# The NSTX Research Program Plan for 2004 – 2008

# MHD Research

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for the NSTX Research Team

*NSTX Five Year Plan Feedback Forum*

*December 12 – 13, 2002*

# Overview of presentation

- MHD of highest $\beta_T$ and $\beta_P$ (long-pulse) discharges
  - Relevant to IPPA 5 and 10 year goals
- Overview research plans
  - Motivated by recent results
    - Global modes, NTM, ELM, fast ion MHD, RWM, etc.
- Summarize with integrated timeline
  - Discuss yearly progression of research goals
  - Discuss tools for achieving those goals

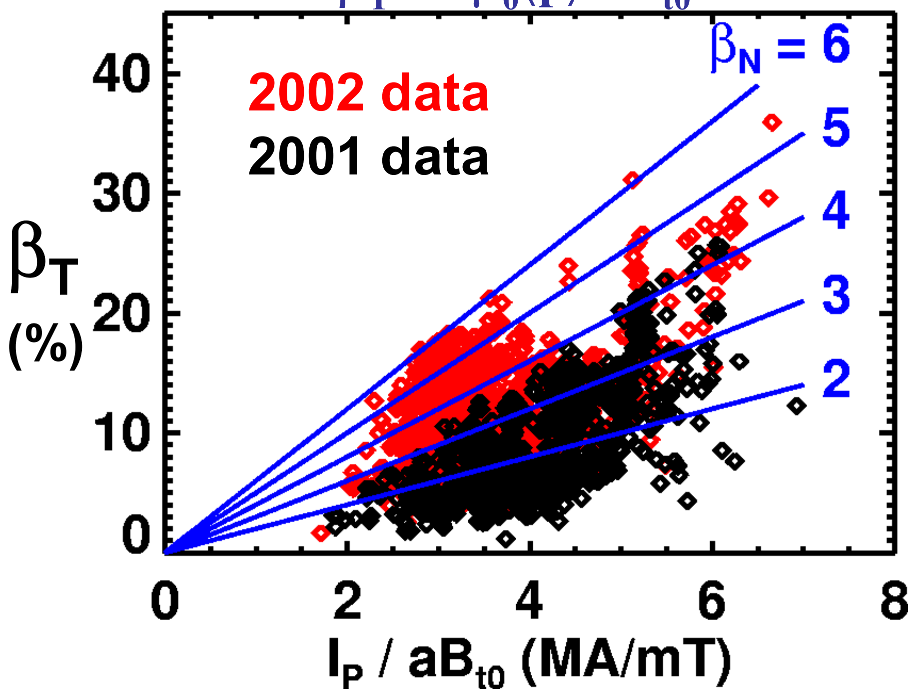
**MHD Goal ⇒ Provide MHD understanding and diagnostics for development of control tools needed to achieve long-pulse, high-β discharges**

# Achieved $\beta_T$=35%, $\beta_N$ = 6.4, $\langle\beta_N\rangle$=4.5

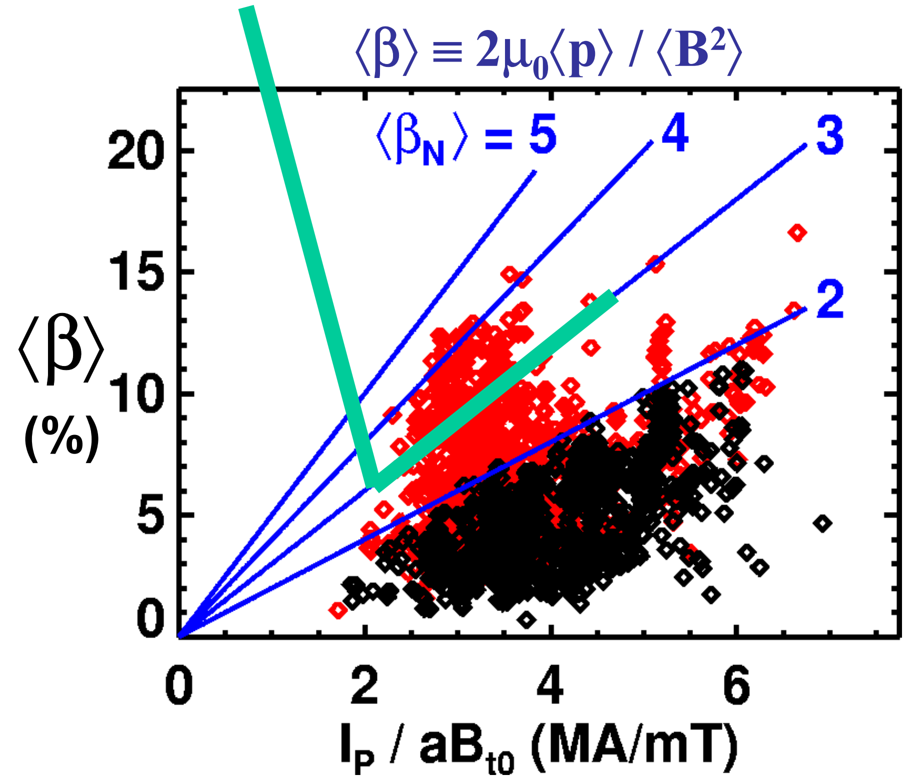
- $\beta_N \approx 6$ achieved for $I_p/aB_{t0}$ = 2 to 6.5 MA/mT
- $\beta_N$ increased 50-100% from previous year

- Recent computations show ***ideal no-wall limit*** **is $\langle\beta_N\rangle \approx$ 3-3.5** independent of $R_0/a$ for q* > 1.7
- **Many shots have now clearly exceeded this limit**

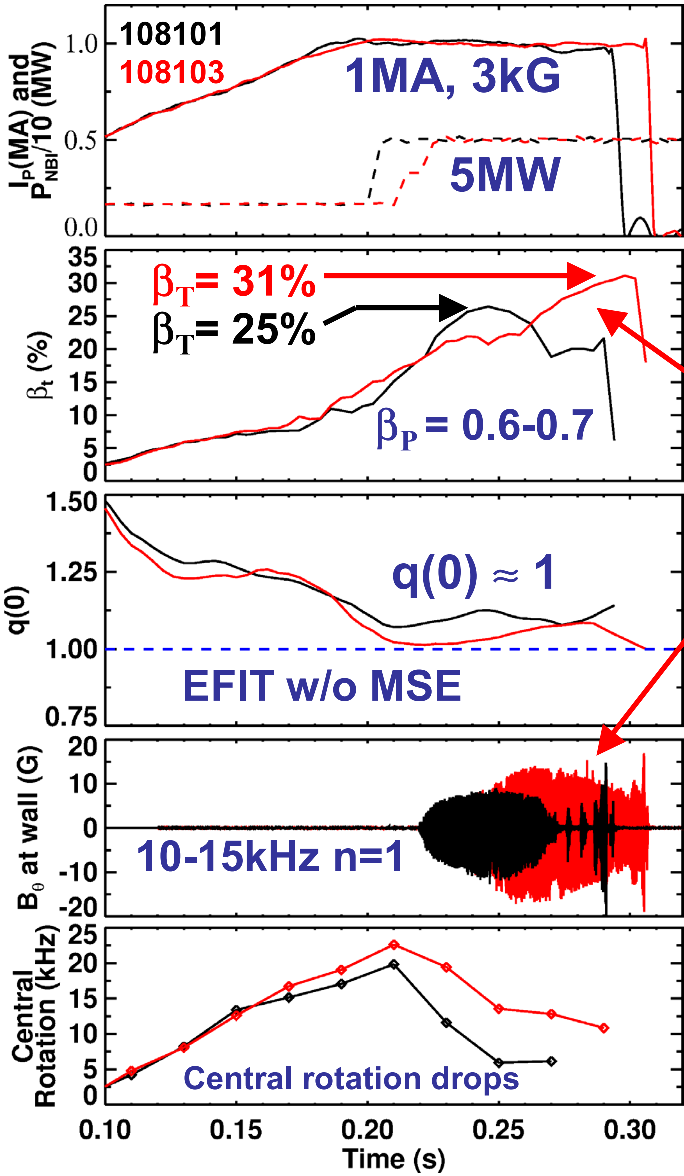
$\beta_T \equiv 2\mu_0\langle p\rangle / B_{t0}^2$




