NSTX MHD Research Program Plan
2004 - 2008

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for the

NSTX Experimental Task Group

NSTX Program Advisory Committee Meeting #14

PPPL - January 21th, 2003

Research Aims to Study MHD Instabilities in the ST, and Methods of Stabilization or Control at High β

- Goal
  - Provide MHD understanding and diagnostics for development of analysis and control tools to achieve long-pulse, high-β plasmas
- Outline
  - Broad Picture: Role of MHD Research in overall NSTX mission
    - Science understanding of optimized, long-pulse, high β stability
  - Detailed Picture: Research Plan Overview
    - Motivation of plans by present data
  - Mid-term (FY04 – FY05): Active instability control
    - Active feedback system design and implementation

MHD plan supports NSTX mission of integrating science, performance, and high β control

FY02 03 04 05 06 07 08 09

Passive stabilization — Active control — Optimized long-pulse stability

MHD

β limiting modes vs. shape, l_i, F_p

RWM identified

NTM β limits

ELMS & Fast ion modes

Wall-stabilized β limits

RWM passive stability and rotation damping

Modes destabilized at $\Delta t \sim \tau_{cr}$

Impact of ELMS, *AE modes

Shape, profile control / optimize

RWM suppression

Stability at low V_ϕ

NTM suppression

β limits & V_ϕ shear stabilization

→ **Combine to optimize stability in long-pulse high beta regimes**

NSTX mission

Highest performance

- $\beta_T = 30\%$, $\Delta t > \tau_E$
  $\beta_N = 5$: > no wall limit
  HH = 1
- $\beta_T = 40\%$,
- $\beta_N = 8$
  $\Delta t >> \tau_E$, HH = 1.4

Solenoid-free

- $J_{NI} > 60\%$, $\Delta t \sim \tau_{skin}$
- Non-solenoid startup demo
- $J_{NI} \sim 100\%$, $\Delta t > \tau_{skin}$
- Solenoid-free up to hi β_p

40% β_T
$\Delta t >> \tau_{skin}$
$\beta_N = 8$
HH = 1.4
70% J_{BS}

Established Plan Addresses 5-Year IPPA MHD Goal

5 Year FESAC (IPPA Report) MHD Science Goal

- ❑ Develop detailed predictive capability for macroscopic stability, including resistive and kinetic effects
  - Progress measured by the level of agreement between predicted and observed stability regimes and by improvements in the stability of operating confinement devices

- **Progress**
  - ❑ Between-shots, quantitative equilibrium reconstruction with kinetic profile information
  - ❑ Quantitative, time-evolved ideal stability analysis as requested
    - No-wall and with-wall β limits
  - ❑ Generating adequate statistics
    - > 1e5 equilibria with Thomson
    - > 4e3 stability cases run
  - ❑ Standard input to further analysis
    - M3D, VALEN, RF codes, etc.

- **Planned Expanded Capability**
  - ❑ Additional between-shots diagnostic input when available
    - MSE, rotation, etc.
  - ❑ Between-shots stability analysis, saved to permanent database
  - ❑ Assess / include rotation effects
    - Present results from M3D
  - ❑ Assess / include kinetic effects
  - ❑ Resistive stability evaluation
    - Resistive DCON, when available

Several key instabilities observed and are being studied

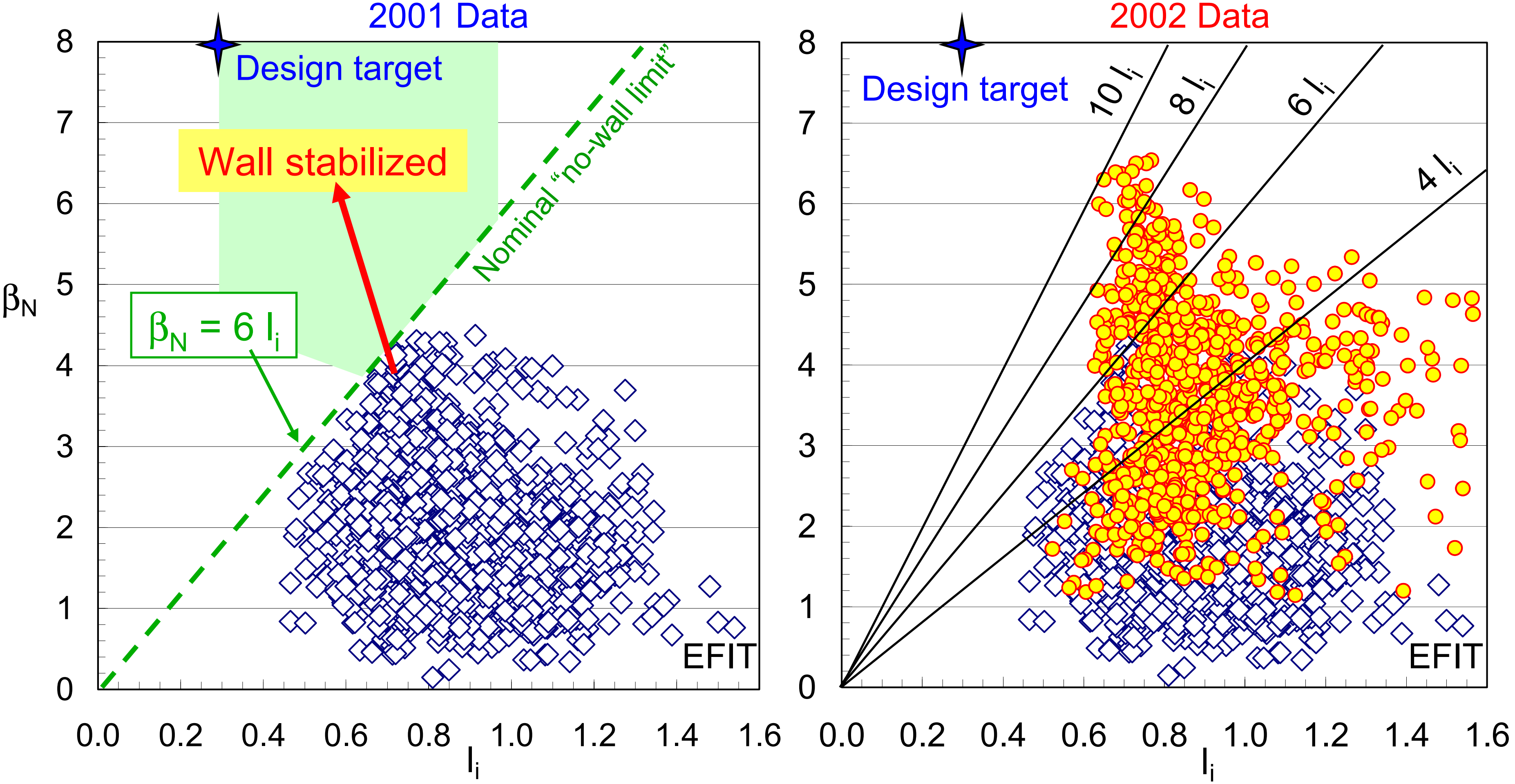
Instability	Beta limiting?
Ideal low-*n* kink/ballooning	yes
Resistive wall modes (RWM)	yes
Neoclassical tearing modes (NTM)	yes
Locked modes	can be
Current-driven kinks	at reduced q_a
Sawteeth	can trigger NTM
Edge localized modes (ELM)	at large amplitude
CAE, TAE, Fishbones	can cause fast ion loss

The plan addresses physics of non-beta limiting, as well as beta limiting modes

Optimizing equilibrium shape and profiles for global stability

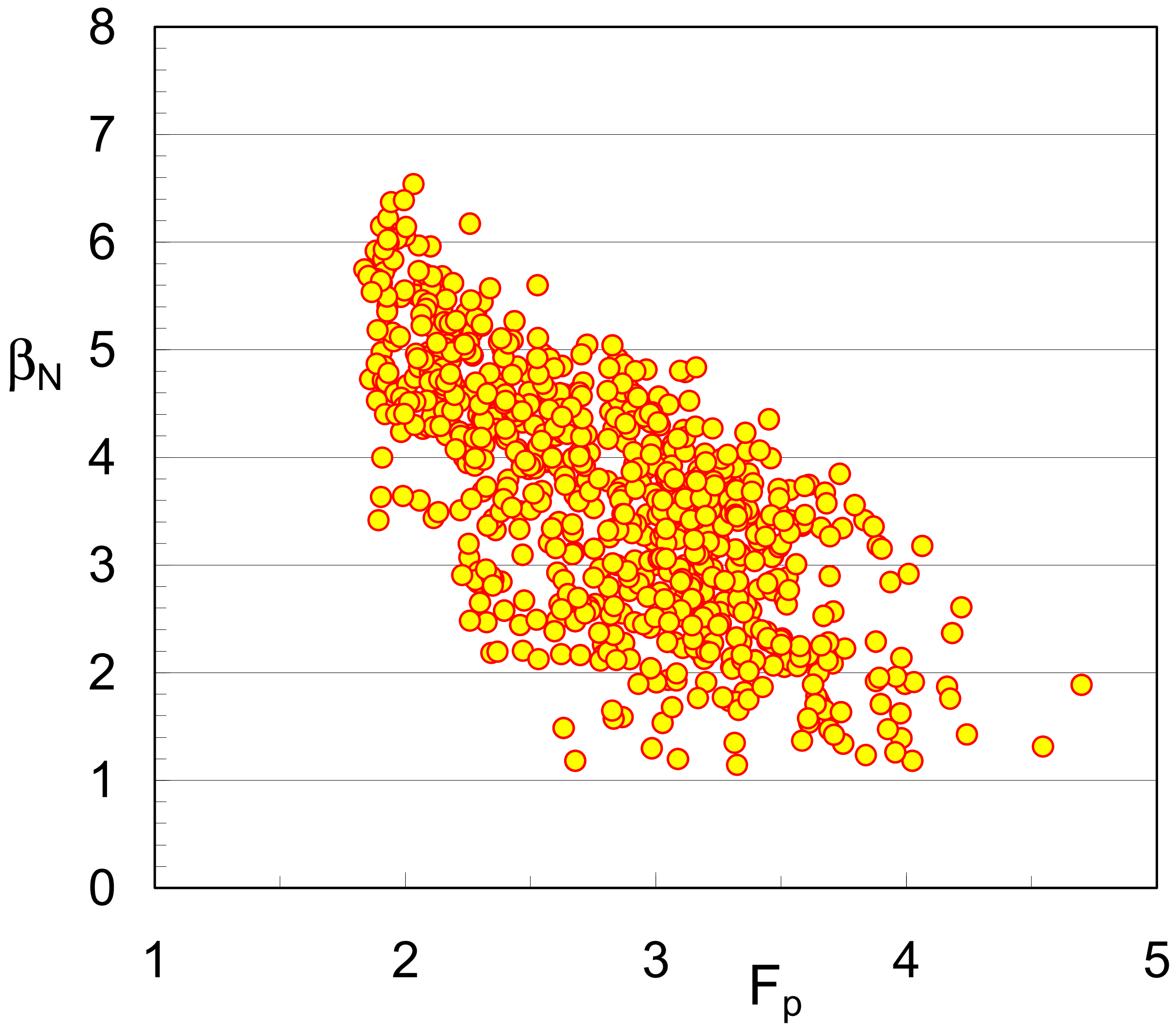
- Long term goal
  - ❑ Develop real-time predictive capability for stability; operate just below with-wall β limit

Plasma operation in low l_i, wall-stabilized space



- Normalized beta, $\beta_N = 6.5$, with $\beta_N/l_i = 9.5$; β_N up to 35% over $\beta_{N\text{ no-wall}}$
- Toroidal beta has reached 35% ($\beta_t = 2\mu_0\langle p\rangle / B_0^2$)

Maximum β_N strongly depends on pressure peaking

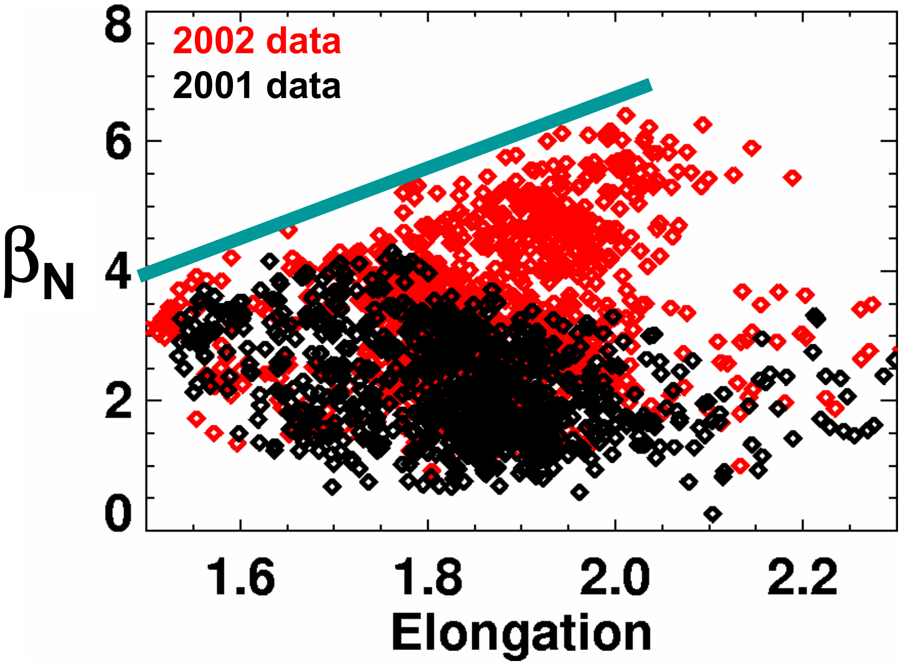


- $F_p = p(0) / \langle p \rangle$
- P profile from EFIT using P_e, diamagnetic loop, magnetics

