Supported by

NSTX MHD Research Proposal

Improved performance through increased understanding and control

Jonathan Menard
Princeton Plasma Physics Laboratory

For the NSTX National Team

DOE Review of
NSTX Five-Year Research Program Proposal
June 30 – July 2, 2003

Columbia U
Comp-X
General Atomics
INEL
Johns Hopkins U
LANL
LLNL
Lodestar
MIT
Nova Photonics
NYU
ORNL
PPPL
PSI
SNL
UC Davis
UC Irvine
UCLA
UCSD
U Maryland
U New Mexico
U Rochester
U Washington
U Wisconsin
Culham Sci Ctr
Hiroshima U
HIST
Kyushu Tokai U
Niigata U
Tsukuba U
U Tokyo
Ioffe Inst
TRINITI
KBSI
KAIST
ENEA, Frascati
CEA, Cadarache
IPP, Jülich
IPP, Garching
U Quebec

Overview of presentation

- MHD of high 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

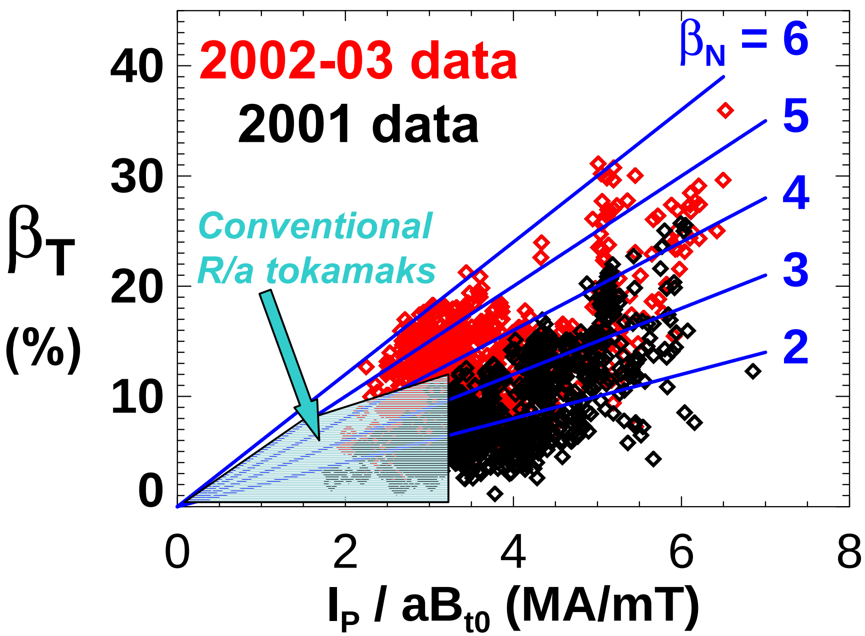
MHD Science Goal $\Rightarrow$ **Provide MHD understanding and diagnostics for development of control tools needed to achieve long-pulse, high-β discharges**

Great progress made in achieving high β

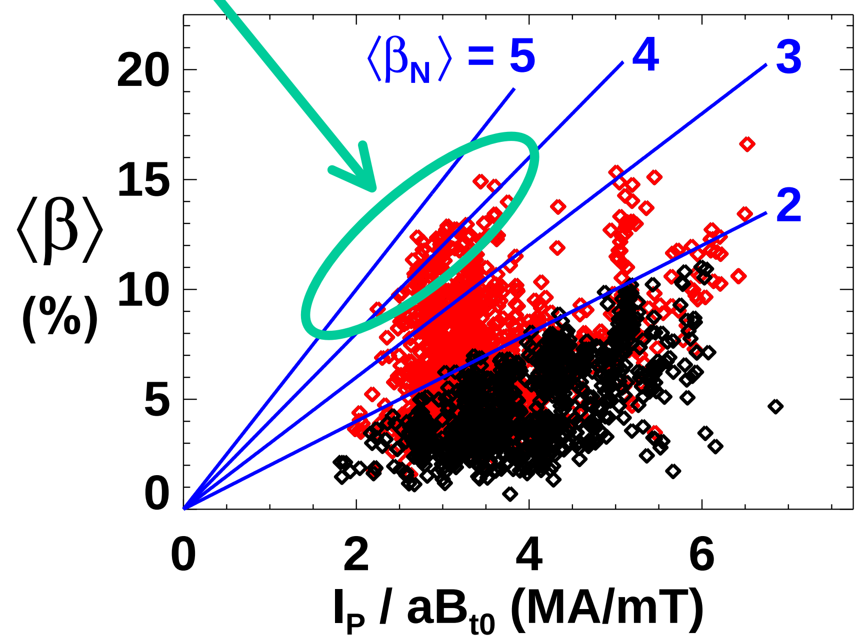
- β_T as high as 35%
- $\beta_N \approx 6$ for $I_p/aB_{T0} = 2 – 6.5$
- β_N increased 50 – 100% within 1+ years of operation
  – H-mode, error-field reduction

- Recent calculations indicate:
  Ideal no-wall limit **$\approx \langle\beta_N\rangle \leq 3.5$**
  (independent of R_0/a for $q^* > 1.7$)
- **Many shots have clearly *exceeded* this scaling**

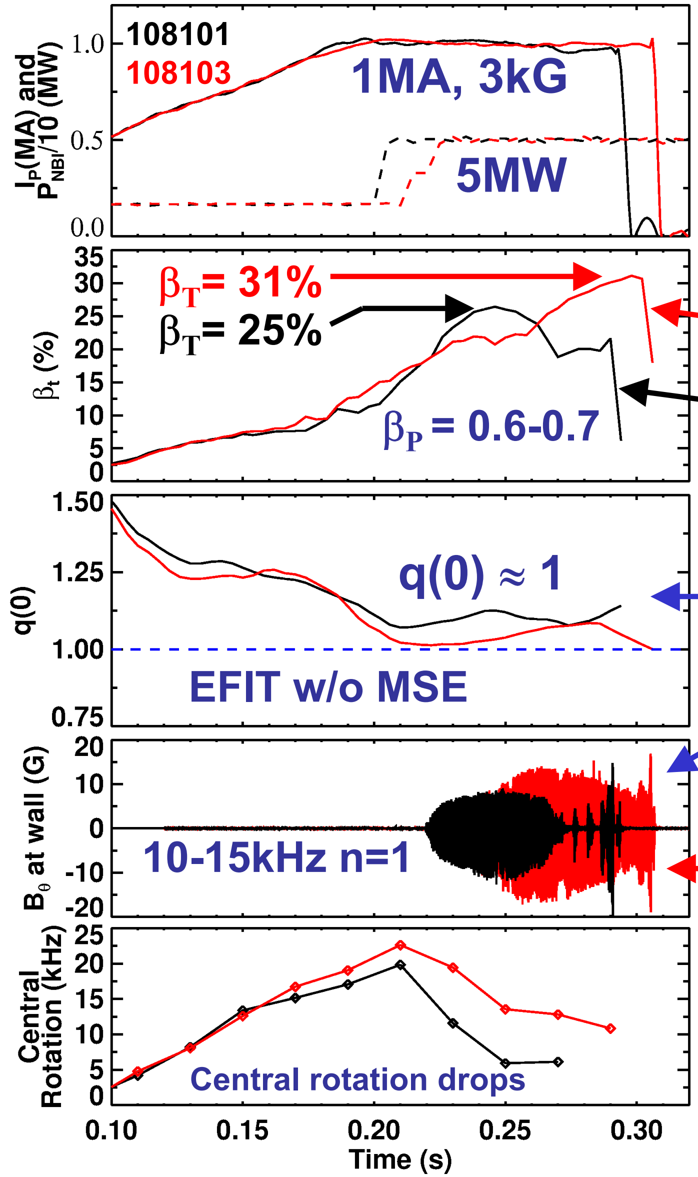
$\beta_T \equiv 2\mu_0\langle p\rangle / B_{T0}^2$



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



Rotation plays strong role in high-β MHD



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

Sometimes β rises throughout shot

Sometimes 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?

