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Macroscopic Stability Research in NSTX

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for the NSTX Research Team

19th NSTX Program Advisory Committee Meeting

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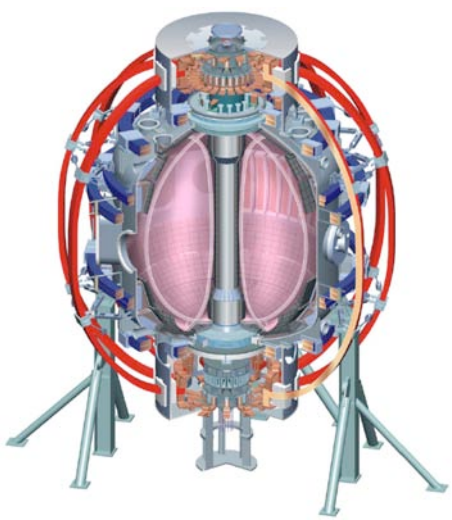

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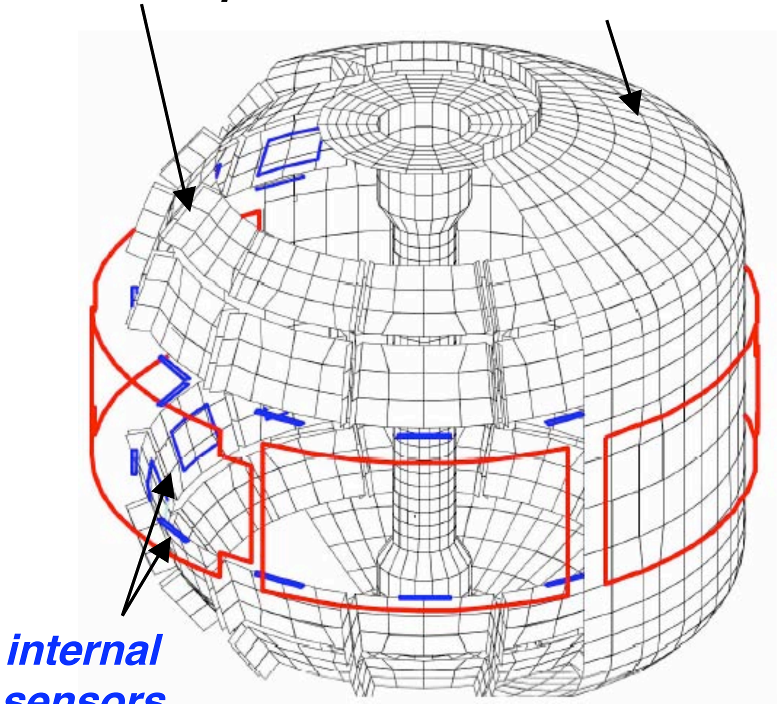
NSTX Contributions to MHD Stability Physics Give Strong Basis for Advanced Operations in ITER & STs

- NSTX research supports tokamak MHD physics in general
  - theories developed/tested on NSTX apply directly to tokamaks
    - Data comparison to theory extends our theoretical understanding; effects due to toroidicity, trapped particles, etc. of greater importance
  - unique operating space (beta, A, etc.) can be accessed to test theory thoroughly

  $\Rightarrow$ *NSTX research builds physics knowledge for all tokamak devices*

- MHD research in the next three years supports ITER & ST
  - new non-axisymmetric coils for active mode control and physics studies will be used to meet NSTX milestones
    - active control of error fields and the resistive wall mode (RWM)
  - active control effort will contribute to ITPA and USBPO MHD Task Force initiative to design joint ELM/RWM control coil for ITER

New Facility and Diagnostic Upgrades Allow Testing of ITER-like Active Mode Control System



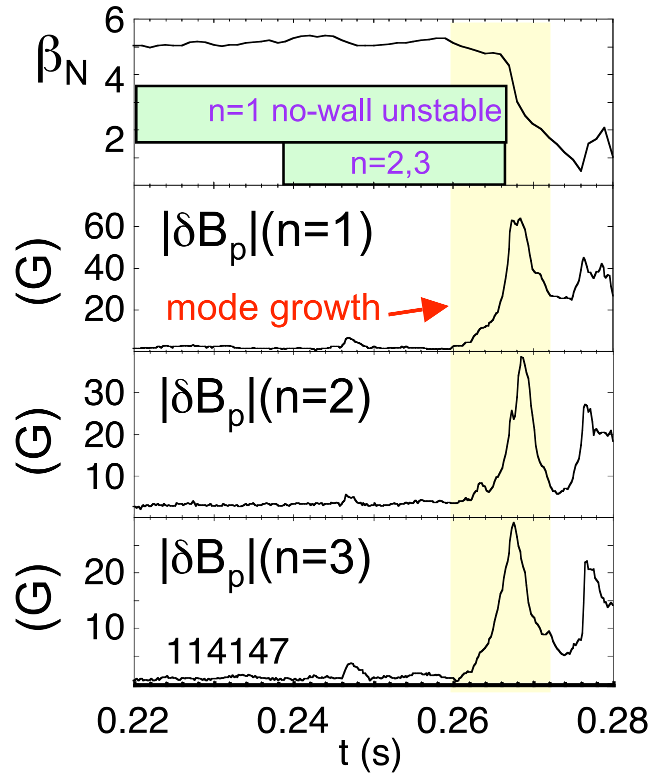
VALEN Model of NSTX (J. Bialek)