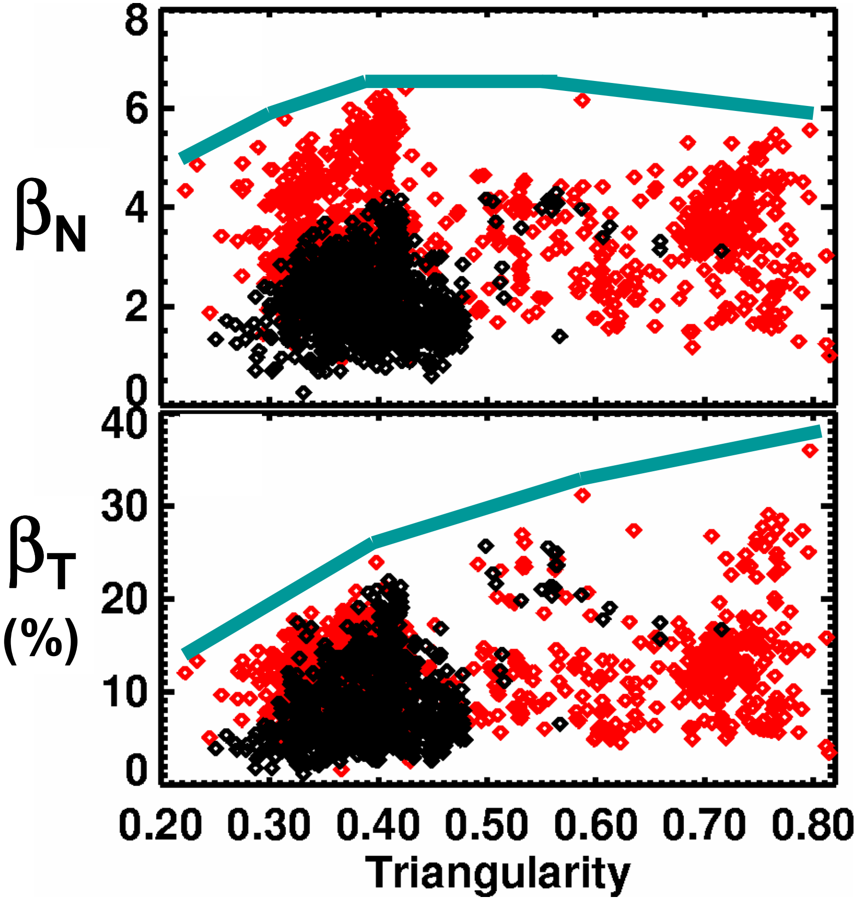
- Time-dependent calculations required to evaluate stability limits and mode structure

High β obtained with strong shaping (high κ, δ)

- β_N increases with increasing elongation
  - β_N degraded for κ > 1.8 in previous run year
- More configurations to explore!

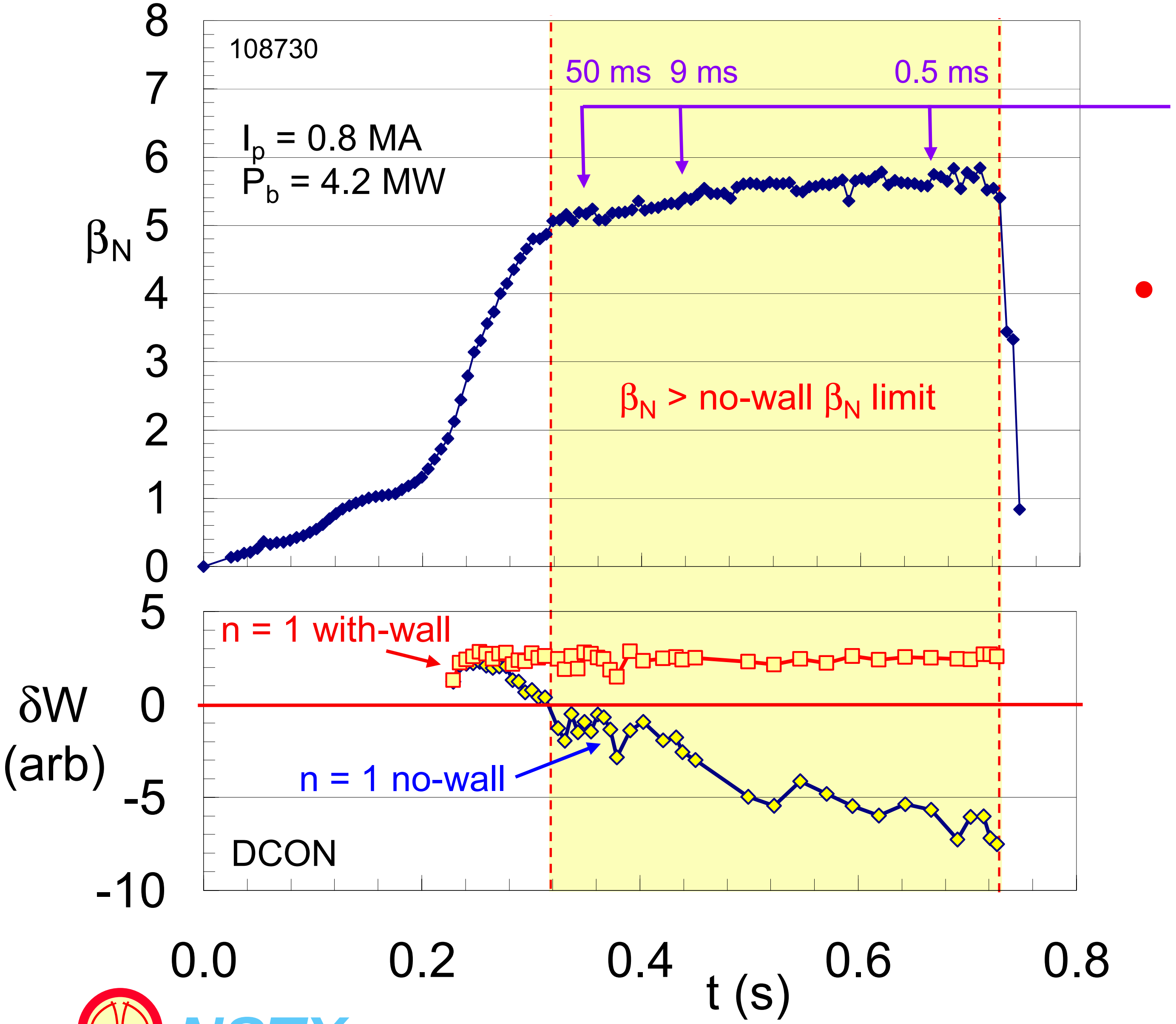


β_N weak function of δ for δ > 0.4



High δ → higher I_p/aB_{t0} & β_T

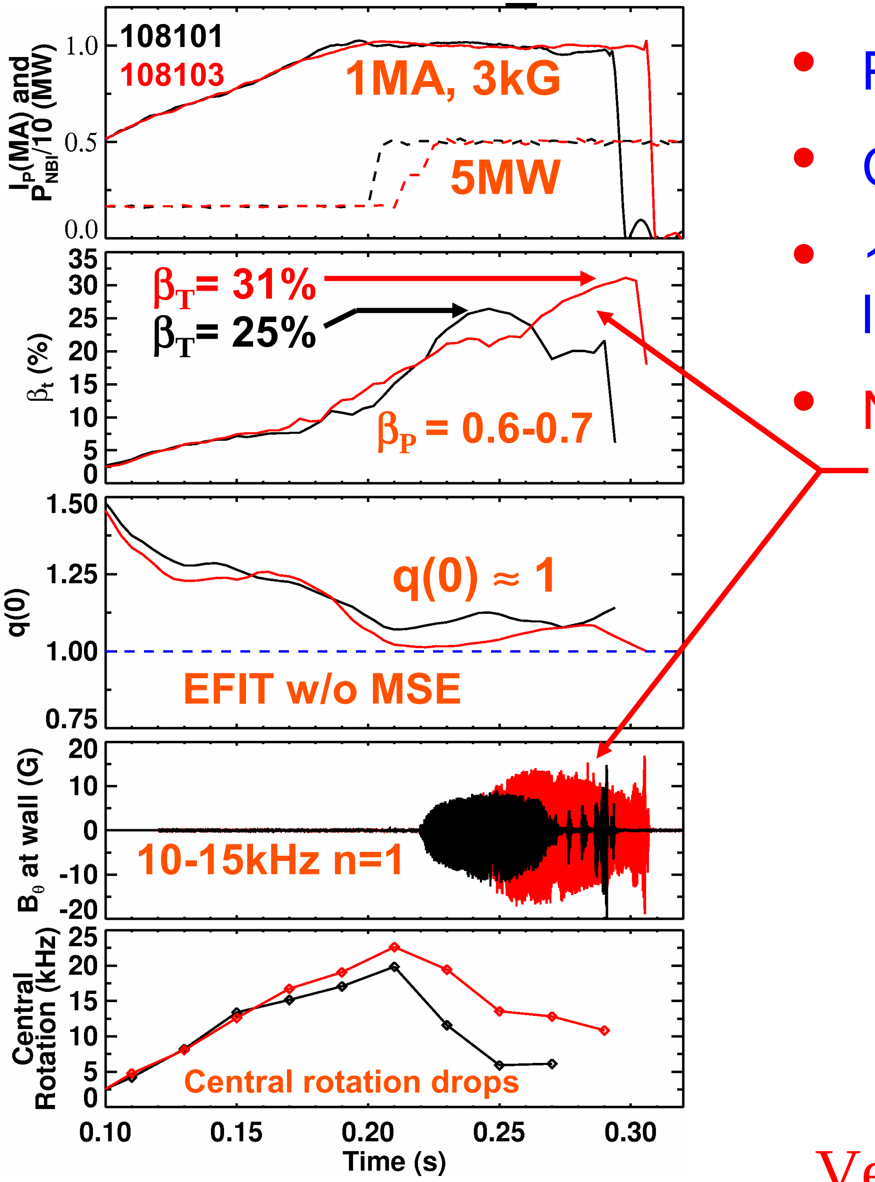
Ideal no-wall β_N limit exceeded and maintained



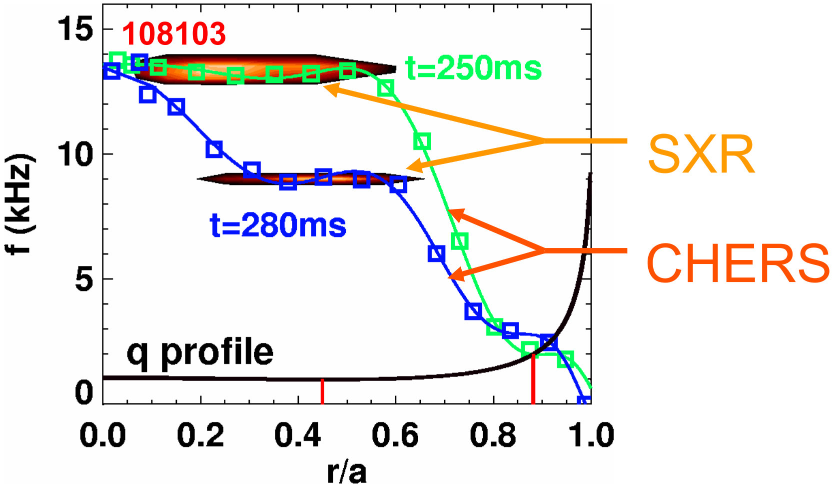
VALEN n=1 RWM growth times

- Ideal no-wall limit violated for 400 ms
  - ☐ $t_{pulse} \sim 8\ \tau_E$
  - ☐ Average of computed τ_{wall} gives pulse length > 20 τ_{wall}

Highest β_T discharges limited by 1/1 modes



- Plasmas operated at high I_p, low q_0
- Core becomes n=1 kink unstable
- 1/1 mode degrades β & rotation, slows, locks → disruption
- Neoclassical drive possible, but…
  - Modes can decay as β rises
  - **Rotation evolution may dominate:**



Very large q=1 radius → fast disruption

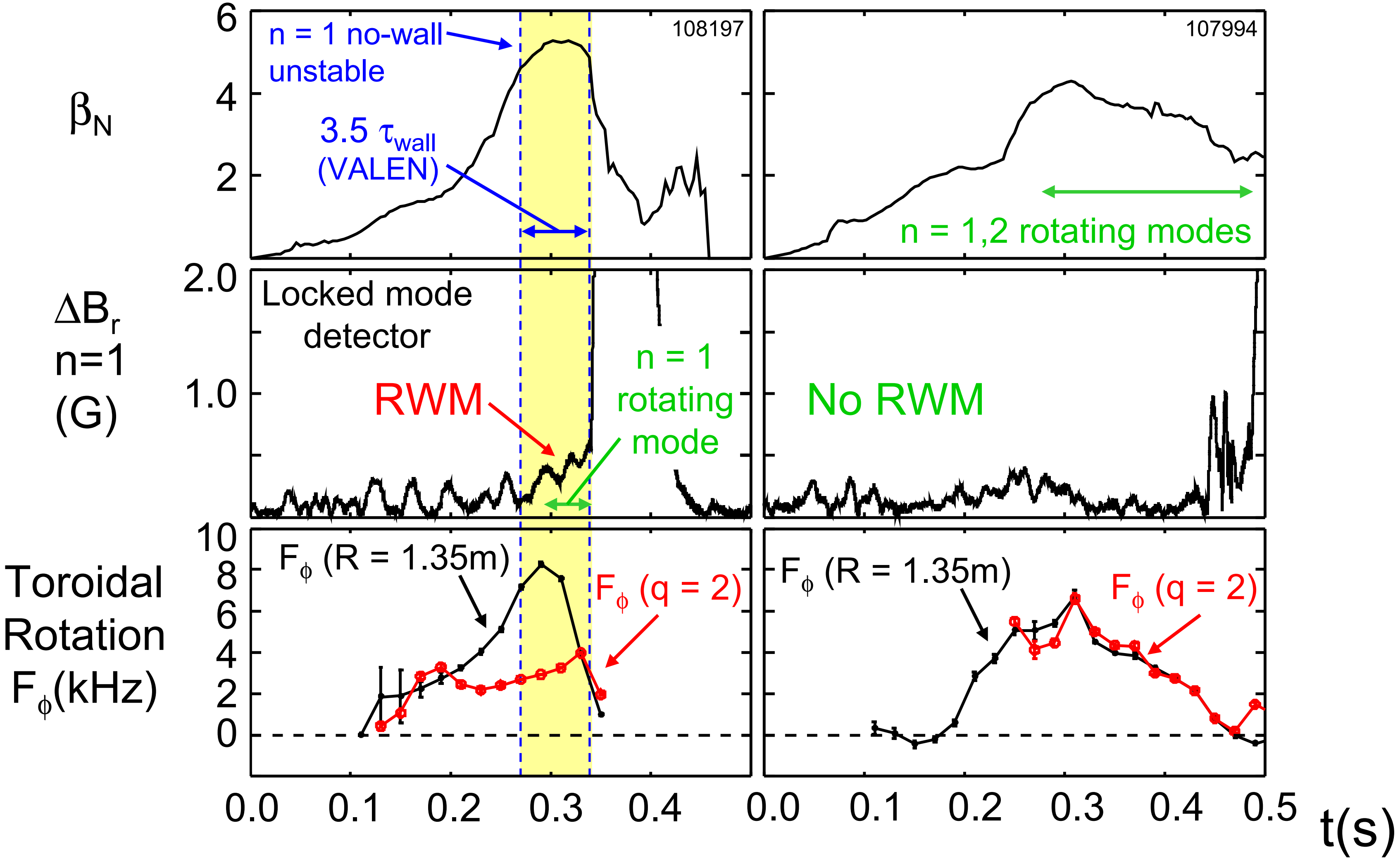
Optimizing equilibrium shape and profiles for global stability

