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Macroscopic Stability (MHD) Physics in NSTX

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NSTX PAC Meeting 21

January 18th, 2007
Princeton Plasma Physics Laboratory
Princeton, NJ

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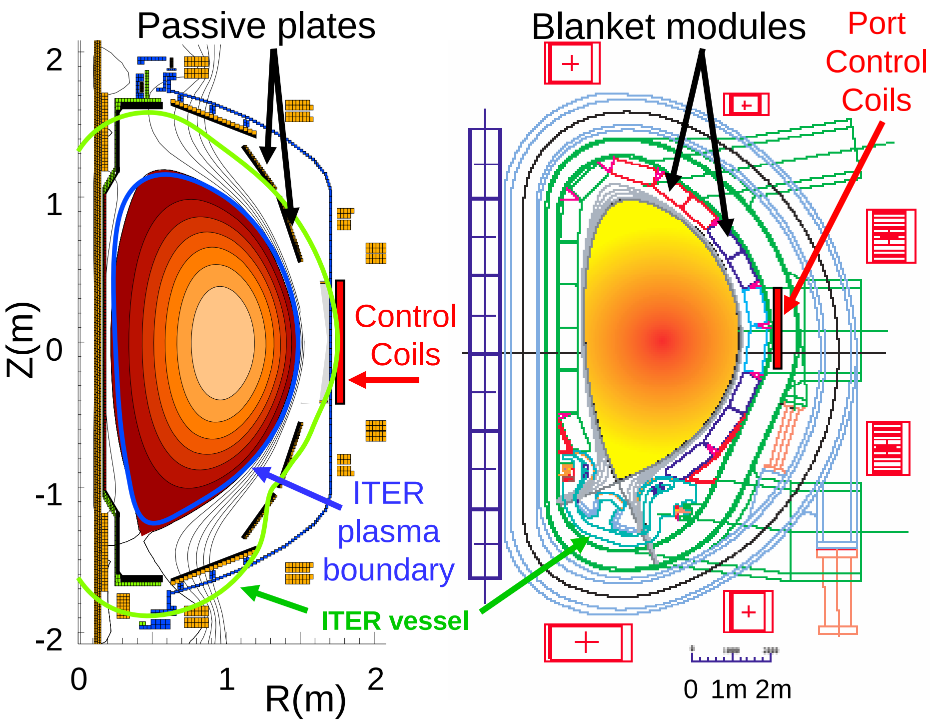
MHD physics research plan provides both focus and balance to address critical fusion program issues

- **Focused plan built from great progress**
  - NSTX milestones addressed
  - High-level publications and invited talks in 2006
- **Balanced research plan addressing program needs**
  - 2 ITER issue cards
  - 4 ITPA tasks
  - Relevant physics for ITER, CTF, KSTAR

NSTX / ITER RWM control



Advantage: low aspect ratio, high β provide high leverage to uncover key tokamak physics (e.g. RWM control, rotation damping, high elongation)

Solid Progress in MHD Research, now Addressing Advanced Goals

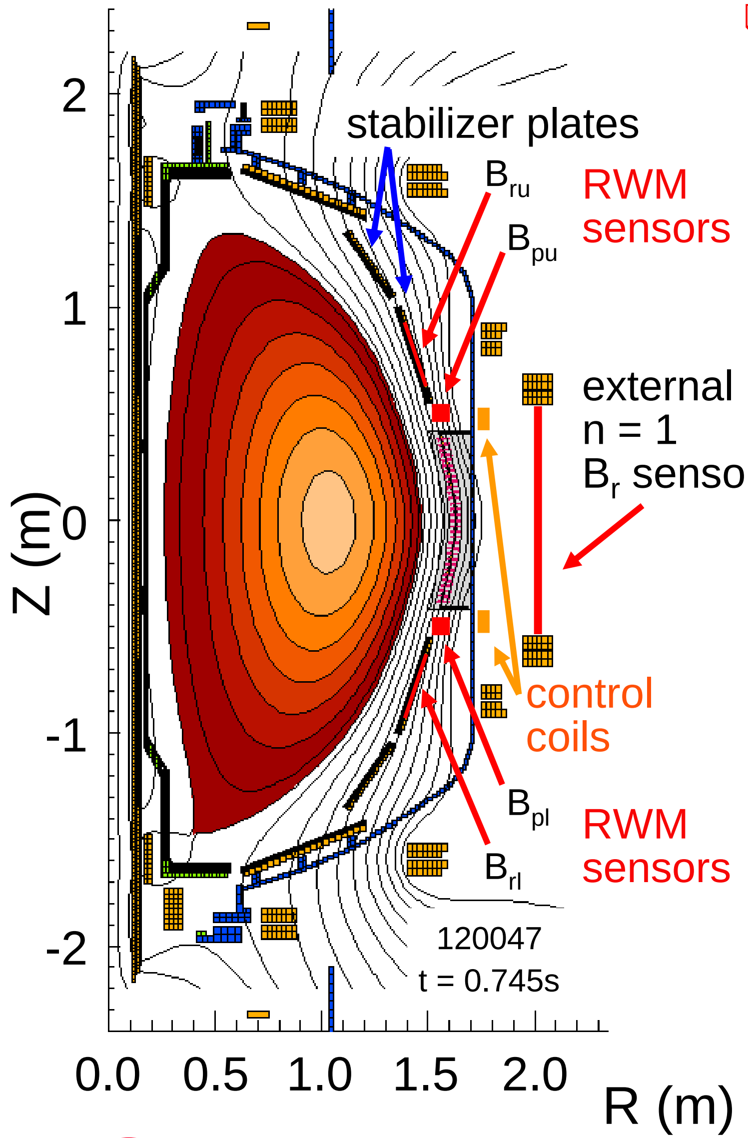
- **Major Accomplishments**
  - RWM active stabilization at low rotation (ITER-relevant) (Sabbagh, PRL **97** (2006) 045004)
  - Observed plasma rotation damping by NTV physics (Zhu, PRL **96** (2006) 225002)
  - Dynamic error field correction increases pulse length (Menard, IAEA FEC 2006 OV/2-4)
  - Unstable n = 1 – 3 RWM observed (Sabbagh, NF **46** (2006) 635)
  - RWM critical rotation is a profile; depends on q, A, ν_i (Sontag, IAEA FEC 2006 EX/7-2Rb) (Reimerdes, PoP **13** (2006) 056107) (Sontag, PoP **12** (2005) 056112)
  - Rotation + ω* effects may provide 1/1 mode saturation (Menard, NF **45** (2005) 539)
  - Stability vs. shape, $P(r)$, l_i studied (Gates, PoP **13** (2006) 056122) (Sabbagh, NF **44** (2004) 560; Menard, PoP 11 (2004) 639)
  - V_ϕ, flux-isotherm, MSE in equilibrium reconstructions (Sabbagh, NF **46** (2006) 635)