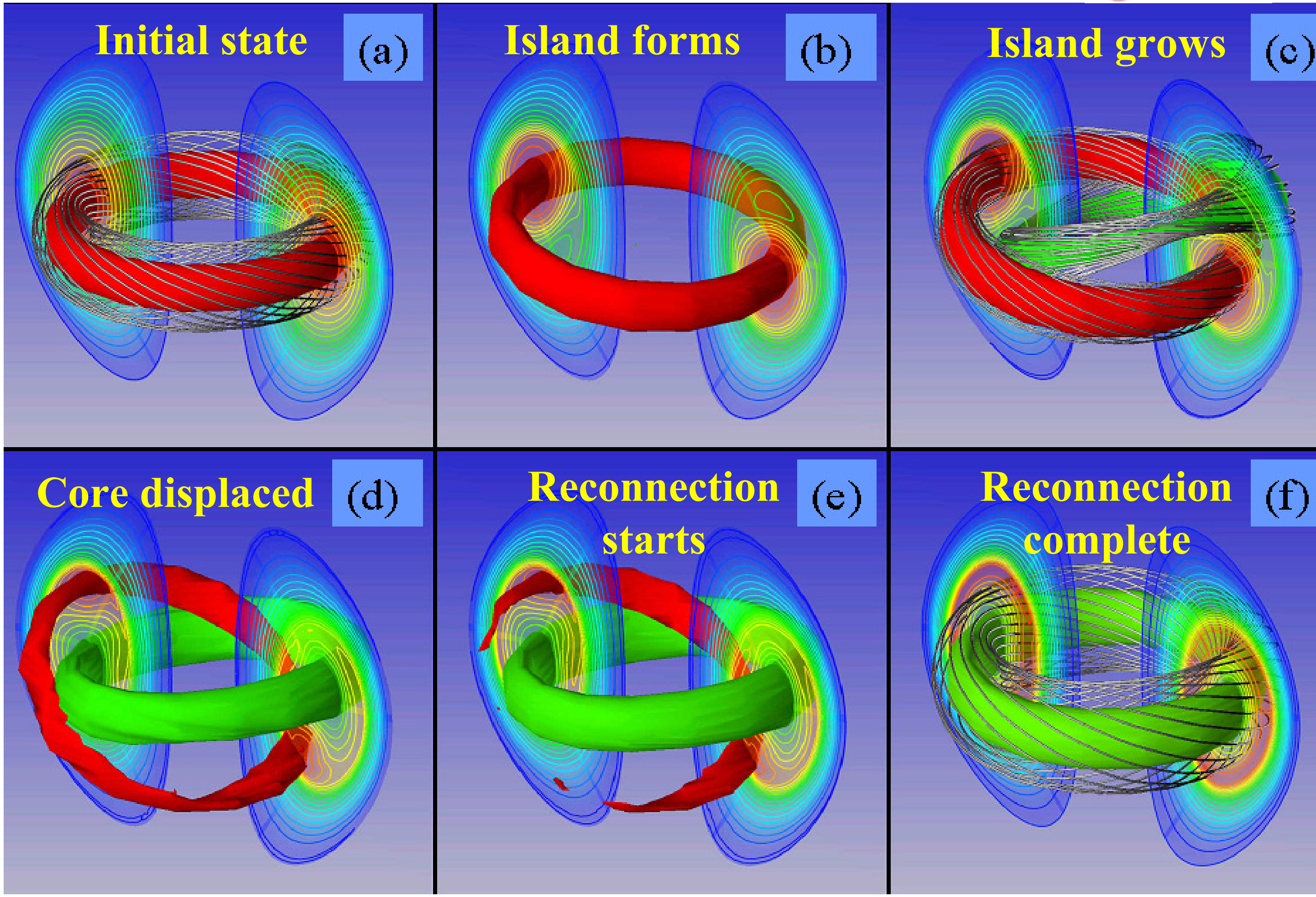
Difference may be ***sustained rotation***

Simulations provide insight into 1/1 mode physics

(from Wonchull Park, M3D code, PPPL)

Simulation without rotation ⇒

B-field lines
Hot core
Cold island

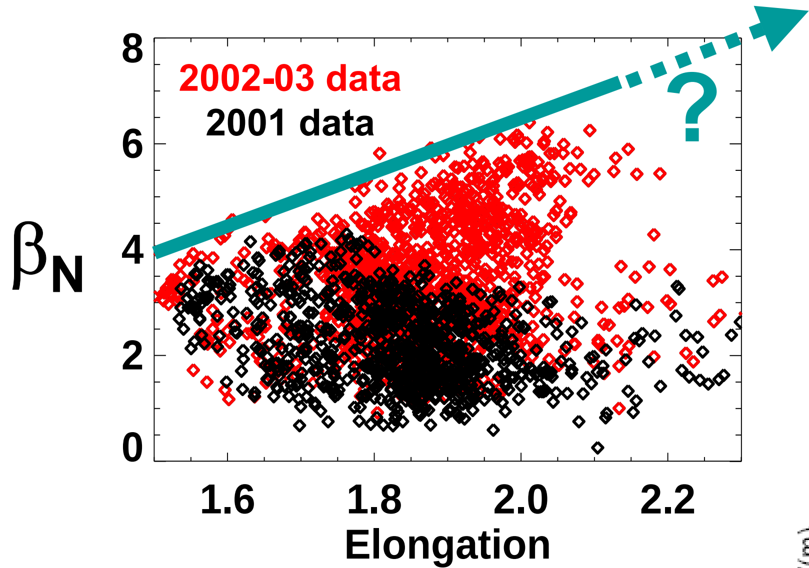


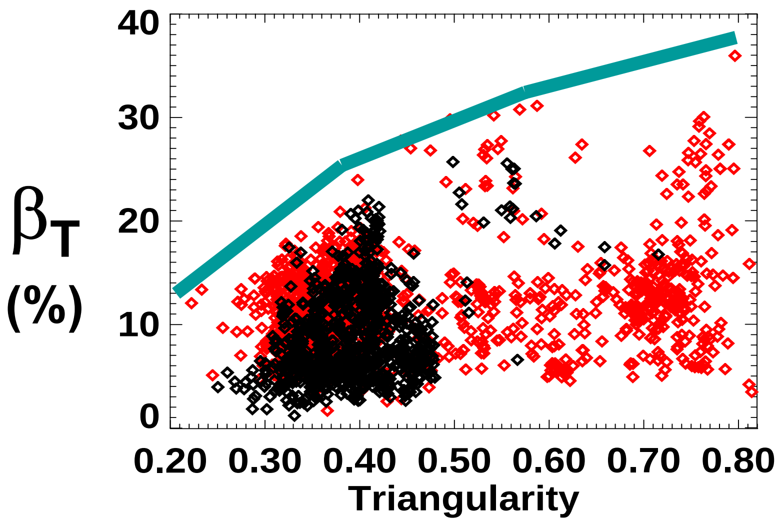
Reconnection interrupted when $\gamma_{shear} \rightarrow \gamma_{growth}$ and ***p*** higher in island