- FY2003
  - ❑ Further optimize κ and δ in LSN and DND discharges to maximize β_T and β_N
  - ❑ Find optimum shape for highest global stability limit compatible with long-pulse
- FY2004
  - ❑ First MSE constrained reconstructions, verify elevated $q_{min} > 2$
    - Develop and assess stability for $q_{min} > 2$ plasmas if measured $q_{min} < 2$
  - ❑ Assess β_N limits as a function of controllably low internal inductance
  - ❑ Assess low-A and kinetic effects on ballooning stability
- FY2005
  - ❑ Characterize J(r) evolution, compare and benchmark code models
  - ❑ Aid in design controllers for heating and current drive actuators
- FY2006
  - ❑ MSE-constrained rtEFITs, first attempts at real-time J(r) control using HHFW, EBW

Studying passive stabilization and RWM physics in ST

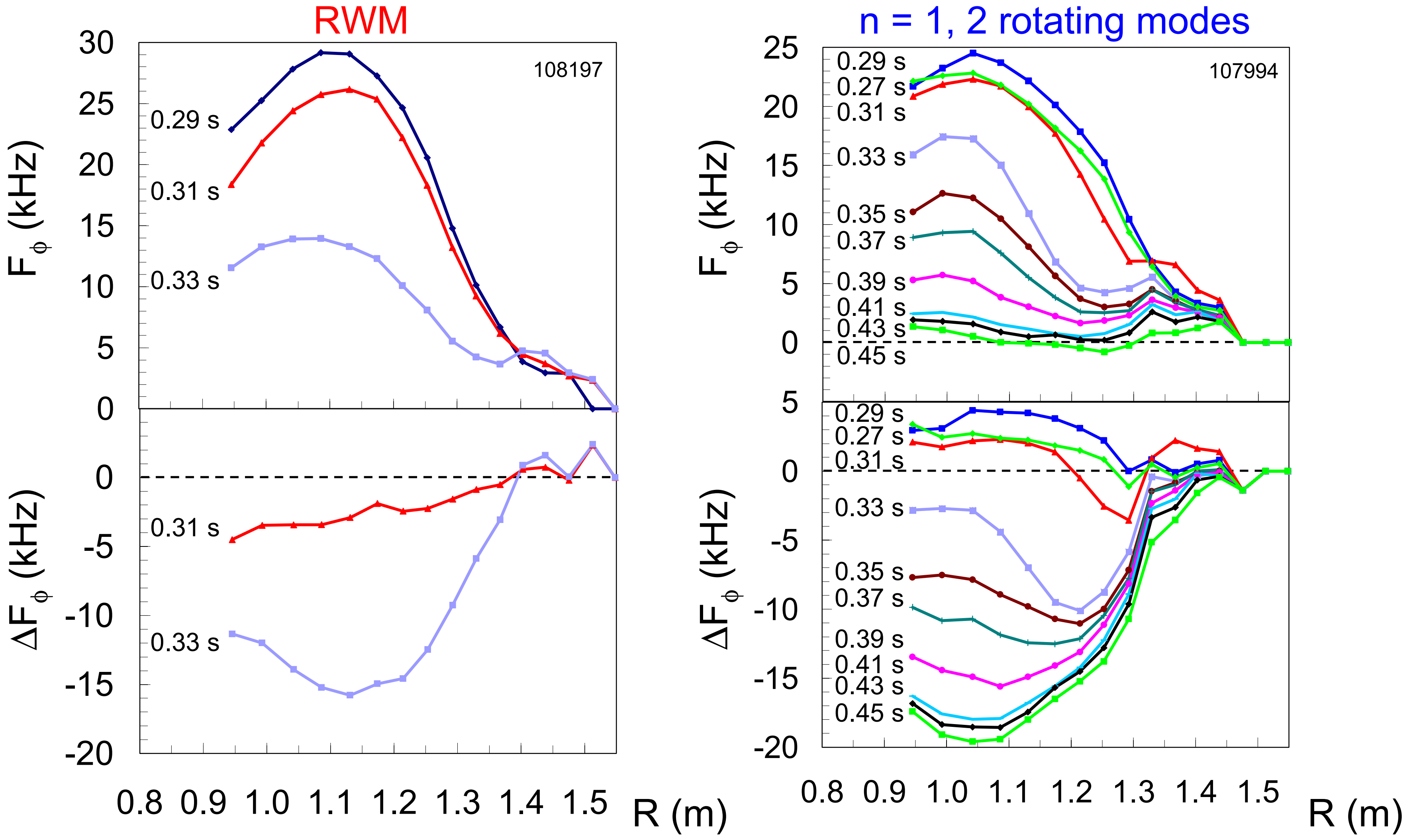
- Long term goal
  - ❑ Document RWM physics in ST, determine stability space, study/minimize rotation damping

Rotation damping rate larger when $\beta_N > \beta_{N\ \text{no-wall}}$



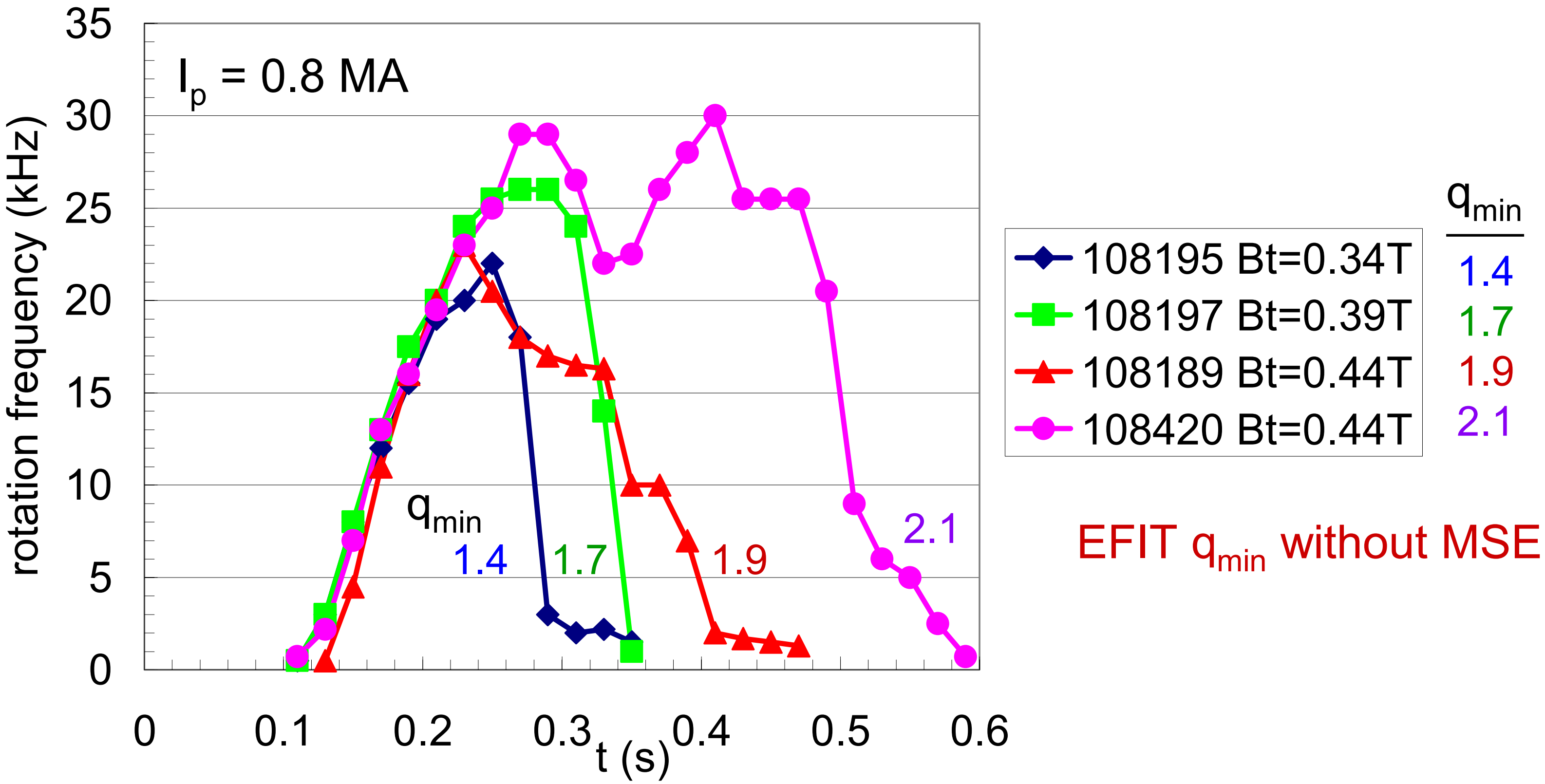
- Rotation damping rate is ~ 6 times larger when $\beta_N > \beta_{N\ \text{no-wall}}$
- RWM signal weak in CY02 experiments: improve sensors

Rotation damping during RWM is rapid and global



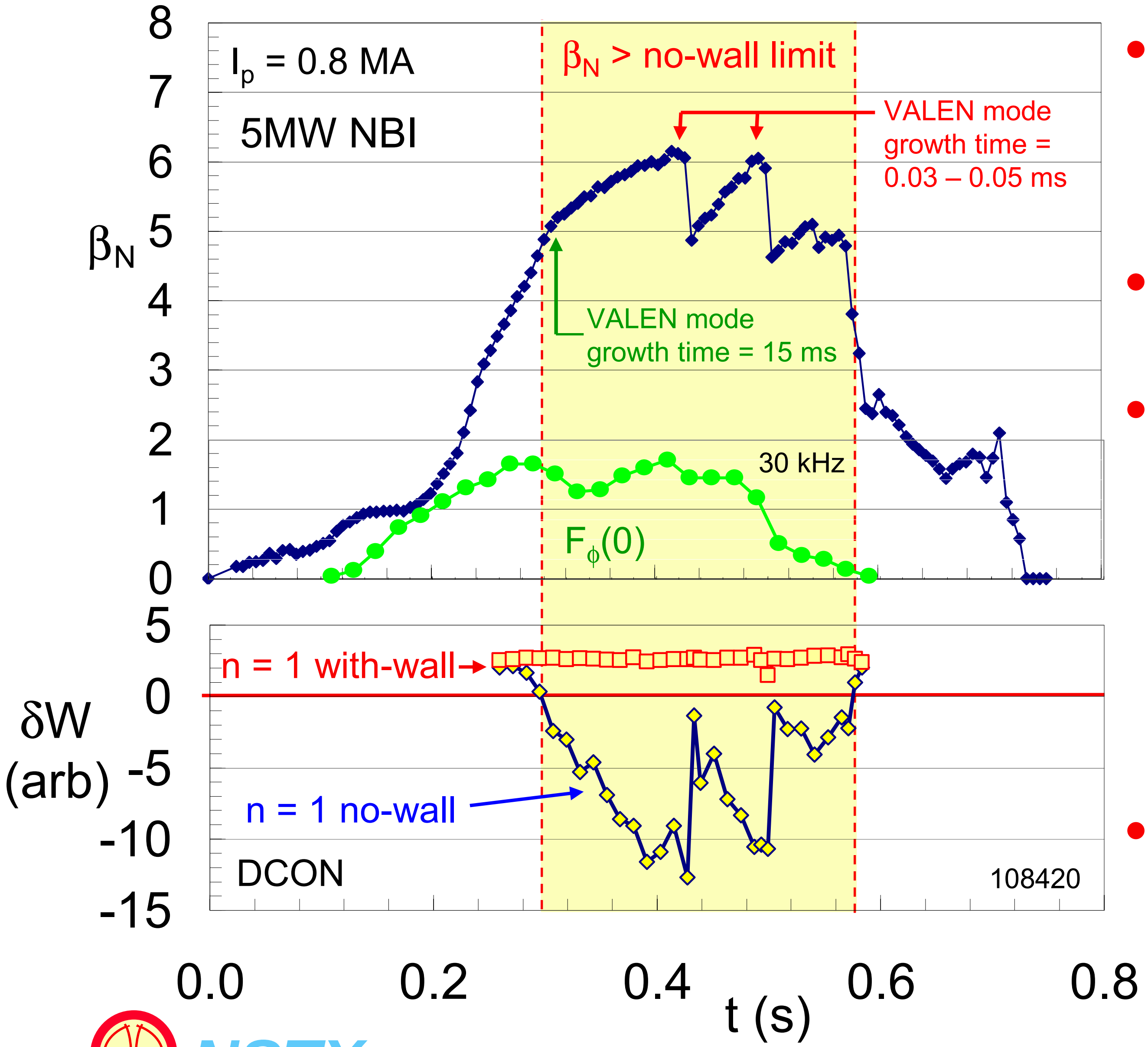
- Field ripple damping by neoclassical parallel viscosity ~ $\delta Br^2 T_i^{0.5}$ being analyzed to explain observed damping profile