6 ex-vessel midplane control coils

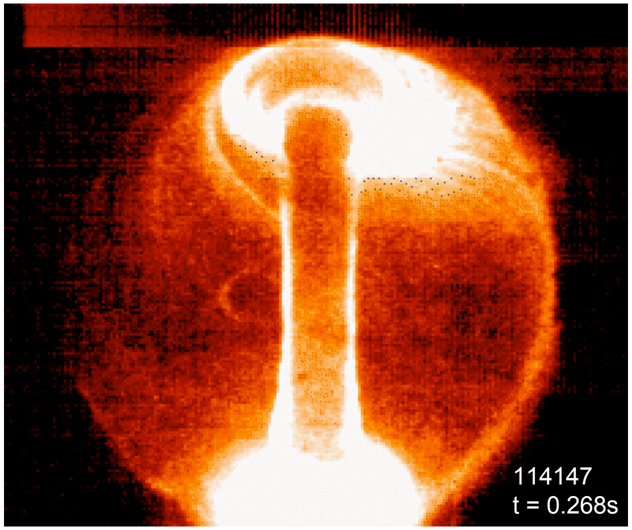
- NSTX mode control system similar to ITER midplane port plug design
- EF/RWM coil and SPA capabilities:
  - 3 opposing coil pairs in anti-series (n=1,3)
    - n=2 interconnection also possible
  - 3 independent SPA circuits - 3.3 kA, 7.5 kHz
  - produce 10-15 G n=1 resonant $B_\perp$ at q=2
- Uses for NSTX:
  - error field correction; active RWM control
  - plasma rotation reduction/control
  - investigate Ω_{crit} profile by perturbing ω_ϕ
  - study resonant field amplification (RFA)
- VALEN code used in system design and subsequent comparison to XP
  - initial comparison to MARS-F underway

Internal Sensors Measure Toroidal Mode Spectrum of RWM for n = 1 - 3

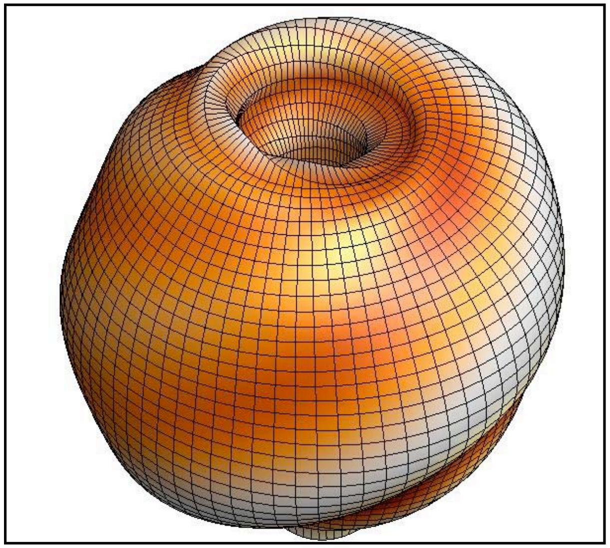
- RWM with n=1-3 components observed during unstable growth phase
  - first observation unstable RWM with n > 1 in a tokamak device
- Reconstructed mode shape similar to visible image
  - internal structure computed with DCON; amplitudes/phases from sensors



RWM with ΔB_p = 92 G

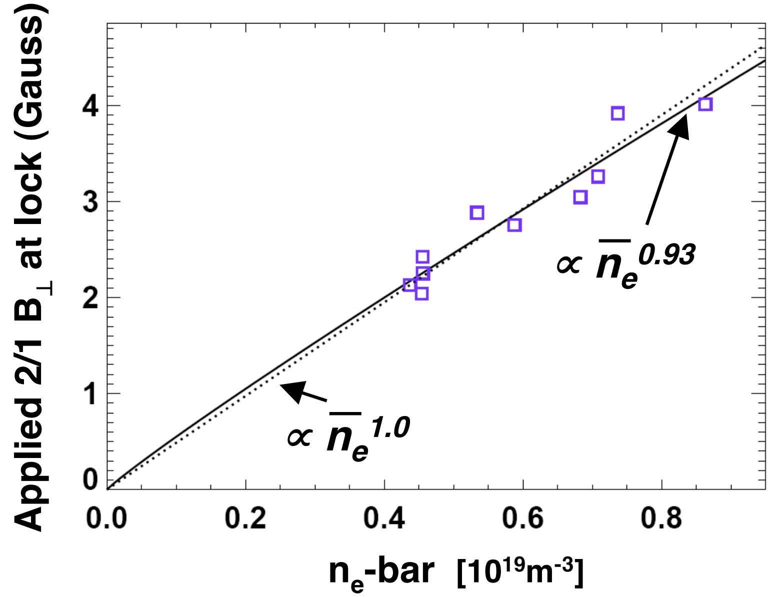


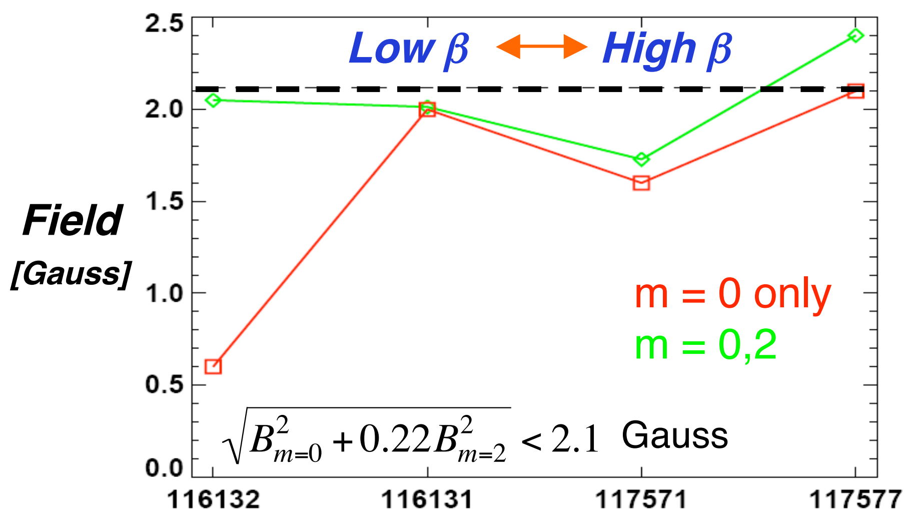
Theoretical ΔB_ψ (x10) with n=1-3 (DCON)



