).

MHD research in 2008 - 2013 period separated into several topics

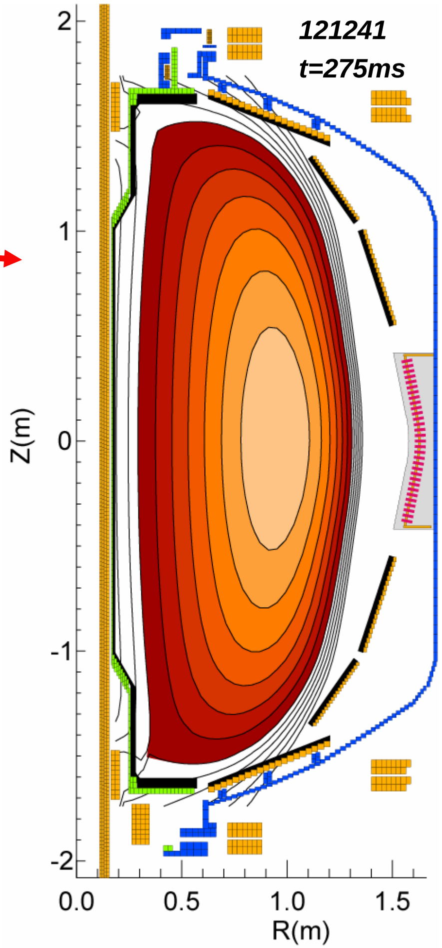
- High plasma shaping and global stability
- Resistive wall mode physics and stabilization
- Dynamic error field correction
- Tearing mode / NTM physics
- Plasma rotation / non-axisymmetric field-induced viscosity
- Mode-induced disruption physics and mitigation

Access and maintain high β_t and β_N at high shaping

Goal: *sustain stable, high beta operation at very high plasma elongation ~ 3 as a proof-of-principle for ST development and to confirm MHD stability theory in this operating space.*

Contributes to: *NHTX, ST-CTF development*

- Present status / issues
  - Sustained $\kappa < 2.6$, $\delta < 0.8$; transient $\kappa = 3$ with record shaping factor, $S \equiv q_{95}(I_p/aB_t) = 41$
  - Highest κ and S plasmas limited to $\beta_N \sim 4 < \beta_N^{\text{no-wall}}$
- Plan summary 2008-2013
  - 2008-2010: Operate with upgraded control computer. Test β feedback control using diamagnetic loop sensor and NBI power.
  - Experiments to extend high S plasmas into wall-stabilized, high $\beta_N > 6$ operating space
  - 2010-2012: Integration of β feedback into real-time EFIT, improve strike point control for Li divertor.
  - 2012-2013: real-time MSE w/real-time V_ϕ for real-time EFIT, β feedback using stability models



D.A. Gates, et al., *Nucl. Fusion* **47**, 1376 (2007).

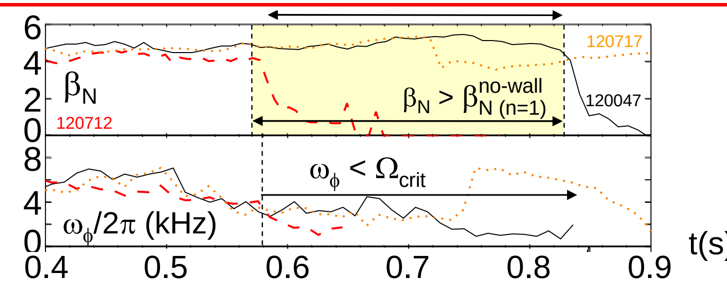
Low A: key understanding for RWM active/passive stabilization

Goal: *Determine RWM passive/active stabilization physics, apply understanding to optimize/ increase reliability of active stabilization at low A, to provide greater confidence in physics used to extrapolate RWM stabilization to future tokamaks, including burning plasma devices.*

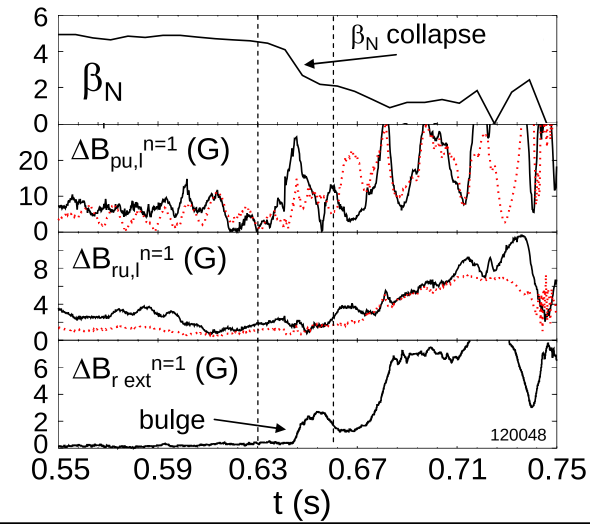
Contributes to: *ITPA MDC-2, ITER issue card RWM-1, USBPO coil design, 2009 milestone*