Core rotation damping decreases with increasing q



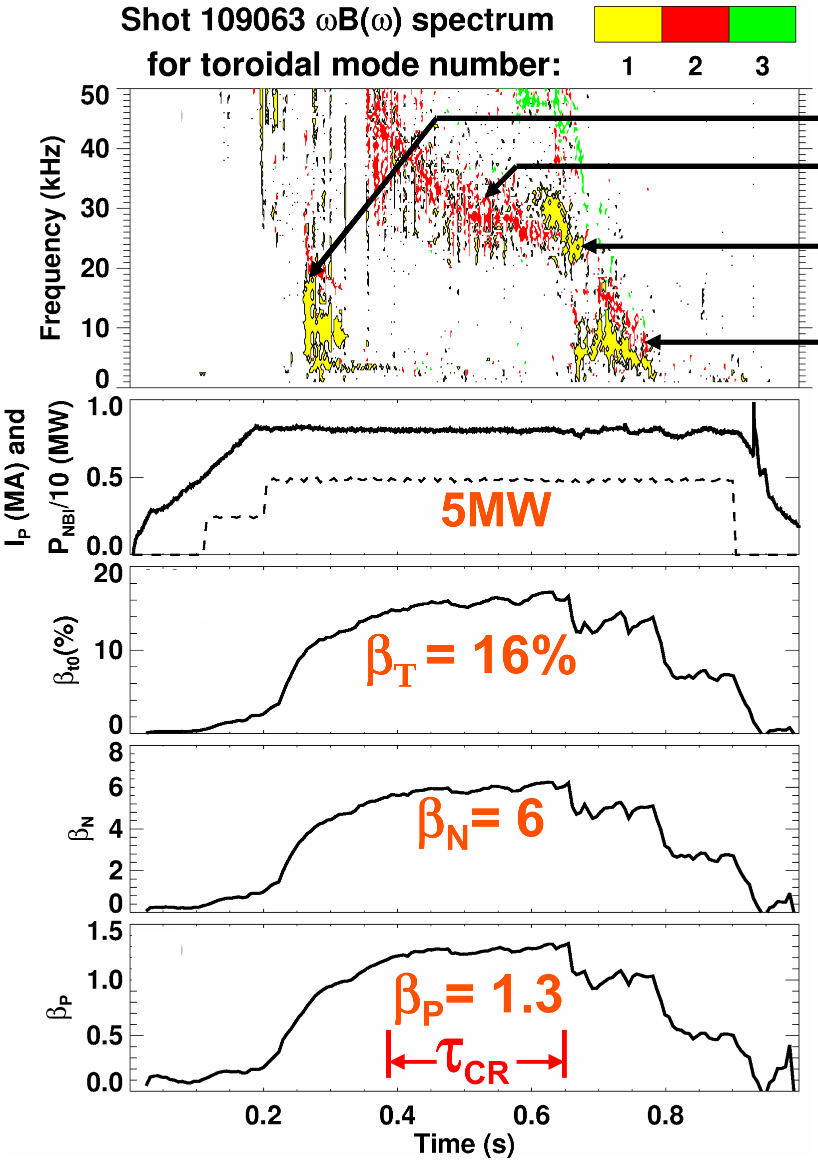
- Database shows plasmas with q_{min} > 2, have longer pulse length exceeding no-wall β_N limit
- Consistent with theory linking rotation damping to low order rational surfaces

Plasma stabilized above no-wall β_N limit for 18 τ_{wall}



- Plasma approaches with-wall β_N limit
  - VALEN growth rate becoming Alfvénic
- $F_\phi(0)$ increases as β_N >> β_N no-wall
- Passive stabilizer loses effectiveness at maximum β_N
  - Neutrons collapse with β_N - suggests internal mode
  - Larger ∇p drive, mode shape change
- TRANSP indicates higher F_p
  - Puts us further over no-wall β_N limit

MHD limiting long pulse, high β_N under active study



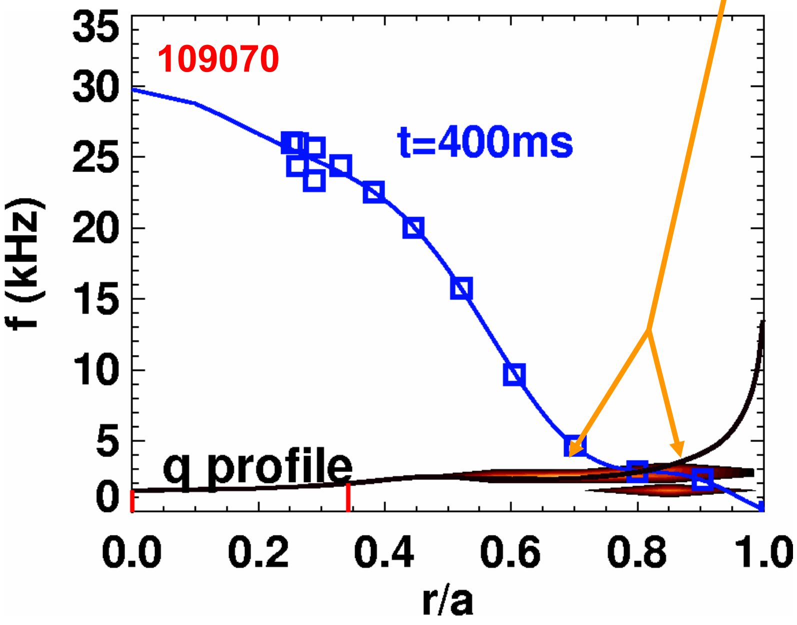
early n=1, transient at high B_T

long-lived n=2 mode in flat-top, NTM?

fast n=1 internal mode leads to β collapse

residual n=1,2 rotating modes, **NTMs?**

Prior to internal collapses,
SXR shows only edge 2/1 or 3/1



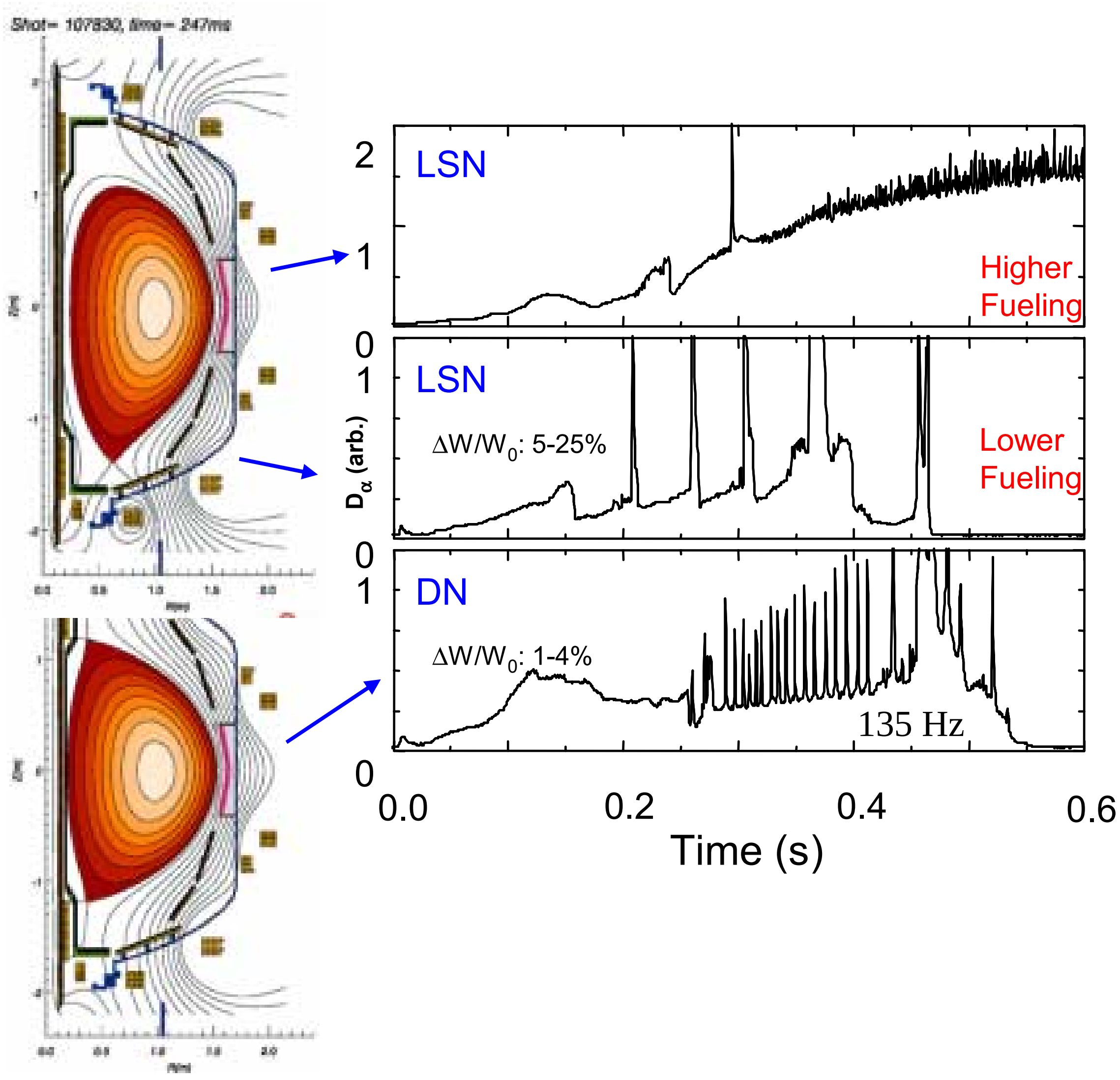
Studying passive stabilization and RWM physics in ST

- FY2003
  - ❑ Continue investigation of unstable RWMs in modifying rotation
    - Compare non-resonant vs. resonant rotation damping theories, aspect ratio dependence
  - ❑ Perform NSTX / DIII-D similarity XP to investigate aspect ratio dependence of RWM induced rotation damping, critical rotation frequency
  - ❑ Perform preliminary theoretical assessment of expected critical rotation frequency for RWM stabilization in NSTX and associated scalings with beta, q profile, shaping
- FY2004
  - ❑ Use equilibria with MSE to assess role of q in RWM stability and rotation damping
  - ❑ Compare theoretical and experimental mode structure using internal sensors
    - n=2 RWM presently computed unstable - attempt to measure it
  - ❑ Begin benchmarking stability codes against measurements in (β_N, V_ϕ space)
- FY2005-future
  - ❑ Using experimental results and comparison to theory, assess rotation required for stabilization of RWM in long-pulse high-β operating regimes.
  - ❑ Use knowledge gained to test active feedback stabilization physics in plasmas with low rotation speed and to project to future ST devices.

Determining the physics of edge localized modes at low A

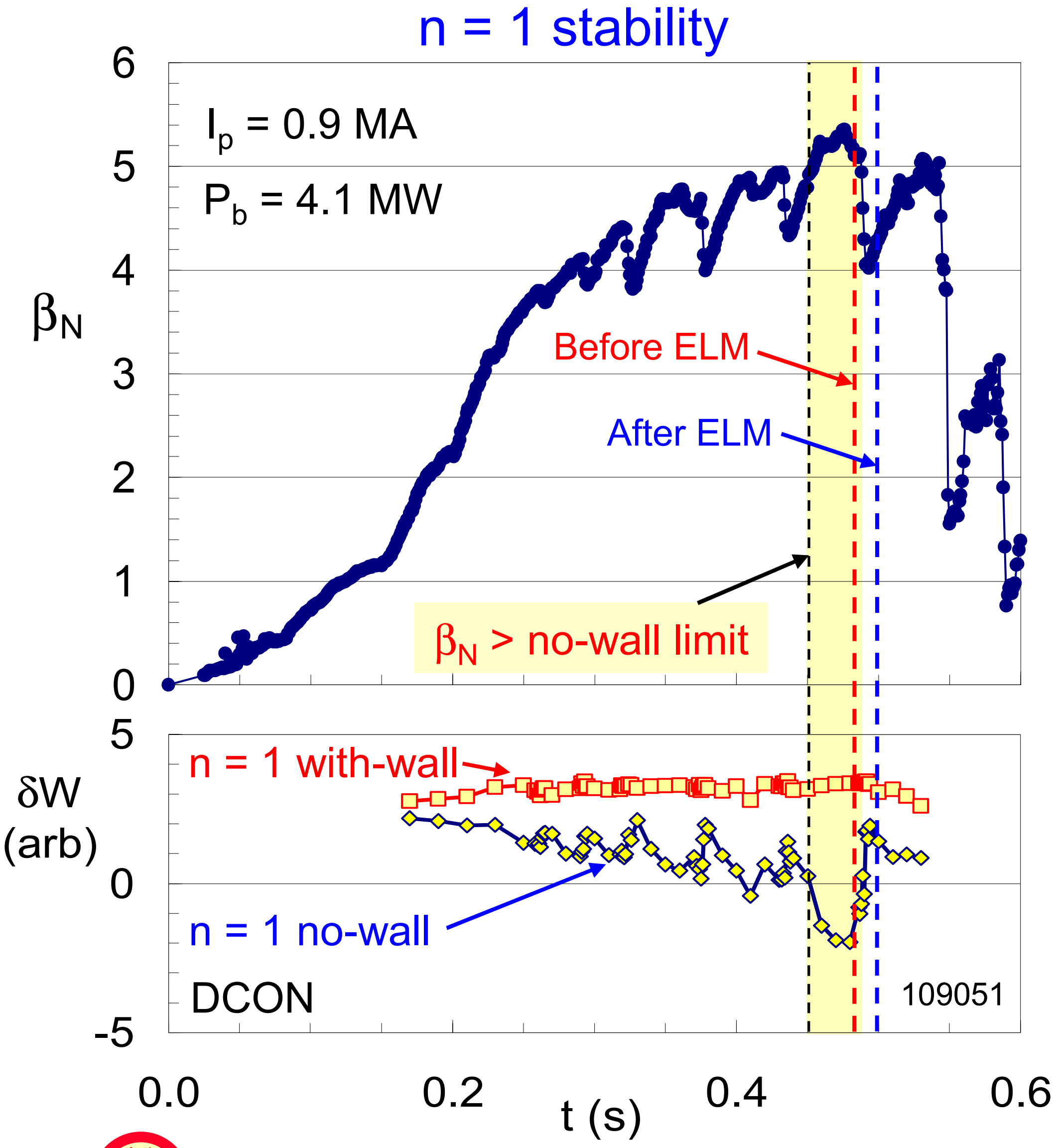
- Long term goal
  - ☐ Characterize ELMs at low aspect ratio; determine stability limits, impact on beta and edge profiles