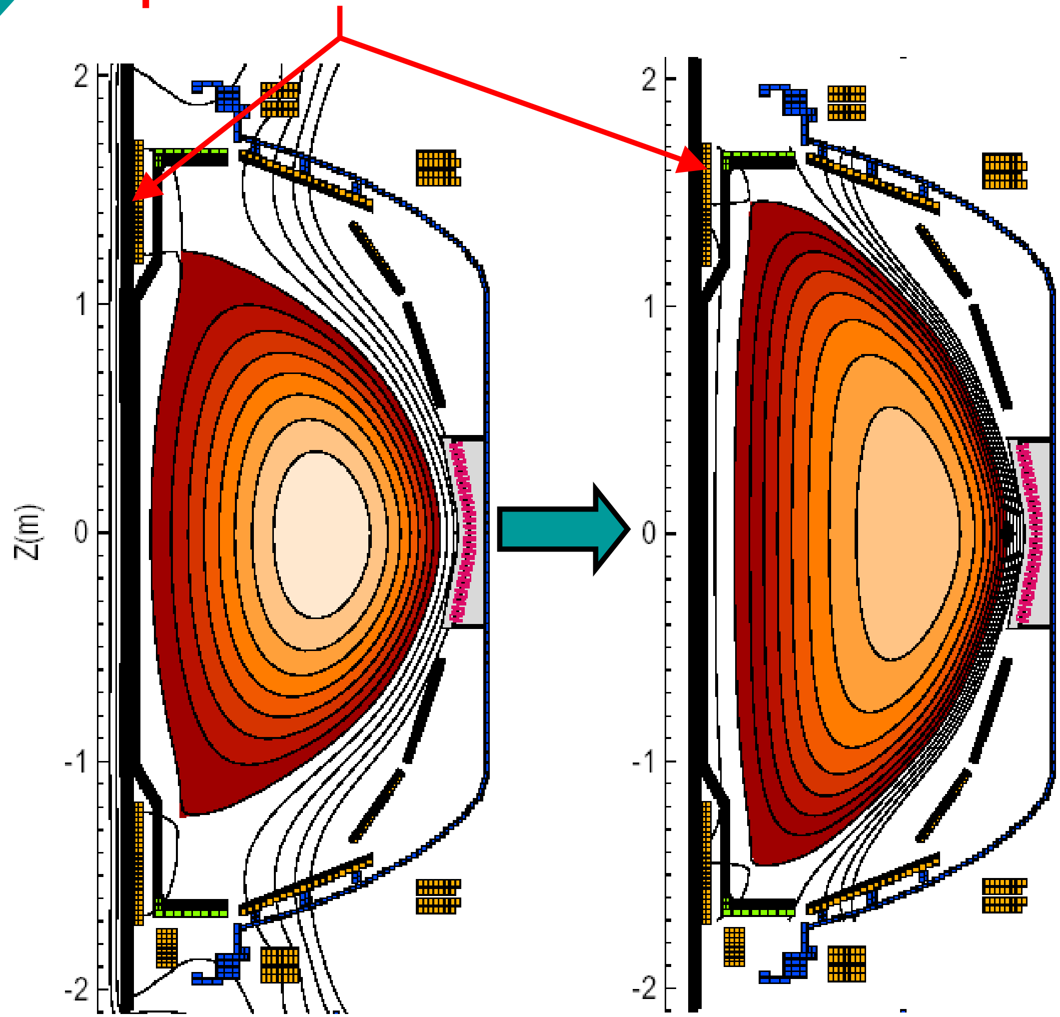
May explain long-lived 1/1 modes in high β_T NSTX discharges