NSTX Data Show Scaling of Locked Mode Threshold With Density and Error Field

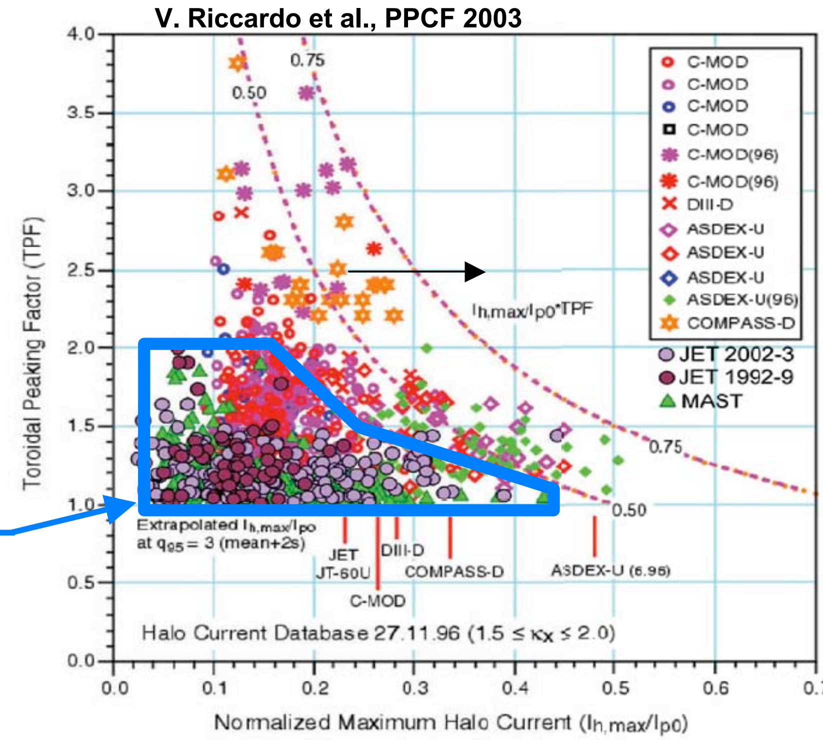
- Contributes to ITPA joint experiment on error field threshold scaling for ITER
  - B-field scaling determines size scaling of error field threshold
- External field applied to cause mode lock as density is varied
  - density scaling nearly linear
  - will widen B and n_e range in 2006 experiments
- Data suggest non-resonant error field significant
  - fit with m = 0, 2 components gives empirical 2.1 G threshold





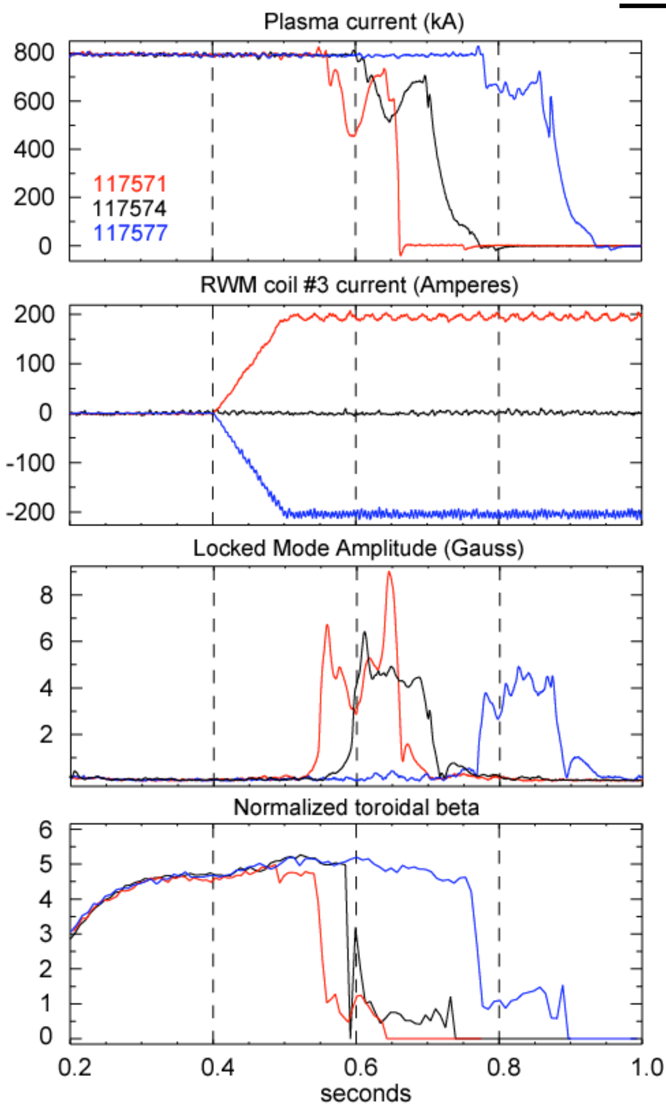
NSTX Will Continue to Make Contributions to Disruption Physics Understanding Needed for ITER & CTF