$\langle\beta\rangle \equiv 2\mu_0\langle p\rangle / \langle B^2\rangle$

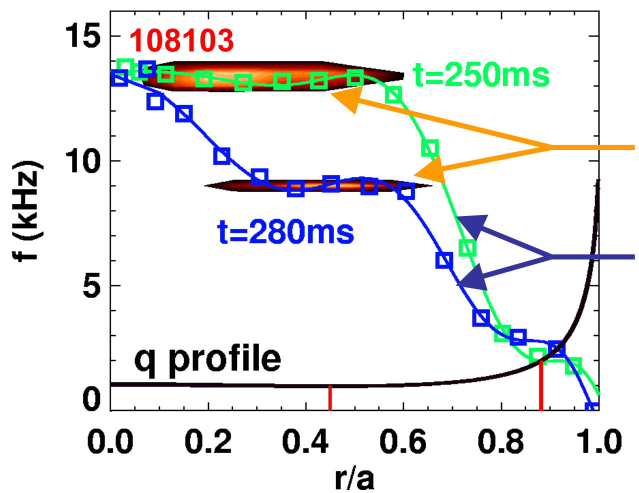


# Highest $\beta_T$ discharges limited by 1/1 modes



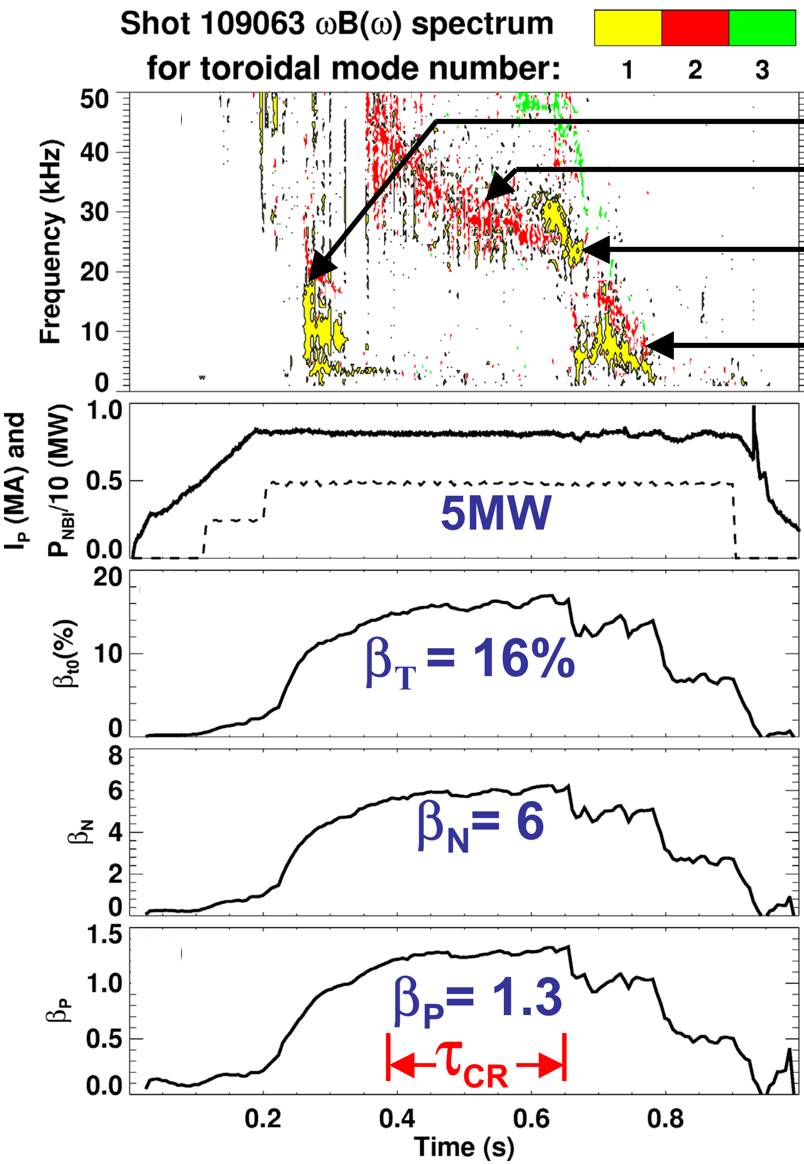

- Core becomes n=1 kink unstable
- 1/1 mode degrades β & rotation, slows, locks → disruption
- Neoclassical drive possible, but…
  - Modes can decay as β rises

**Rotation evolution may dominate:**




Very large q=1 radius → fast disruption

# MHD events in long-pulse discharges:



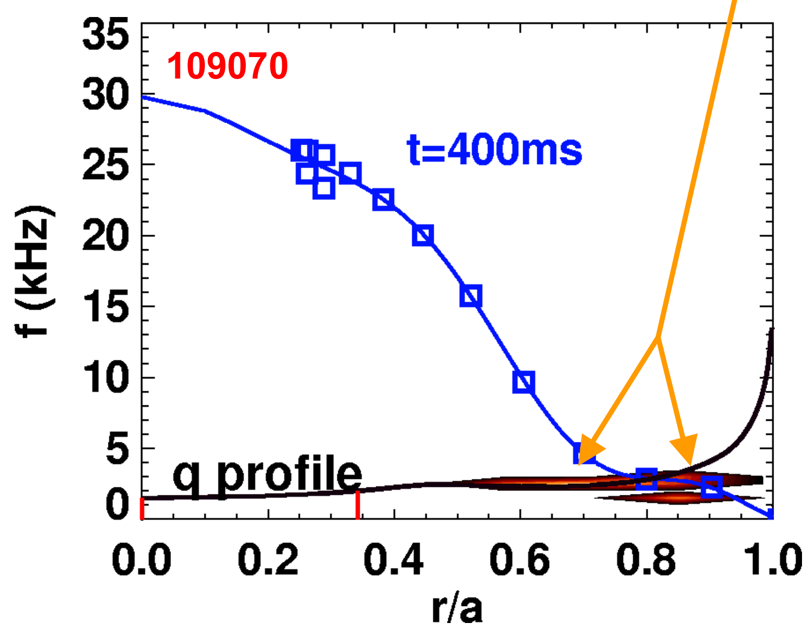

early n=1, transient at high $B_T$

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

**fast n=1 internal mode disrupts β**

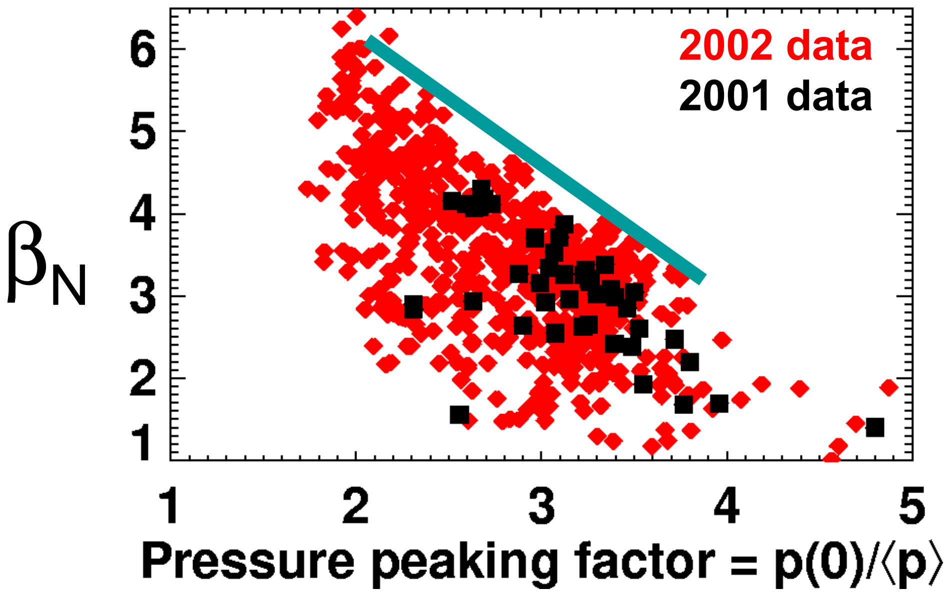
residual n=1,2 rotating modes, **NTMs?**

