The NSTX Research
Program Plan for 2004 – 2008

MHD Research Overview

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for the NSTX Research Team

NSTX Five Year Plan Review

June 30, 2003

Overview of presentation

- MHD of highest β_T and β_P (long-pulse) discharges
  - Relevant to IPPA 5 and 10 year goals
- Overview of 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

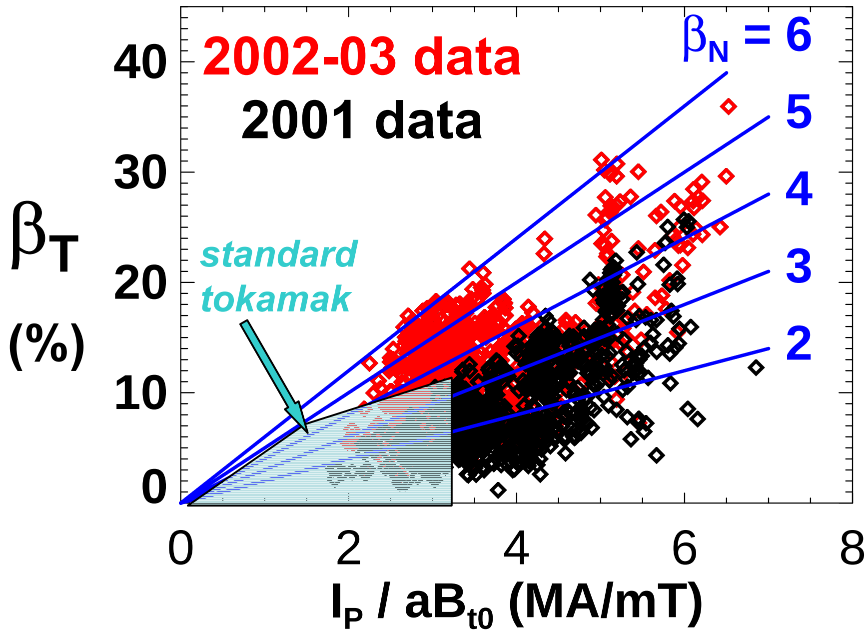
MHD Goal ⇒ Provide MHD understanding and diagnostics for development of control tools needed to achieve long-pulse, high-β discharges

Achieved β_T=35%, β_N = 6.4, $\langle\beta_N\rangle$=4.5

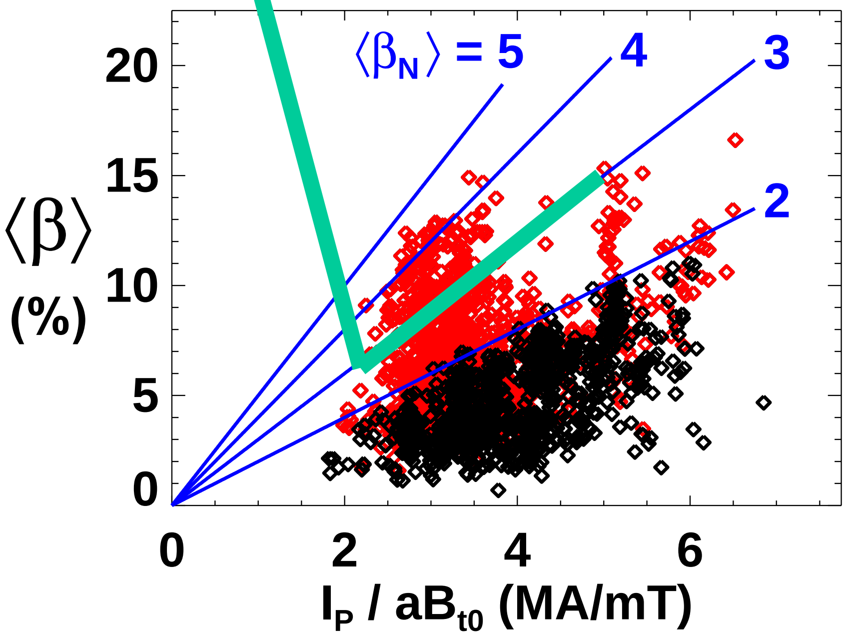
- $\beta_N \approx 6$ achieved for I_p/aB_{t0} = 2 to 6.5 MA/mT
- β_N increased 50-100% from within 1+ run year

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

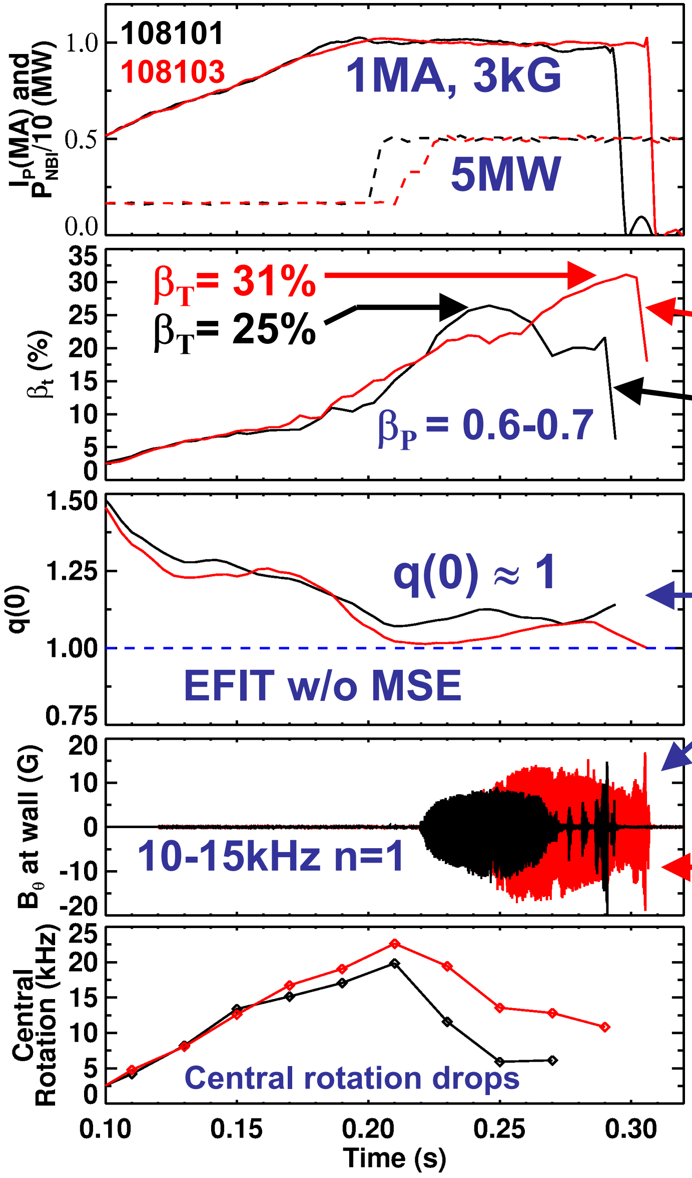
$\beta_T \equiv 2\mu_0\langle p\rangle / B_{T0}^2$



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



Highest β_T discharges limited by m/n=1/1 modes



- I_P=1MA, B_T=0.3T, P_{NBI}=5MW
  - Both discharges terminate rapidly
- Before rapid termination….