ELM stability is sensitive to shape, fueling

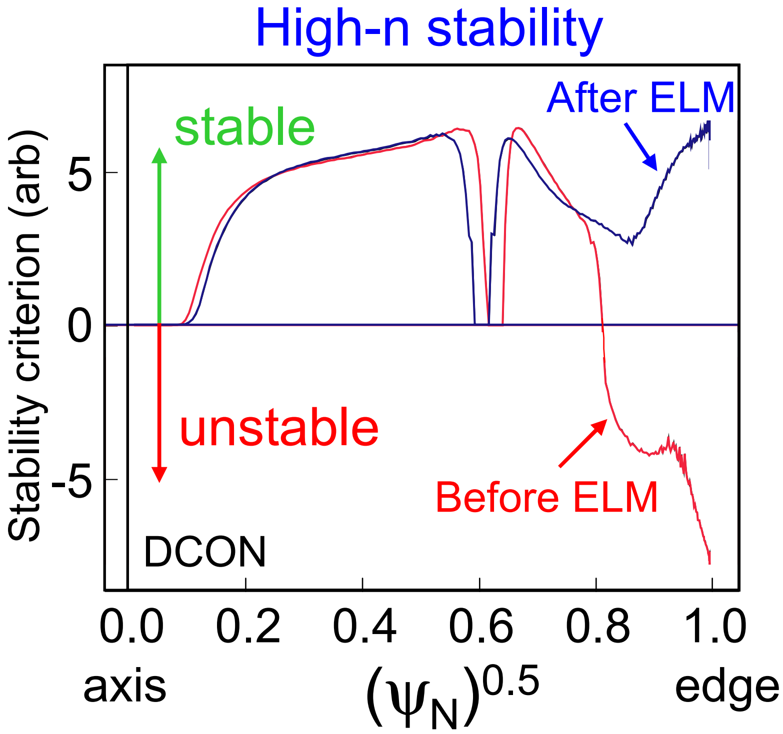


- Long pulse H-modes optimized empirically
  - LSN shaping increased while retaining small-ELM edge
- Edge density, collisionality likely impacting edge J_{BS}
- Assess ballooning stability, *n*-number, amplitude/width of ELM and compare to theory

Ideal high-n ballooning unstable before giant ELM



n = 1 stability



High-n stability

- Computed as high-n stable after ELM
- n = 1 stabilized by wall
  - ❑ No-wall β_N limit exceeded before last ELM

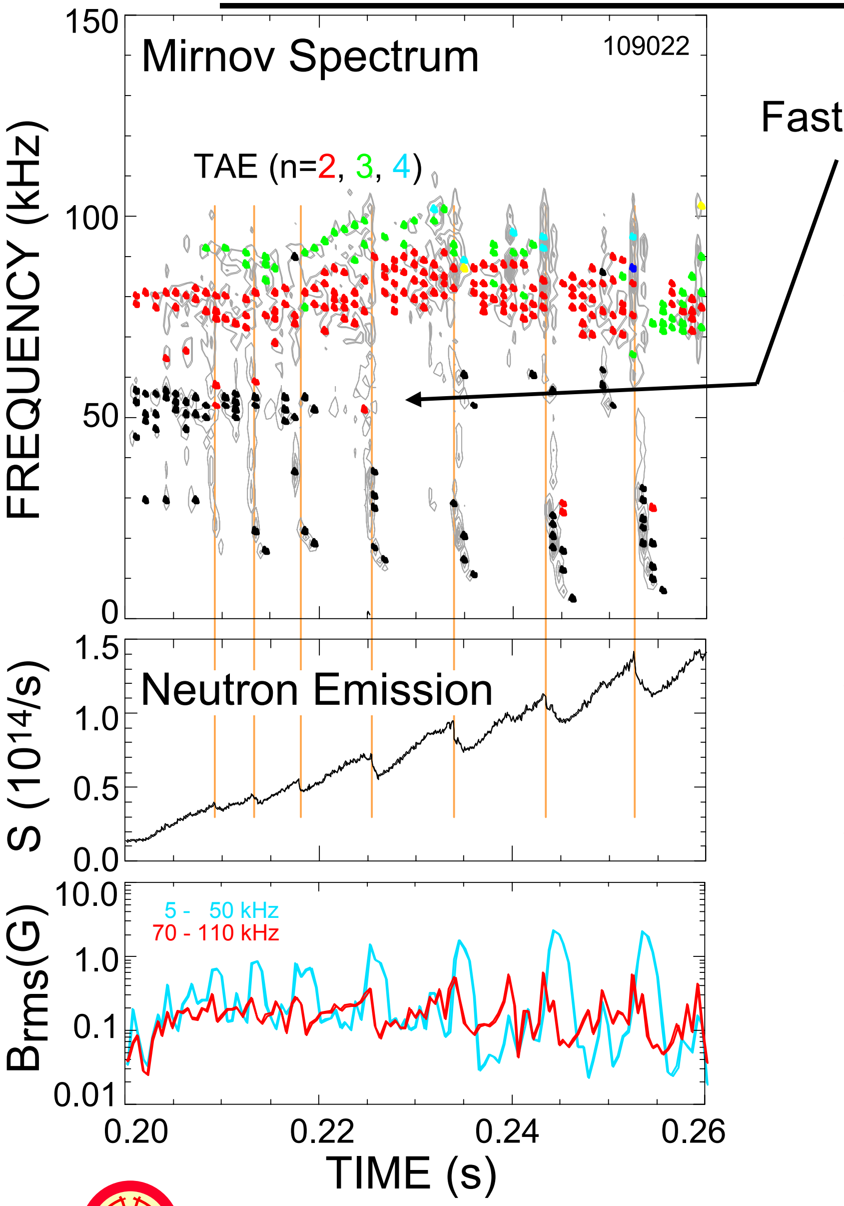
Determining physics and impact of ELMs at low A

- FY2003
  - ❑ Assess impact of divertor configuration, shaping, collisionality, and plasma-wall gap on ELM stability
  - ❑ Characterize pedestal energy loss in various ELMing regimes and secondary destabilization of NTMs and other modes due to ELMs
- FY2004
  - ❑ Commission high-n array to measure ELM toroidal mode number
  - ❑ Correlate measured mode numbers with ELM type
- FY2005
  - ❑ Use high resolution edge profile diagnostics to perform preliminary measurements of ELM structure
- FY2005-2008
  - ❑ Correlate ELM stability threshold, mode structure, and toroidal mode numbers to predictions from ELM stability codes (ELITE, DCON, PEST)
  - ❑ Using kinetic EFITs with MSE, reconstruct discharges from controlled experiments designed to excite different types of ELMs

Studying Fast ion MHD in ST Geometry

- Long Term Goal
  - ☐ Determine effect of A and q on fast ion MHD mode structure, gap structure, spectra; determine role in beta limits and fast ion loss

TAE & Fishbone can cause fast ion losses

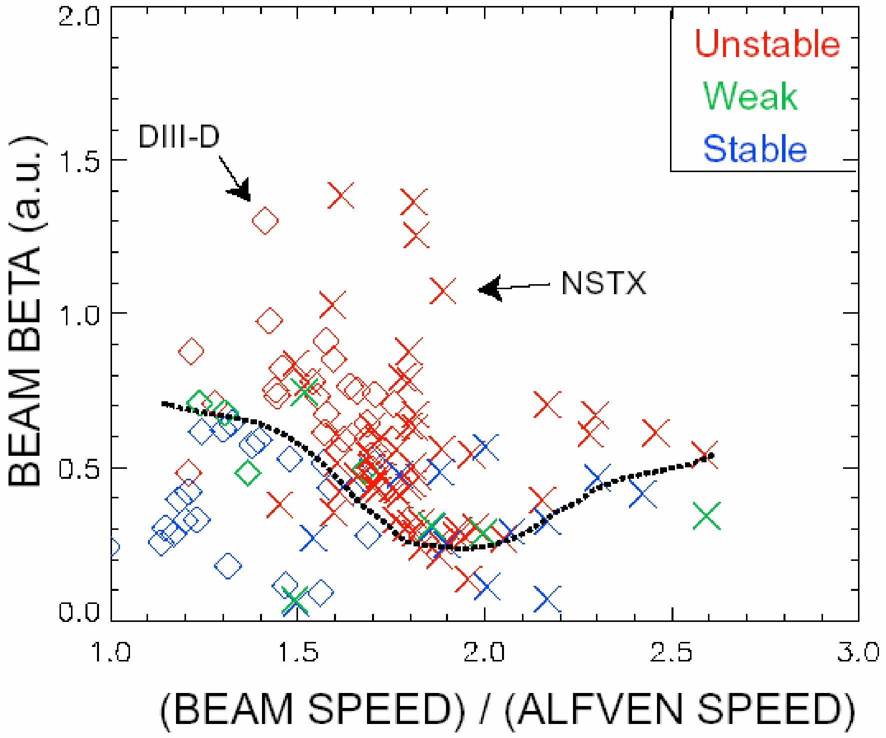


Fast ion bounce fishbone (n=1)

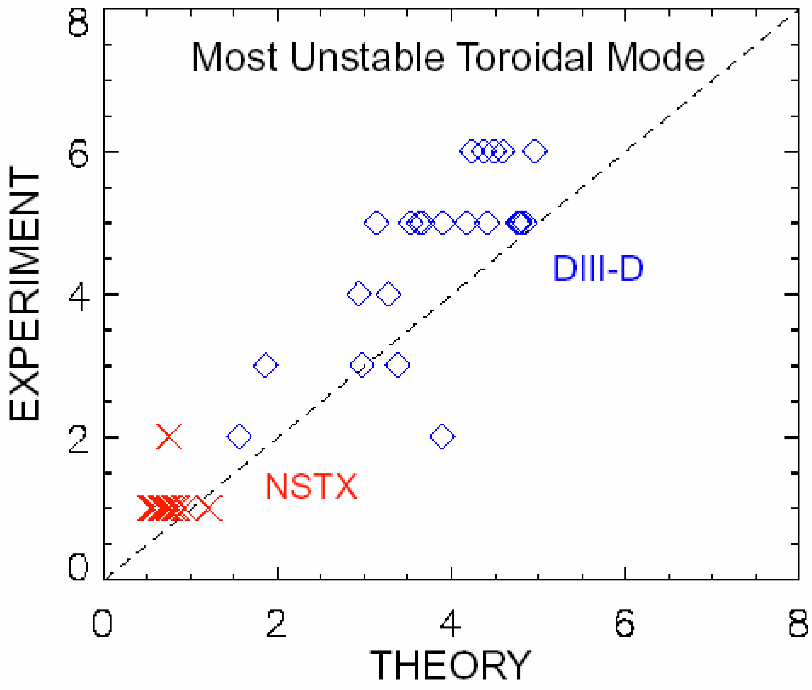
- Neutrons are beam-target; $-\delta S \propto \delta n_{fi}$
- Instabilities are TAE and fast ion bounce "fishbones"
- TAE bursts cause initial, fast drop, fishbones later, slower drop.
- Correlation of fishbone and TAE bursts suggests coupling.
- In L-mode, sometimes correlated with D_α drops.

DIII-D/NSTX TAE Similarity Experiments Conducted

Similar TAE Thresholds



TAE Mode Number Scales as Expected



- TAEs chirp routinely on NSTX, not DIII-D
  - ❑ Assess differences in gap or q shear

- Higher q at fixed B_t in NSTX yields lower mode number

Studying Fast ion MHD in ST Geometry

- FY2003
  - ❑ Assess role of fast ion-driven modes in high β_P NSTX internal disruptions
- FY2004
  - ❑ Measure CAE and TAE poloidal amplitude distribution and poloidal wavelength with full outboard poloidal Mirnov array
  - ❑ Assess role of q profile in determining gap structure for TAE modes (need MSE)
  - ❑ Quantitatively correlate fast ion losses with MHD characteristics (using FLIP)
    - Determine the energy of lost ions; infer region of distribution function driving instability
- FY2005
  - ❑ Measure internal structure of TAE, CAE, and GAE modes
    - Utilize fluctuation signatures and frequencies to distinguish modes
    - Utilize reflectometer, EBW spectrometer, or upgraded bandwidth SXR
  - ❑ Compare to theory and modeling with NOVA, HINST, and HYM (need MSE)
- FY2004-future
  - ❑ Develop beam ion profile diagnostic to determine fast ion pressure profile
  - ❑ Assess influence of fast ion MHD on fast ion population properties
    - neutron rate, power deposition, fast ion angular momentum
  - ❑ Use profile shape in ideal stability calculations, fast ion MHD instability drive

FY03 MHD XP Prioritization – NSTX Forum 9/2002

(Number of run days reallocated at MHD group meeting 12/19/02)

- MHD Experimental Presentations

❑ SOL Current during ELMS	0 days (piggyback)
❑ Stability limits at increased elongation and reduced l_i	(1-1.5 days)
❑ RWM stabilization physics at low A	(1 day)
❑ NSTX/DIII-D RWM similarity experiment	(1 day)
❑ RWM rotation damping physics	(1 day)
❑ Ohmic locked mode studies with short duration NBI	(1 day)
❑ Beta limit dependence on triangularity	(1 day)
❑ Compressional Alfven Eigenmodes	(1 day)
❑ ELM physics in NSTX	(1 day)
❑ CAE / GAE – possible similarity XP with DIII-D	(1 day)
❑ Fishbones, TAE	(1 day)
❑ Neoclassical Tearing Modes	(1 day)
❑ Resilience of low A plasmas to high-n ballooning modes	(requires MSE)

12 week run ↑

12 week run with contingency ↑

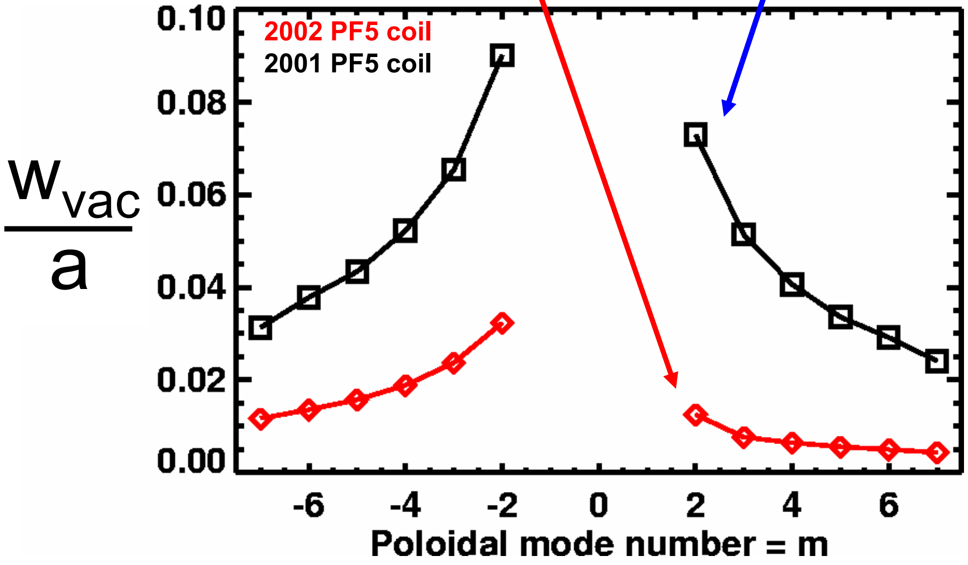
- See talk on FY-03 Run (by Stan Kaye) for greater detail