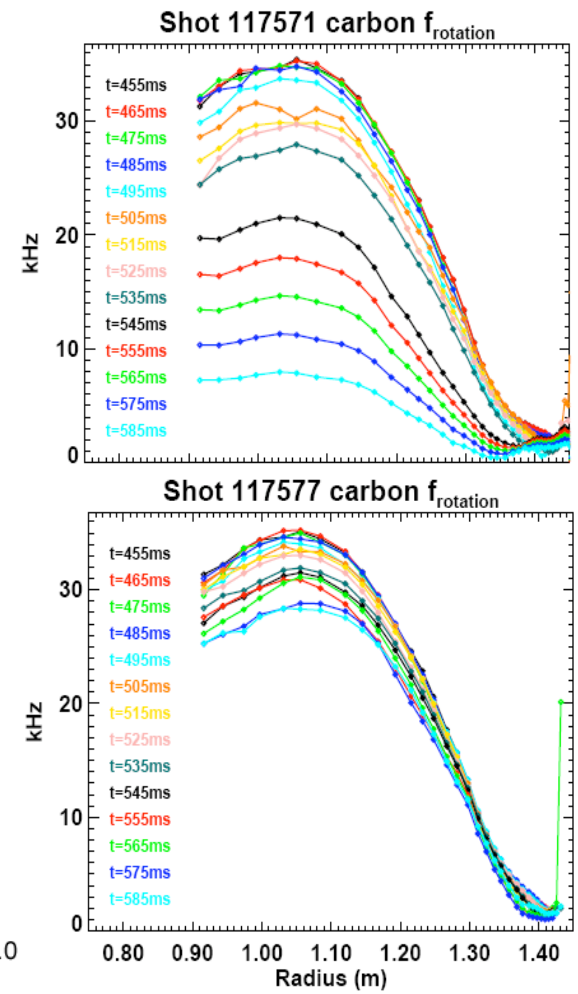
- Disruptions may pose serious risk to internal components of ITER and CTF:
  - EM forces from current quench (CQ)
  - PFC damage from thermal quench (TQ)
  - multi-MA runaway electron (RE) plasmas
  - ⇒ very high priority issue for ITER/ITPA
- ST advantage: reduced halo current forces
  - Pomphrey, *et al.* NF (1998)
  - MAST: measures smaller peak halo currents
  - NSTX: measures longer TQ times preceding CQ (Semenov *et al.*, PoP 2003)



- NSTX Plans for 2006-2008:
  - contribute additional I_P quench-rate and new I_{halo} data to ITPA ITER disruption database
  - install segmented halo Rogowski coils to measure toroidal peaking factors
  - better diagnose TQ evolution with tangential X-ray camera and multi-color USXR arrays
  - develop disruption onset and precursor detection
    - Correlate onset with linear/non-linear MHD stability calcs ⇒ disruption prediction
  - develop CQ, TQ, and RE impact projections for CTF based on ITER studies

Correction of Error Fields Necessary for Sustained High-β Operation





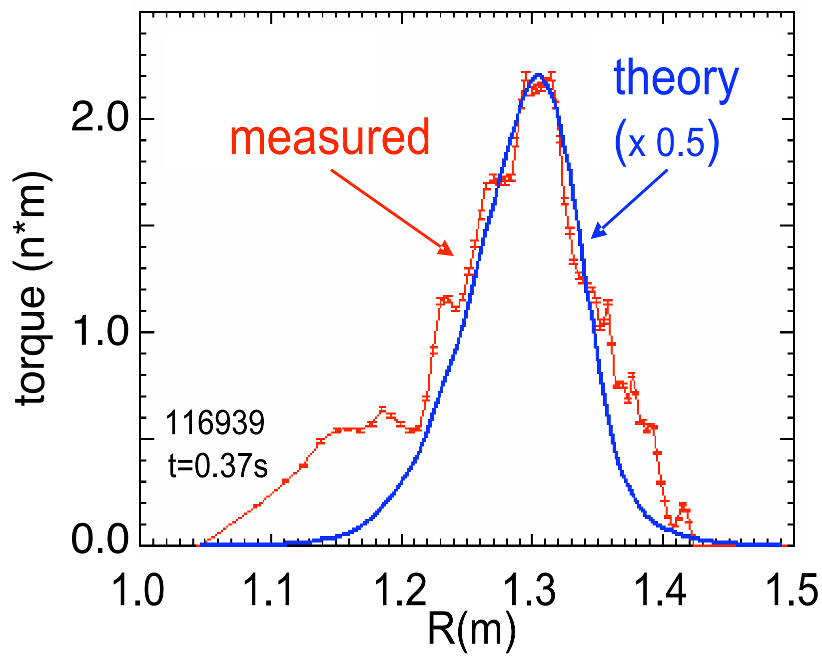
- Error field reduction key to ITER
- Pulse length extended at high-β_N
- Rotation damped in “non-correcting” direction
  - leads to earlier island locking and/or RWM formation
- Rotation decrease slowed in “correcting” direction
- Error field is time-variant due to motion of TF coil
  - inferred TF motion from error field structure
  - consistent with variation in TF joint resistance
- 2006 XPs to focus on dynamic error field correction

NSTX Verifying Generalized Rotation Damping Calculation Applicable for All Aspect Ratios