Sometimes, β rises throughout discharge

Most times, β saturates, then drops

When q(0) is near 1 and β_T > 20%, 10-15kHz n=1 instability appears

n=1 mode larger in high β shot (!)

How is drop in β avoided?

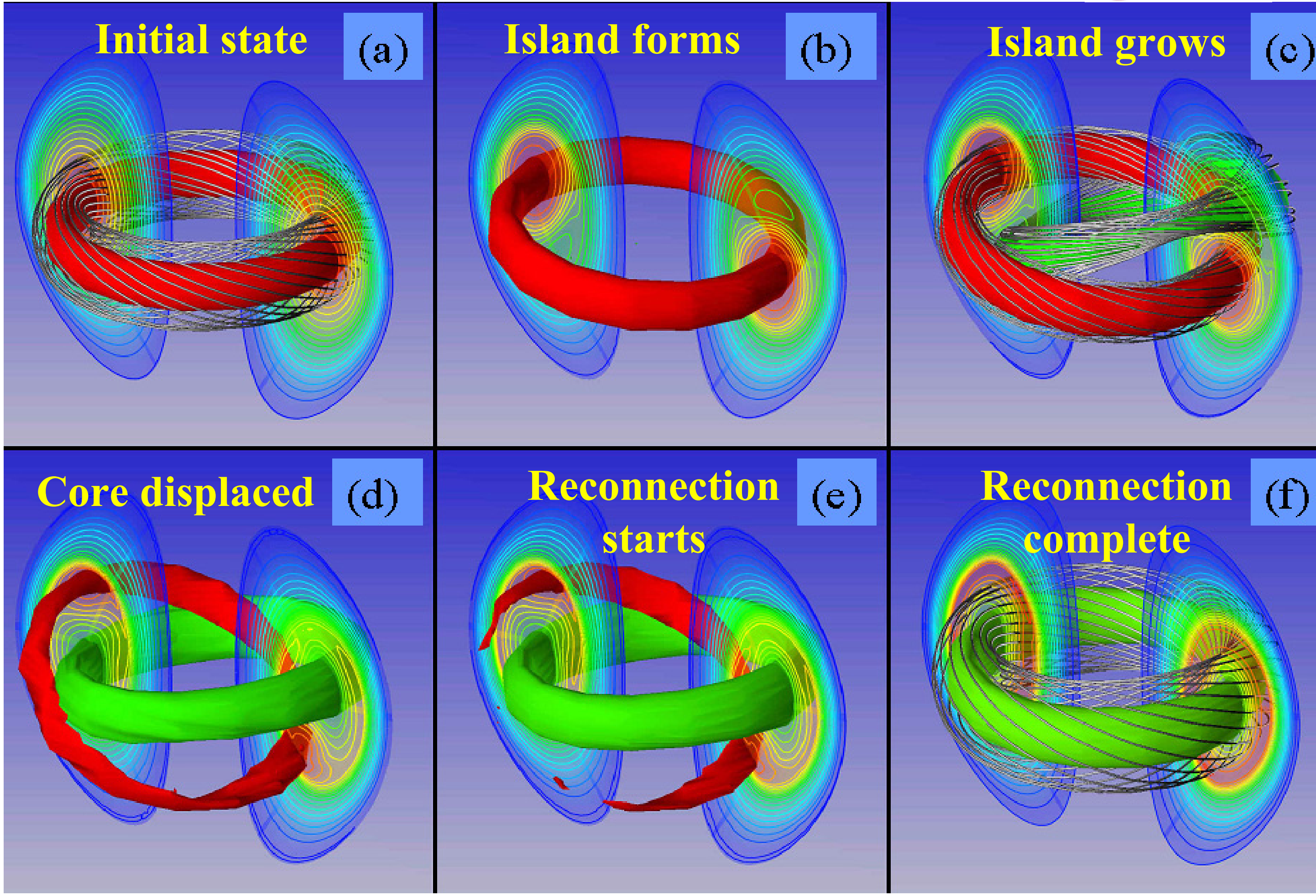
Difference appears to be ***sustained rotation***

Instability dynamics from non-linear simulations

(from Wonchull Park, M3D code, PPPL)