Error Fields, Locked modes, and RWM Active Feedback

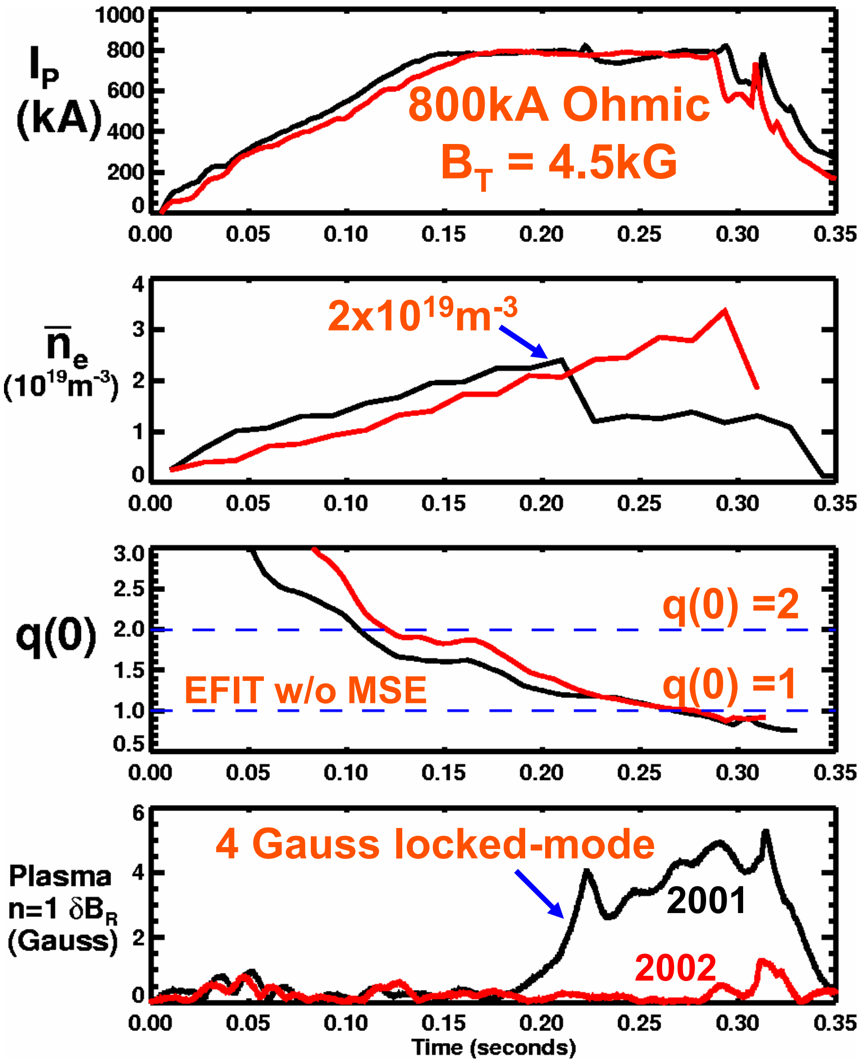
- Long range goals
  - ❑ Determine mode locking thresholds and reduce error field
  - ❑ Design and implement active feedback system for dynamic error field correction and RWM stabilization

Reduced error field has yielded reduced mode locking

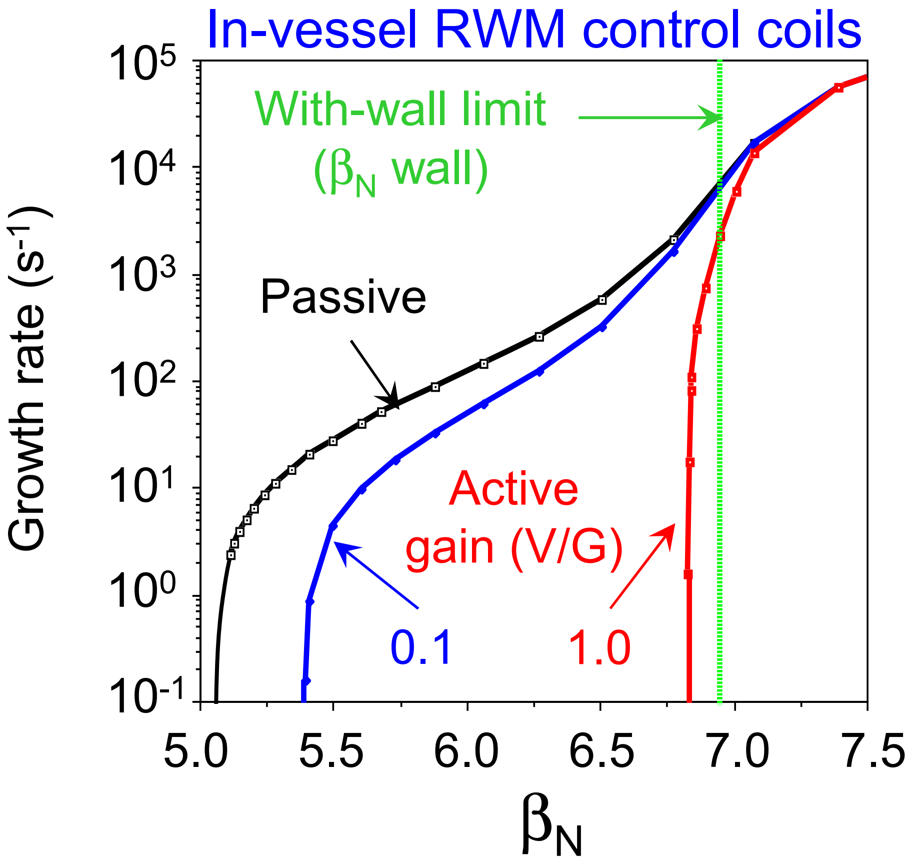
- Partially responsible for CY02 long pulse operation
- Vertical field coils found to generate large n=1 δB_r (CY01)
  - Coils subsequently re-shaped
- Vacuum island widths now ***reduced to < 1cm*** (from 5cm)

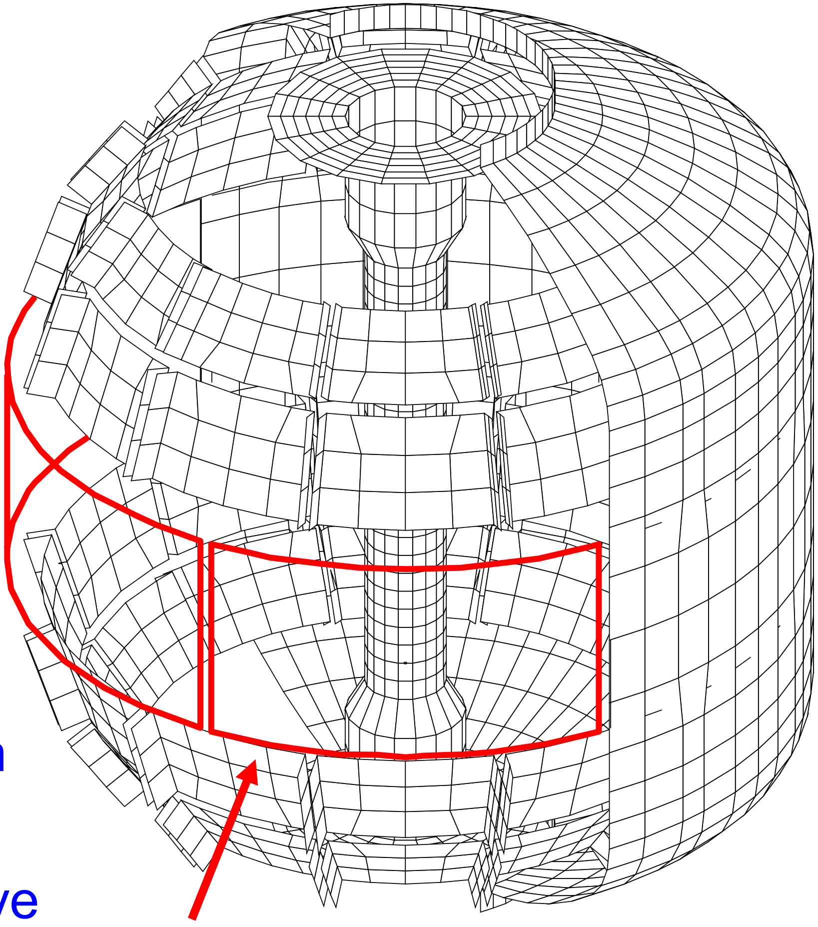


(NSTX operates with m > 0 resonant)



Active control might sustain 94% of with-wall β limit

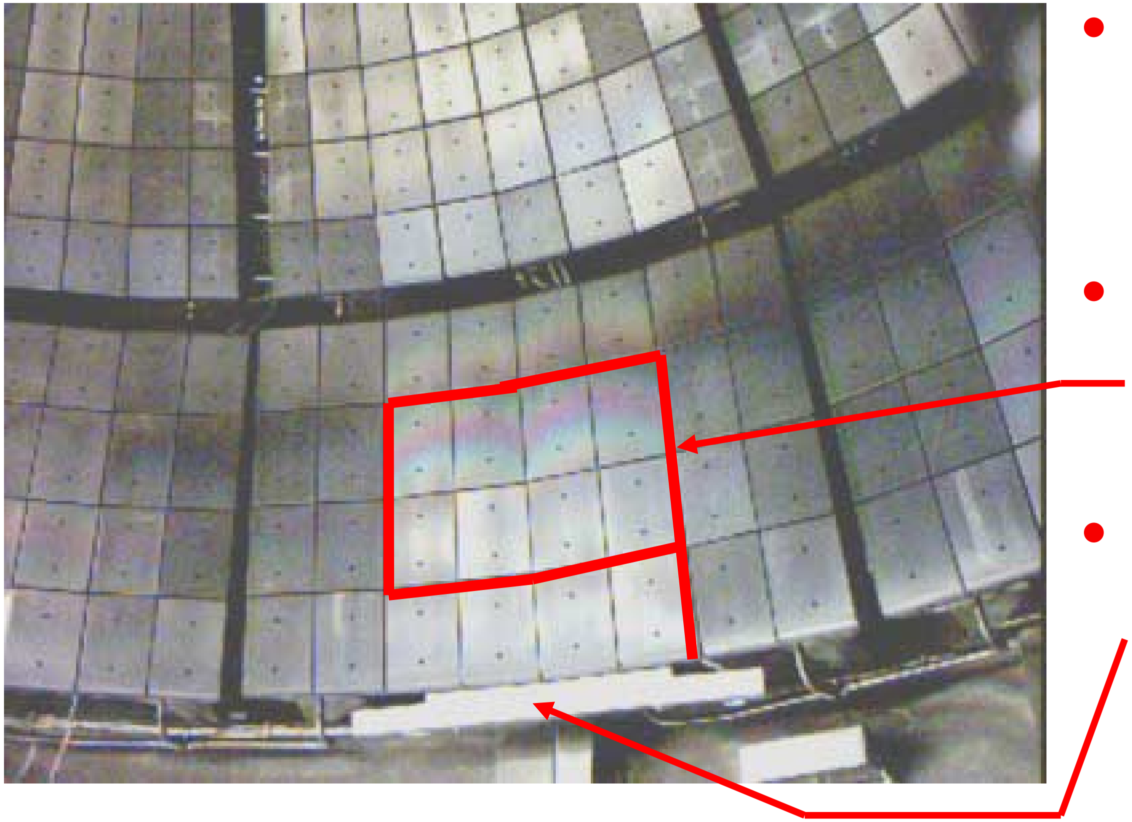

In-vessel RWM control coils


VALEN model of NSTX
(cutaway view)

Modeled active feedback coils

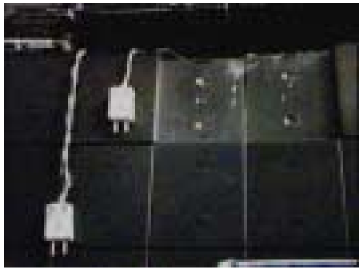
- System with ex-vessel control coils can reach 72% of $\beta_{N\ wall}$
- System with control coils among passive plates can only reach 50% of $\beta_{N\ wall}$

New internal magnetic field sensors installed to study locked modes and RWMs



- Full toroidal coverage
  - 24 $B_\perp$ and 24 B_P
    - Each 12 above, 12 below
- $B_\perp$ measured by single turn loop
  - Embedded in tiles
- B_P measured at ends of primary plates
  - Glass insulated Cu wire wound on macor forms
  - SS304 shields

Thermocouple connectors allow easy installation and upgrade potential (PnP)