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



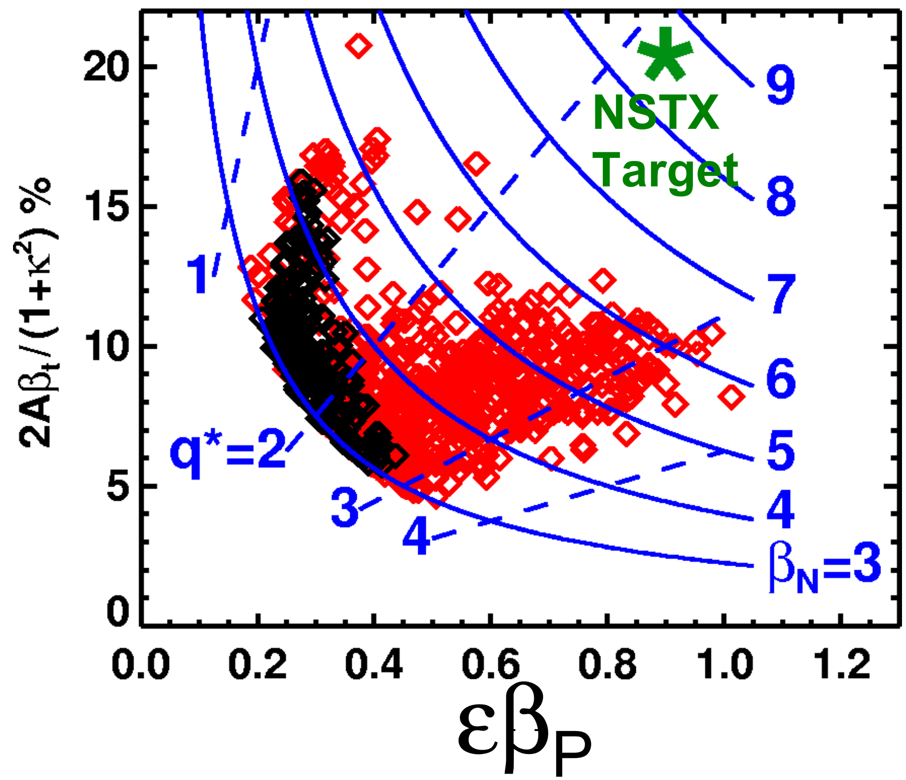
# H-mode profiles increased $\beta_N$ & $\beta_P$ limits

- Decreased pressure peaking observed to increase $\beta_N$
- Expected for n=1 kink limit




*EFIT p(ψ) loosely constrained by electron pressure profile shape to capture variation in pressure peaking*

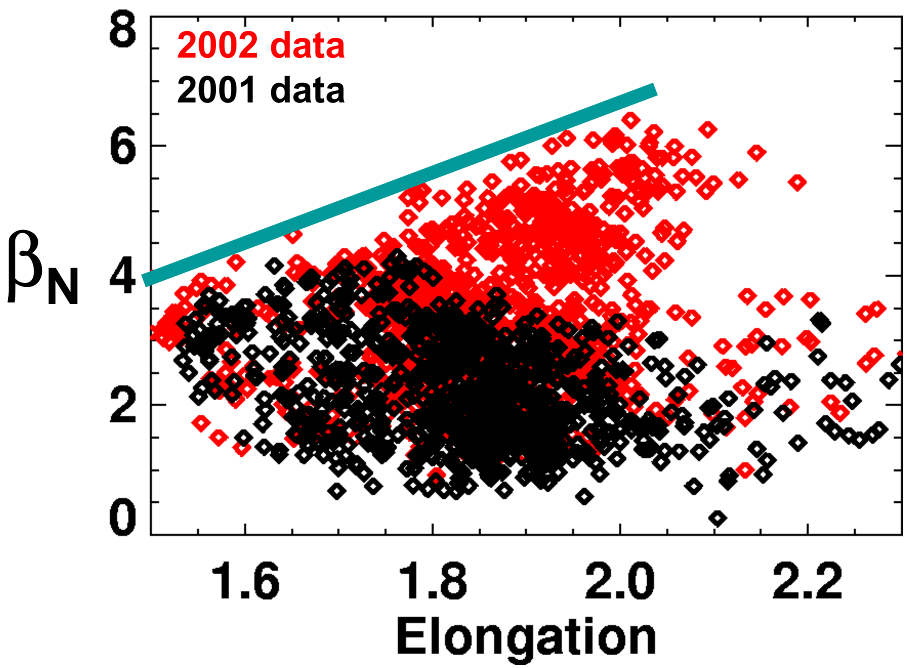
- Reached $\beta_P = 1.4$ **(× 2.5 higher)**



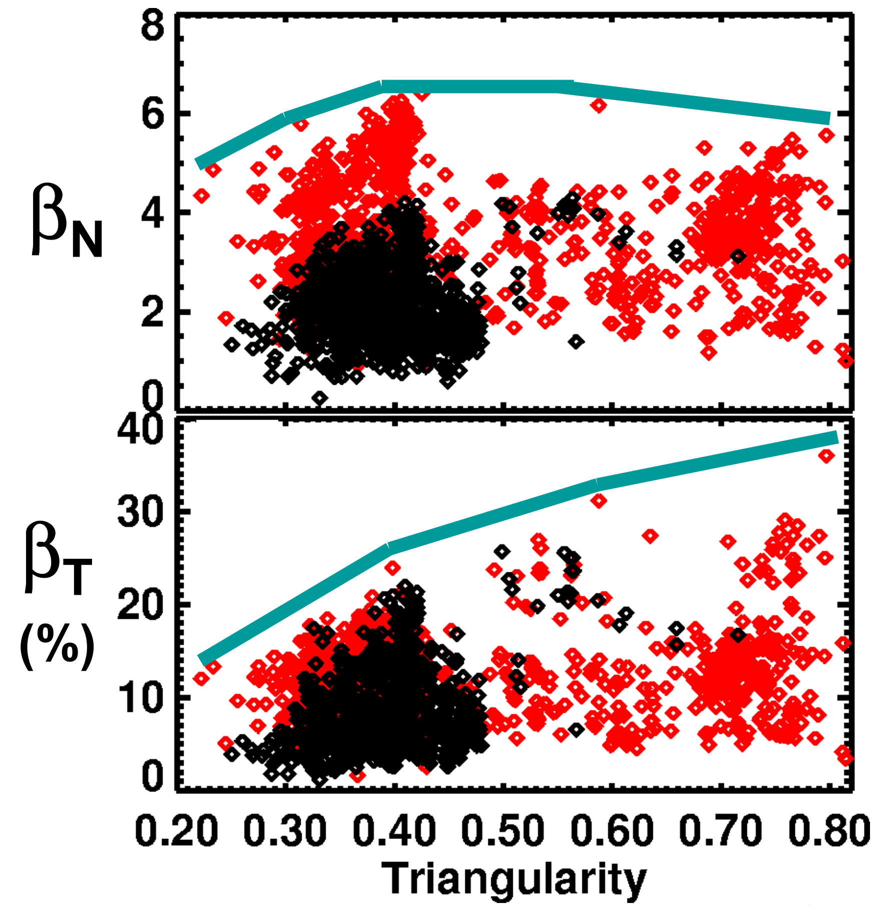

- **Reduced mode-locking of 2/1 tearing modes in H-mode**

# High β obtained with high κ and δ

- $\beta_N$ increases with increasing elongation
  - $\beta_N$ degraded for $\kappa > 1.8$ in previous run year