Stability results motivate shaping enhancements

Split PF1A ⇒ $\kappa \rightarrow 2.4$ at $\delta=0.8$







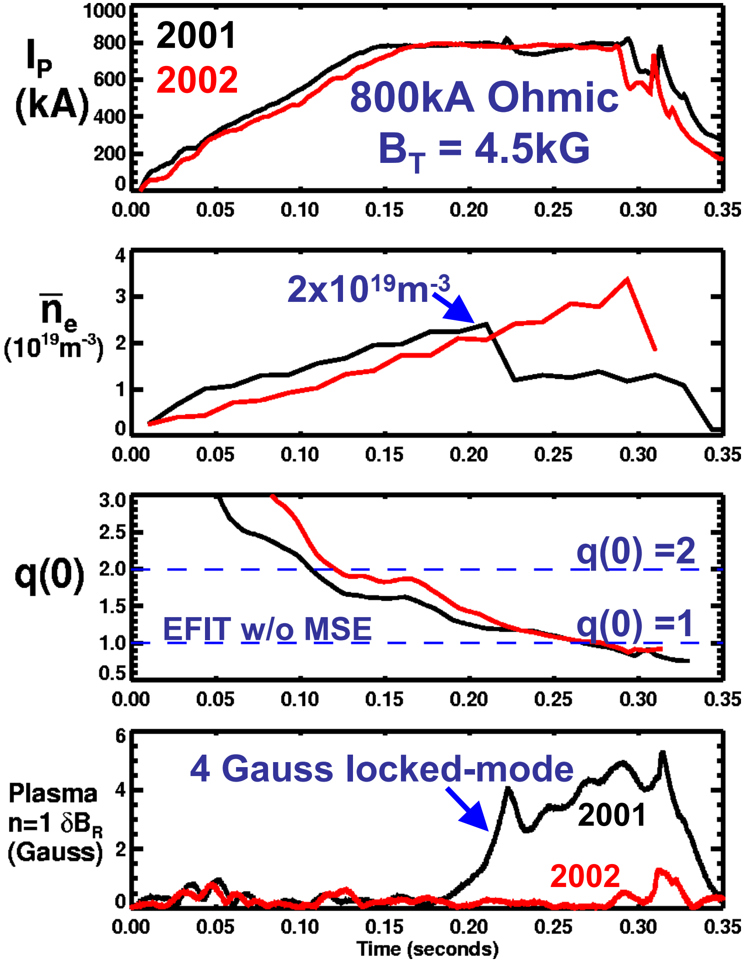
Proposed path to β_T=40%, 100% NICD

Measure, control, and optimize shape and profiles

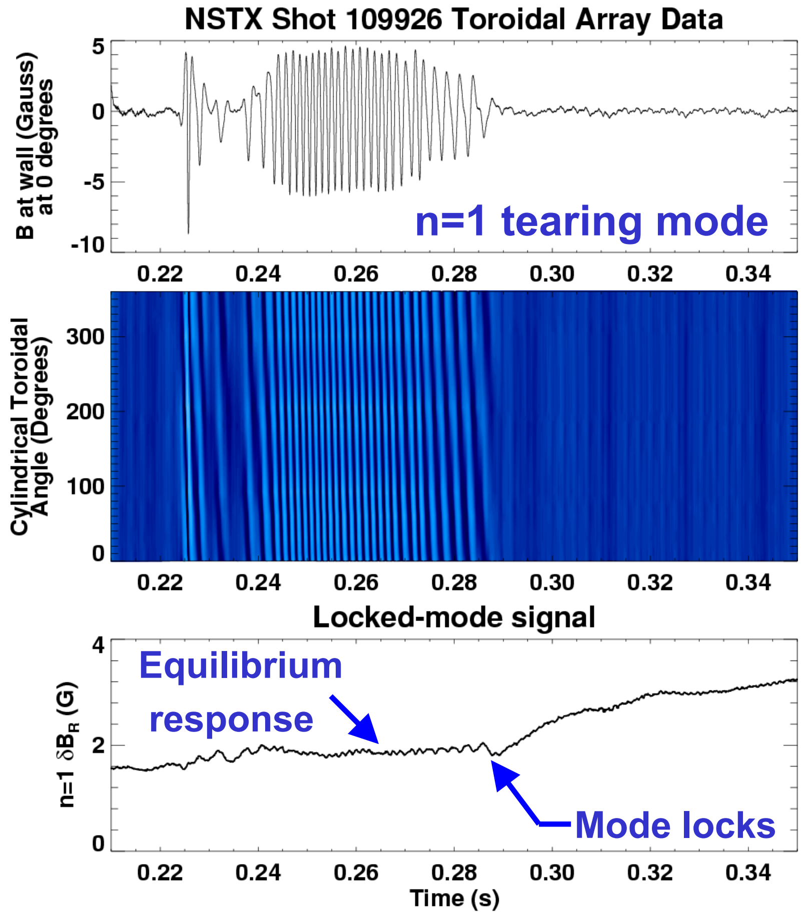
- Study impact of enhanced plasma shaping
  - Continue stability studies vs. κ and δ with present PF1A *(FY03-05)*
  - Utilize split-PF1A to increase κ and control x-points *(FY05,6-08)*
- Perform J-profile variations and measurements
  - First MSE constrained reconstructions *(FY04-05)*
  - Measure J-profile early during discharge ramp-up *(FY05)*
  - Scan I_P ramp-rate for high-β_T and β_P and optimize performance *(FY04-06)*
  - Assess low-A and kinetic effects on ballooning stability *(FY04-06)*
- Benchmark and utilize equilibrium evolution codes *(FY04-06)*
  - Characterize J(r), p(r) evolution, benchmark TSC, TRANSP, other
  - Use codes to identify stable high-β targets with high NICD fraction
- Control J profile *(FY06-08)*
  - MSE-constrained rtEFITs
  - Attempt real-time J(r) control using HHFW, EBW
  - Combine J profile and shape control, study MHD as $\beta_T \rightarrow 40\%$, $f_{NICD} \rightarrow 100\%$
- Develop real-time predictive capability for stability *(FY04-08)*

Locked-modes highlight role of non-axisymmetric fields

- PF5 vertical field coils found to generate large n=1 δB_r in 2001
- Coils subsequently re-shaped:



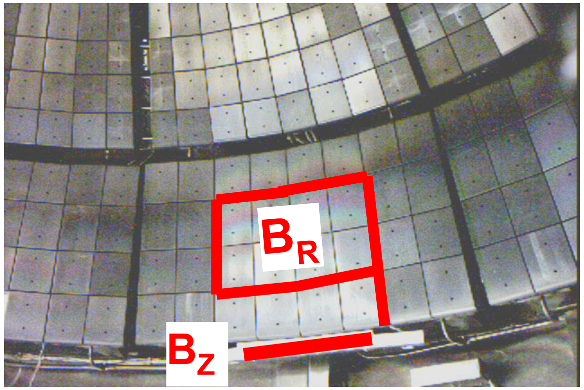
- Mode-locking only observed at low n_e, B_T
- Modes still lock to preferred locations



800kA, 2×10^{19} m^{-3}, 3.5kG

Active coils will allow studies of non-axisymmetric physics

- RWM physics and active feedback ***(see S. Sabbagh talk)*** *(FY04-08)*
- Study locked-mode physics
  - Measure locked-mode structure with new internal sensors *(FY04)*
  - Use new sensors to infer sources of error-field *(FY04-05)*
  - Apply known error-fields to elucidate locking physics *(FY04-06)*
- Study rotation damping with NBI and high-β
  - Vary applied error-field to minimize rotation damping *(FY04)*
  - Compare coil currents to those computed to minimize EF *(FY04-05)*
  - Develop pre-programmed error-field correction algorithms *(FY04-05)*
  - Study impact of applied field near and above no-wall limit *(FY04-06)*
- Develop active control capabilities *(FY04-06)*
  - Utilize real-time internal sensor measurements and deploy dynamic error-field correction algorithms