Simulation without rotation ⇒

B-field lines
Hot core
Cold island

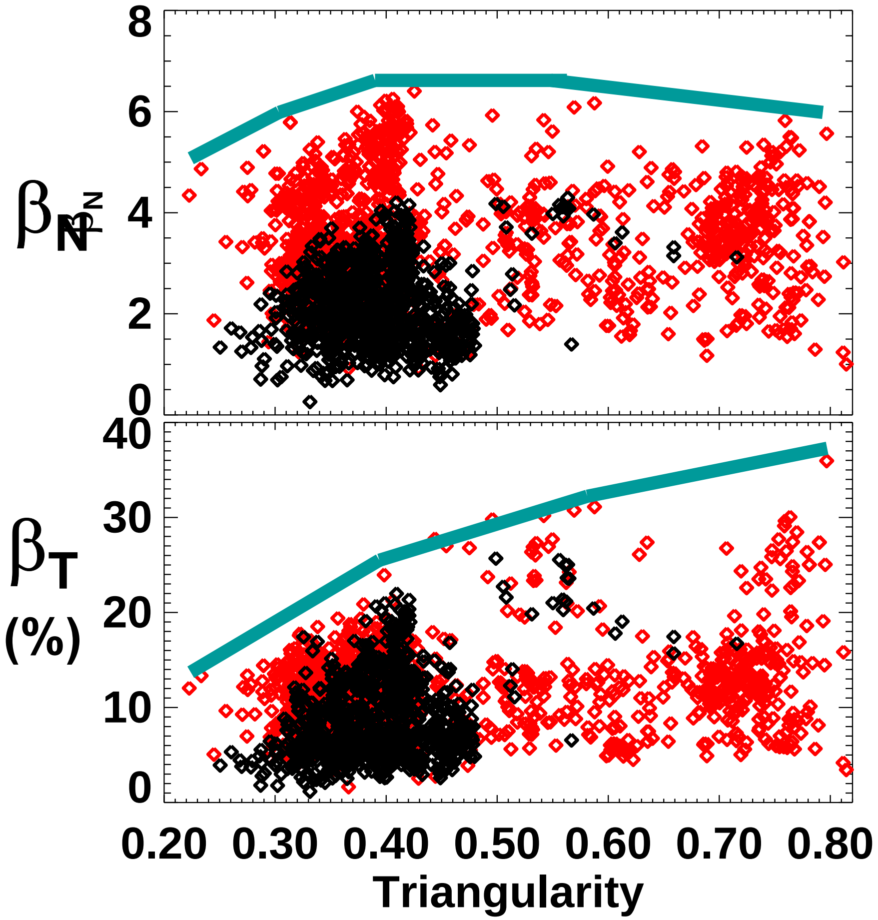


With sufficient rotational flow and shear, reconnection can be interrupted

May explain long-lived 1/1 modes in high β_T NSTX discharges

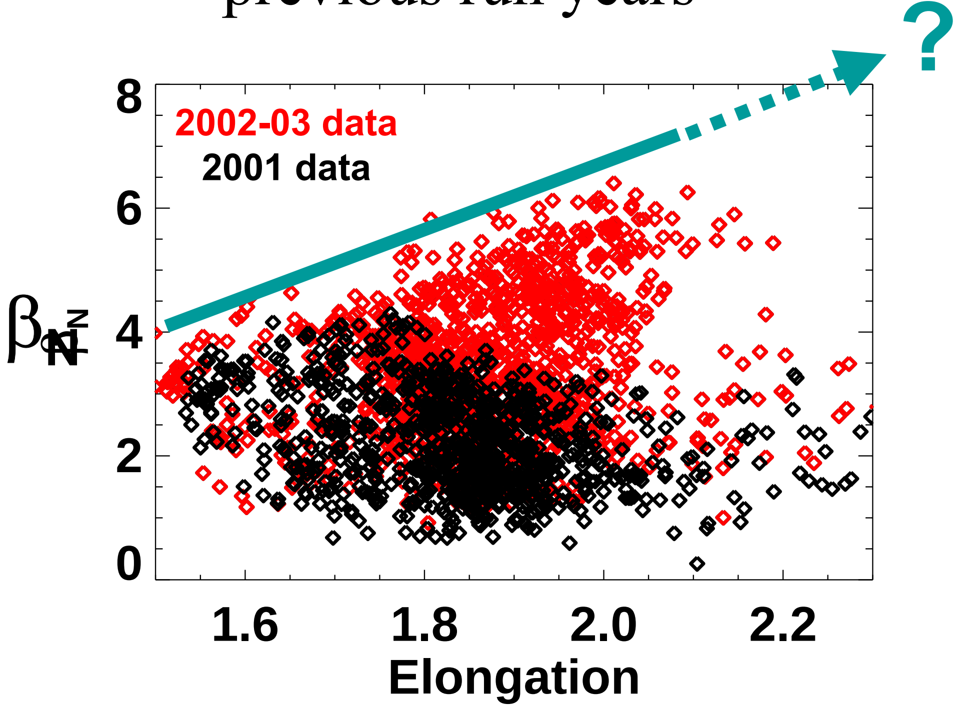
High β obtained with high κ and δ

β_N weak function of δ for $\delta > 0.4$



High $\delta \rightarrow$ higher I_p/aB_{t0} & β_T

- β_N increases with increasing elongation
  - β_N degraded for $\kappa > 1.8$ in previous run years



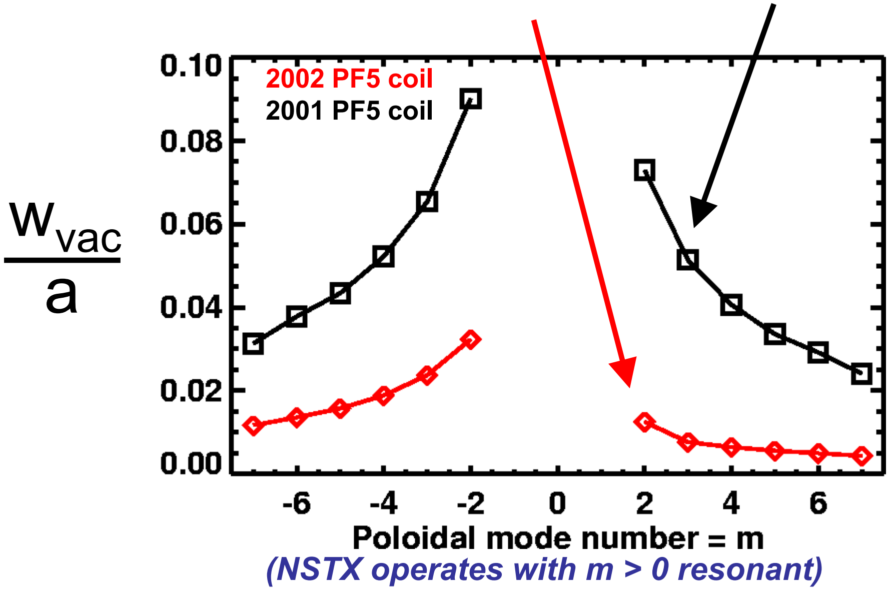
- **Motivates PF1A upgrade**

Influence of shape and profiles on global stability

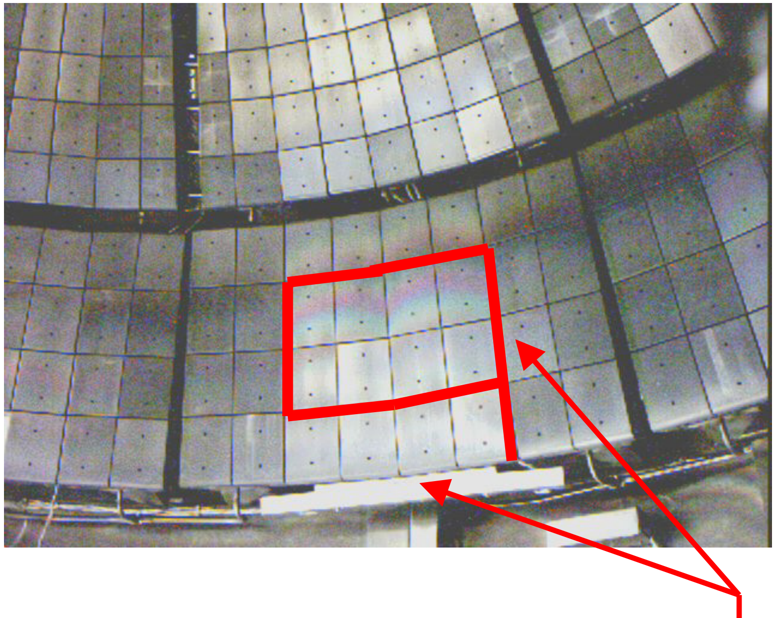
- FY2003-04
  - Further optimize κ and δ in LSN and DND discharges to increase β_T and β_N
  - Assess MHD stability vs. shape and I_P ramp-rate in long-pulse, high-β discharges
    - Utilize *shifted* PF1A if available to increase elongation at high triangularity
- FY2004-05
  - First MSE constrained reconstructions early during discharge ramp-up
  - Assess β_N limits as a function of ***controllably*** low internal inductance
    - Develop and assess stability for q(0) > 2 plasmas if not already naturally occurring
  - Assess low-A and kinetic effects on ballooning stability
- FY2004-06
  - Characterize J(r), p(r) evolution, compare to TSC (and other) models, and benchmark
  - Use benchmarked TSC to identify stable high-β targets with high NICD fraction
- FY2006-08
  - MSE-constrained rtEFITs, first attempts at real-time J(r) control using HHFW, EBW
  - Utilize split-PF1A to increase κ while controlling strike point and pumping
  - Combine current profile and shape control, study MHD as $\beta_T \rightarrow 40\%$, $f_{NICD} \rightarrow 100\%$
- FY2003-future
  - Work to develop real-time predictive capability for stability, operate just below limits.

Error-fields reduced, but not eliminated

- PF5 vertical field coils found to generate large n=1 δB_r in 2001
- **Coils subsequently re-shaped**
- **PF5** vacuum island widths now ***reduced to < 1cm*** (from 5cm)



- Other static and transient error fields are known to exist
  - need to be quantified and corrected



- New internal RWM & EF sensors
  - Measure mode structure
  - Identify sources of error field
  - Provide feedback signals
    - error field correction
    - RWM feedback

Error fields and locked modes

- FY2003-04
  - Use low-density locked-modes to aid inference of error-field sources.
  - Commission internal RWM/EF sensor array electronics.