- Accurate calculation of rotation damping in NSTX requires complete model
  - EM torque on magnetic islands describes resonant component
    - R. Fitzpatrick, NF **7** (1993) 1049.
  - non-resonant damping due to neoclassical toroidal viscosity (NTV)
    - K.C. Shaing, Phys. Fluids **29** (1986) 521.
  - NTV must include trapped particle effects for quantitative agreement
    - $1/A^{1.5}$ scaling at low collisionality
  - full NTV calculation in correct geometry gets within a factor of 2
    - far better agreement than previously published results in other devices

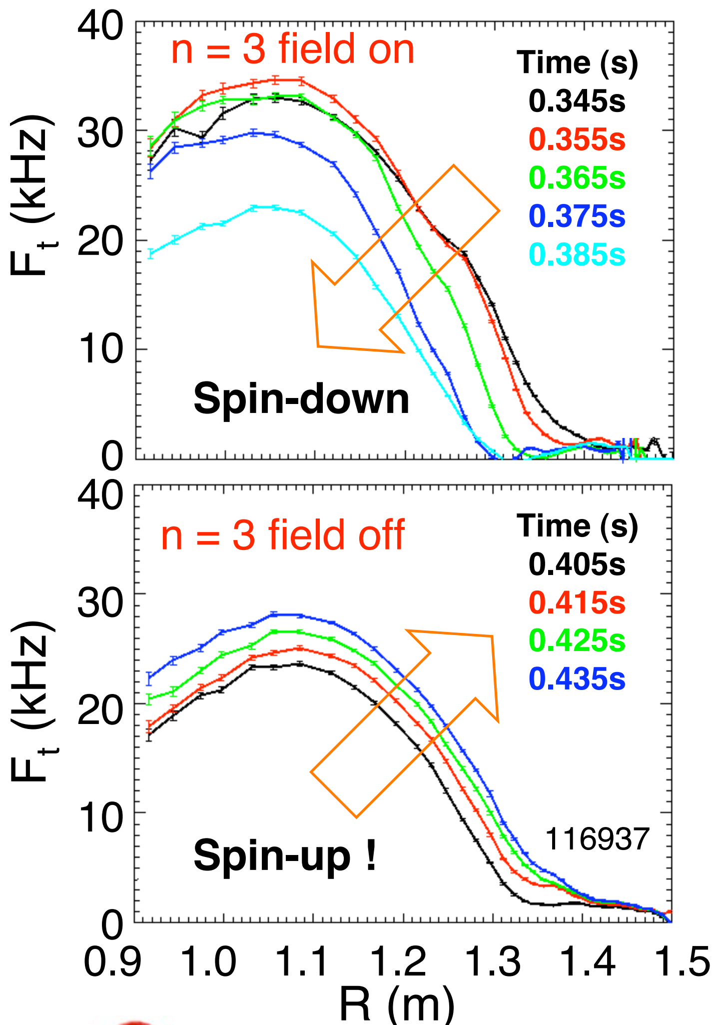
Plateau Torque: $\propto \delta B^2 T_i^{0.5}$

Low Collisionality Torque: $\propto \delta B^2 (T_i/\nu_i)(1/A)^{1.5}$

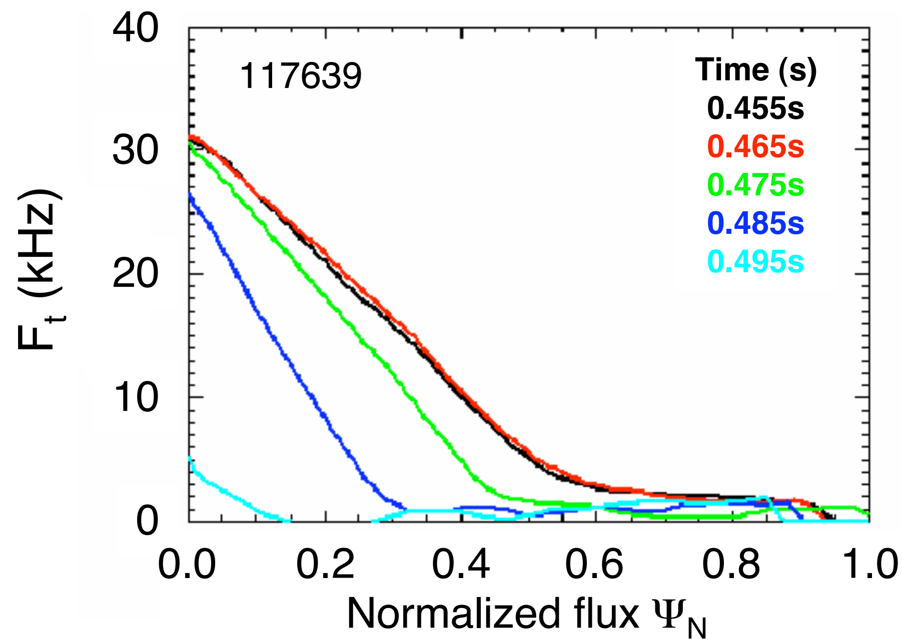


Applied Non-Axisymmetric Fields Allows Plasma Rotation Profile Control in NSTX

n = 3 DC square wave pulse



- Rotation profile controlled by either n = 1 or 3 fields
  - allows detailed study of rotational RWM stabilization
- Low rotation target for ITER-relevant study created in a controlled manner
  - rotation greatly reduced over 70% of poloidal flux before RWM goes unstable