- **Emphasis on 2007 Milestone; preparing for 2009 Milestone**

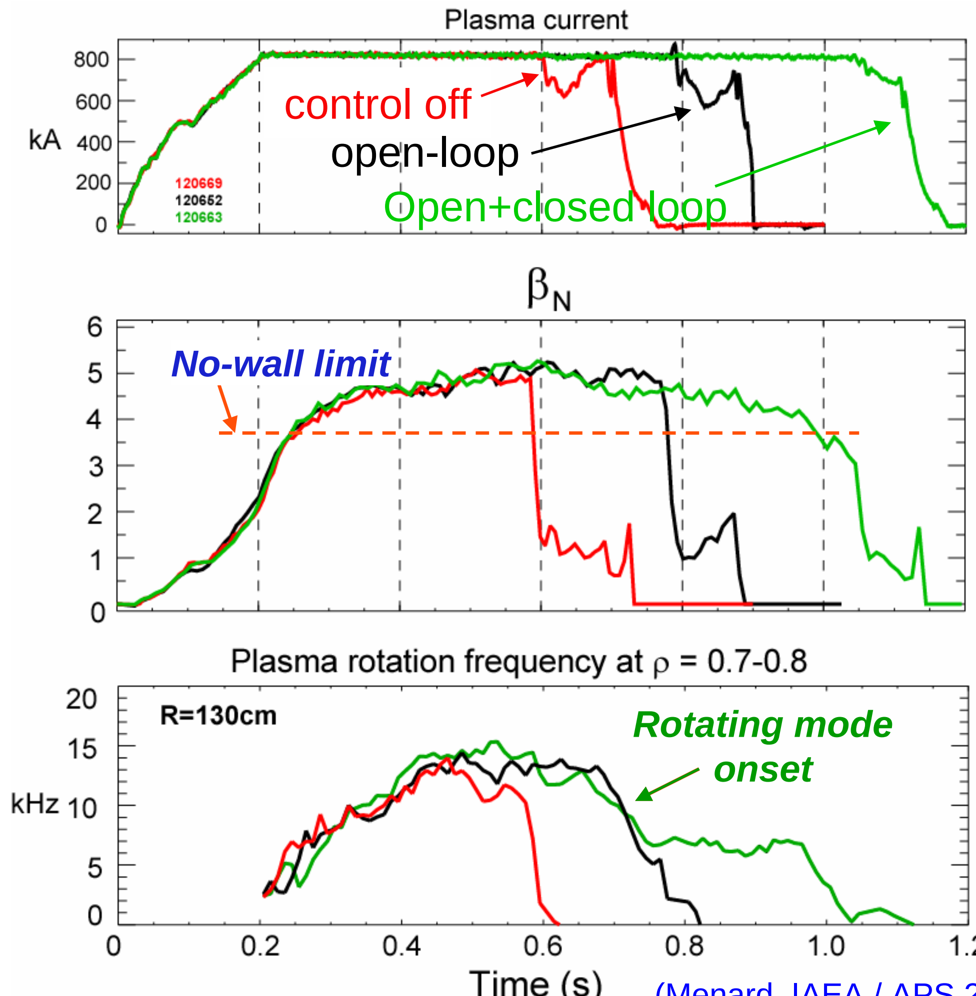
R(07-2): "Characterize effectiveness of closed-loop RWM control & dependence on rotation using ITER-like control coils."

R(09-2): "Understand physics of RWM stabilization and control as a function of plasma rotation."

RWM active control system, rotation control installed

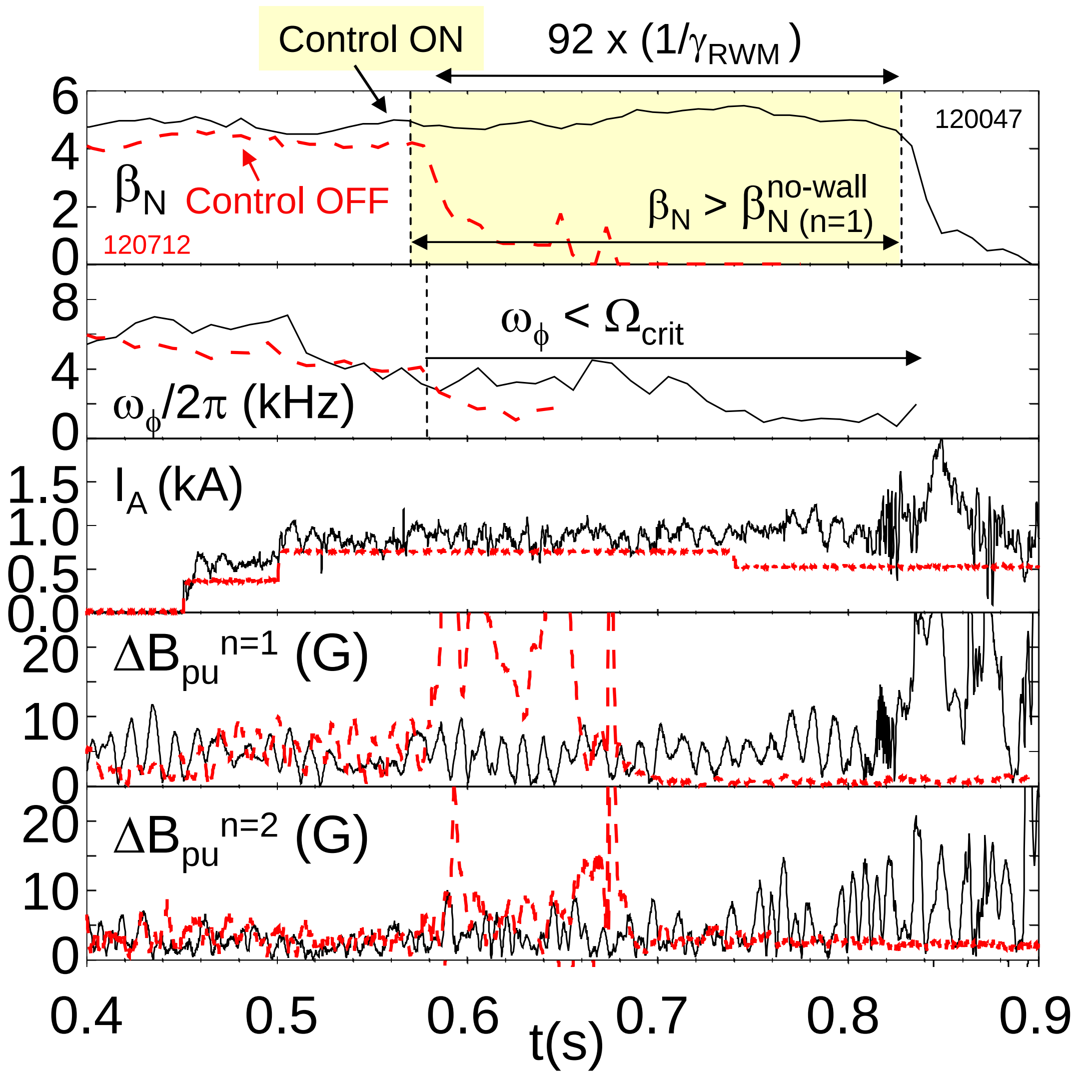


- Dynamic error field correction (DEFC) sustains plasma rotation, increases pulse length
  - Combination of open + closed loop control yielded best result