- FY2004
  - Install active coil set.
  - Commission TFTR Transrex supply and Switching Power Amplifier (SPA)
  - Vary applied error-field to minimize rotation damping near and above no-wall limit.
  - Compare optimal currents to those predicted to minimize error-fields

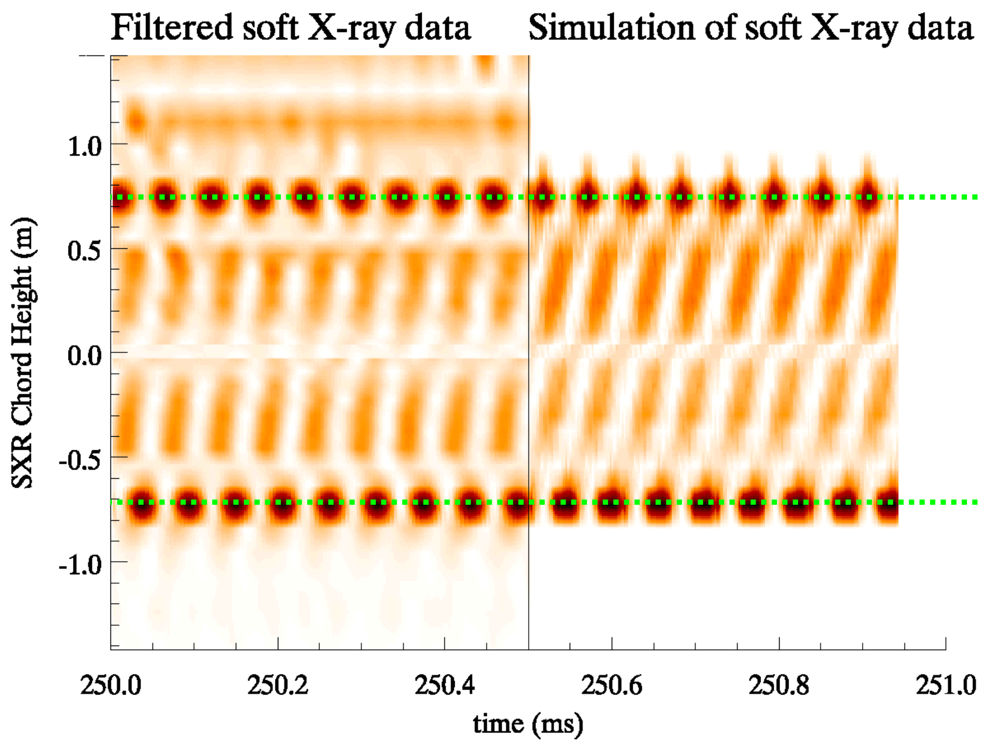
- FY2004-05
  - Purchase and install data acquisition for PCS to acquire needed magnetic sensor signals in real-time for fast feedback control.
  - Implement calibration algorithms for in-vessel RWM/EF sensor signals.

- FY2005-06
  - Utilize real-time internal sensor measurements during plasma operations and develop dynamic error-field correction algorithms.
  - Supplement/replace pre-programmed correction with dynamic error-field correction.

3/2 NTMs often observed in FY2001

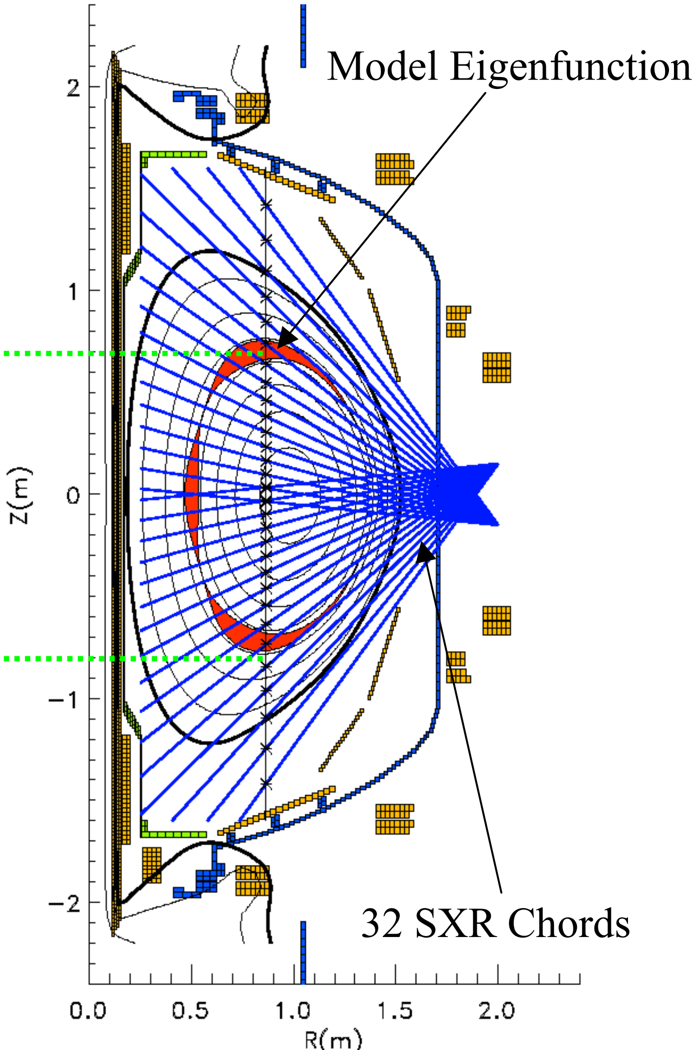
β_P limit increased significantly in 2002 (from 0.6 to 1.4)