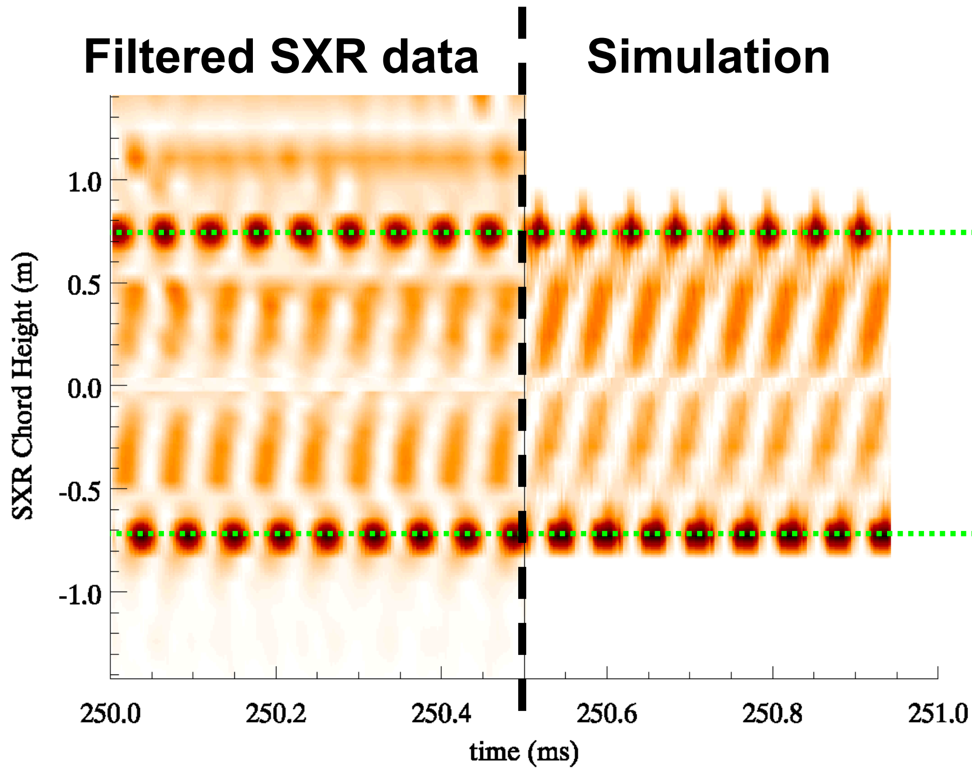


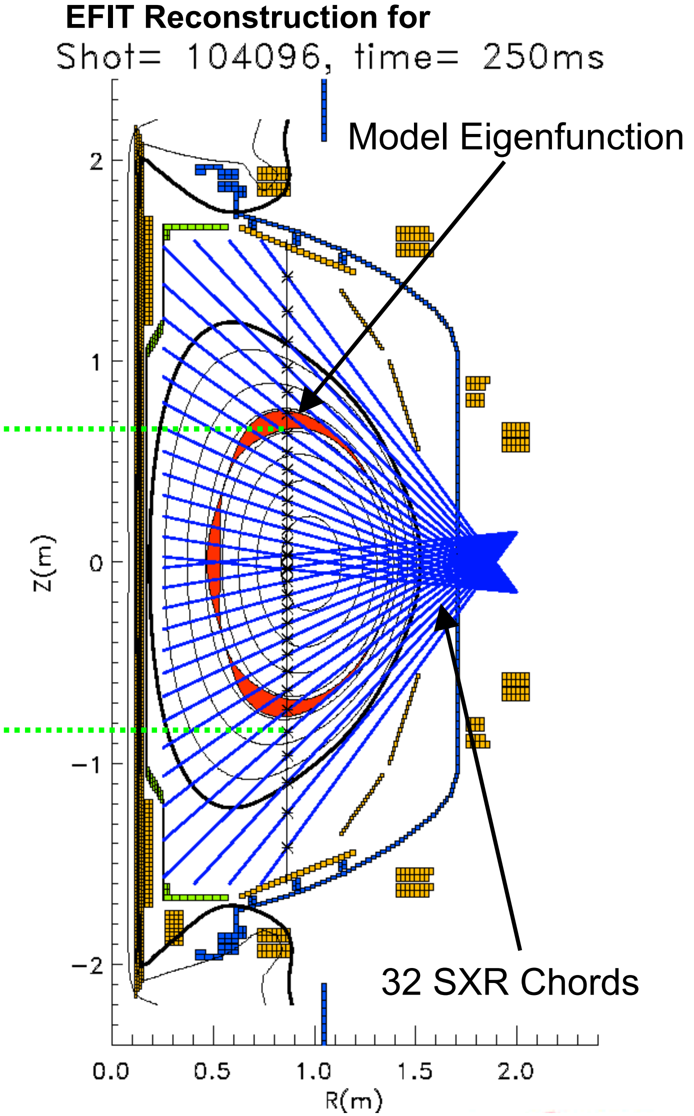
New internal RWM/EF sensors

NTMs often limited performance in FY01

β_P limit increased significantly in FY02 ($0.6 \rightarrow 1.4$)

- **EXAMPLE:** SXR data indicates odd-parity mode with inversion radius = 3/2 mode rational surface from EFIT





Understand and control NTMs

- Enhance code capabilities
  - Implement more accurate wall shape model in PEST-III *(FY03)*
  - Add Mirnov signal model for wall-stabilized tearing modes *(FY03-04)*
  - Compare model to experimental data *(FY03-08)*

- Enhance diagnostic coverage and physics understanding
  - Assess seeding mechanisms for NTMs in various regimes *(FY04-06)*
  - Investigate non-linear coupling of NTMs of different helicities *(FY04-06)*
  - Work with MAST NTM group on NTM similarity experiments *(FY04-06)*
  - Measure *m*-numbers with new poloidal Mirnov array *(FY05-06)*
  - Infer island widths from measurements and improved modeling *(FY05-06)*

- NTM control *(FY06-08)*
  - Alter NTM stability with global J-profile variations from EBW-CD
  - Use EBW-CD to test direct NTM stabilization

Understand and optimize ELM stability

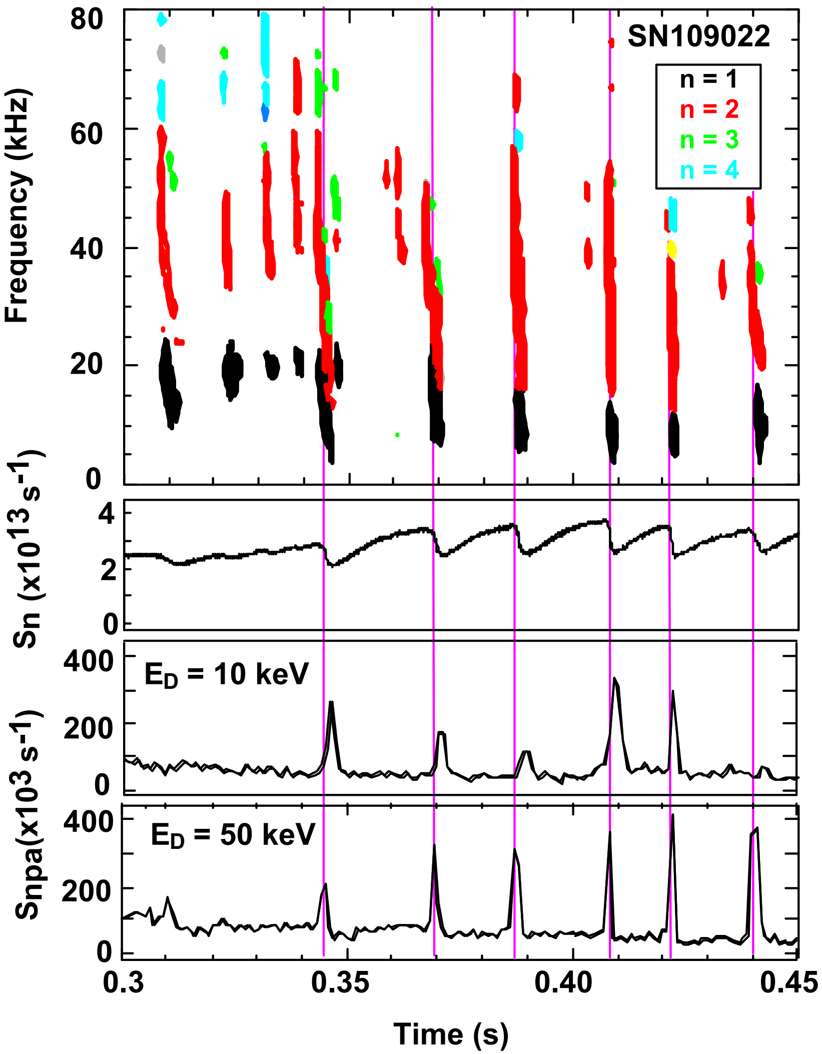
- Determine operational dependencies *(FY04-05)*
  - Explore impact of shaping, collisionality, and gaps on ELM stability
  - Correlate destabilization of NTMs with ELM activity