(Menard, IAEA / APS 2006)

RWM actively stabilized at low, ITER-relevant rotation

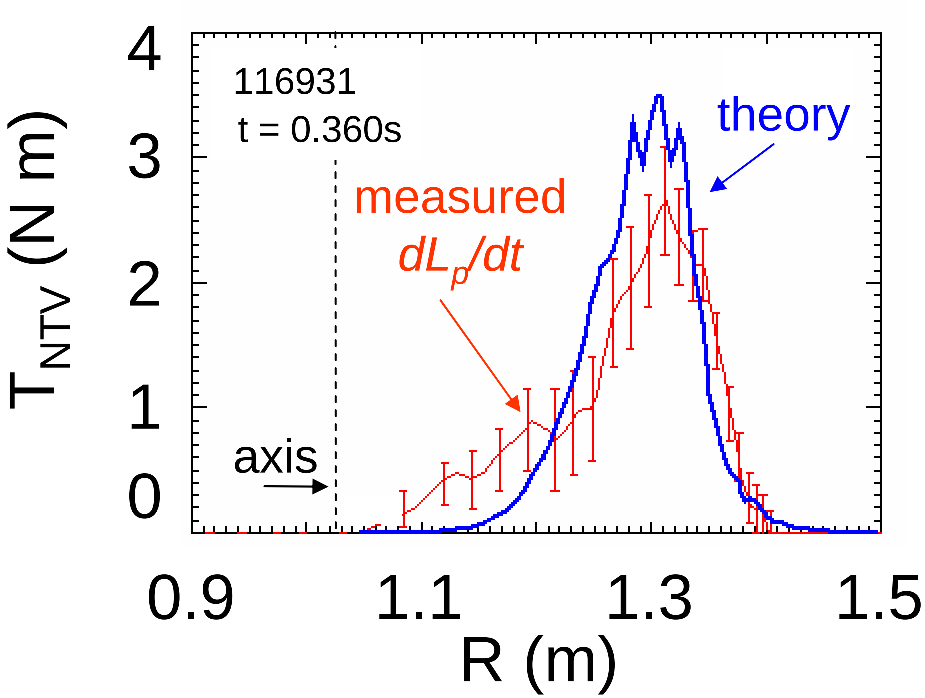


- First such demonstration in low A tokamak
  - Long duration > $90/\gamma_{RWM}$
  - Exceeds DCON $\beta_N{}^{no\text{-}wall}$ for n = 1 and n = 2
  - n = 2 RWM amplitude increases, mode remains stable while n = 1 stabilized
  - n = 2 internal plasma mode seen in some cases
- Plasma rotation ω_ϕ reduced by non-resonant n = 3 magnetic braking
  - Non-resonant braking to accurately determine RWM critical rotation, Ω_{crit}

(Sabbagh, et al., PRL **97** (2006) 04500. ; APS 2006 Invited; IAEA 2006 Post-deadline)

Observed rotation decrease follows NTV theory

n = 3 applied field configuration



(Zhu, et al., PRL **96** (2006) 225002.)

- First quantitative agreement using full neoclassical toroidal viscosity theory (NTV)
  - Due to plasma flow through non-axisymmetric field
  - Computed using experimental equilibria
  - Trapped particle effects, 3-D field spectrum important
- Viable physics for simulations of plasma rotation in future devices (ITER, CTF)
  - Scales as $\delta B^2 (p_i/\nu_i)(1/A)^{1.5}$
  - Low collisionality, ν_i, ITER plasmas expected to have higher rotation damping

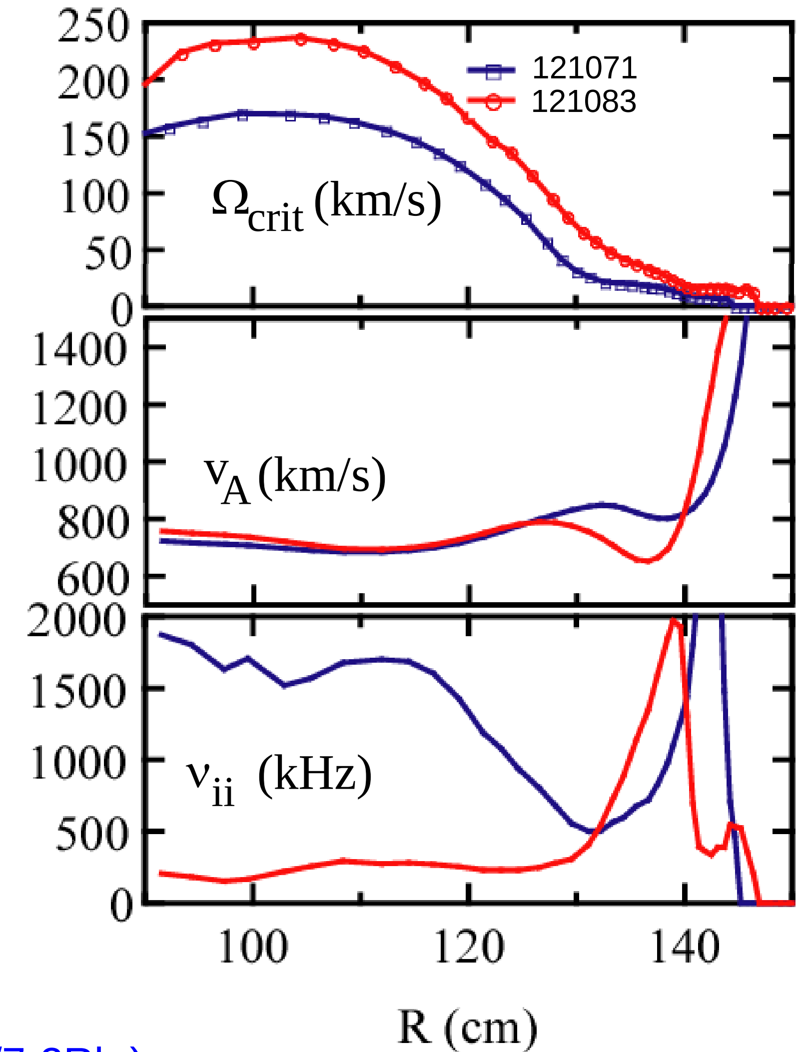
NSTX

Increased Ion Collisionality Leads to Decreased Ω_{crit}

- Plasmas with similar v_A
- Consistent with neoclassical viscous dissipation model
  - at low γ, increased ν_i leads to lower Ω_{crit}

    (K. C. Shaing, Phys. Plasmas **11** (2004) 5525.)
- ITER plasmas with lower ν_i may require higher degree of RWM active stabilization

Further analysis and 2007 XPs aim to uncover RWM stabilization physics (FY09 Milestone)