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



Filtered soft X-ray data

Simulation of soft X-ray data



EFIT Reconstruction for

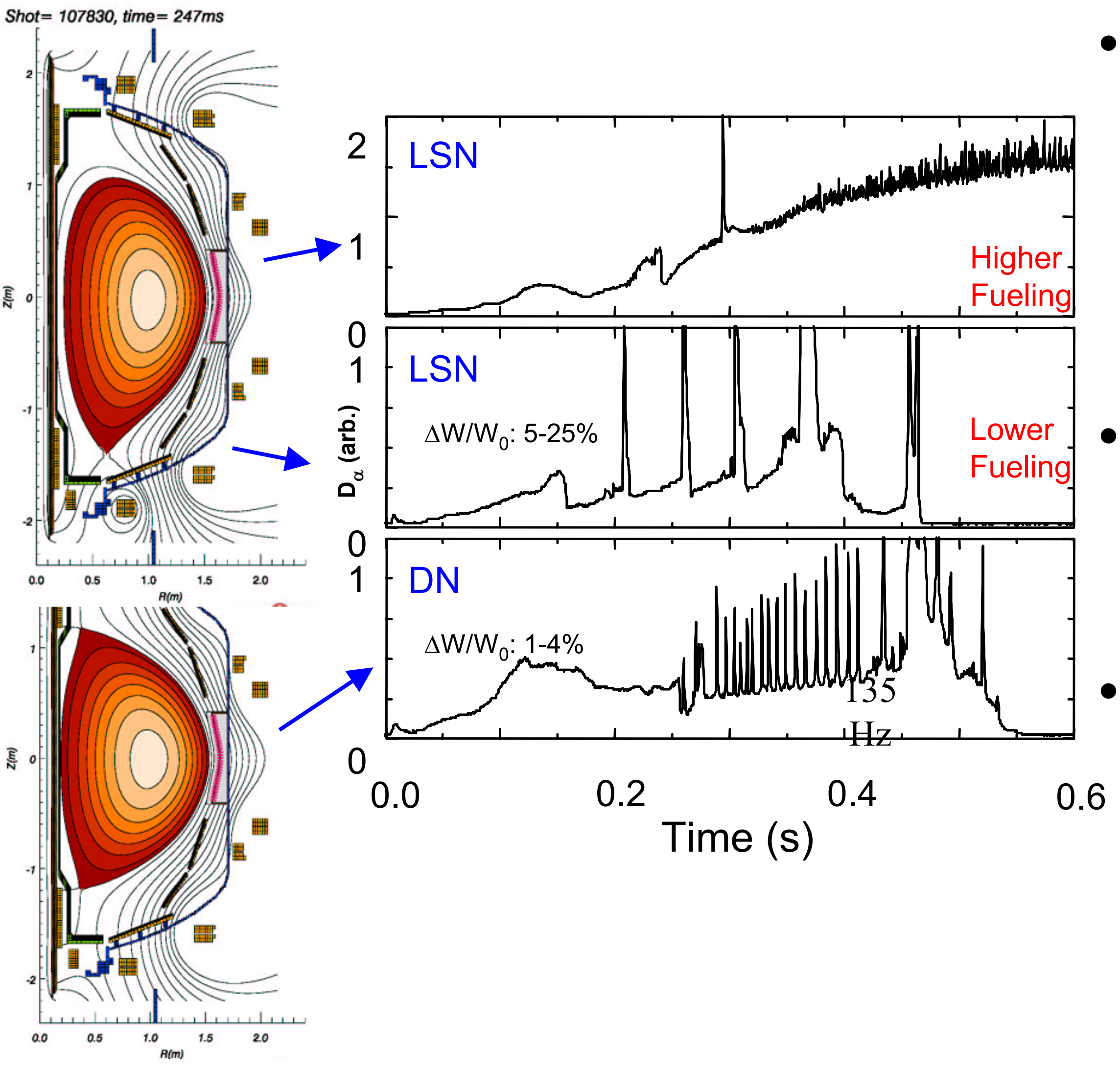
Shot= 104096, time= 250ms

Neoclassical tearing modes

- FY2003-04
  - Implement more accurate wall shape model in PEST-III and add Mirnov signal model for wall-stabilized tearing mode stability studies. Compare to experimental data.

- FY2004-05
  - 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
- FY2005-06
  - Measure *m*-numbers with new poloidal Mirnov array, correlate with q profile, SXR
  - Infer island widths from measurements and improved modeling
    - Assess CD needs for EBW CD feedback stabilization of the NTM.
- FY2006-08
  - Assess changes in NTM stability due to changes in J-profile from EBW current drive
  - Assess EBW power requirements for NTM stabilization
  - Demonstrate direct NTM suppression with pre-programmed control of launcher and plasma conditions. Verify CD requirements with NTM modeling of stabilization.
- FY08-future
  - Incorporate EBW launcher control into PCS
  - Demonstrate active feedback stabilization/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*-number and amplitude/width of ELM

Edge localized modes

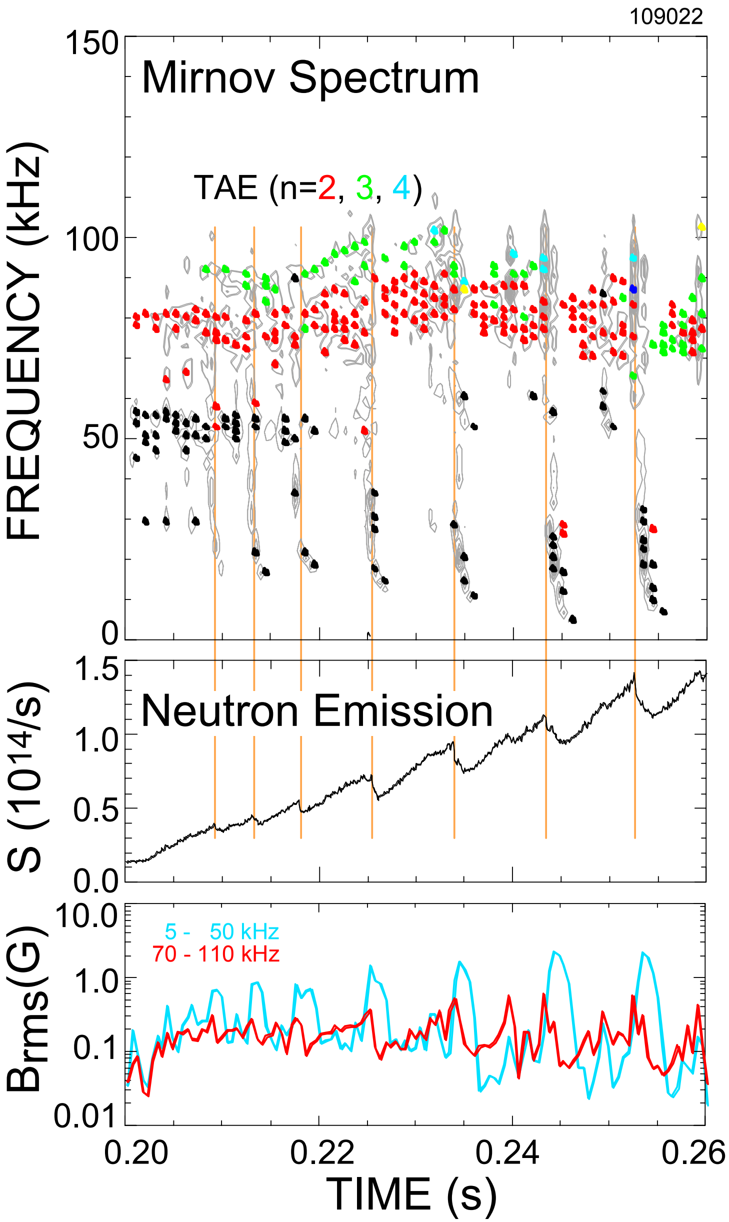
- FY2003-04
  - Explore impact of shaping, collisionality, and gaps on ELM stability
  - Characterize ΔW_{PED} and destabilization of NTMs in various ELMing regimes

- FY2004-05
  - Commission very high-*n* array data acquisition for measurement of ELM *n*-numbers.
  - Correlate measured mode numbers with ELM type.

- FY2005-06
  - Use reflectometer or other high-resolution near-edge profile diagnostic to perform preliminary measurements of ELM structure.

- FY06-08
  - 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.