- Enhance diagnostic coverage
  - Install very-high-*n* array to measure of ELM *n*-numbers *(FY04-05)*
  - Begin measurement of edge gradients and ELM structure *(FY05-06)*
    - Use reflectometer, edge Thomson, reciprocating probe
  - Correlate measured mode numbers and ∇p with ELM type *(FY04-06)*

- Compare observed stability characteristics to theory *(FY06-08)*
  - Perform controlled experiments to excite different ELM types
    - Kinetic EFITs with MSE and core and edge p-profile information
    - Explore impact of enhanced shaping from split-PF1A
  - Study ELM threshold, mode structure, and toroidal mode numbers
    - Compare to results from codes ELITE, DCON, PEST, and/or GATO
    - Correlate ELM type with edge second-stability access

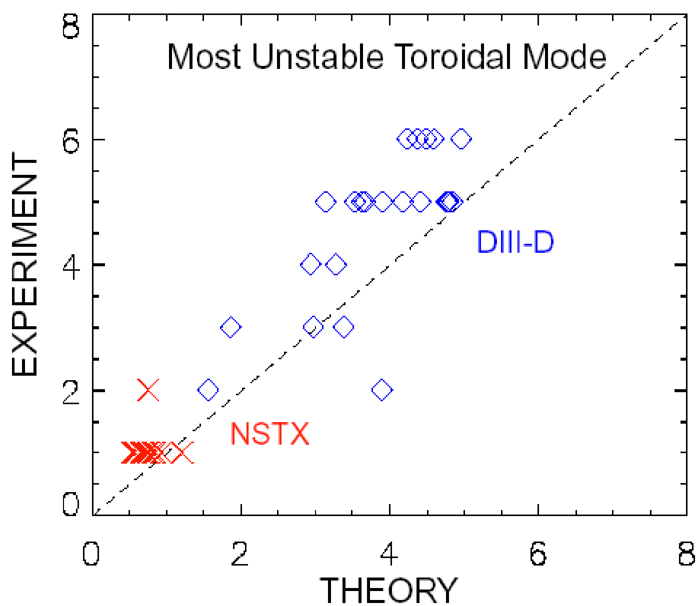
- Optimize edge stability for long-pulse operation *(FY04-08)*

Fishbone & TAE can cause fast ion losses



- n > 1 modes interpreted to be TAE
  - n = 1 as "bounce" fishbones
- Transport of core fast ions by n=2 mode
  - Fast ions then destabilize n=1, ions lost

NSTX/DIII-D Similarity Experiment Finds TAE Mode Number Scales as Expected



NSTX Accesses $v_{Fast} > v_{Alfvén}$ Physics

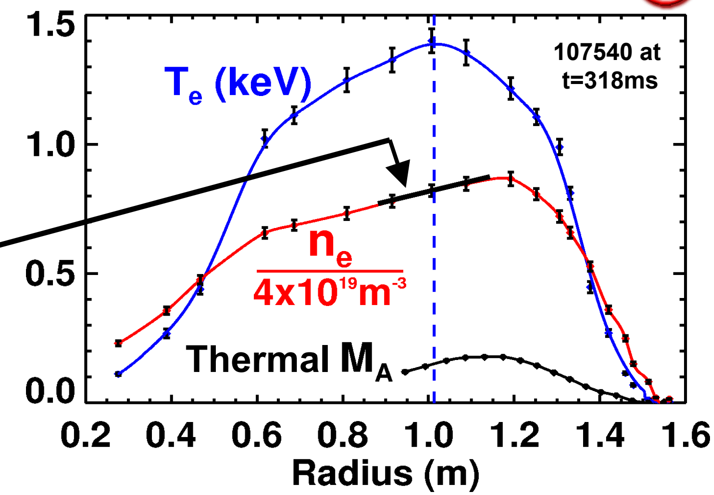
Relevant to ITER, ICCs and Future ST Devices

- Assess impact of fast-ion-driven MHD on high-β_P operation *(FY03-05)*
- Perform inter-machine research *(FY03-05)*
  - CAE similarity experiments on NSTX and DIII-D
- Enhance diagnostic coverage
  - Measure CAE poloidal amplitude distribution and wavelength *(FY04-05)*
    - Use new outboard poloidal Mirnov array
  - Study role of q profile (MSE) on gap structure of TAE modes *(FY04-05)*
  - Understand fast-ion loss physics *(FY04-05)*
    - Correlate neutron rates with fast-ion loss measurements (FLIP, NPA)
    - Correlate lost ion energy w/ mode amplitude, *n*-number, and frequency
  - Measure internal structure of fishbone, TAE, CAE, and GAE *(FY05-07)*
    - Reflectometer, upgraded-bandwidth SXR, and EBW spectrometer
  - Develop beam-ion profile diagnostics for fast-ion pressure profile *(FY04-future)*
    - Vertical scanning NPA, neutron collimator, D-D fusion product detector
    - Use profile shape in ideal and hybrid stability calculations
    - Assess influence of fast-ion MHD on fast-ion population properties
      - Neutron rate, power deposition, fast-ion angular momentum, etc.
- Compare to theory and modeling with NOVA, HINST, HYM *(FY05-07)*

Fast rotation modifies equilibrium, stability

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

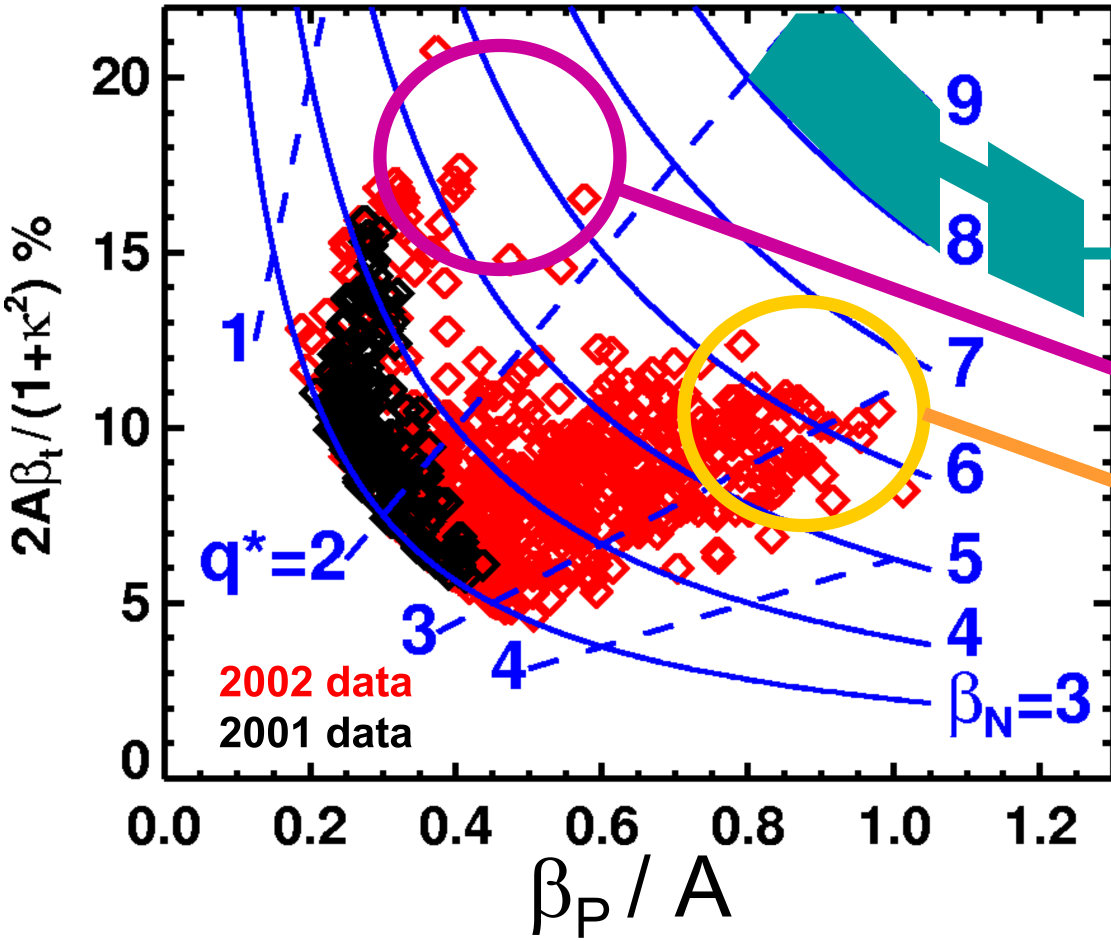
At axis, $R[d\log(n_e)/dR] = 2M_A^2 / \beta_{local}$
(includes thermal and fast ions)