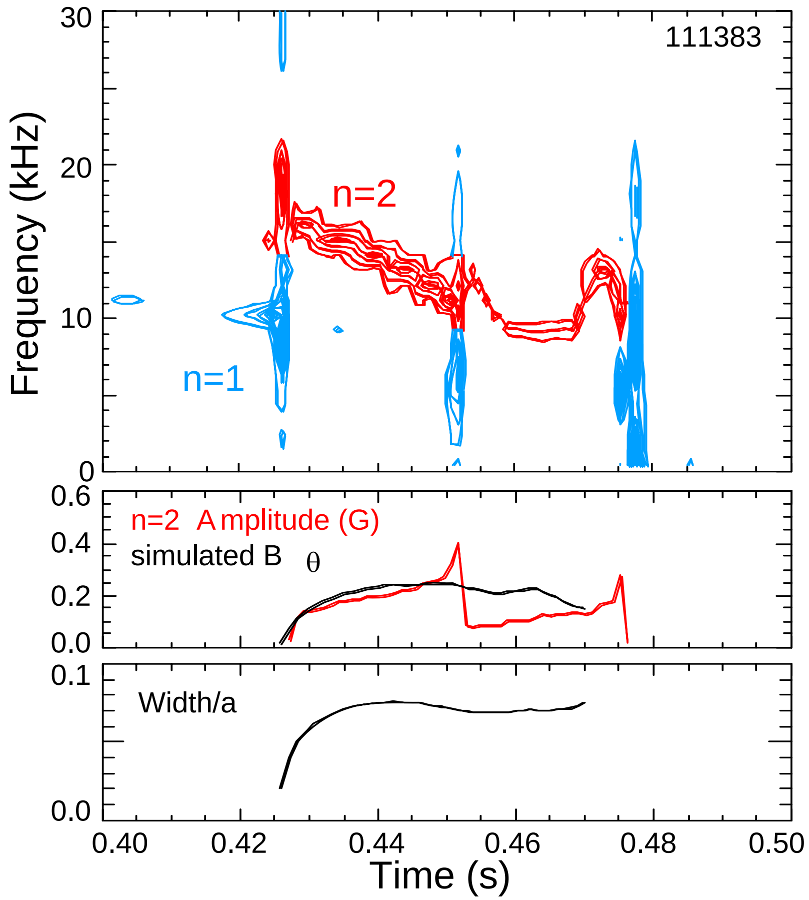
(Sontag, et al., IAEA FEC 2006 paper EX/7-2Rb.)

Low A, high β favorable for NTM seeding / stabilization study

- Several modes (e.g. sawteeth*, RWMs**) seed low frequency MHD modes in NSTX
  - Can led to soft beta limit, or plasma rotation reduction resulting in disruption
  - Large q = 1 radius, high β, mode coupling at low-A makes seeding process easier
  - NTM stabilization effects amplified at low-A (GGJ $\propto \varepsilon^{3/2}$) – NTM less deleterious
- NTM study planned 2007 - 2009
  - Characterize modes: are these NTMs, TMs, or internal kinks?
  - Exploit 12 channel MSE, reflectometer, fast multi-filter USXR capabilities
  - Mitigate deleterious effects of modes

*Fredrickson, et al., Bull. Am. Phys. Soc. 2004
Sabbagh, et al., NF **44 (2004) 560.

Sawtooth excitation of n = 2



- Sawtooth excites n = 2, but n = 2 can decrease post-crash

Selected 2007 Experiments Address Near-Term Research Plan

	MHD ETG Prioritized Experiments (from NSTX Forum – Dec 2006)	ST devel.	ITER	toroidal physics
	Assessment of intrinsic error fields after TF centering	x	x	
	RFA detection optimization during dynamic EF correction	x		x
	RWM active stabilization and optimization – ITER scenario	x	x	x
	• Assessment of RWM mode stiffness	x		x
	• n = 3 magnetic braking w/ optimal n = 1 error field correction		x	x
5	Fast Soft X-ray Camera (FSXIC) Imaging of MHD	x		x
days	Exploration of stability limits at high I_N with strong shaping	x		x
	B and q scaling of low-density locked-mode threshold at low-A	x	x	x
	• Measurements of plasma boundary response to applied 3D field			x
	RWM suppression physics at low aspect ratio	x	x	x
	• RWM D3D+ joint experiment – ε, β, $V_\phi(\psi)$ effects on $\Omega_{crit}(\psi)$		x	x
	NTV dissipation physics: n = 2 perturbations and ν_i	x	x	x
	• Toroidal flow damping by island-induced NTV	x	x	x
10	Marginal island width of NTMs in NSTX	x	x	x
days	NTM threshold at low plasma rotation	x	x	x

(Red highlight = addresses NSTX milestone)

(PAC charge question #1 criteria)

NSTX

MHD Research 2007+ logically follows past results (I)

PAC request

- RWM control
  - Reduced latency feedback; also artificially increase (ITER support)
  - Added feedback sensors; examine/eliminate mode deformation
  - Test optimized control techniques offline ‘07, implement ’09
- Plasma rotation
  - Resonant damping, islands, damping mitigation for steady-state ops
  - Further evaluation of NTV physics causing v_ϕ damping (ITER, etc.)
  - Density control (ion collisionality) to support physics study
- RWM stabilization physics
  - Present study shows Ω_{crit} is profile, decreases with increasing ν_i
  - Determine underlying physics of RWM stabilization (’09 milestone)
  - Rotation/profile, ν_i, RWM active control beneficial (required) tools for study

MHD Research 2007+ logically follows past results (II)

- NTM
  - Characterization of mode as NTM (vs. kink, or classical tearing)
  - Improved diagnostics for mode determination / stability analysis
    - MSE (in plan), multi-filter SXR, fast scanning profile reflectometer
  - leverage low A to determine ε dependence of mode stability
  - Utilize non-resonant magnetic braking for studies at low rotation

PAC request

- Shaping / configuration
  - Self-consistent current profile (β dependent) for steady-state ops
    - real-time β feedback; expanded MSE for stability studies
  - High κ ~ 3 studies for CTF, passive plate coupling, RWM feedback
- Disruptions
  - Continue low density locked mode scaling study (ITER support)
  - Halo current evaluation (w/ new Rogowski coils) useful for ITER, CTF

PAC request

Proposed research plan for 2008+ addresses advanced physics understanding, ST, and ITER support

Present → **Planned**

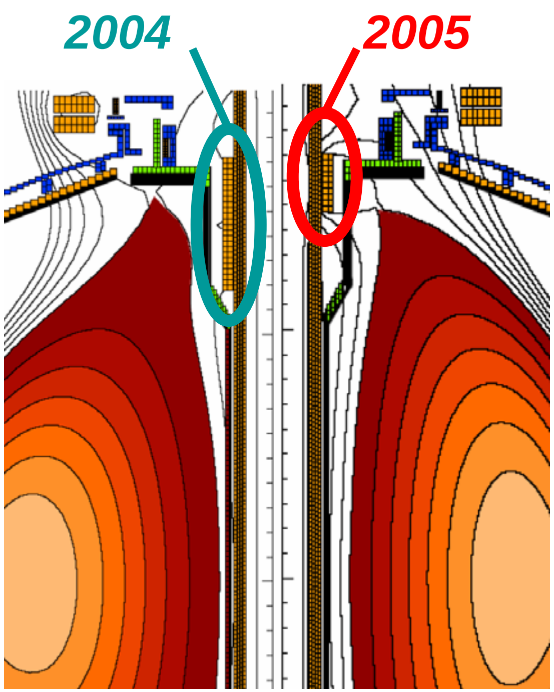
- Initial RWM active control → "optimized" RWM control
- RWM "critical rotation" → full understanding of stabilization physics
- Plasma rotation physics/initial control → full study, active control
- Initial NTM studies → full NTM characterization, mitigation studies
- NSTX config. → CTF configuration (shape, stabilizers)
- Disruption database studies → expanded disruption studies