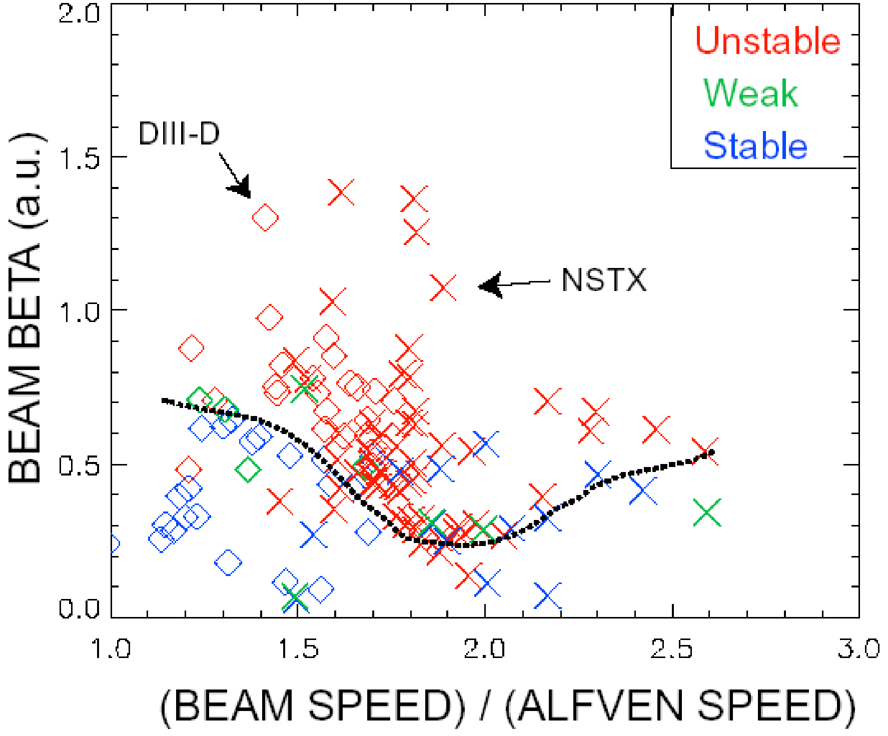
Fishbone & TAE can cause fast ion losses



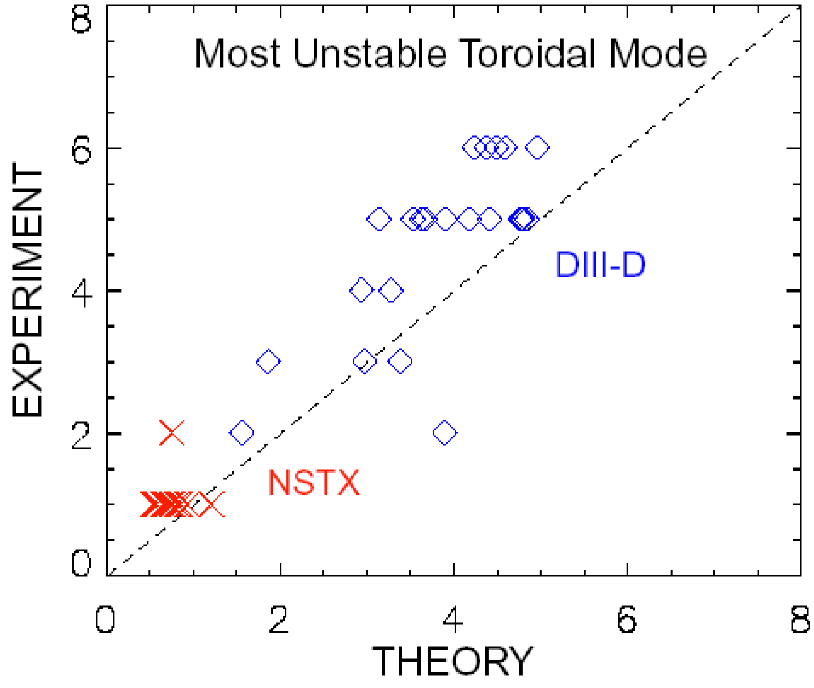
- Neutrons are beam-target; $-\delta S \propto \delta n_{fi}$
- Instabilities are TAE and "fishbones"
- TAE bursts cause initial, fast drop, fishbones later, slower drop.
- Correlation of f.b. and TAE bursts suggests coupling.
- In L-mode, sometimes correlated with D_α drops.
- Loss also seen in iFLIP

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

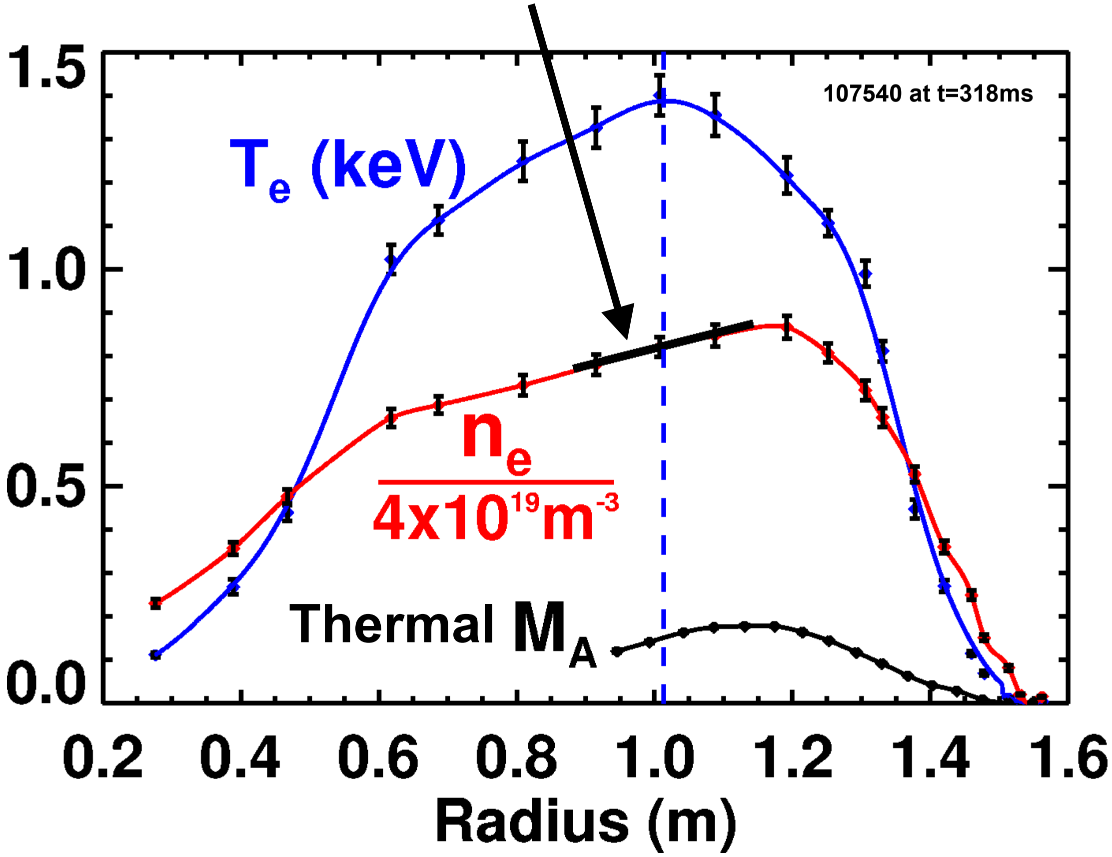
- FY2003-04
  - Perform similarity experiments on NSTX and DIII-D investigating the CAE
  - Assess if fast ion-driven play a role in high β_P disruptions (requires MSE).
- FY2004-05
  - Perform first measurements of CAE poloidal amplitude distribution and poloidal wavelength with new outboard poloidal Mirnov array (at Bay H).
  - Assess role of q profile in controlling gap structure for TAE modes.
  - Correlate fast-ion loss measurements from FLIP with mode amplitude, frequency, etc. and determine the energy of ions preferentially lost.
- FY2005-07
  - Utilize internal diagnostics including reflectometer, EBW spectrometer, or upgraded bandwidth SXR to measure internal structure of TAE, CAE, and GAE.
  - Compare to theory and modeling with NOVA, HINST, and HYM.
- FY04-future
  - Develop beam-ion profile diagnostic to determine fast-ion pressure profile.
  - Use profile shape in ideal and hybrid stability calculations
  - Assess influence of fast-ion MHD on fast-ion population properties, such as neutron rate, power deposition, fast-ion angular momentum, etc.