- Plan summary 2008-2013
  - 2008-2011: RWM active stab. sensor, parameter variation study, investigate underlying stabilization physics
  - Methods of decreasing possibility of RWM poloidal deformation, investigate SOLC / multiple modes in stabilization
  - RWM passive stabilization physics research to further examine V_{ϕ}, profile, ω_A, ν_i, A, e.g. trapped particle precession resonance (joint XPs)
  - 2008-2009: Design high-*n* control coil (NCC); adv. stabilization algorithms
  - 2010-2011: *n* > 1 RWM study during *n* = 1 stabilization, measure SOLC
  - 2012-2013: non-magnetic sensors, NCC use for stabilization

Active *n = 1* RWM stabilization in NSTX…



…can show poloidal deformation of mode, stability loss



S.A. Sabbagh, et al., Phys. Rev. Lett. **97**, 045004 (2006).

Dynamic Error Field Correction critical to maintain high β_N

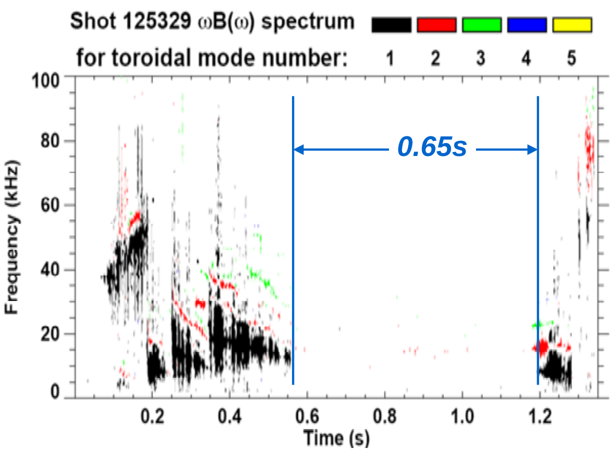
Goal: *Determine sources of dynamically changing error field due to inherent asymmetries in the device and plasma physics responsible for amplification of these sources. Apply techniques that will dynamically cancel these fields to maintain plasma rotation and stability.*

Contributes to: *ITER issue card RWM-1, ITER issue card AUX-1*

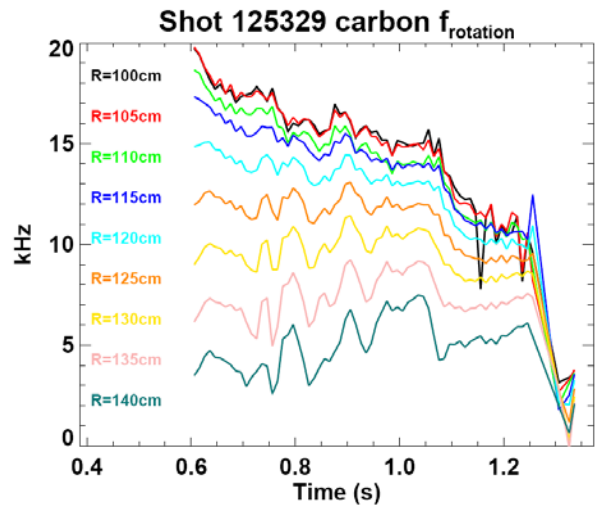
- Plan summary 08-13
  - 2008-2012: investigate sources / physics of dynamic error field, resonant field amplification
  - implement correction methods n = 1-3
  - 2012-2013: Utilize new NCC to expand capability of DEFC ($n \leq 6$) to sustain plasma rotation and high β_N

NSTX Record Pulse Length in I_p = 0.9 MA Plasma with *combined* n = 1 DEFC and n = 3 EFC

n = 1 rotating mode suppressed



Plasma rotation maintained



J.E. Menard, et al. NSTX XP702 (2007).

