Resistive Wall Mode Stabilization and Plasma Rotation Damping Considerations for Maintaining High Beta Plasma Discharges in NSTX

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NSTX is Addressing Global Stability Needs for Maintaining Long-Pulse, High Performance Plasmas

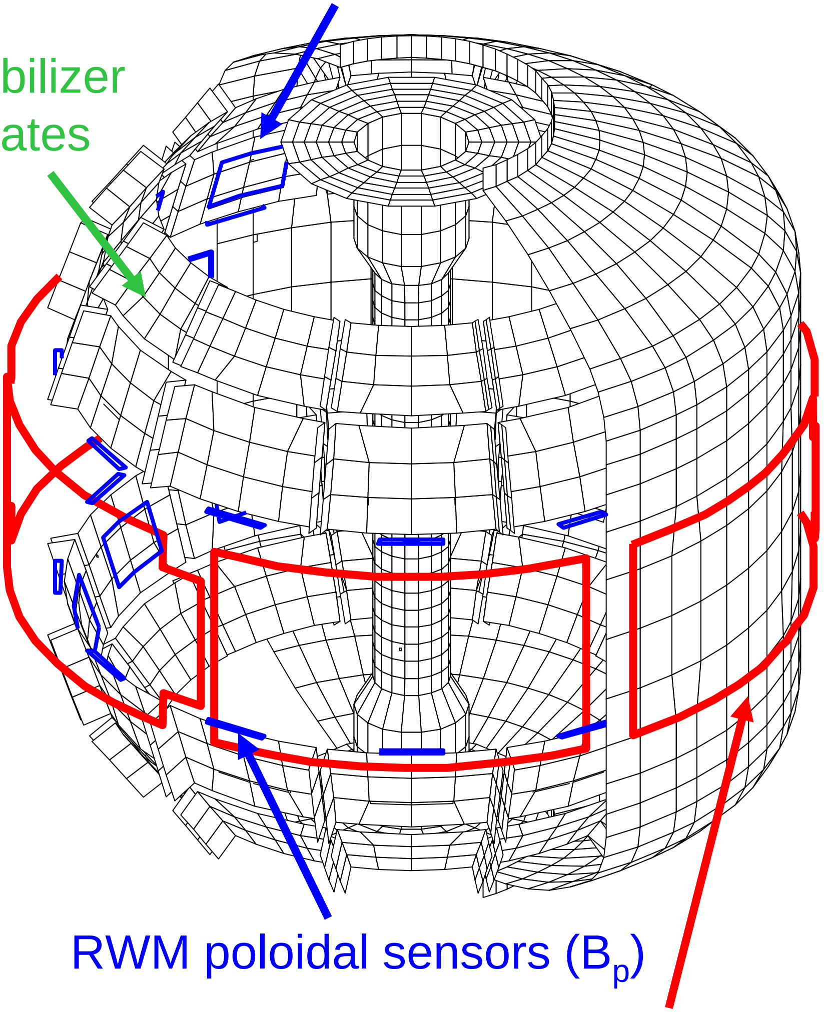
- Motivation
  - Achieve high β_N with sufficient physics understanding to allow confident extrapolation to spherical torus applications (e.g. ST Component Test Facility, ST-Pilot plant, ST-DEMO)
  - Sustain target β_N of ST applications with margin to reduce risk
  - Leverage unique ST operating regime to test physics models, apply to ITER