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
- Contributing to saturation of 1/1 modes at high-β?

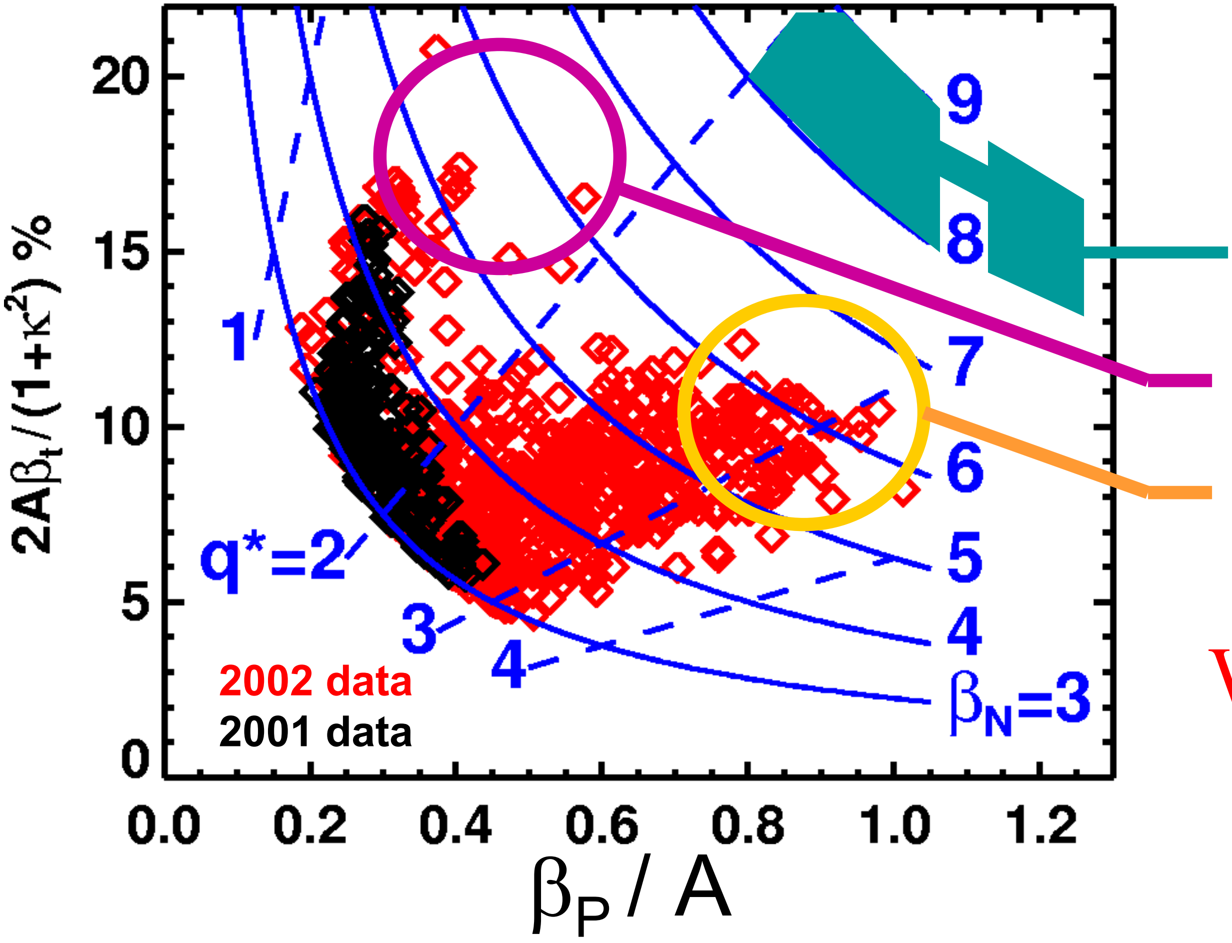
Influence of rotation on equilibrium and stability

- FY2003-04
  - Begin to include rotation effects in equilibrium reconstructions (EFIT).
    - Assess change in inferred stored energy due to inclusion of v_ϕ.
  - 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
  - Study influence of flow and flow-shear on ballooning mode stability

Steady-state ST requires high β_P

- Self-driven current fraction $\propto \beta_P \equiv 2\mu_0\langle p\rangle / B_P^2$
- $\beta_T \propto \beta_N^2 / \beta_P \Rightarrow$ Need very high β_N for steady state