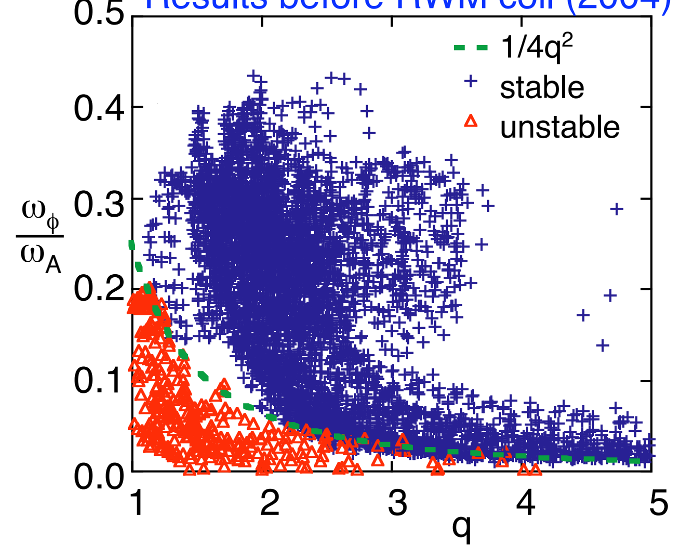


Controlled Rotation Damping Allows Examination of Critical Rotation Profile

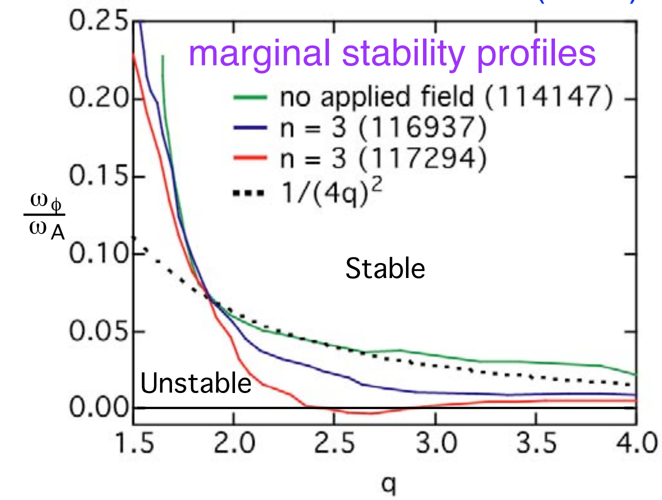
- Study of minimum plasma rotation profile required for passive stability
  - needed to design appropriate active control systems in future devices such as ITER & CTF
- First work (FY 2004) found $1/q^2$ stability boundary as predicted by theory*
  - trapped particle effects weaken ion Landau damping
  - toroidal inertial enhancement more important
- Unique capability to modify rotation profile and passive stability added in 2005
- Recent rotation control results indicate rotation outside of q = 2.5 not required for stability
  - ⇒ could ease active control requirements for ITER & CTF
- Key research now aimed to find underlying dissipation mechanism for passive stability

*A. Bondeson, M. Chu, Phys. Plasmas **3** (1996) 3013.

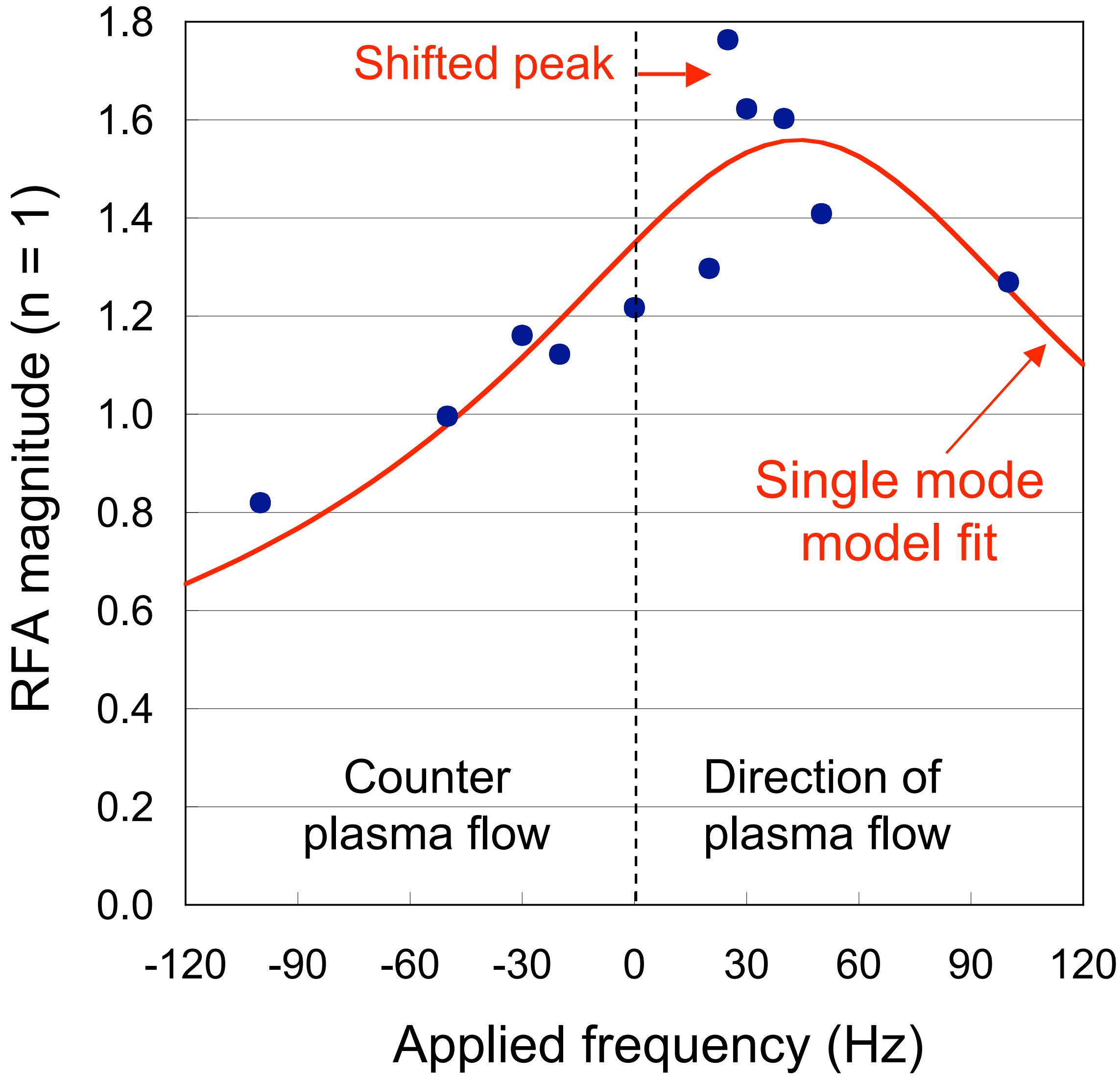
Results before RWM coil (2004)