Papers: FTP/2-2
FTP/2-3
FTP/P6-20

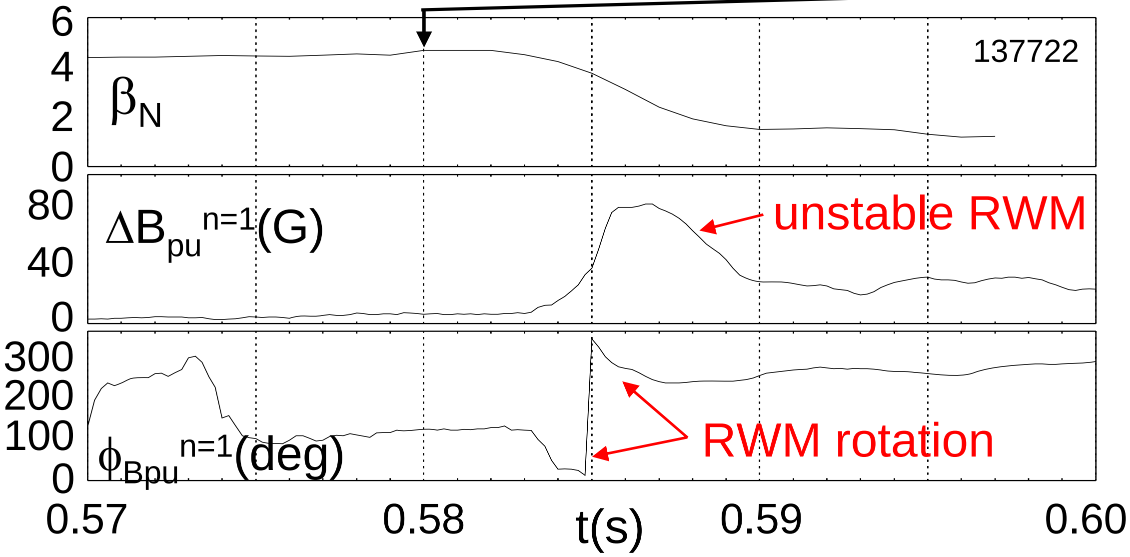
- Physics Research Addressed
  - Resistive wall mode (RWM) destabilization at high plasma rotation
  - RWM active control advancements
  - Combined control systems to maintain $<\beta_N>_{pulse}$ at varied ω_ϕ
  - Physics of 3D fields to control plasma rotation
  - Multi-mode RWM spectrum in high β_N plasmas

NSTX is a spherical torus equipped for passive and active global MHD control, application of 3D fields

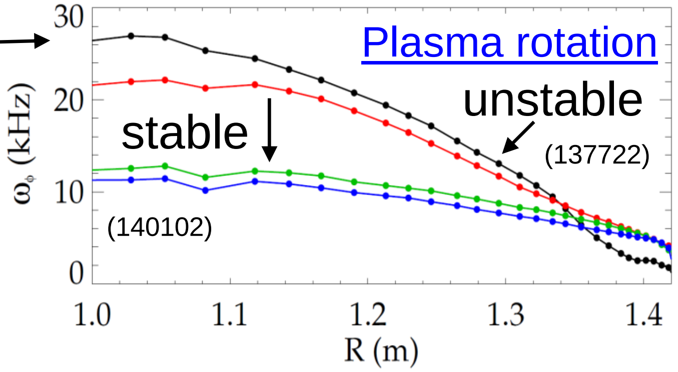
- ❑ High beta, low aspect ratio
  - ❑ R = 0.86 m, A > 1.27
  - ❑ $I_p < 1.5$ MA, $B_t = 5.5$ kG
  - ❑ $\beta_t < 40\%$, $\beta_N < 7.4$
- ❑ Copper stabilizer plates for kink mode stabilization
- ❑ Midplane control coils
  - ❑ n = 1 – 3 field correction, magnetic braking of ω_ϕ by NTV
  - ❑ n = 1 RWM control
- ❑ Varied sensor combinations used for RWM feedback
  - ❑ 48 upper/lower B_p, B_r