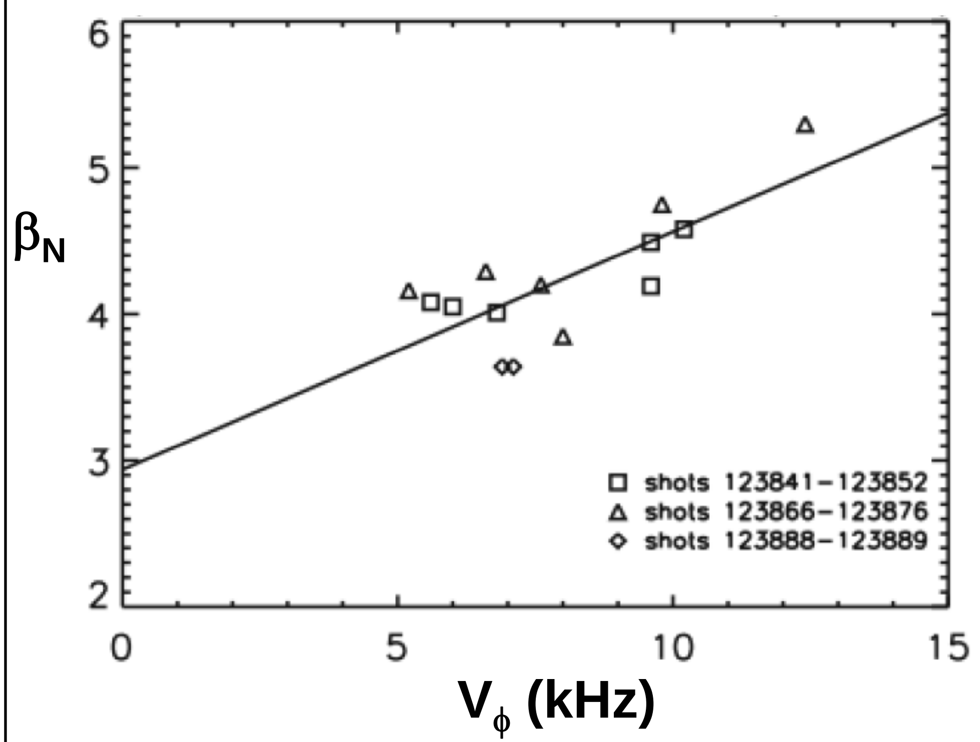
Investigate explicit *A* dependences on tearing stability

Goal: *Generate critical data at low A, high β and β_p, large ρ_i to verify tearing mode physics for burning plasma experiments. Investigate mode impact on β, V_ϕ, fast particle redistribution; low A operation as being theoretically favorable for stability.*

Contributes to: *ITPA MDC-3, ITPA MDC-4*

- Plan summary 2008-2013
  - 2008-2011: Increase simulation capacity: modified Rutherford equation at low-*A*, PEST3, rDCON, NIMROD, M3D
  - Compare sawtooth seeded 2/1, 3/2 with spontaneous modes; compare to higher *A*. Determine seeding mechanisms.
  - 2010-2012: NTM onset β_N vs. ρ^*, ν^*, V_ϕ, V_ϕ shear, compare to higher *A*
  - 2011-2013: Develop discharges that minimize mode impact. Assess EBWCD results for potential stabilization.
  - 2012-2013: Comparison of NTM experiments to theory/simulation developed

2/1 onset β_N vs. toroidal rotation



E.J. Strait, et al., NSTX XP 740 (2007).

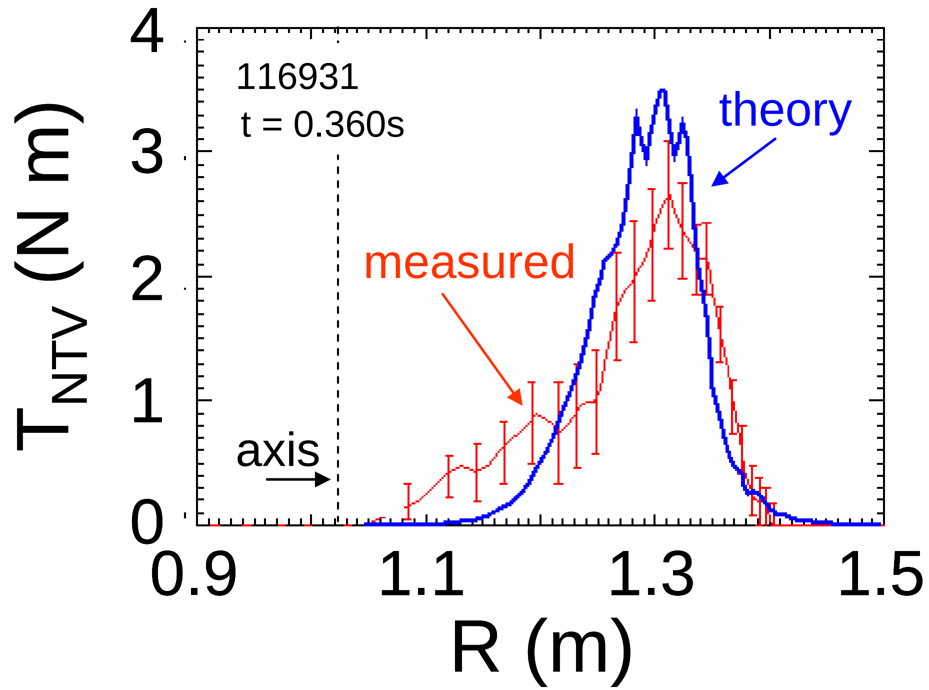
Control V_ϕ, profile using knowledge of plasma viscosity