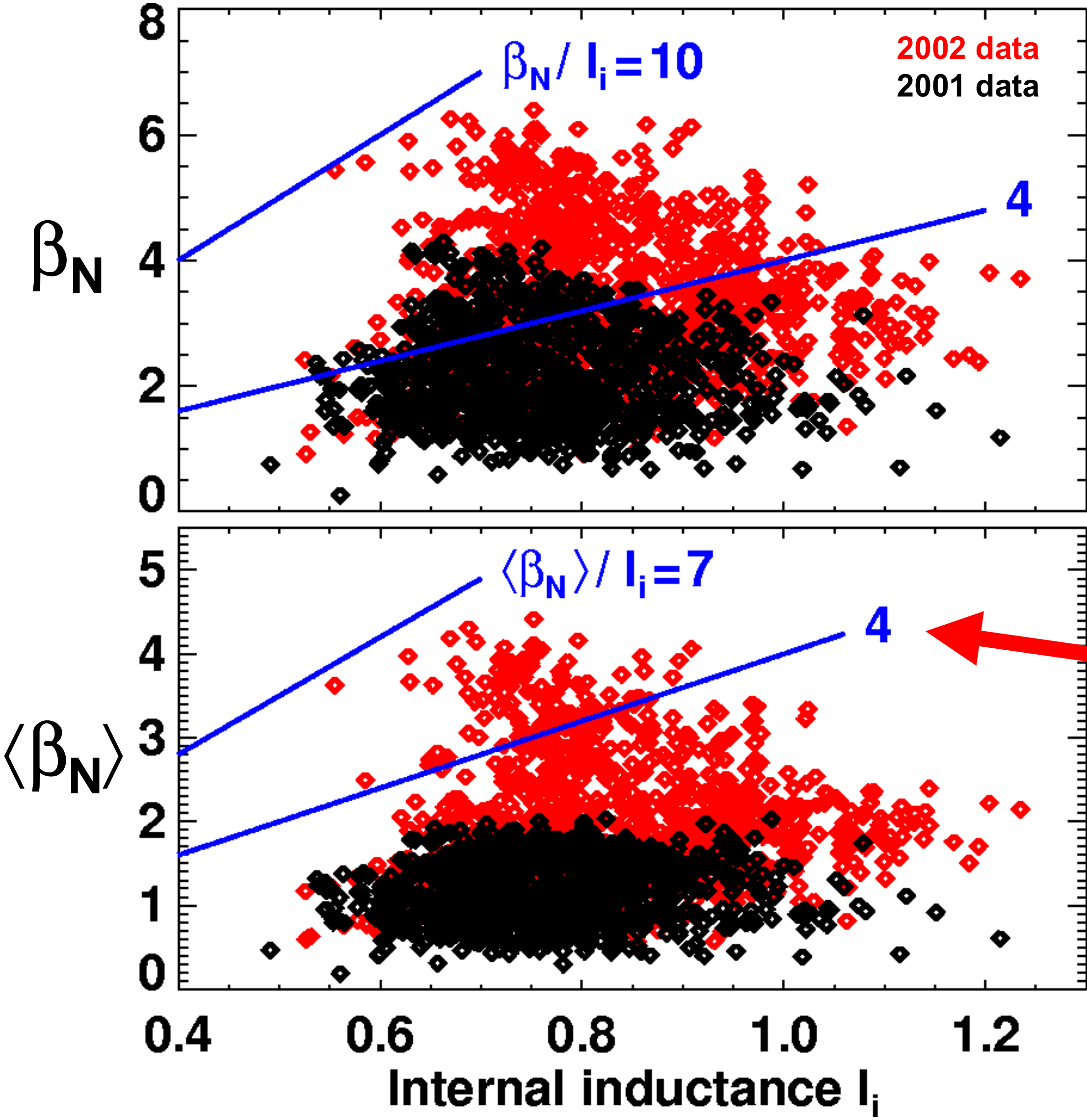



**$\beta_N$ weak function of δ for δ > 0.4**




**High δ → higher $I_p/aB_{t0}$ & $\beta_T$**

# High $\beta_N$ achieved at low internal inductance




- $\beta_N >> 4\ l_i$
  - $\beta_N$ increasing with lower $l_i$ for $l_i > 0.6$
  - Will this trend hold at even lower $l_i$?

  **NSTX design target has $\beta_N = 8.5$, $l_i = 0.25$**

- $\langle\beta_N\rangle$ also $>> 4\ l_i$

- Need more data at lower $l_i$ to define limit

  ***lower $l_i$ achievable with increased $\kappa$***

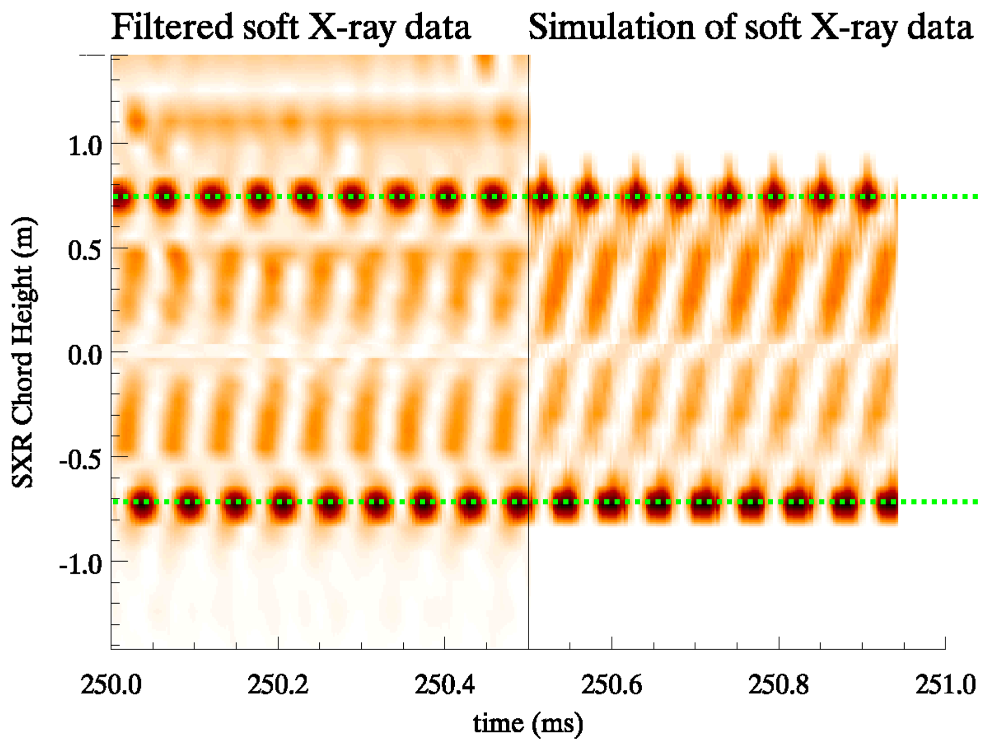
# Influence of shape and profiles on global stability

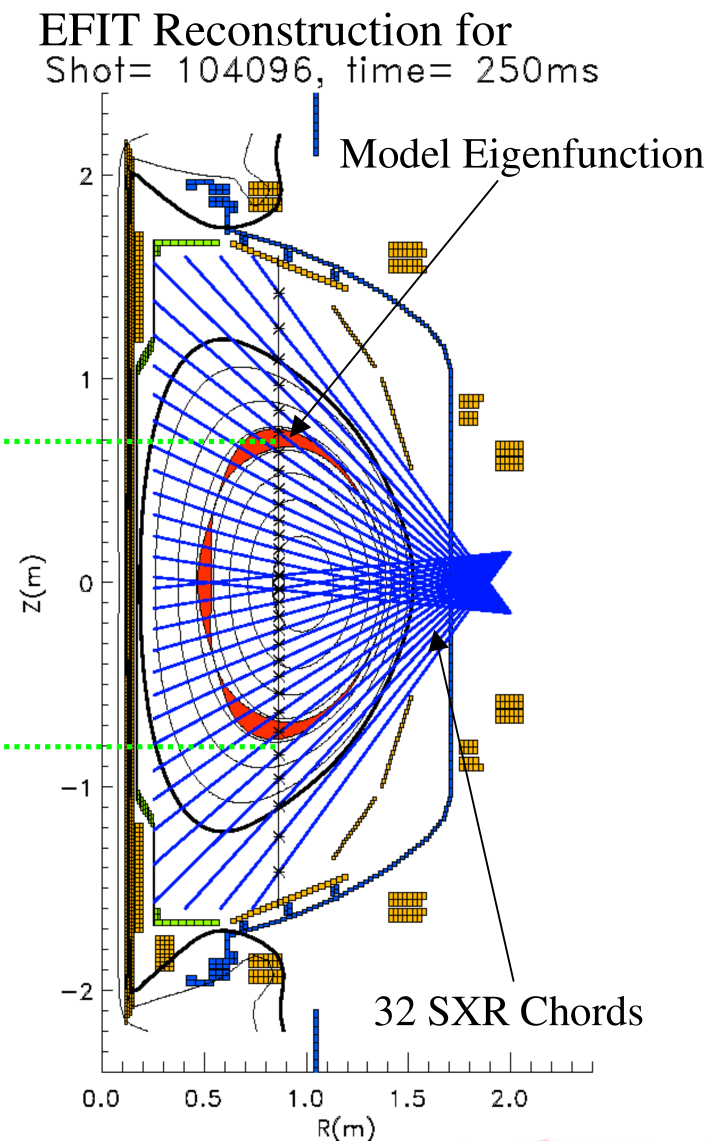
- FY2003
  - Further optimize $\kappa$ and $\delta$ in LSN and DND discharges to maximize $\beta_T$ and $\beta_N$
  - Find optimum shape for highest global stability limit compatible with long-pulse
- FY2004
  - First MSE constrained reconstructions early during discharge ramp-up
  - Assess $\beta_N$ limits as a function of ***controllably***
  - Develop and assess stability for q(0) > 2 plasmas if not already naturally occurring
  - Assess low-A and kinetic effects on ballooning stability
- FY2005
  - Characterize J(r) evolution, compare to TSC (and other) models, and benchmark
  - 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
- FY2003-future
  - Work to develop real-time predictive capability for stability, operate just below limits.