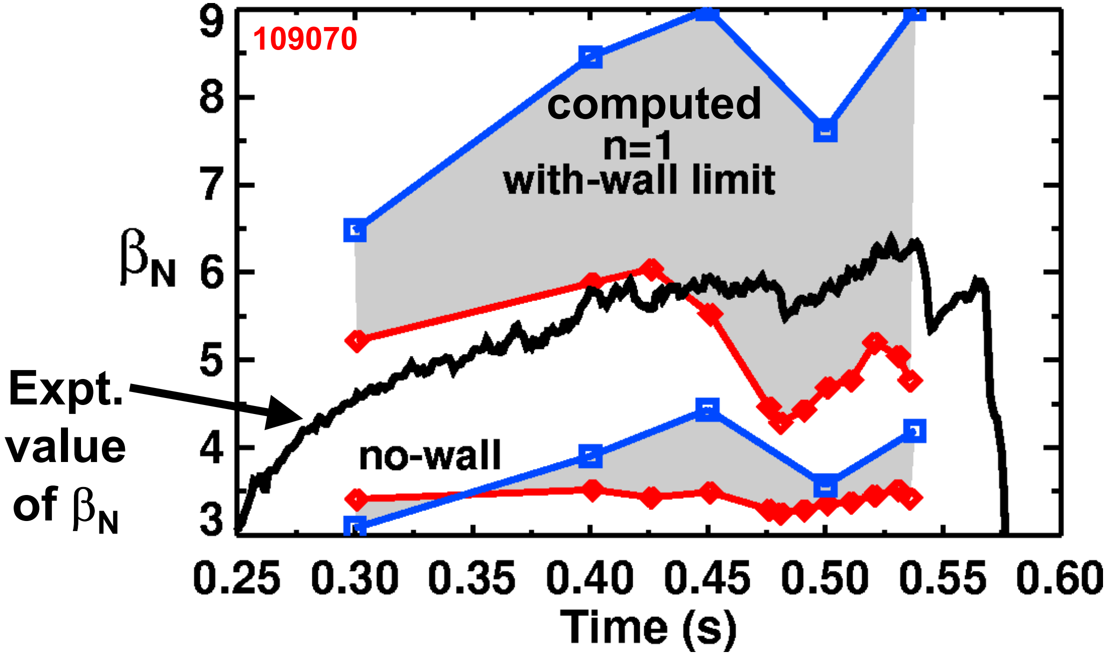
NSTX β_T=40%
Target equilibria

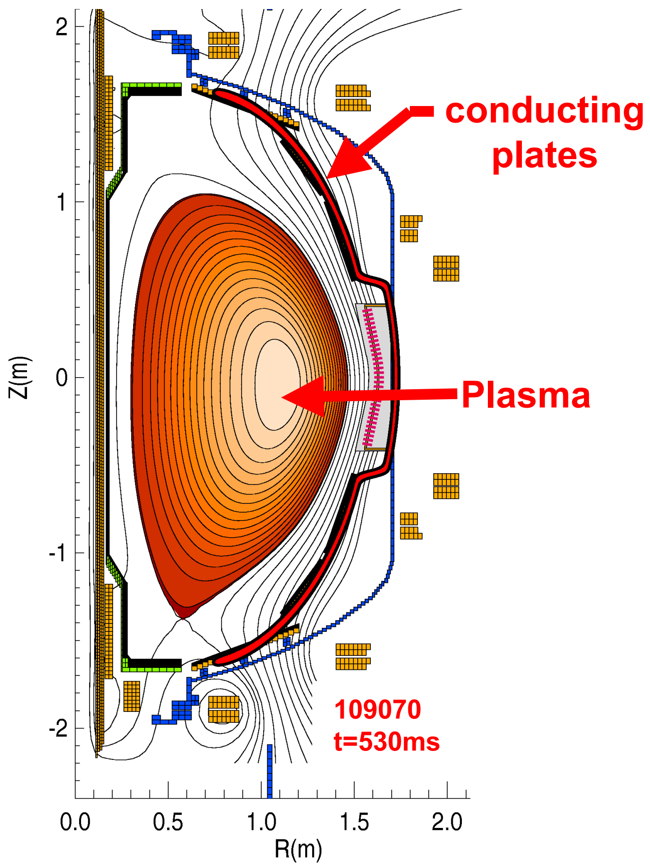
High β_T and β_N

High β_P and β_N

Want q* ≈ 2-3 at
high $\beta_N > 8$

Many high β_P shots are above no-wall limit





Theory and other experiments (DIII-D):

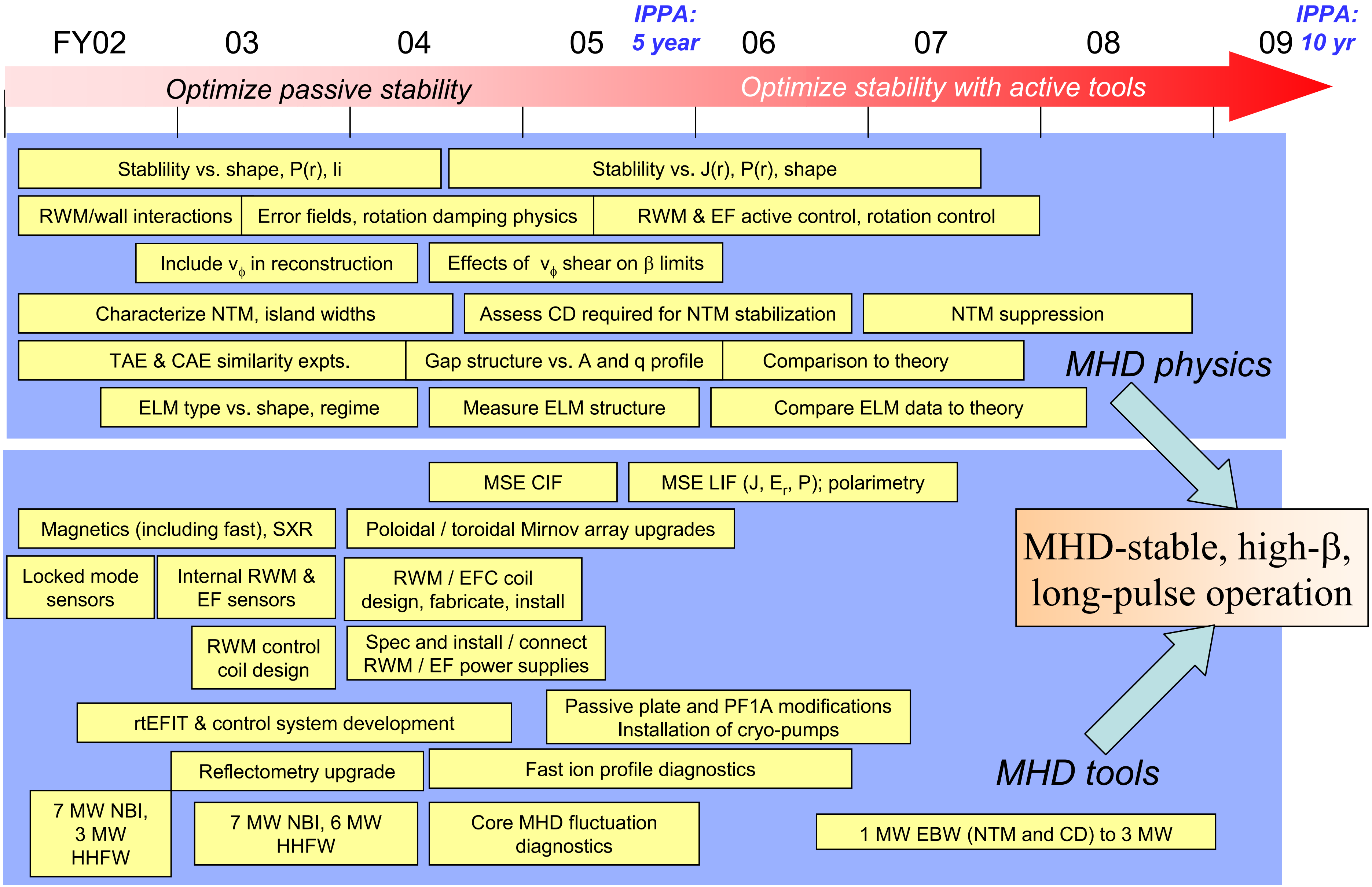
⇒ **conducting wall + rotation & dissipation can stabilize resistive wall mode (RWM)**

NSTX high β_P shots may be approaching <u>ideal-wall</u> limit

- ***Motivates RWM physics studies and active feedback system***

⇒ See next talk by S. Sabbagh

SUMMARY MHD GOAL: Provide MHD understanding and diagnostics for development of control tools needed to achieve stable, long-pulse, high-β discharges



FY02 | 03 | 04 | 05 | 06 | 07 | 08 | 09

IPPA: 5 year (after 05)

IPPA: 10 yr (after 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 tools

- MSE CIF
- MSE LIF (J, E_r, P); polarimetry
- Magnetics (including fast), SXR
- Poloidal / toroidal Mirnov array upgrades
- Locked mode sensors
- Internal RWM & EF sensors
- RWM / EFC coil design, fabricate, install
- RWM control coil design
- Spec and install / connect RWM / EF power supplies
- rtEFIT & control system development
- Passive plate and PF1A modifications Installation of cryo-pumps
- Reflectometry upgrade
- 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) to 3 MW

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