***Goal:** Continue to develop quantitative, first-principles physics models of non-axisymmetric field-induced plasma viscosity for both resonant and non-resonant field, and apply results to create new techniques for imparting toroidal momentum to the plasma.*

Contributes to: *ITPA MDC-2, ITPA MDC-12, ITER issue card AUX-1*

- Plan summary 2008-2013
  - 2008-2011: Continue testing viscosity theory from resonant /non-resonant fields; design NCC
  - Focus on key parameters: ν_i, q, β_N, V_ϕ, n; for future devices
  - 2011-2012: 2nd beam line to vary torque at fixed power
  - 2012-2013: Use NCC to test viscosity theories ($n \leq 6$)
  - Real-time V_ϕ control using CHERS sensors, basic sources and sinks of plasma toroidal momentum
  - 2013: real-time V_ϕ control using additional momentum sources
  - Attempt momentum *input* with NCC

Measured $d(I\Omega_p)/dt$ profile and theoretical NTV torque (n = 3 field configuration)



W. Zhu, et al., *Phys. Rev. Lett.* **96,** 225002 (2006).

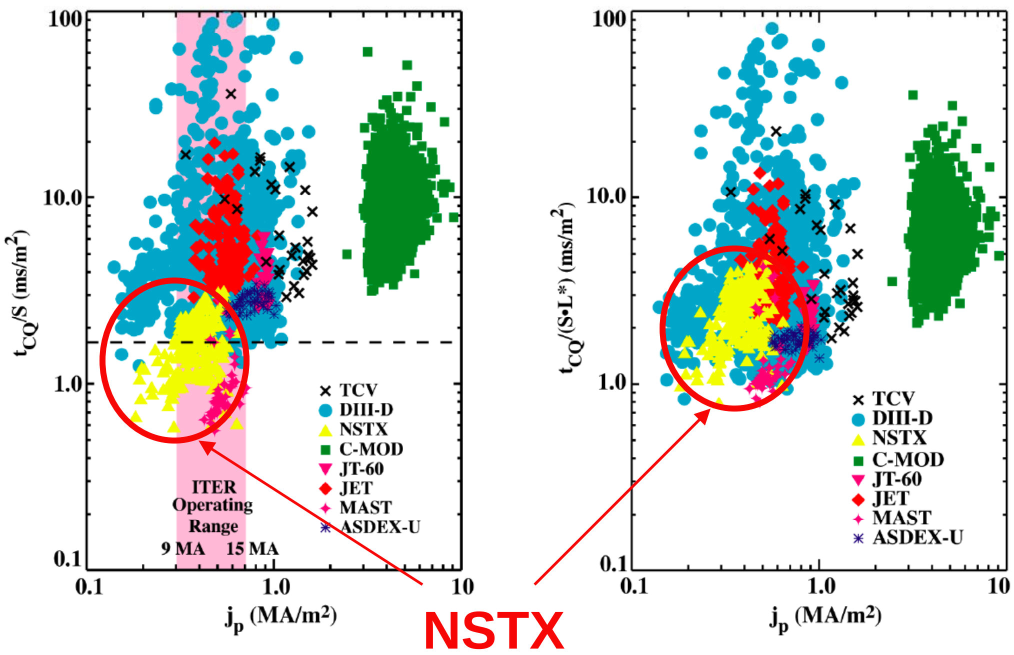
Analyze disruption characteristics, causal modes, avoidance