- <u>Include flow effects in equilibrium and stability codes:</u>
  - Include rotation in equilibrium reconstructions (EFIT) *(FY03-04)*
  - Continue to assess flow stabilization of kink modes (M3D) *(FY03-05)*
  - Use **FLOW** equilibrium code for interpreting experimental data *(FY04-06)*
    - Infer changes in fast ions from changes in central gradient
  - Cross-check against fast ion profile data (NPA, FLIP, etc.) *(FY04-06)*
  - Develop *linear stability code* based on **FLOW** equilibrium *(FY04-future)*
    - Study influence of flow and flow-shear on ballooning 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



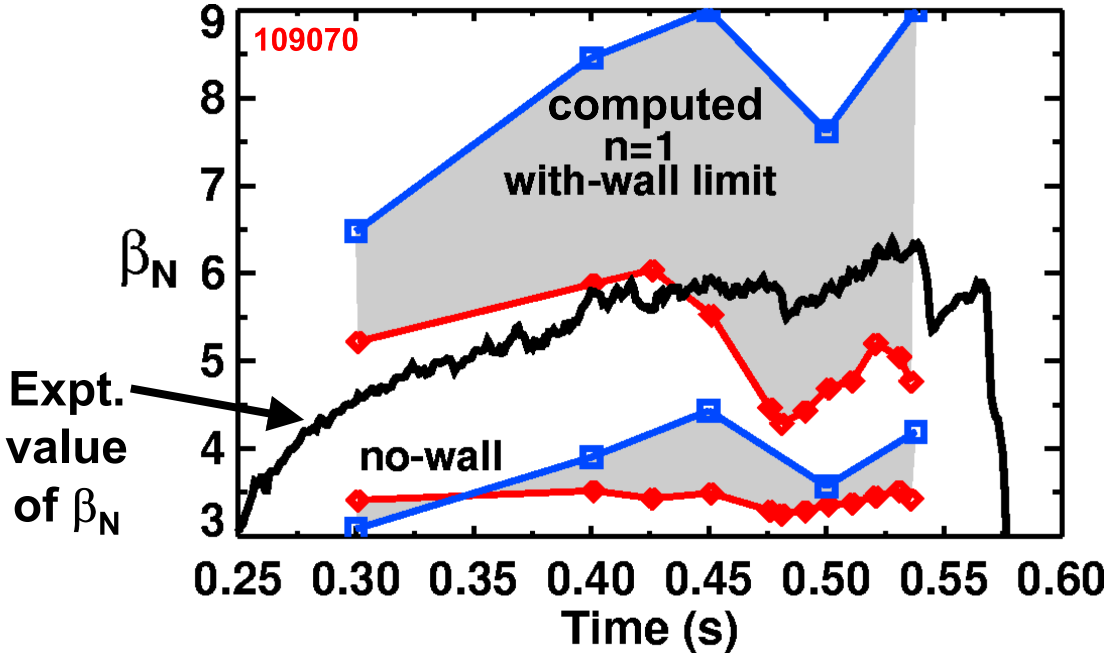
NSTX β_T=40%
Target equilibria

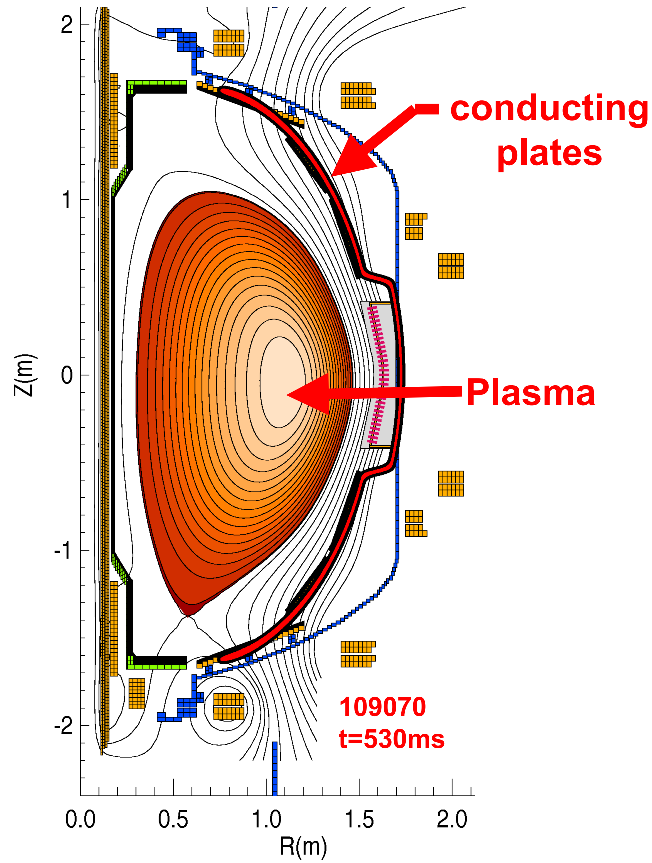
High β_T and β_N

High β_P and β_N

Want q* ≈ 2-3 at high β_N > 8

Many high-β_P shots operate above no-wall limit





Theory and other experiments (DIII-D):