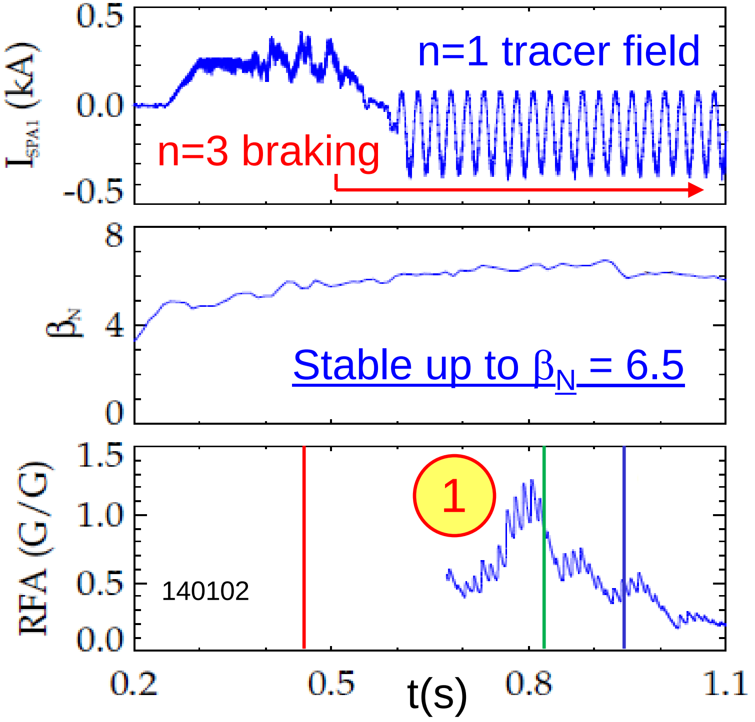
Low plasma rotation level (~ 1% ω_{Alfven}) is insufficient to ensure RWM stability, which depends on ω_ϕ profile



RWM unstable plasma



Plasma rotation



MHD spectroscopy (stable plasma)

- RWM unstable plasma
  - Instability occurs at relatively high rotation level, and not at highest β_N (4.7)
- RWM stable plasma
  - MHD spectroscopy: increased resonant field amplification (RFA) indicates reduced stability ①
  - Plasma moves to more stable regime (lower RFA) at lower rotation (β_N up to 6.5)

Modification of Ideal Stability by Kinetic theory (MISK code) investigated to explain experimental RWM stabilization

- ❑ Reason: simple critical ω_ϕ threshold stability models do not fully describe RWM marginal stability in NSTX Sontag, et al., Nucl. Fusion **47** (2007) 1005.
- ❑ Kinetic modification to ideal MHD growth rate
  - ❑ Trapped / circulating ions, trapped electrons, etc.
  - ❑ Energetic particle (EP) stabilization

$$\gamma\tau_w = -\frac{\delta W_\infty + \delta W_K}{\delta W_b + \delta W_K}$$

Hu and Betti, Phys. Rev. Lett **93** (2004) 105002.

- ❑ Stability depends on
  - ❑ Integrated ω_ϕ profile: resonances in δW_K (e.g. ion precession drift)
  - ❑ Particle collisionality, EP fraction

ω_ϕ profile (enters through ExB frequency)