Results after RWM coil (2005)



Resonant field amplification (RFA) dependence on applied $n = 1$ field frequency determined using new coil set



$$RFA = \frac{B_{plasma}}{B_{applied}}$$

- Applied field phased to propagate in toroidal direction
- Peak in RFA shifted in the direction of plasma flow
  - peak near 30 Hz
- Shifted resonance of stable RWM expected from theory / experiment
  - observed in DIII-D (H. Reimerdes, NF 45 (2005) 368.)
  - increases understanding/ confidence for active RWM stabilization

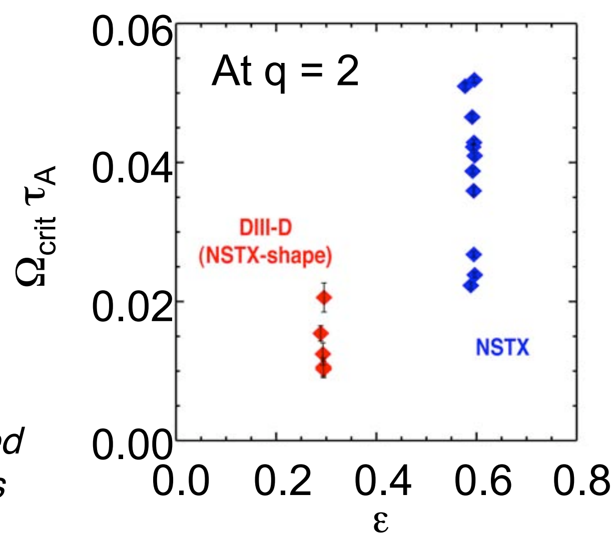
Joint NSTX/DIII-D ITPA Experiment on RWM Physics Started

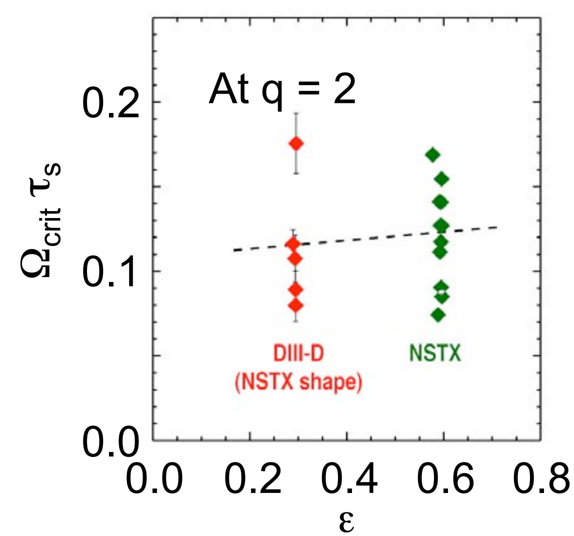
- Exploring aspect ratio scaling of RWM critical rotation
  - leads to understanding of stabilizing dissipation mechanism
- Experiment matches RWM onset conditions as much as possible
  - DIII-D poloidal cross section matched in high-β_N NSTX discharges
  - magnetic braking used to drop below critical plasma rotation profile
- NSTX requires higher rotation for stability when rotation normalized to Alfven speed*
  - sound speed normalization removes ε dependence

$$V_A = \frac{B_t(0)}{\sqrt{4\pi n(r) m_i}}$$

$$V_s = \sqrt{\frac{kT_e + \gamma k T_i}{m_i}}$$

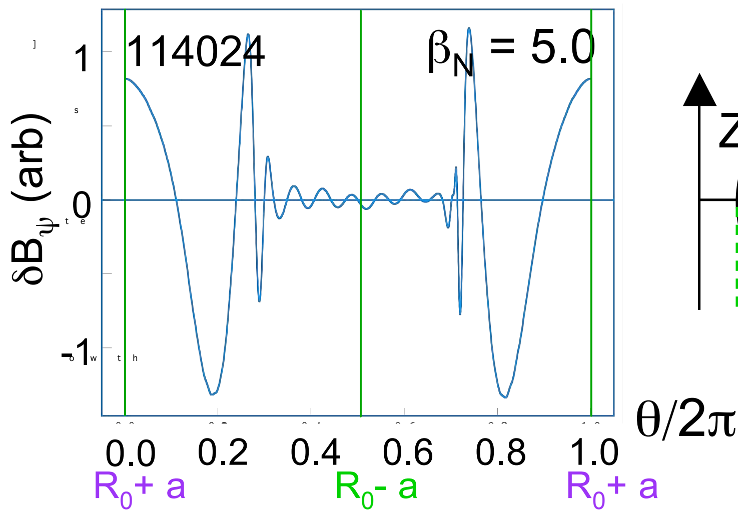
**H. Reimerdes, et al., accepted for publication, Phys. Plasmas*