# 3/2 NTMs often observed in FY2001,

## $\beta_P$ limit increased significantly in 2002 (from 0.5 to 1.5)

- SXR data indicates odd-parity mode with inversion radius = 3/2 mode rational surface from EFIT
- Simulated eigenfunction agrees



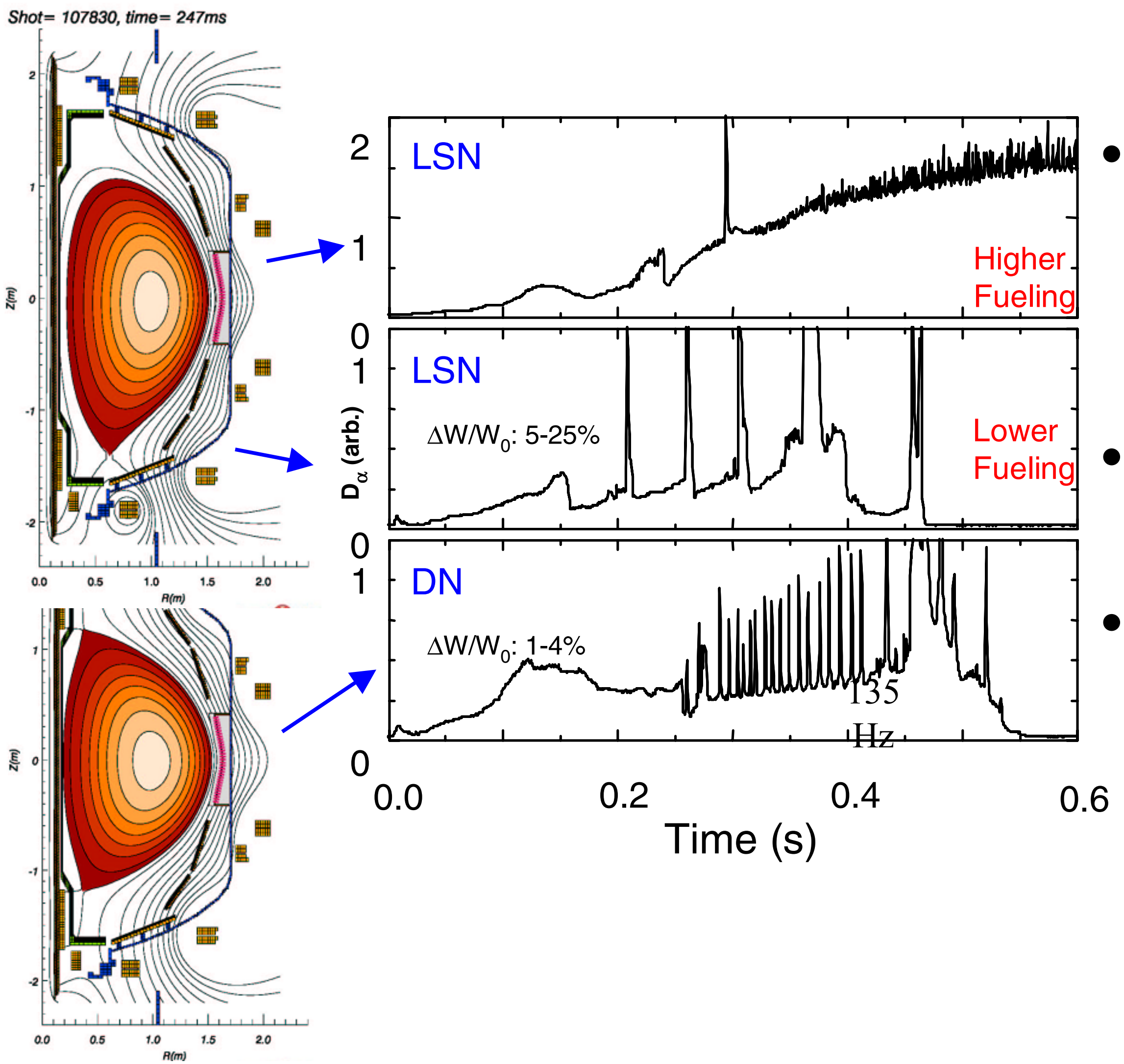
# Neoclassical tearing modes: FY03-05

- FY2003
  - Prepare neoclassical tearing mode codes to more routinely assess mode stability once q(ψ) profile information is becomes available, important for H-mode shots.
  - Implement more accurate wall shape model for wall-stabilized TM stability studies, and begin implementation of simulated Mirnov sensor responses.
- FY2004
  - Measure poloidal mode numbers magnetically utilizing new poloidal Mirnov array.
  - Assess seeding mechanisms for NTMs in various NSTX operating regimes.
  - Investigate non-linear coupling of NTMs of different helicities.
  - Work with MAST NTM experts on NTM similarity experiments
- FY2005
  - Correlate magnetically inferred *m/n* and possibly EBW radiometer.
  - Determine if modes are excited "spontaneously" via proximity to an ideal limit or if seeded directly from other observable MHD modes.
  - Infer island widths from measurements and improved modeling to assess CD needs for EBW CD feedback stabilization of the NTM.

# Neoclassical tearing modes: FY06-07

- FY2006
  - Perform preliminary assessment of changes in NTM stability due to global changes in current profile resulting from EBW current drive and electron heating.
  - Assess EBW power requirements for NTM stabilization based on initial measurements of CD efficiency and required CD for mode stabilization.
- FY2007
  - Demonstrate direct NTM suppression with pre-programmed control of launcher and plasma conditions.
  - Verify CD requirements with island suppression measurements and modeling of NTM stabilization physics.
- FY2008
  - Incorporate EBW launcher control into PCS and demonstrate first active feedback suppression of the NTM.

# ELM stability sensitive to shape, fueling

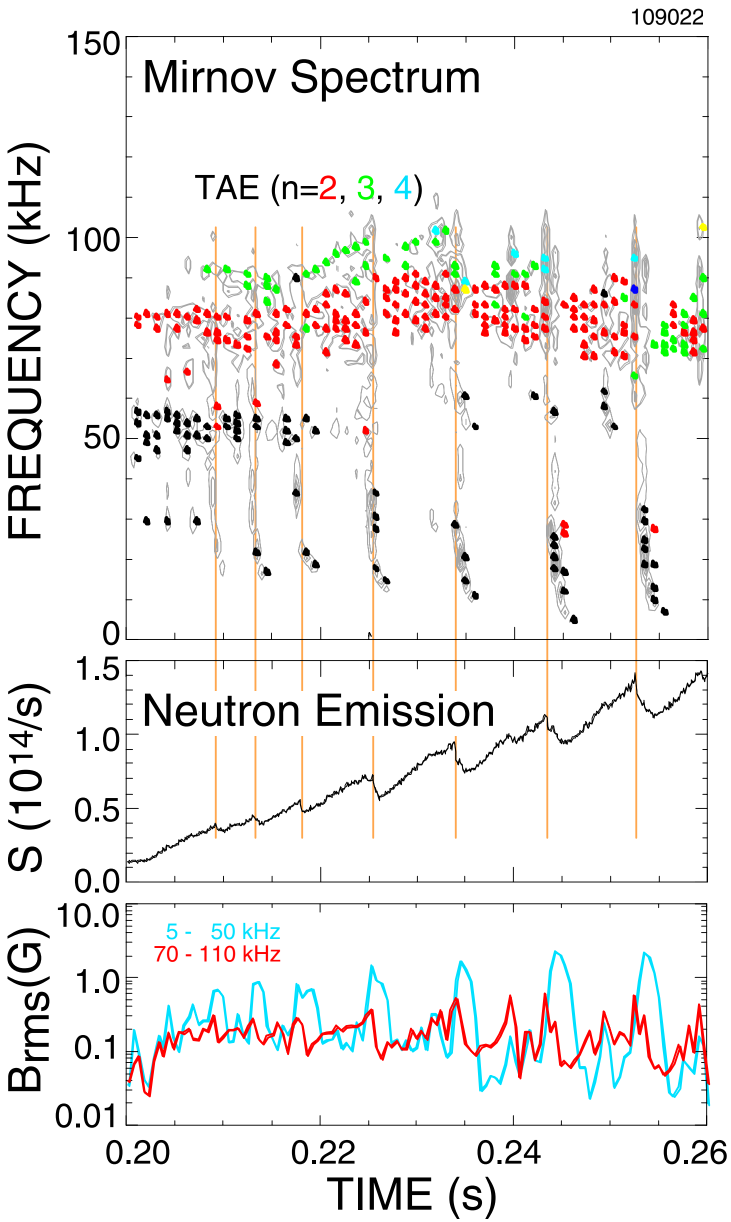



- Long pulse H-modes optimized empirically
  - LSN shaping increased while retaining small-ELM edge
- Edge density, collisionality likely impacting edge $J_{BS}$
- Hypothesize that access to ballooning second stability impacts *n* amplitude/width of ELM

# Edge localized modes

- FY2003
  - Continue to perform experiments to assess impact of divertor configuration, shaping, collisionality, and plasma-wall gaps on ELM stability properties.
  - Characterize pedestal energy loss in various ELMing regimes and secondary destabilization of NTMs and other modes due to ELMs.
- FY2004
  - Commission very high-n array for measurement of ELM toroidal mode numbers.
  - Correlate measured mode numbers with ELM type.
- FY2005
  - Use reflectometer or other high resolution near-edge profile diagnostic to perform preliminary measurements of ELM structure.
- FY2006-2008
  - Using kinetic EFITs with MSE and all available profile information, reconstruct discharges from controlled experiments designed to excite different types of ELMs.
  - Compare ELM stability threshold, mode structure, and toroidal mode numbers to predictions from ELM stability codes such as ELITE, DCON, GATO, or PEST.