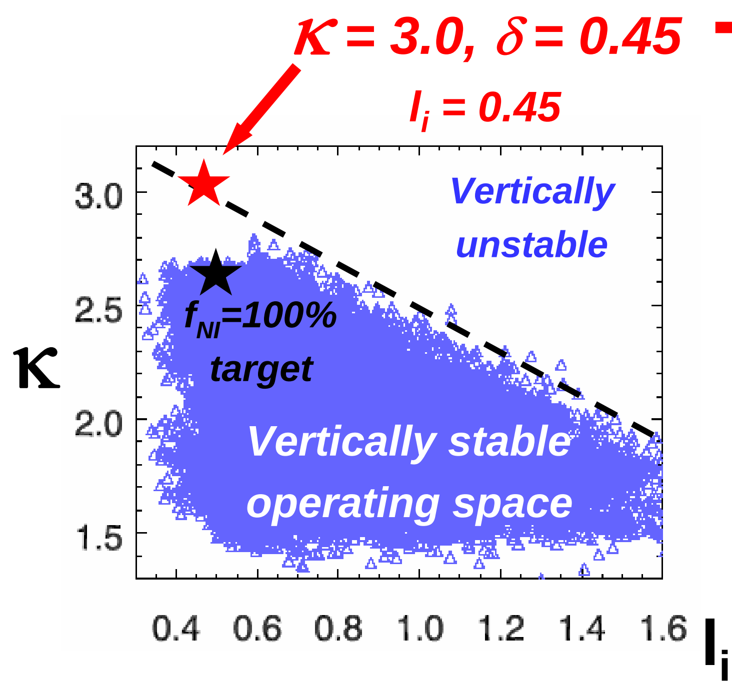
Additional slides

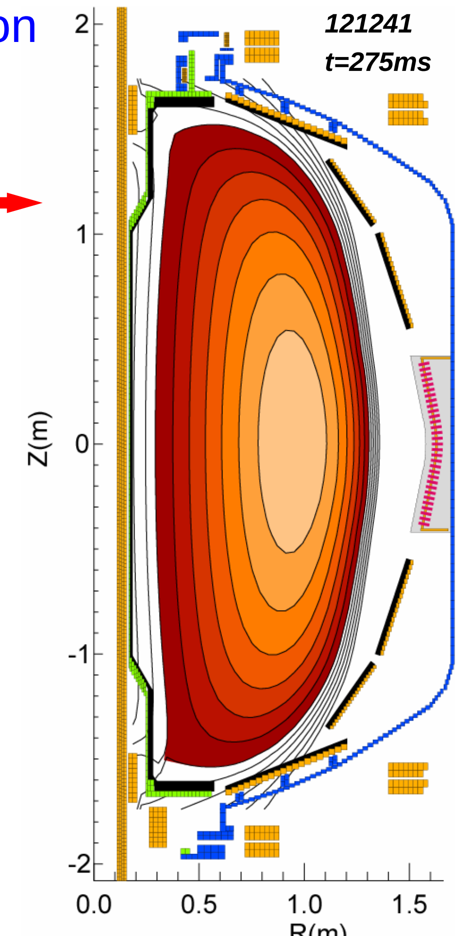
Extreme elongation at low l_i opens possibility of higher β_P, f_{BS} operation at high β_T

- Five-year plan shape target already reached
- Sustained $\kappa \geq 2.8$ (reached $\kappa = 3$) for many τ_{WALL} using rtEFIT isoflux control
  - Allowed by divertor coil upgrade in 2005, **no** in-vessel vertical position control coils
- Stability analysis of new operational regime under investigation
- High κ research important for CTF design studies

Divertor coil upgrade





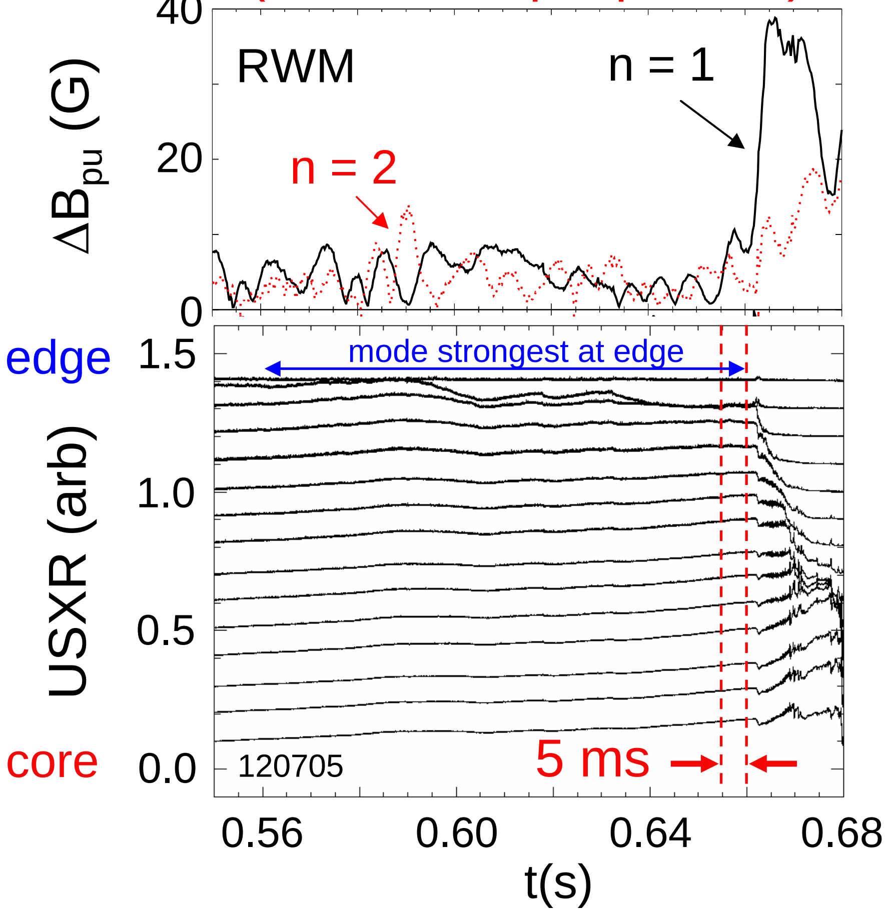


(Gates, et al., PoP **13** (2006) 056122.)
(Gates, et al., NF **46** (2006) 17.)