Goal: *Derive understanding of disruptions by characterizing instabilities that lead to them. Apply understanding to disruption avoidance or control of impact. Analyze disruption effects at low A, high beta by measuring halo current, thermal, and current quench characteristics.*

Contributes to: *ITER issue card DISR-1*

- Plan summary 2008-2013
  - 2009-2011: Further characterize modes that lead to disruptions, operational boundaries
  - Implement halo current diagnostics, connection between modes and halo currents, scaling of magnitude /peaking with plasma parameters
  - Simulate thermal and current quench at low A
  - 2011-2012: Detection of impending disruptions based on real-time measurements
  - 2012-2013: Develop disruption mitigation strategies, based on successful detection techniques

Area-normalized (left), Area and l_i-normalized (right) I_p quench time vs. toroidal J_p (ITER DB)

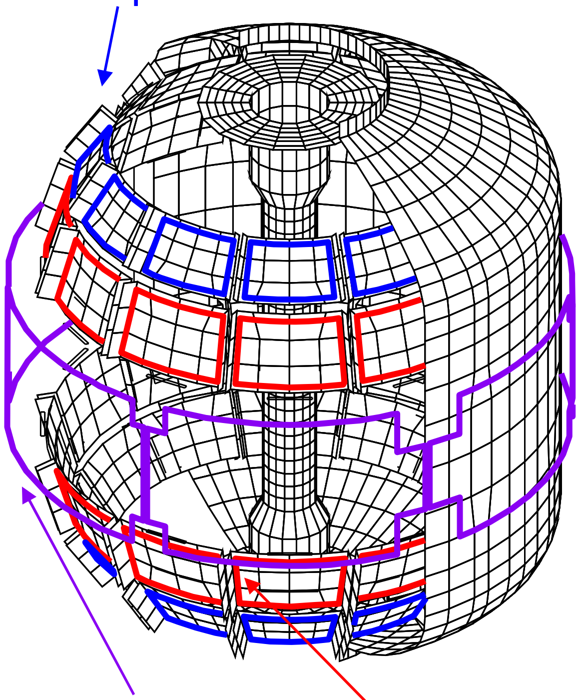


J.C. Wesley et al., *21st IAEA Fusion Energy Conference* (Chengdu, China 2006), paper IT/PI-21.

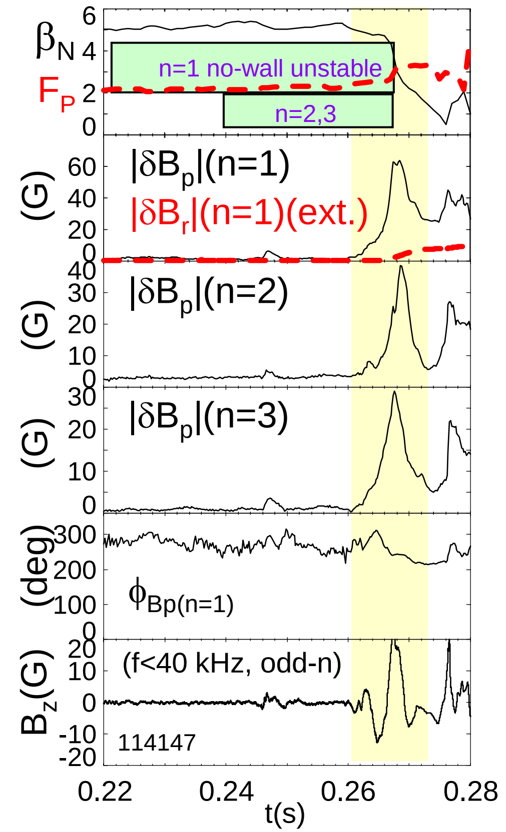
New capabilities planned to address numerous goals

- **Planned capabilities 2009 - 2013**
  - Non-axisymmetric control coil (NCC) – at least four applications
    - RWM stabilization (n > 1, higher β_N)
    - DEFC with $n \leq 6$
    - ELM mitigation (n = 6)
    - Rotation control ($n \leq 6$; n > 1 propagation)
  - Non-magnetic RWM sensors; advanced RWM active feedback control algorithms (ITER, etc.)
  - Alteration of stabilizing plate materials / electrical connections
  - Scrape-off layer currents (SOLC) / passive plate current measurement

Proposed Internal Non-axisymmetric Control Coil (NCC)



RWM with n > 1 RWM observed



(Sabbagh, et al., Nucl. Fusion **46**, 635 (2006).)

NSTX

Macroscopic Stability Research Timeline (Sept. 2007)