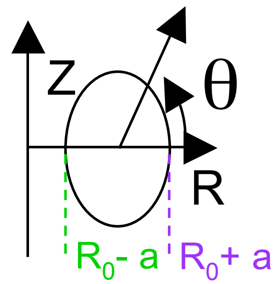




NSTX is Only ST Capable of Active RWM Control - Will Complement Research at Higher A

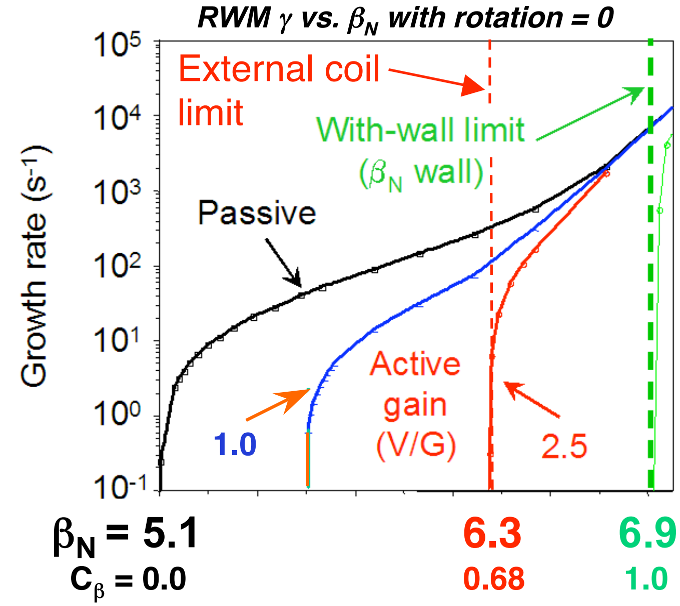
RWM eigenfunction strongly ballooning at high β, low-A → outboard coils effective



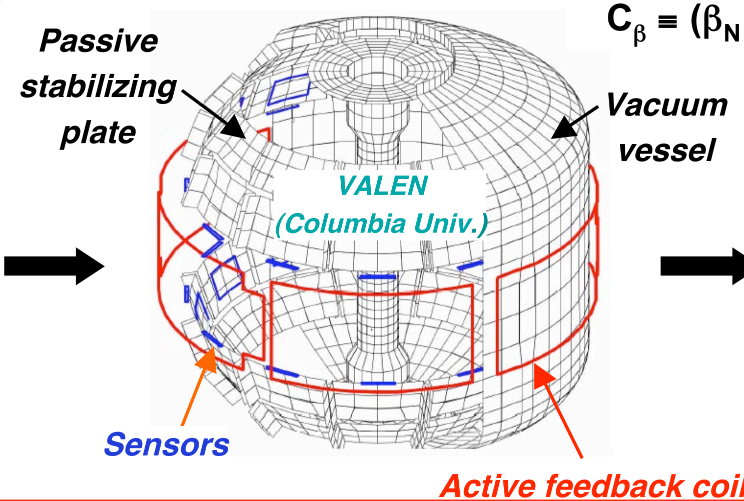


(DCON – LANL)

NSTX feedback system has mid-plane coils and nearby (blanket-like) **passive plates - similar to ITER midplane port plug design**



$C_\beta \equiv (\beta_N - \beta_{Nnowall}) / (\beta_{Nwall} - \beta_{Nnowall})$



Feedback stabilize RWM at C_β = 68% when $\Omega_\phi \ll \Omega_{\phi\text{-crit}}$

Planned 2006-2008 NSTX MHD Experiments Use New Capabilities to Address Milestones & ITPA

Prioritized Experimental Plan from NSTX Research Forum

	milestone	ITPA
FY 2006:		
- Error field correction: XPs by Menard and Strait	06-02	
- Active RWM control: Sabbagh	06/07-02	MDC-02
- RWM passive stability boundary: Sontag		MDC-02
- High toroidal β via plasma shaping: Gates		
- Low density locked mode threshold: Menard	06-02	MDC-06
FY 2007 - 2008 : (proposed for 2006, inadequate run time)		
- NTM scaling: Fredrickson		MDC-04
- n > 1 RFA : Sabbagh	07-02	MDC-02
- n > 1 rotation damping: Sabbagh	07-02	
- NSTX/DIII-D RWM similarity: Sontag	07-02	MDC-02
- Detection of n > 1 residual error fields: Menard	07-02	
- High toroidal β via error field reduction: Gates		

- Priorities for 2007-8 to be determined at future Research Opportunity Forums

MHD Research Plan Uses Recent Upgrades To Contribute to ITPA (ITER) and ST Research Goals

- All necessary hardware for initial EF reduction / RWM control XPs installed and operational
- Have already made progress toward milestone completion
  - performed basic (static) error field correction studies
    - dynamic correction required due to time-varying error fields
  - active coil used to study RWM physics
    - passive stabilization dependence on plasma rotation profile
    - NTV non-resonant plasma rotation damping
    - resonant field amplification dependence on $n = 1$ applied field frequency
- Planned control experiments progress from dynamic EFC to RWM control over next two years
  - only difference is degree of latency allowable in control system
  - RWM control study to begin in FY 2006 to ensure success by FY 2007
- Additional experiments to study critical RWM physics relevant to ITER & next generation ST
  - strong attention to comparing theory with experiment in each study