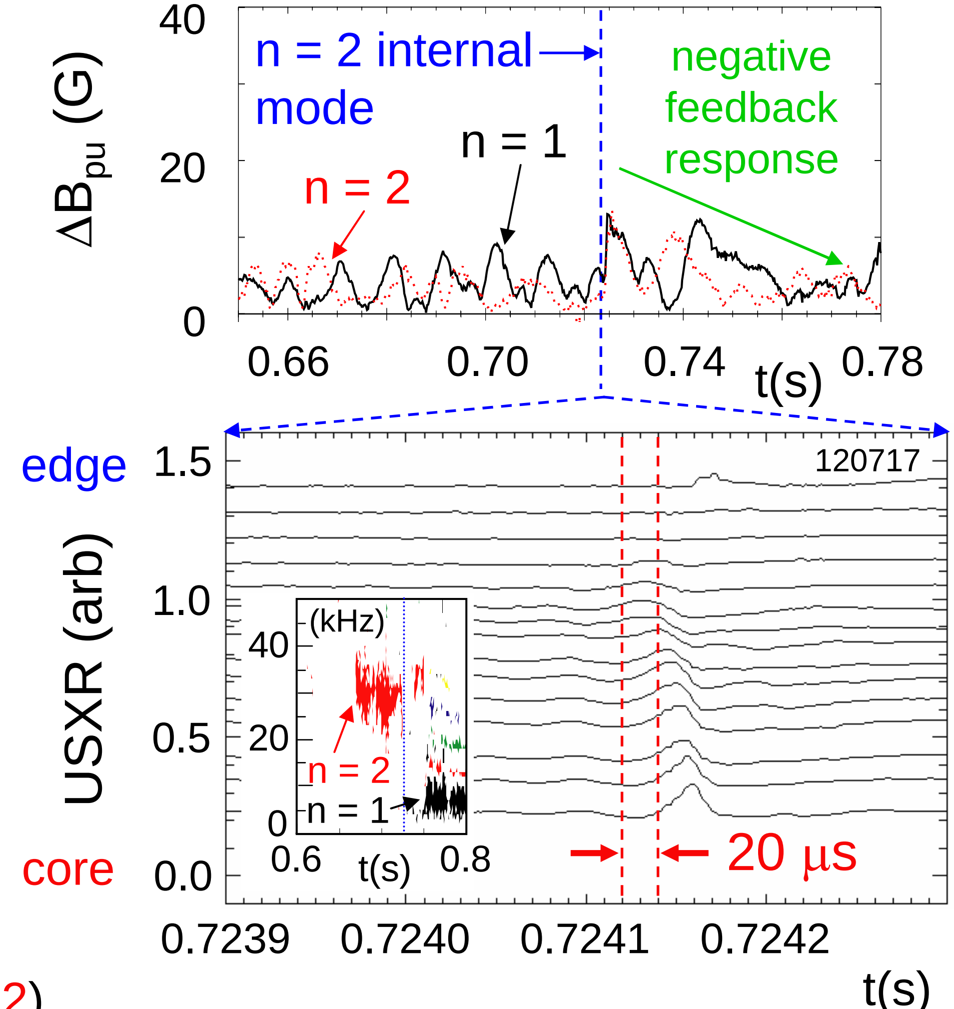
NSTX

n = 2 RWM does not become unstable during n = 1 stabilization

Control OFF
(RWM disrupts plasma)



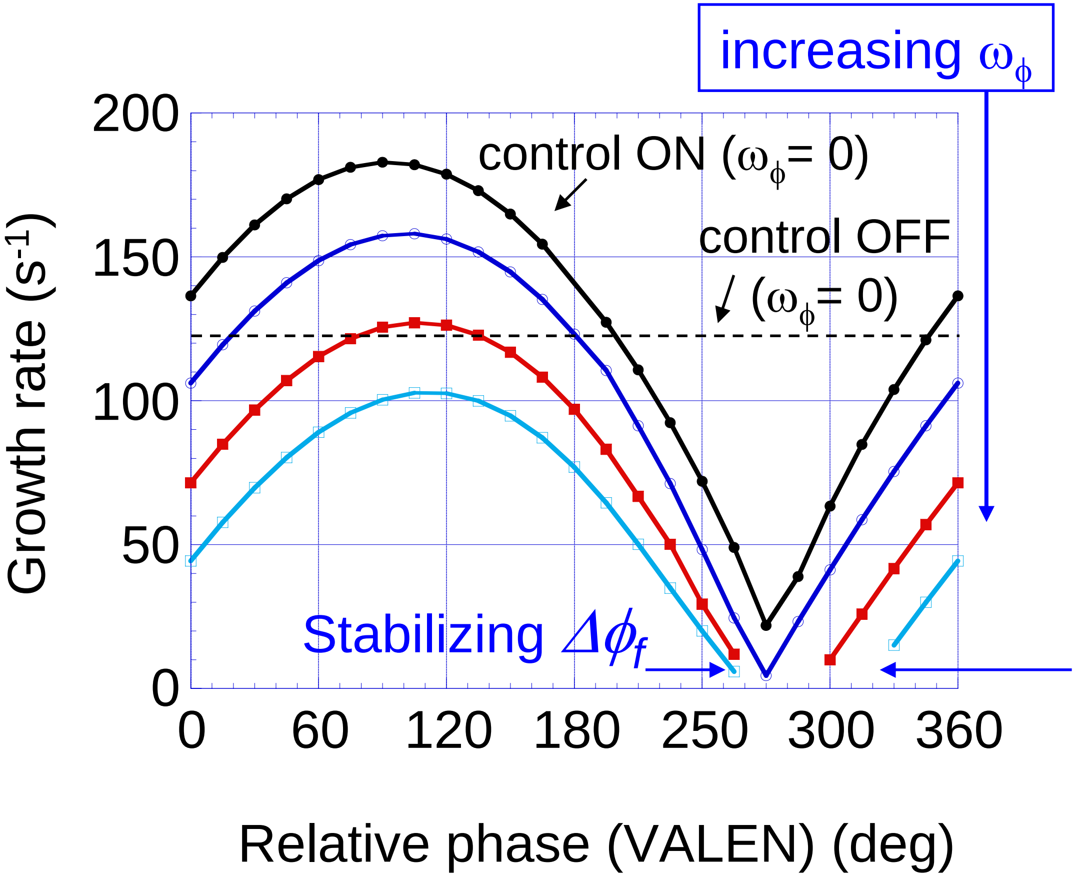
Control ON
(fast β_N drop, plasma recovers)



- Internal mode ~ 25 kHz
  - Plasma rotation ~ 12 kHz (n = 2)