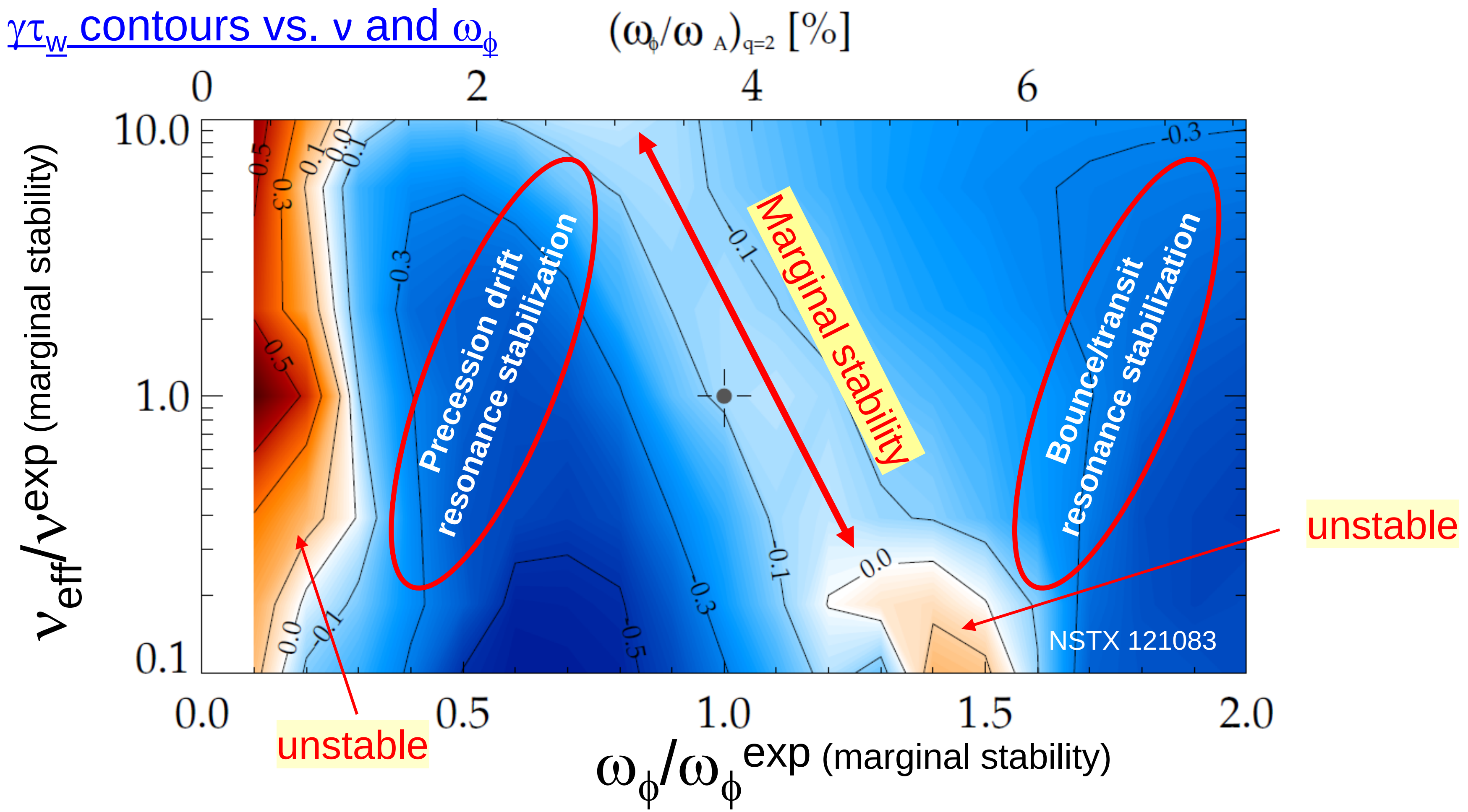
Trapped ion component of δW_K (plasma integral)

$$\delta W_K \propto \int \left[\frac{\omega_{*N} + \left(\hat{\varepsilon} - {}^{3}\!/_{2}\right)\omega_{*T} + \omega_E - \omega - i\gamma}{\langle\omega_D\rangle + l\omega_b - i\nu_{eff} + \omega_E - \omega - i\gamma}\right]\hat{\varepsilon}^{\frac{5}{2}} e^{-\hat{\varepsilon}} d\hat{\varepsilon}$$

← Energy integral

precession drift bounce collisionality

MISK calculations consistent with RWM destabilization at intermediate plasma rotation; stability altered by collisionality