- Internal ➔ more sensitive
- Use as sensors for future active feedback system

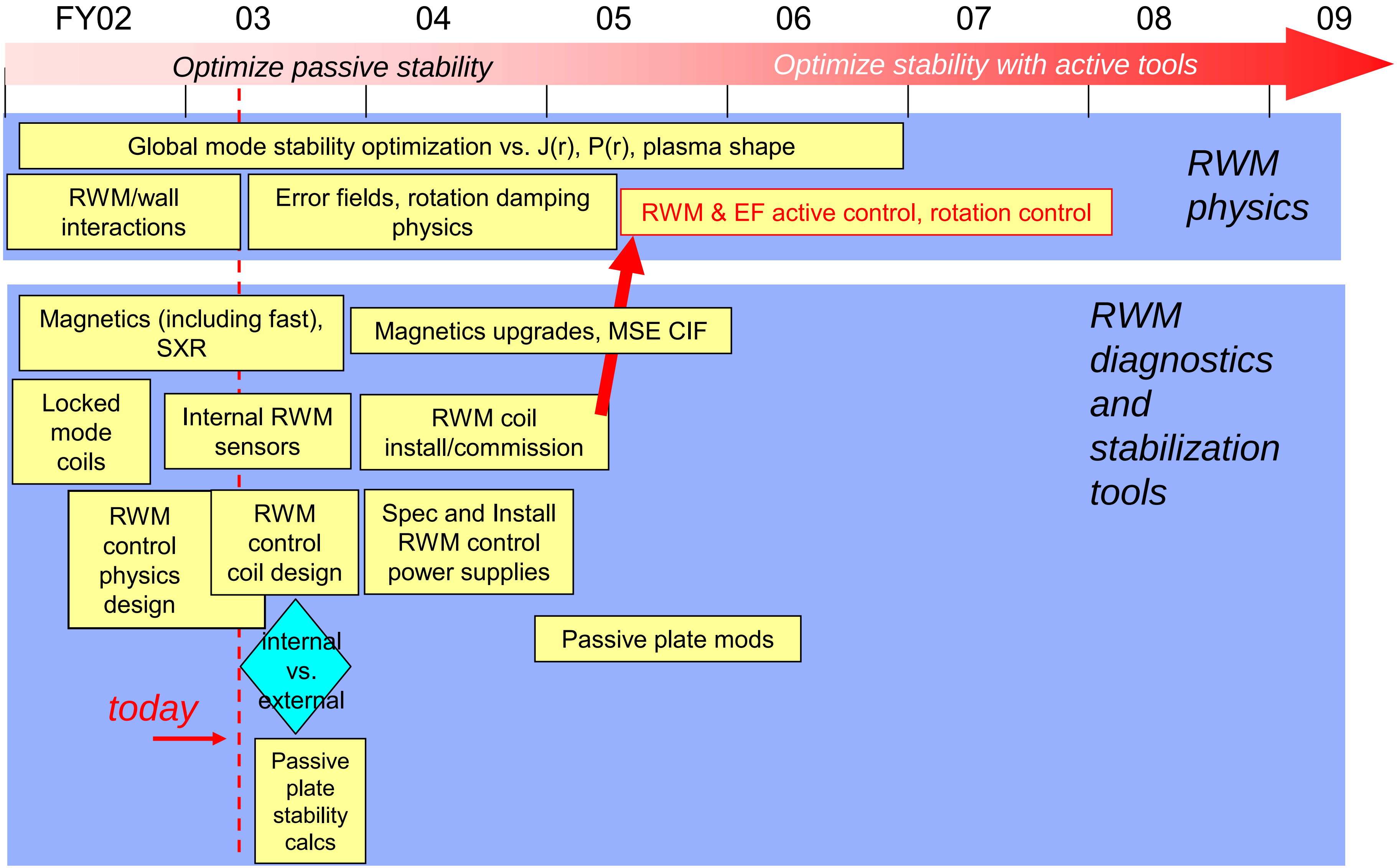
Diagnosing dynamic error fields / locked modes

- FY2003
  - Commission internal RWM/EF sensor array electronics
  - Calibrate sensors including effects of non-axisymmetric positions
  - Asses sources of residual error field such as PF coils, PF coil leads, and passive plate eddy currents
  - Perform experiments using low density locked modes and beam pulses to determine locking threshold vs. density, rotation, and proximity to no-wall limit
  - Use locking position to aid inference of error field sources
- FY2004
  - Correct error fields directly where possible through re-alignment
  - Include findings in RWM active feedback system requirements

Implementing and evaluating active feedback for global MHD

- FY2003
  - Finalize physics design of active coil sets using DCON+VALEN analysis
  - Decide on either internal or external coil set, and begin engineering design
  - Initiate procurement of power supplies
    - Simultaneously correct error fields and provide fast feedback for RWM control.
- FY2004
  - Procure, install, and commission active coil set and active coil supplies
  - Purchase and install DAQ for PCS
- FY2005
  - Complete interface of supply controls to PCS
  - First use of active feedback on RWM and EF, algorithm optimization
- FY2006
  - Develop feedback algorithms to stabilize the RWM up to the ideal-wall limit
  - Maintain high β plasmas with plasma rotation below the critical rotation frequency
    - Flow damping from non-resonant error field excitation using active coils and/or controlled error field amplification of the RWM are possible means
  - Use non-resonant error fields to modify NTM island formation
- FY2007-future
  - Utilize RWM/EF feedback to operate close to ideal-wall limit in optimized long-pulse discharges
  - Assess long-pulse impact of stochastic divertor boundary on edge profiles and divertor heat flux

RWM stabilization research follows a logical timeline



FY02 03 04 05 06 07 08 09

Optimize passive stability

Optimize stability with active tools

RWM physics

Global mode stability optimization vs. J(r), P(r), plasma shape

RWM/wall interactions

Error fields, rotation damping physics

RWM & EF active control, rotation control

RWM diagnostics and stabilization tools

Magnetics (including fast), SXR

Magnetics upgrades, MSE CIF

Locked mode coils

Internal RWM sensors

RWM coil install/commission

RWM control physics design

RWM control coil design

Spec and Install RWM control power supplies

internal vs. external

Passive plate mods

today

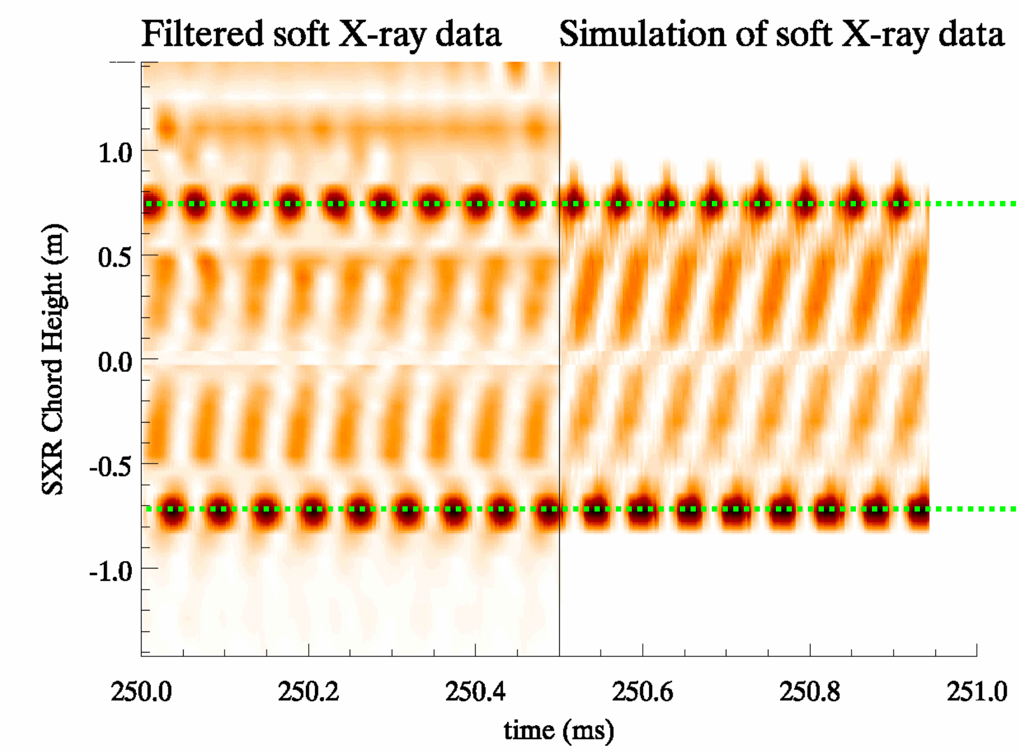
Passive plate stability calcs

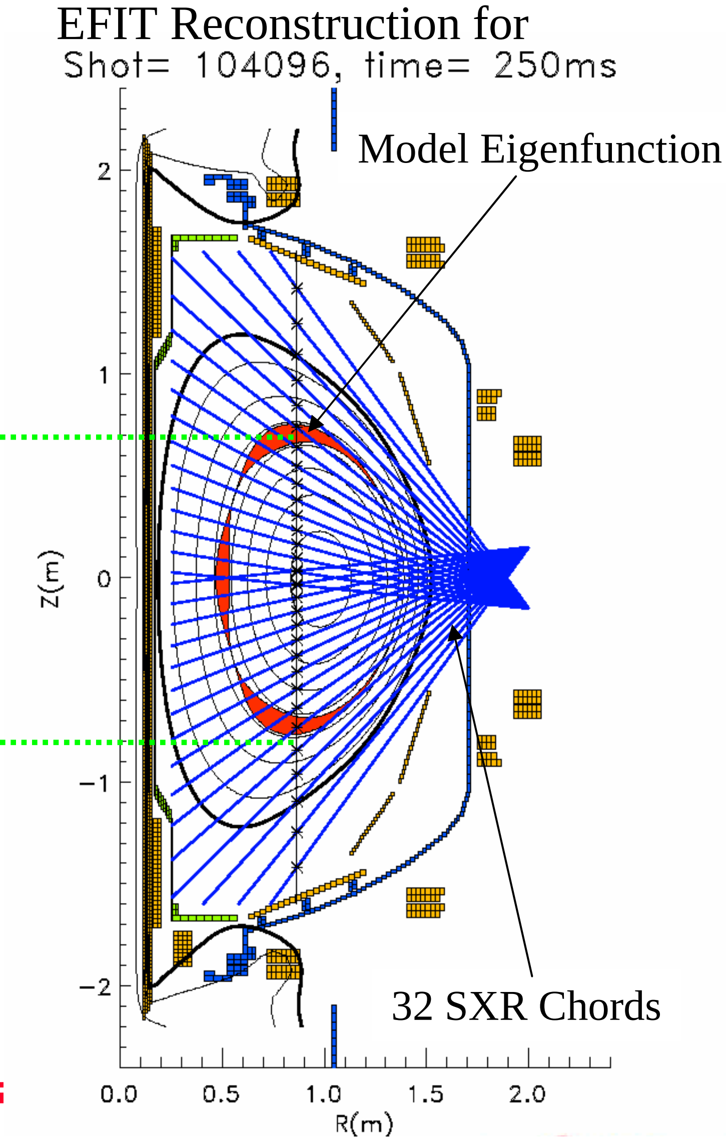
Stabilization of neoclassical tearing modes in long pulse plasmas

- Long term goal
  - Study NTM physics at low A and demonstrate direct NTM suppression in long-pulse plasmas

3/2 NTMs often observed in FY2001

- Simulated eigenfunction, modeled growth rate agrees
  - SXR data indicates odd-parity mode with inversion radius at 3/2 mode rational surface from EFIT
- β_p limit increased from 0.5 to 1.5 in 2002
  - NTM still may be a problem at long-pulse

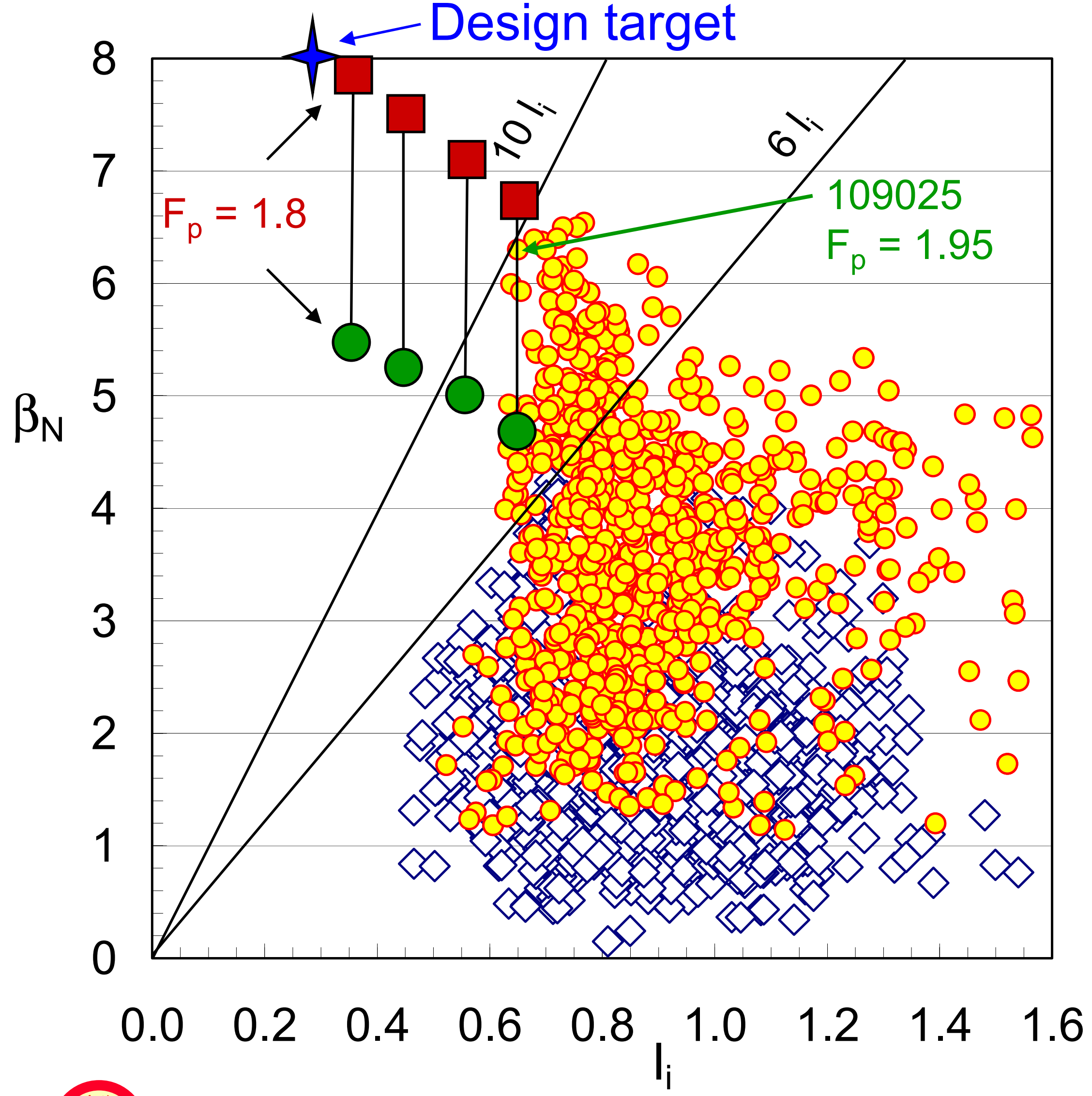




Stabilization of neoclassical tearing modes in long pulse plasmas

- FY2003
  - Prepare codes to routinely assess mode stability once MSE q profile is available
  - Implement more accurate wall shape model for wall-stabilized TM stability studies, begin implementation of simulated Mirnov sensor responses
- FY2004
  - Measure poloidal mode numbers using new poloidal Mirnov array
  - Assess NTM seeding mechanisms and investigate non-linear coupling of different helicities
  - Work with MAST NTM experts on NTM similarity experiments
- FY2005
  - Correlate magnetically inferred *m/n* data to island position from SXR and possibly EBW
  - Determine mode excitiation via proximity to an ideal limit or direct seeding from other MHD modes
  - Infer island widths from measurements; improve modeling to assess CD needs for EBW CD feedback
- FY2006
  - Perform assessment of changes in NTM stability due to changes in current profile resulting from EBW
  - Assess EBW power requirements for NTM stabilization based on initial measurements of CD efficiency and required CD for mode stabilization
- FY2007 - 08
  - Demonstrate direct NTM suppression with pre-programmed control of launcher and plasma conditions
  - Verify CD requirements with island suppression measurements and NTM stabilization modeling
  - Incorporate EBW launcher control into PCS and demonstrate first active feedback NTM suppression