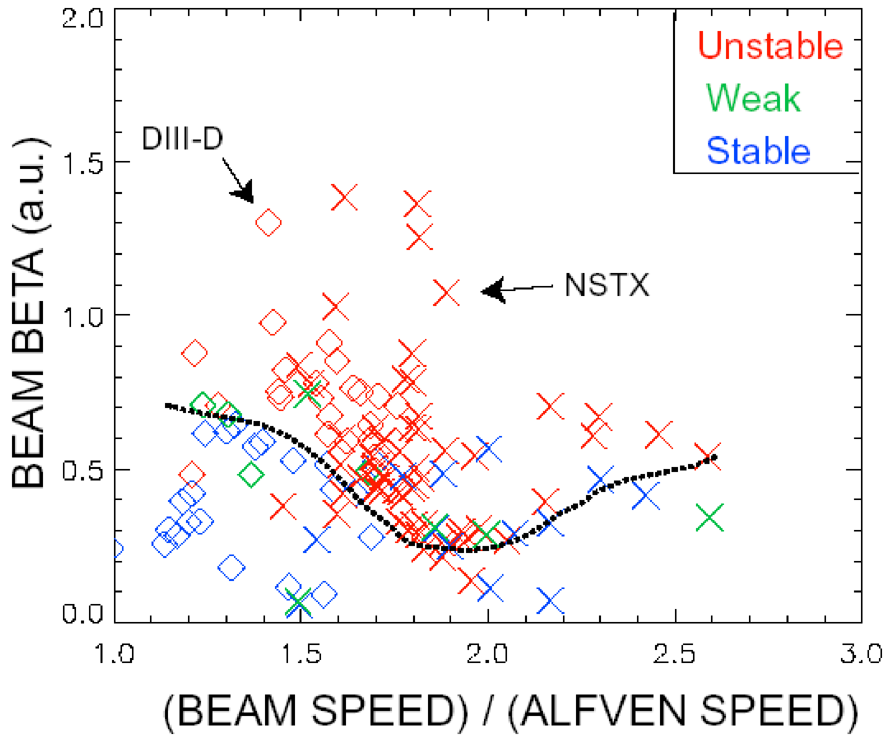
# Fishbone & TAE can cause fast ion losses



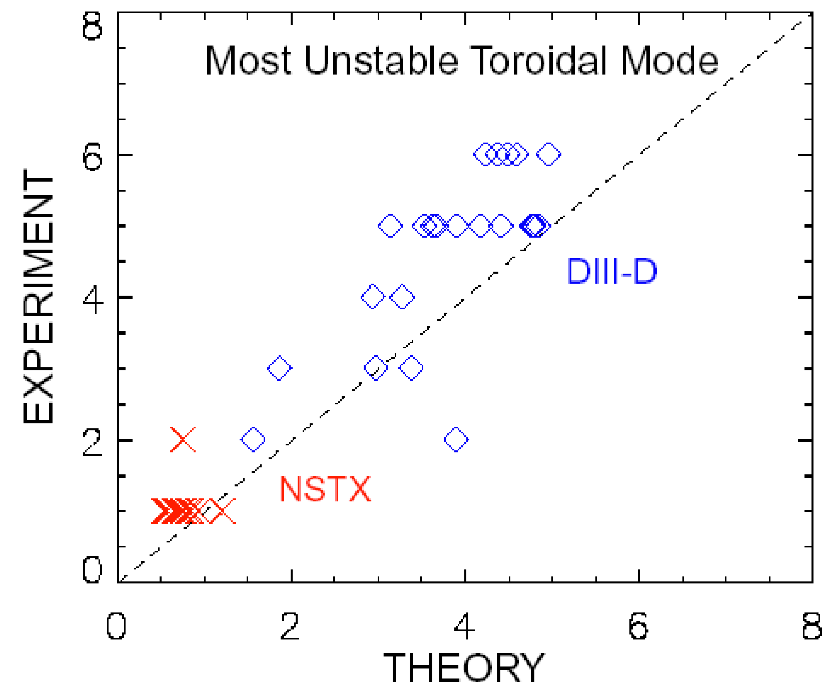

- Neutrons are beam-target; $-\delta S \propto \delta n_{fi}$
- Instabilities are TAE and "fishbones"
- TAE bursts cause initial, fast drop, fishbones later, slower drop.
- Correlation of f.b. and TAE bursts suggests coupling.
- In L-mode, sometimes correlated with $D_\alpha$ drops.
- Loss also seen in iFLIP

# DIII-D/NSTX TAE Similarity Experiments

## Similar TAE Thresholds




## TAE Mode Number Scales as Expected




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

# Fast ion MHD

- FY2003
  - Perform CAE (and more TAE) similarity experiments on NSTX and DIII-D
    - Assess role of toroidicity on characteristic frequencies, thresholds, growth rates, etc.
  - Assess if fast ion-driven modes play a role in high $\beta_P$ NSTX internal disruptions
    - Investigate low frequency modes such as fishbone or rTAE (f=20-40kHz)

- FY2004
  - Perform first measurements of 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 (using FLIP) with MHD characteristics
    - Determine the energy of ions preferentially lost.
    - Infer region of distribution function driving instability.

# Fast ion MHD (continued)

- FY2005
  - Utilize internal diagnostics including reflectometer, EBW spectrometer, or upgraded bandwidth SXR to measure internal structure of TAE, CAE, and GAE modes.
  - Utilize fluctuation signatures and frequencies to distinguish between modes.
  - Compare to theory and modeling with NOVA, HINST, and HYM (need MSE).
  - Assess if "pitch-angle anisotropy model" can explain drive for instabilities and thus how much energy is available to drive modes.

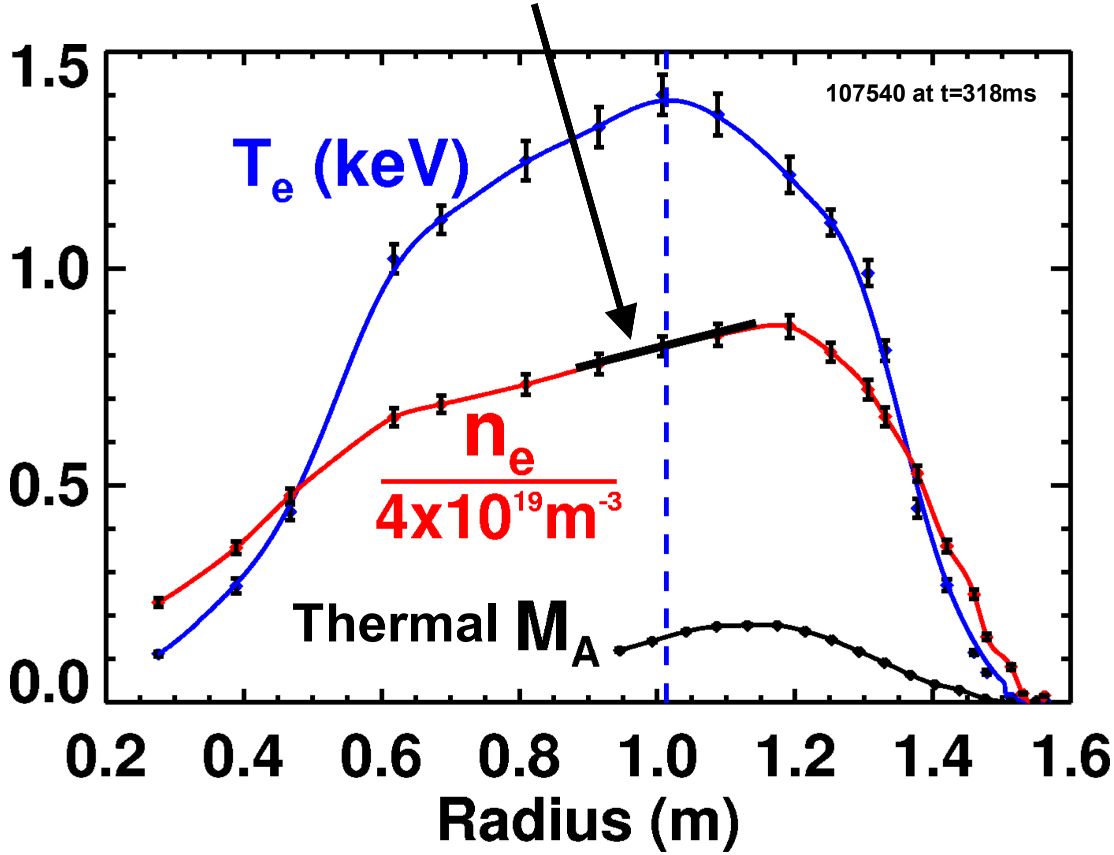
- FY2004-future
  - Develop beam ion profile diagnostic to determine fast ion pressure profile.
  - Use profile shape in ideal stability calculations, fast ion MHD instability drive
  - Assess influence of fast ion MHD on fast ion population properties
    - neutron rate, power deposition, fast ion angular momentum, etc.
  - Techniques to be considered:
    - neutron collimator (leading candidate)
    - an array of active neutral particle detectors
    - D-alpha light from re-neutralized beam ions.