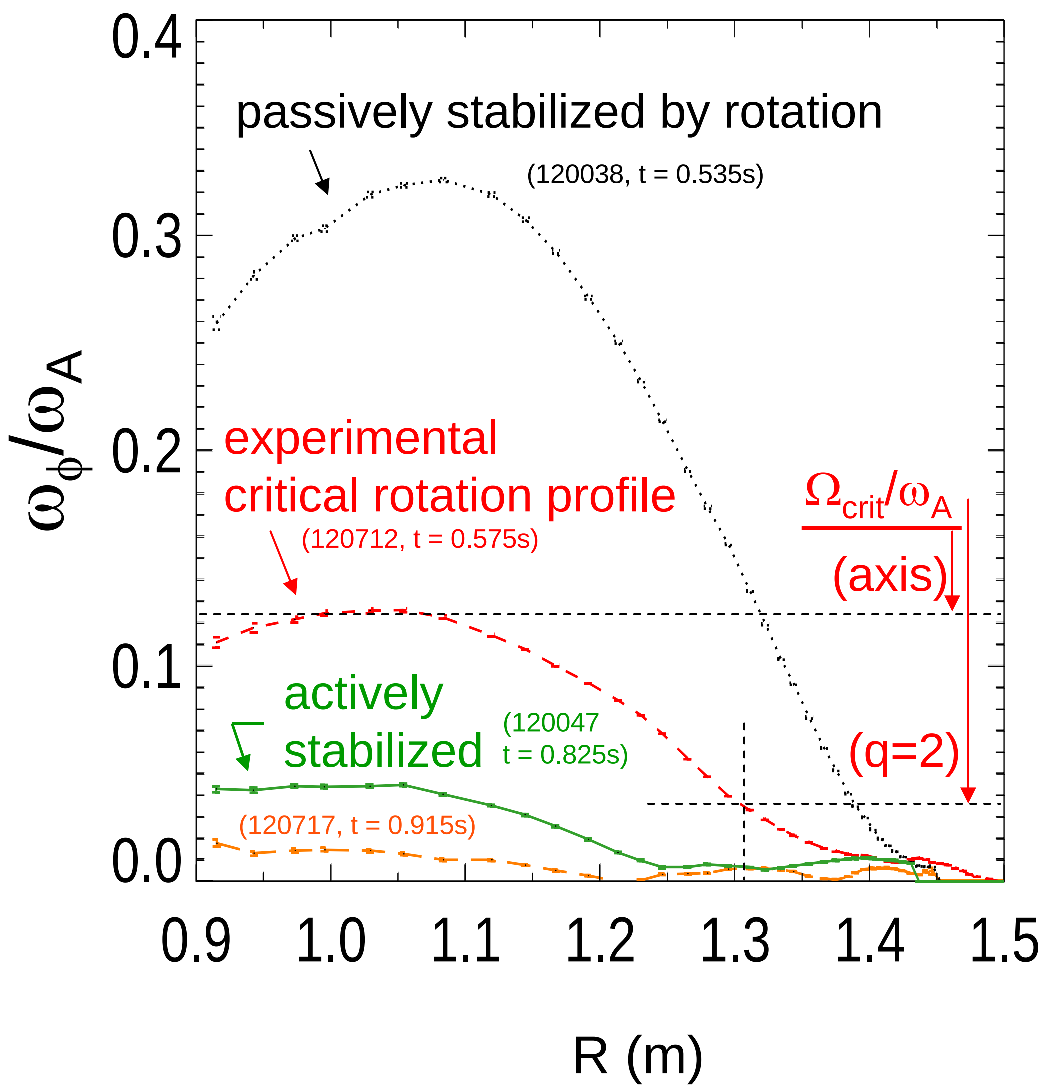
NSTX

VALEN-3D analysis demonstrates optimal relative phase $\Delta\phi_f$ for RWM active control



- First VALEN-3D analysis with both active and passive stabilization ($\omega_\phi > 0$)
- Unfavorable $\Delta\phi_f$ drives mode growth
- Stable range of $\Delta\phi_f$ increases with increasing ω_ϕ
- Optimal $\Delta\phi_f$ for active stabilization at $\omega_\phi = 0$ bracketed by results with $\omega_\phi > 0$.

Rotation reduced far below RWM critical rotation profile

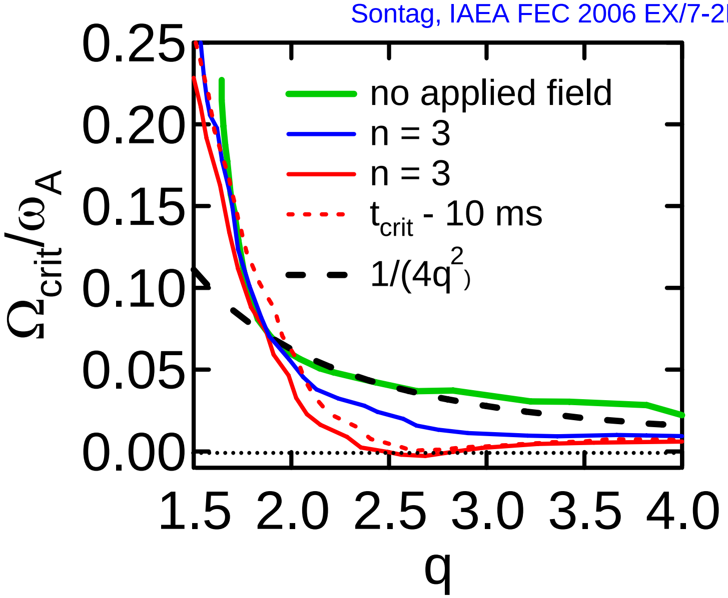


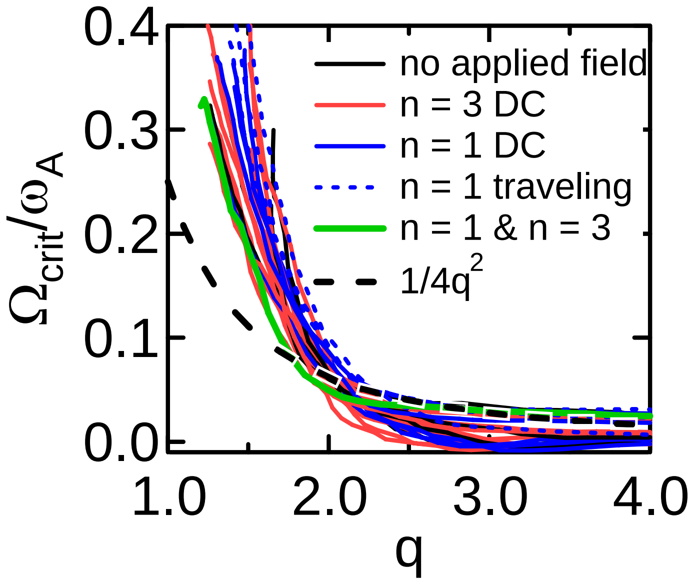
- Rotation typically fast and sufficient for RWM passive stabilization
  - Reached $\omega_\phi/\omega_A = 0.48|_{axis}$
- Non-resonant n = 3 magnetic braking used to slow entire profile
  - The $\omega_\phi/\omega_A < 0.01|_{q=2}$
  - The $\omega_\phi/\Omega_{crit} = 0.2|_{q=2}$
  - The $\omega_\phi/\Omega_{crit} = 0.3|_{axis}$
  - Less than ½ of ITER Advanced Scenario 4 $\omega_\phi/\Omega_{crit}$ (Liu, et al., NF **45** (2005) 1131.)
- Rotation profile responsible for passive stabilization, not just single radial location