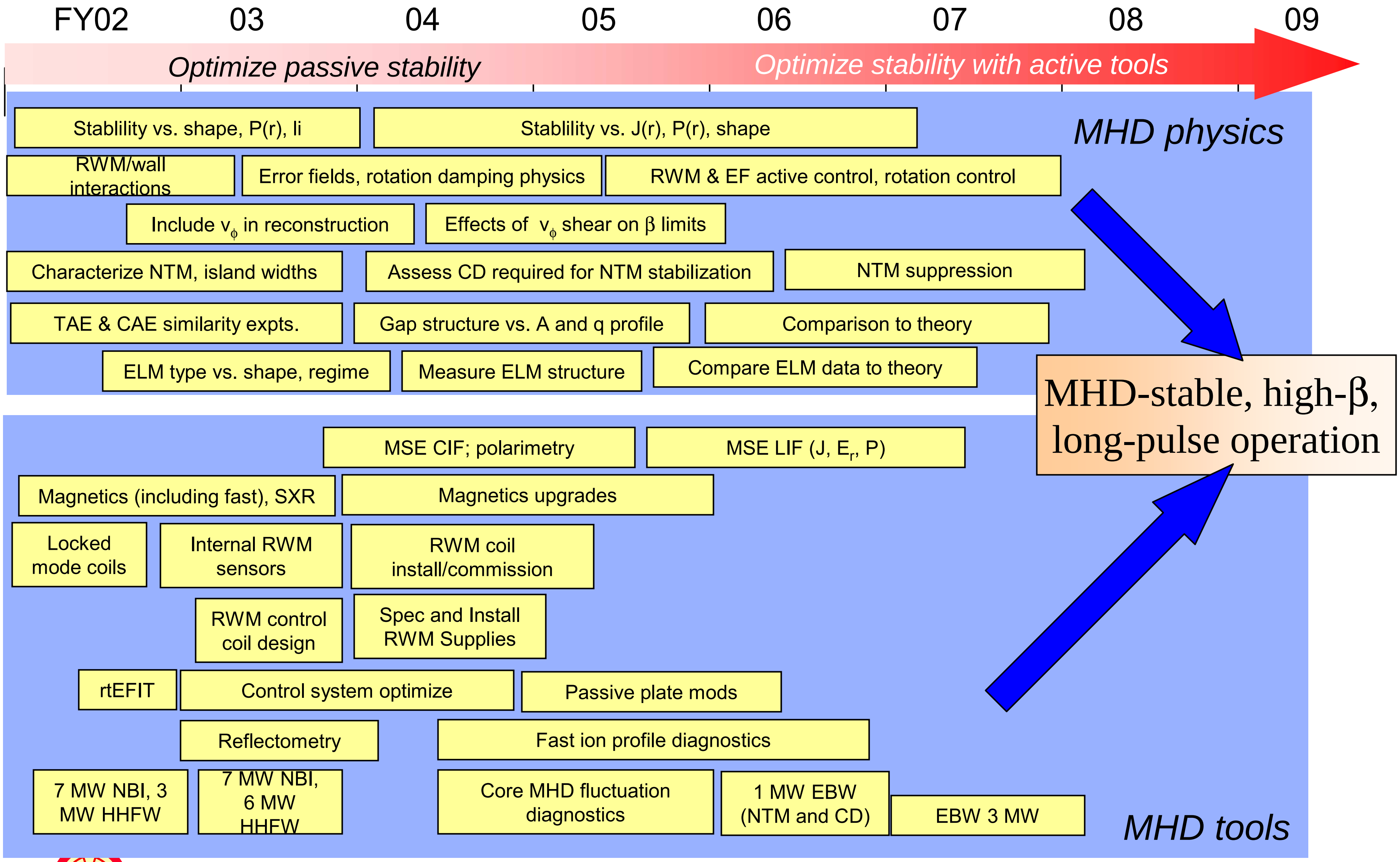
Access to β_N = 8 conceptual design target exists



- 🟥 With-wall β limit
- ● No-wall β limit

- Pressure peaking factor close to existing EFIT experimental reconstructed value
- Need to maintain elevated q_{min} as I_p is increased

Summary: Detailed MHD Plan aims for science understanding yielding long pulse, high β, controlled ST plasma operation



FY02 03 04 05 06 07 08 09

Optimize passive stability

Optimize stability with active tools

MHD physics

Stablility vs. shape, P(r), li

Stablility vs. J(r), P(r), shape

RWM/wall interactions

Error fields, rotation damping physics

RWM & EF active control, rotation control

Include v_ϕ in reconstruction

Effects of v_ϕ shear on β limits

Characterize NTM, island widths

Assess CD required for NTM stabilization

NTM suppression

TAE & CAE similarity expts.

Gap structure vs. A and q profile

Comparison to theory

ELM type vs. shape, regime

Measure ELM structure

Compare ELM data to theory

MHD-stable, high-β, long-pulse operation

MSE CIF; polarimetry

MSE LIF (J, E_r, P)

Magnetics (including fast), SXR

Magnetics upgrades

Locked mode coils

Internal RWM sensors

RWM coil install/commission

RWM control coil design

Spec and Install RWM Supplies

rtEFIT

Control system optimize

Passive plate mods

Reflectometry

Fast ion profile diagnostics

7 MW NBI, 3 MW HHFW

7 MW NBI, 6 MW HHFW

Core MHD fluctuation diagnostics

1 MW EBW (NTM and CD)

EBW 3 MW

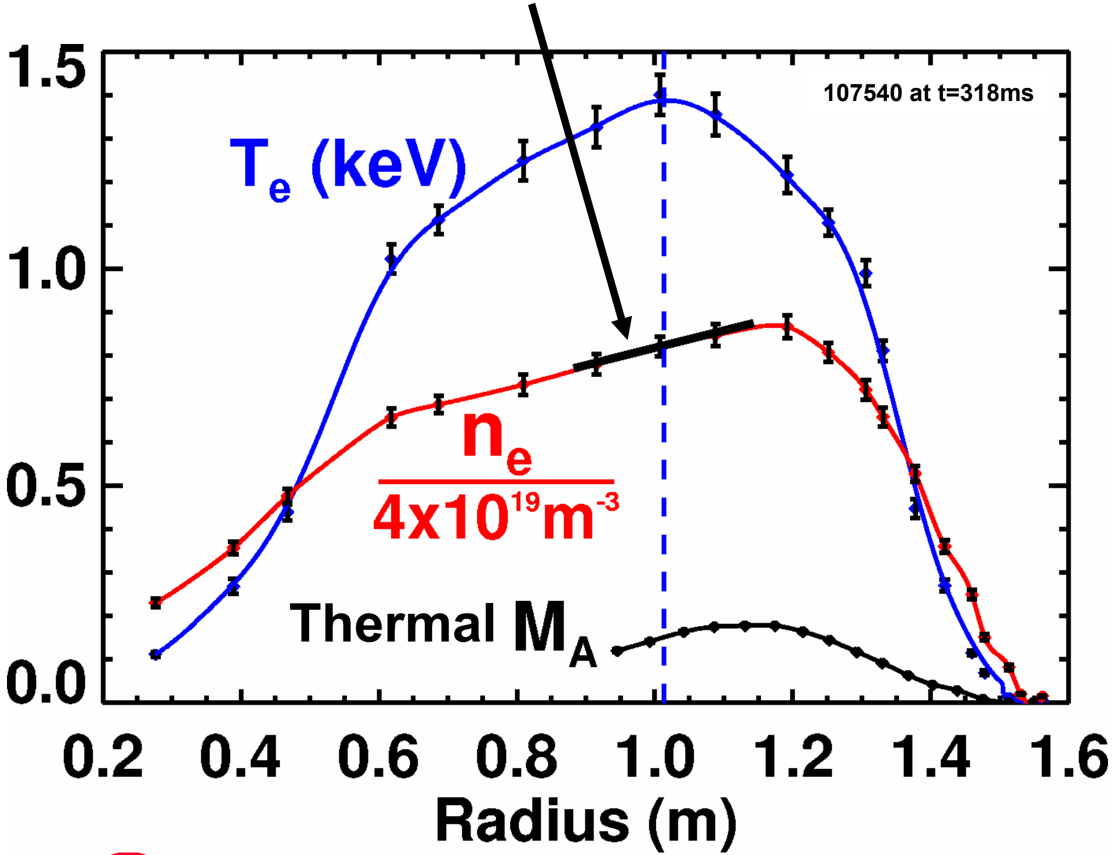
MHD tools

Supporting MHD Physics Slides Follow

Fast rotation can modify equilibrium, stability

- Local thermal $M_A \equiv v_\phi / v_A$ as high as 0.3
  - ⇒ Maximum density at $R > R_{axis}$

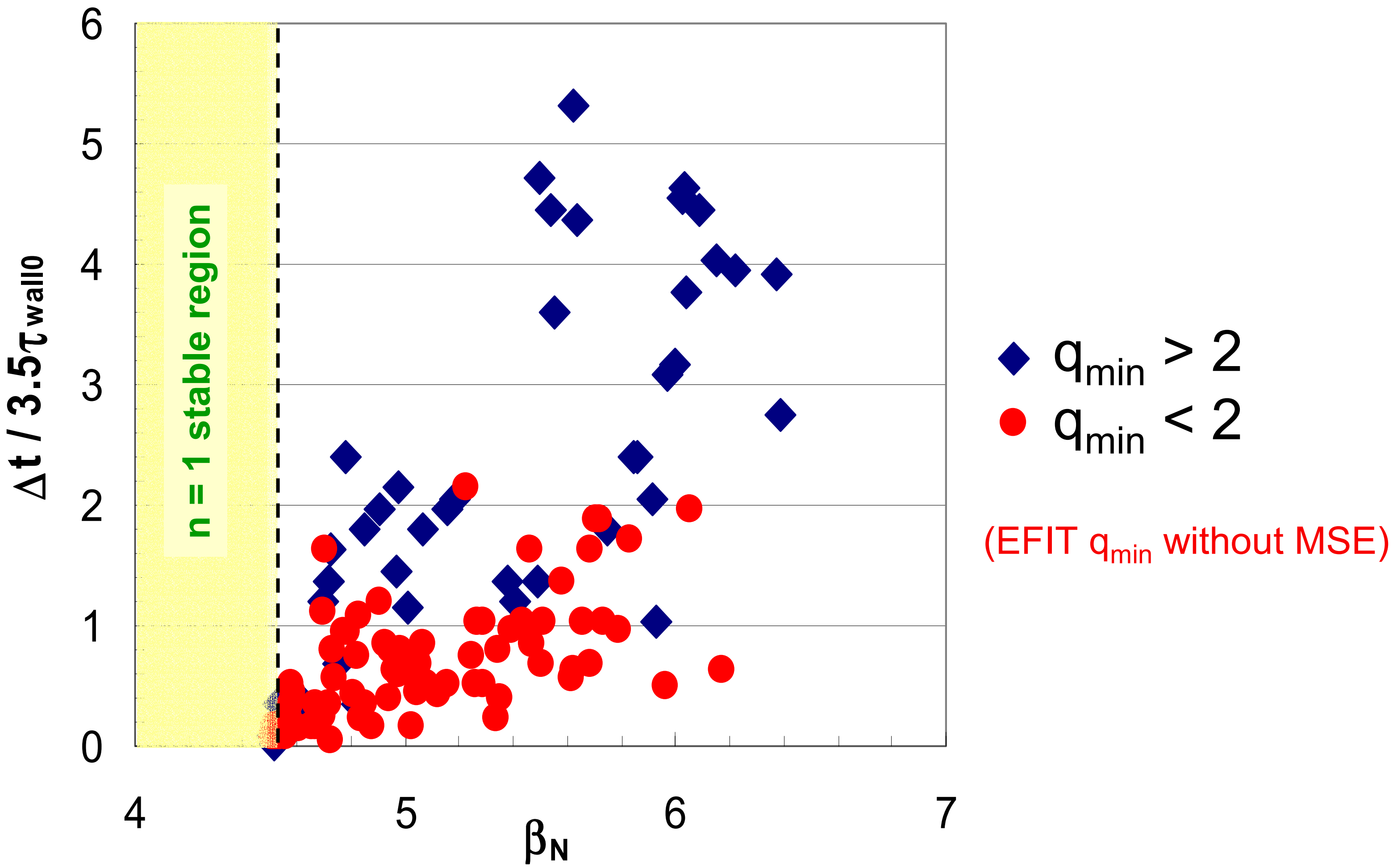
At axis, $R[d\log(n_e)/dR] = 2M_A^2 / \beta_{local}$ *(includes thermal and fast ions)*



M3D Simulations

- Toroidal flow-shear computed to reduce internal kink growth rates up to factor of 3
- 2-fluid effects & hot particles also stabilizing

High β_N plasmas with $q_{min} > 2$ have longer pulse length



- Typically (15 ms < τ_{wall} < 25 ms), $\tau_{wall0} \equiv 20$ ms
- (1.8 < F_p < 2.3); n=1 mode typically computed stable for $\beta_N < 4.5$