# Fast rotation can modify equilibrium, stability

- Local thermal $M_A \equiv v_\phi / v_A$ as high as 0.3

  $\Rightarrow$ 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
- Contributing to saturation of 1/1 modes at high-$\beta$?

# Influence of rotation on equilibrium and stability

- FY2003
  - Begin to include rotation effects in equilibrium reconstructions (EFIT).
    - Assess change in inferred stored energy due to inclusion of $v_\phi$.
  - Continue to assess shear flow stabilization of core kink modes (M3D).
  - First use of **FLOW** equilibrium code for interpreting experimental data

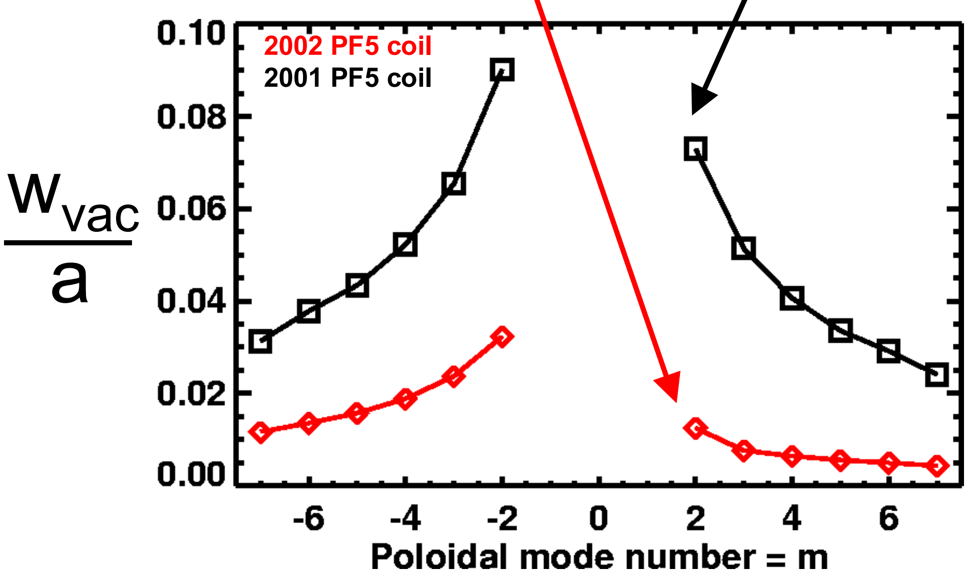
- FY2004-future
  - Compare fast ion centrifugal force to thermal, and possibly use changes in central gradient to infer changes in fast ion population due to MHD
  - Cross check against beam ion profile diagnostics if available, NPA, FLIP
  - Develop linear stability code based on **FLOW** including anisotropy

# Reduced error-field → reduced mode locking

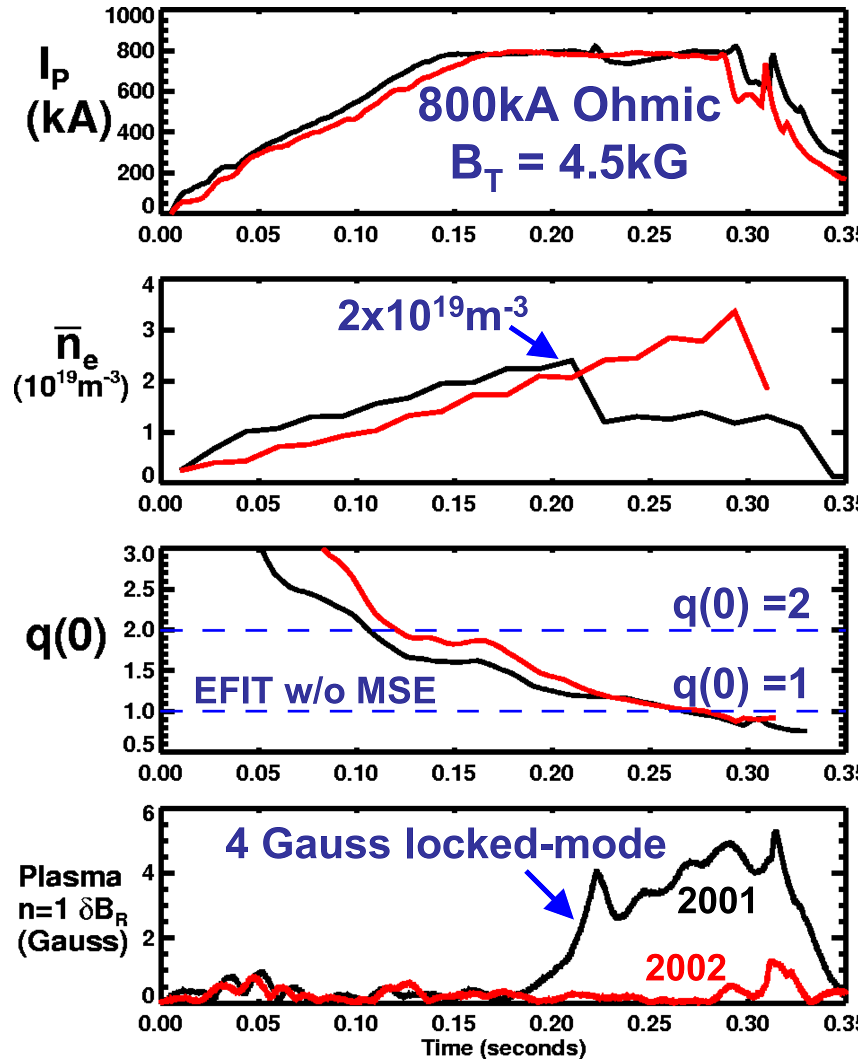
- Vertical field coils found to generate large n=1 $\delta B_r$

**Coils subsequently re-shaped**

Vacuum island widths now ***reduced to < 1cm*** (from 5cm)




*(NSTX operates with m > 0 resonant)*



# Error fields and locked modes

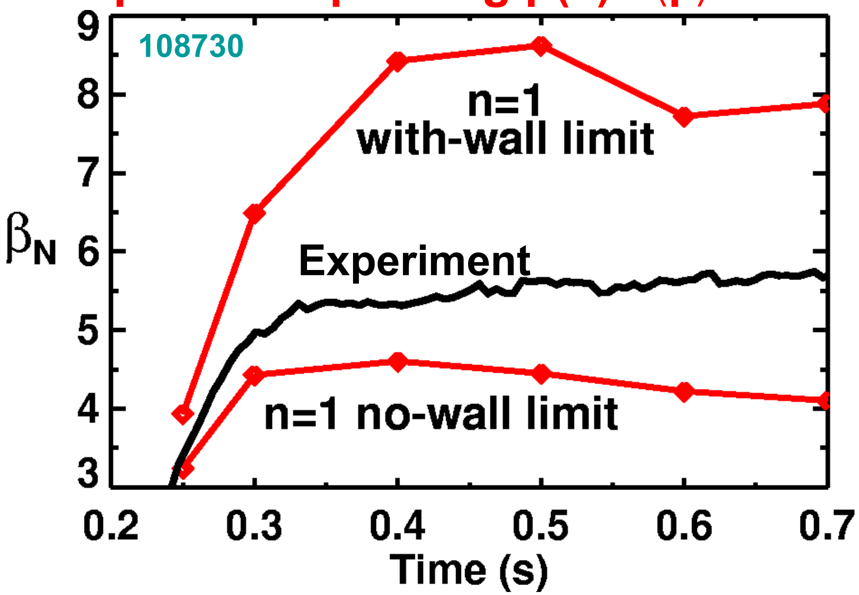
- FY2003
  - Commission internal RWM/EF sensor array electronics.
  - Gather engineering data on primary passive plate positions
  - Calibrate sensors including effects of non-axisymmetric positions.
  - Begin assessment of sources of residual error field such as PF coils, PF coil leads, or passive plate eddy currents.
  - Begin experiments using low density locked modes and beam pulses to determine locking threshold as a function of density, rotation, and proximity to no-wall limit, to check threshold against inferred error field sources.
  - Use locking position to aid inference of error field sources.