Rotation profile shape important for RWM stability

- Benchmark profile for stabilization is $\omega_c = \omega_A/4q^2$ *
  - predicted by Bondeson-Chu semi-kinetic theory**
- High rotation outside q = 2.5 not required for stability
- Scalar Ω_{crit}/ω_A at q = 2 , > 2 not a reliable criterion for stability
  - consistent with distributed dissipation mechanism

Sontag, IAEA FEC 2006 EX/7-2Rb





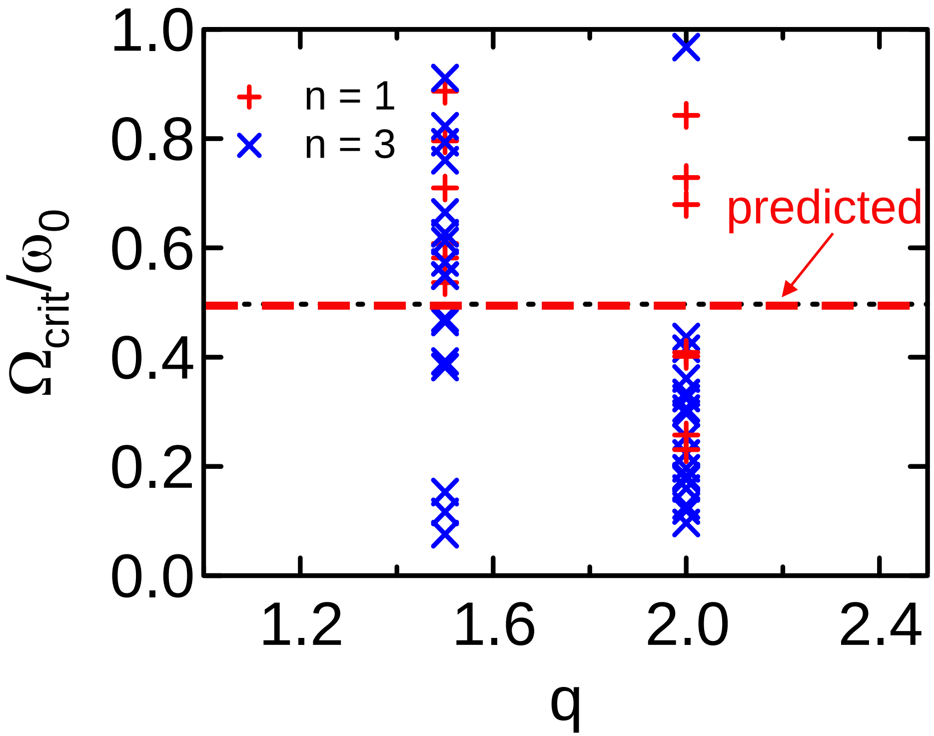
*A.C. Sontag, et al., Phys. Plasmas **12** (2005) 056112.
A. Bondeson, M.S. Chu, Phys. Plasmas **3 (1996) 3013.

NSTX

Ω_{crit} not correlated with Electromagnetic Torque Model

- Rapid drop in ω_ϕ when RWM unstable may seem similar to 'forbidden bands' model
  - theory: drag from electromagnetic torque on tearing mode*
  - Rotation bifurcation at $\omega_0/2$ predicted
- No bifurcation at $\omega_0/2$ observed
  - no correlation at q = 2 or further into core at q = 1.5
  - Same result for n = 1 and 3 applied field configuration

NSTX Ω_{crit} Database



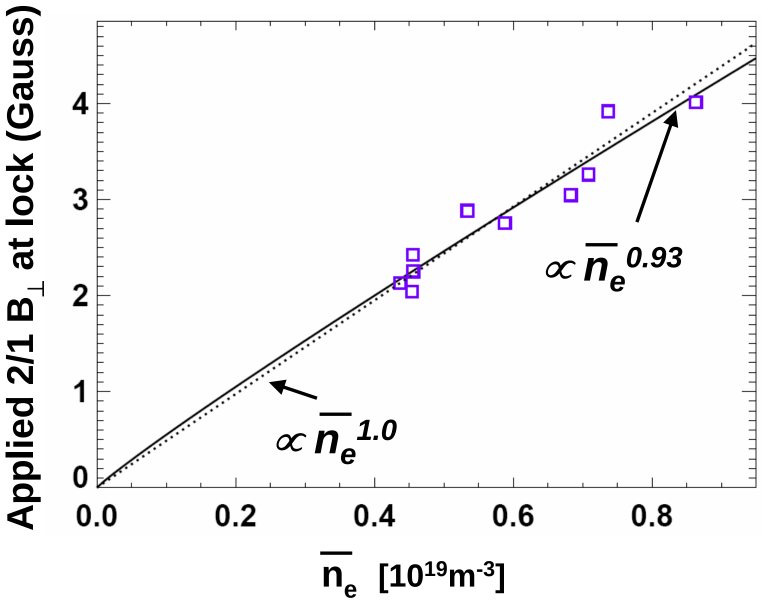
($\omega_0 \equiv$ steady-state plasma rotation)

Sontag, IAEA 2006

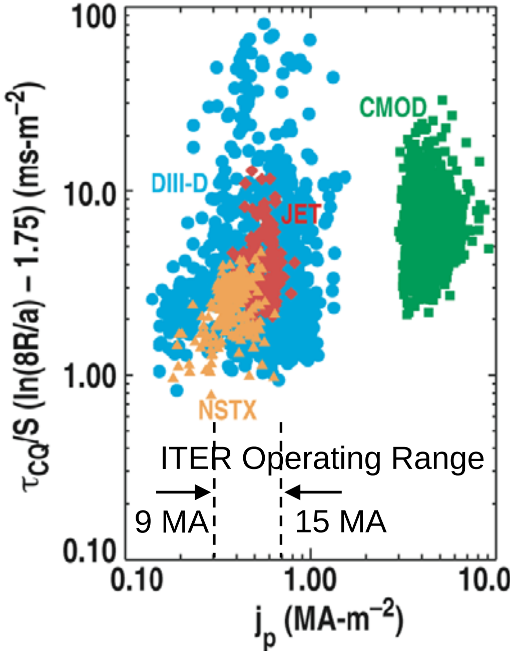
*R. Fitzpatrick, Nucl. Fusion **33** (1993) 1061.

Program adaptation to support ITPA / ITER locked mode threshold and disruption studies

(1) Locked mode threshold



(2) Disruption studies



(GA report A25385)

- NSTX contributing low-A, low B data
  - density scaling nearly linear, similar to higher-A
  - Will contribute B, q scaling data for ITER size scaling
- NSTX data contributes dependence of current quench time, τ_{CQ} on A
  - Important test of theory for ITER, CTF
  - τ_{CQ} independent of plasma current density when A dependence of plasma inductance is included