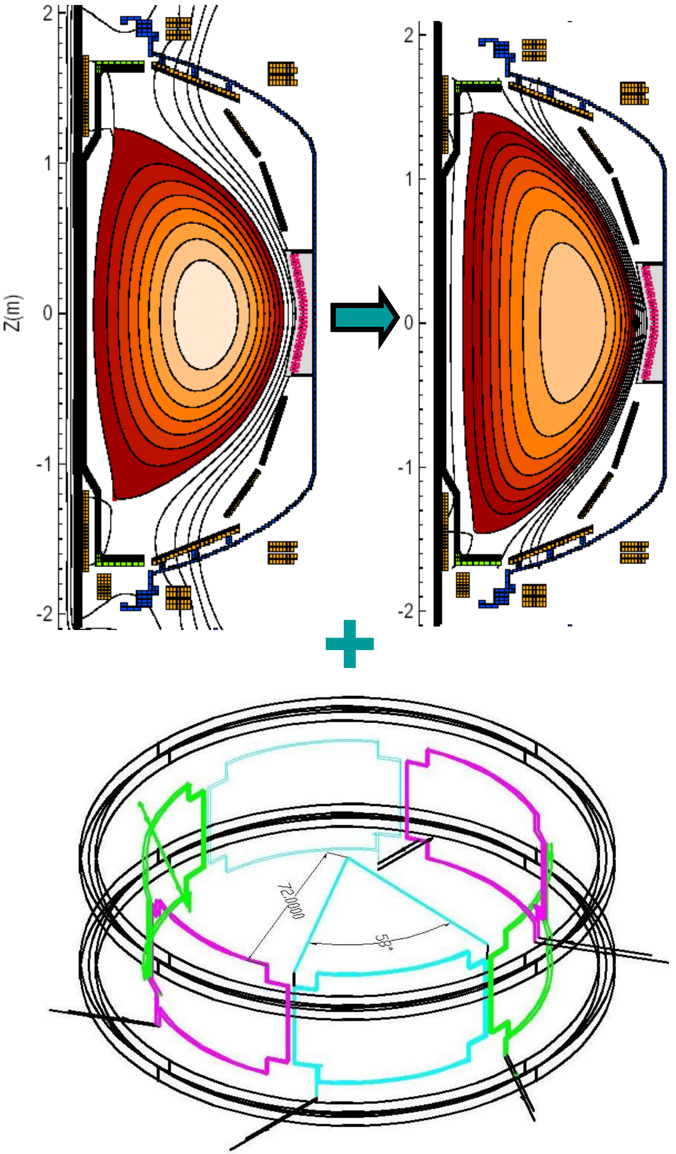
⇒ conducting wall + rotation & dissipation can stabilize resistive wall mode (RWM)

NSTX high β_P shots are approaching ideal-wall limit

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

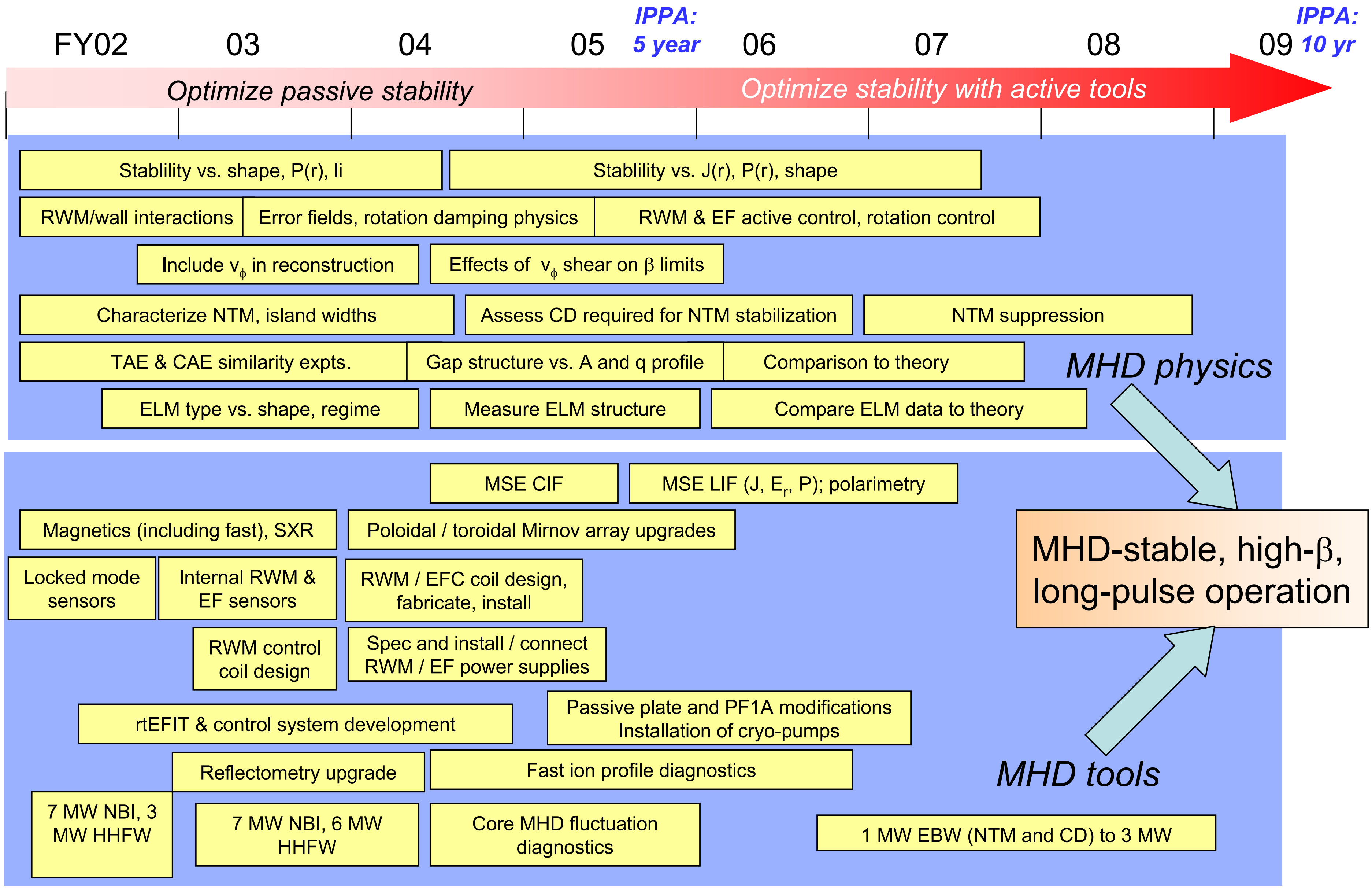
⇒ See next talk by S. Sabbagh

Data and modeling point way to exciting performance



- Higher κ to increase bootstrap current
  - High-β scenarios with 100% NICD
- Enhanced intrinsic stability
  - High δ for good stability at high κ
  - Broad p & J profiles for high ideal-wall β_N
  - Elevated q(0) > 2 to eliminate low m/n
    - Eliminate NTM at its source
    - Optimize CD from BS, NBI, and EBW
- Active control of MHD
  - Error-field suppression and RWM control
  - NTM feedback using EBW

Proposed MHD Research Timeline



SCIENTIFIC GOAL:

Provide MHD *understanding* and *diagnostics* for development of *control* tools needed to achieve

Stable, long-pulse, high-β discharges

The plan proposed to achieve this goal will:

- Enhance shaping, perform J-profile measurement and control
- Do EF & RWM physics and control w/ non-axisymmetric coils
- Enhance diagnostics and use J-profile tools for NTM physics
- Enhance ELM diagnostics and understanding - optimize edge
- Understand fast-ion MHD - impact on future devices
- Understand and incorporate flow in equilibrium and stability