- FY2004
  - After utilizing internal sensor measurements to infer sources of error field, correct error fields directly where possible through re-alignment.
  - Include findings in RWM power supply current requirements as needed.

# Stability analysis finds $\beta > \beta_{no\text{-}wall}$ for many $\tau_E$, $\tau_{wall}$

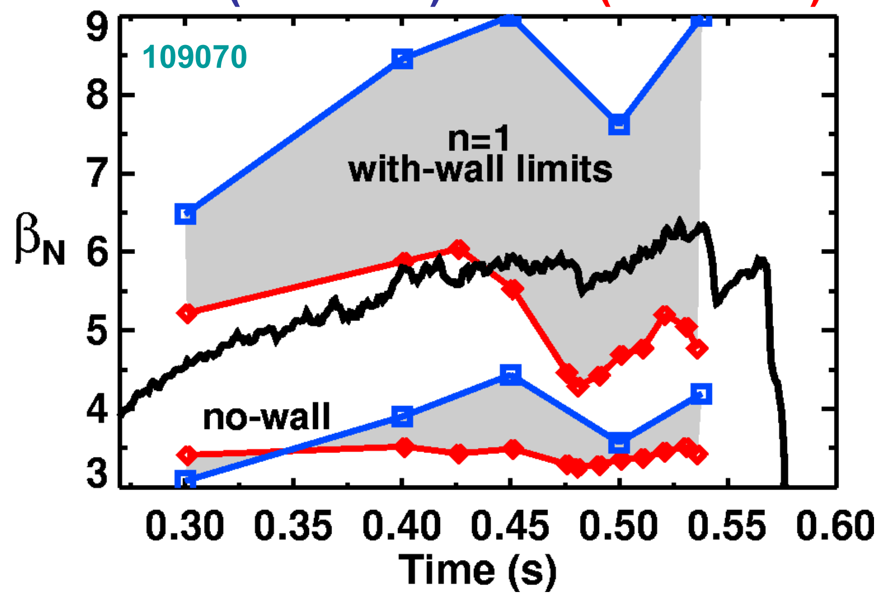
Reversed-shear q(ψ) with q(min) > 2

Use TRANSP p(ψ) which has
**pressure peaking p(0) / ⟨p⟩ = 2.5**




Nearly monotonic q(ψ) with q(0) < 2

Vary pressure peaking p(0) / ⟨p⟩ =
**2.0 (PK-EFIT) to 2.7 (TRANSP)**

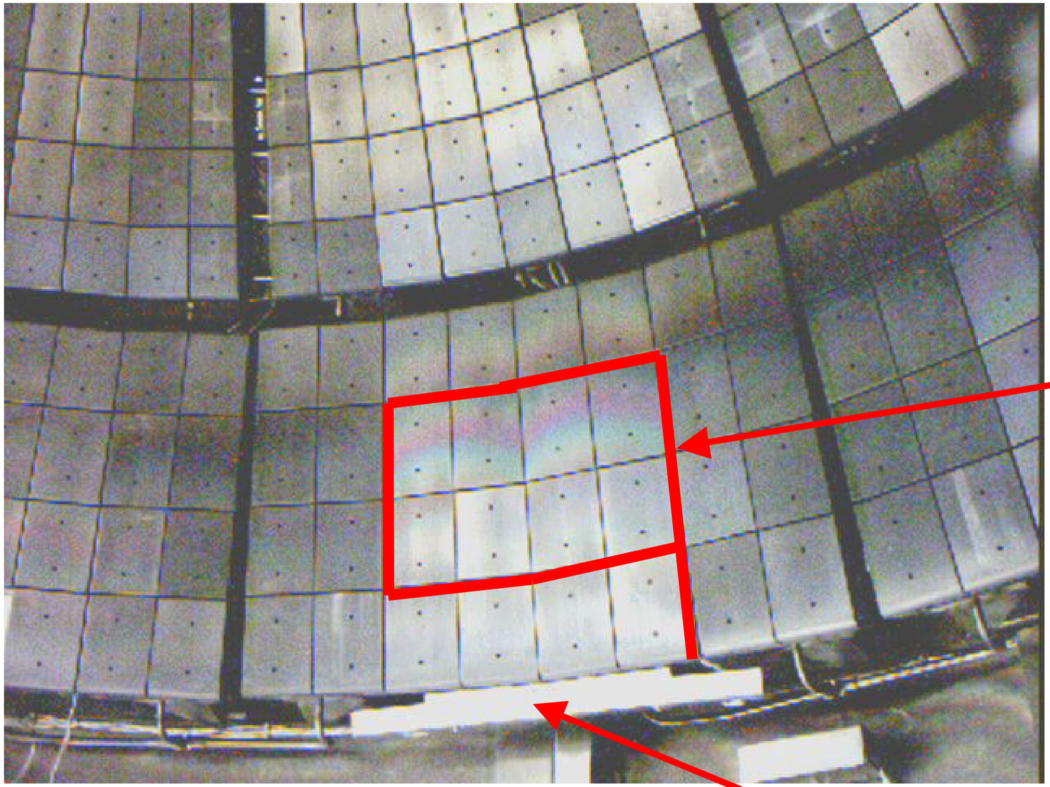



- n=1 no-wall limit $\beta_N$ = 3.5 to 4.5 clearly exceeded
- With-wall limit sensitive to p & q profile shapes:
  - **Limit lowered by monotonic q(ψ) with q=2 in plasma**
  
    **Limit lowered with increased p(ψ) profile peaking**

# RWM physics, passive stabilization

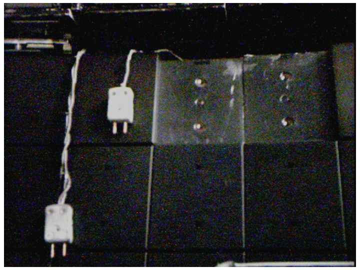
- FY2003
  - Perform NSTX/DIII-D/MAST similarity experiments designed to investigate aspect ratio dependence of RWM stability physics and no-wall stability boundaries
  - Investigate role of finite amplitude unstable RWMs in modifying rotation
  - Using MARS code, perform preliminary theoretical assessment of expected critical rotation frequency for RWM stabilization in NSTX and associated scalings with beta, safety factor profile, and shaping
- FY2004
  - Use equilibria with MSE to assess role of $q(\psi)$ in RWM stability, rotation damping
  - Begin benchmarking codes against measurements
    - **Example**: In regimes where RWM is passively unstable above the no-wall limit, benchmark codes such as DCON+VALEN and/or MARS+VACUUM used in predicting RWM structure, growth-rate, and frequency, against measurements from the internal RWM/EF magnetic sensor set.
- FY2005-future
  - Using experimental results and comparison to theory, assess rotation required for stabilization of RWM in long-pulse high-$\beta$ operating regimes.
  - Use knowledge gained to test active feedback stabilization physics in regimes with low rotation speed and to project to future ST devices.

# Each primary plate will measure $B_\perp$ and $B_P$



- 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
  - Centered in plate
- $B_P$ 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)



# Active RWM stabilization: FY03-05

*See next talk by S. Sabbagh for more details: physics & feedback system*

- FY2003
  - Finalize designs of "strawman" active coil sets using DCON+VALEN analysis.
  - Decide on either internal or external coil set, and design it.
  - Initiate procurement of power supplies
    - Should simultaneously correct error fields and provide fast feedback for RWM control.

- FY2004
  - Procure, install, and commission active coil set.
  - Specify, procure, and commission 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

# Active RWM stabilization: FY06-08

- FY2006
  - In regimes where RWM is passively unstable above the no-wall limit, develop feedback algorithms to stabilize the RWM up to the ideal-wall limit.
  - Develop techniques to control rotation speed independent of beam heating power to decouple rotation from β.
    - 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.
  - Generate stochastic divertor boundary with non-axisymmetric coils
    - Assess impact on edge profiles and divertor heat flux in long-pulse

**<u>SUMMARY GOAL:</u> Provide MHD understanding and diagnostics for development of feedback on shape, β, J(r), RWM, EF, & NTM, using rtEFIT, heating, RWM coils, and CD to achieve high-beta, long-pulse operation with good MHD stability properties.**