$\gamma\tau_w$ contours vs. ν and ω_ϕ

Precession drift resonance stabilization

Marginal stability

Bounce/transit resonance stabilization

unstable

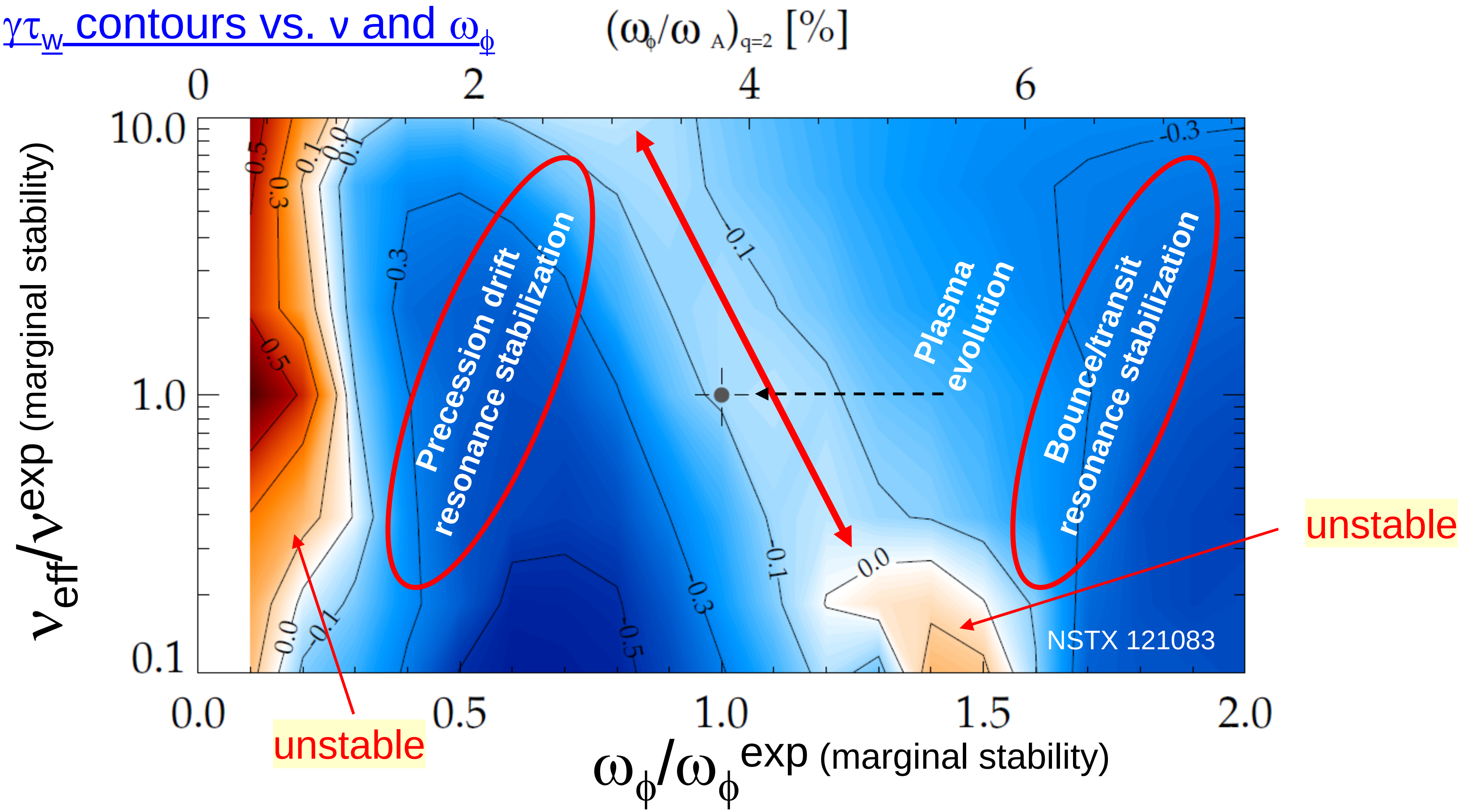
unstable

NSTX 121083

- Destabilization appears between precession drift resonance at low ω_ϕ, bounce/transit resonance at high ω_ϕ

J.W. Berkery, et al., PRL **104** (2010) 035003
S.A. Sabbagh, et al., NF **50** (2010) 025020

MISK calculations consistent with RWM destabilization at intermediate plasma rotation; stability altered by collisionality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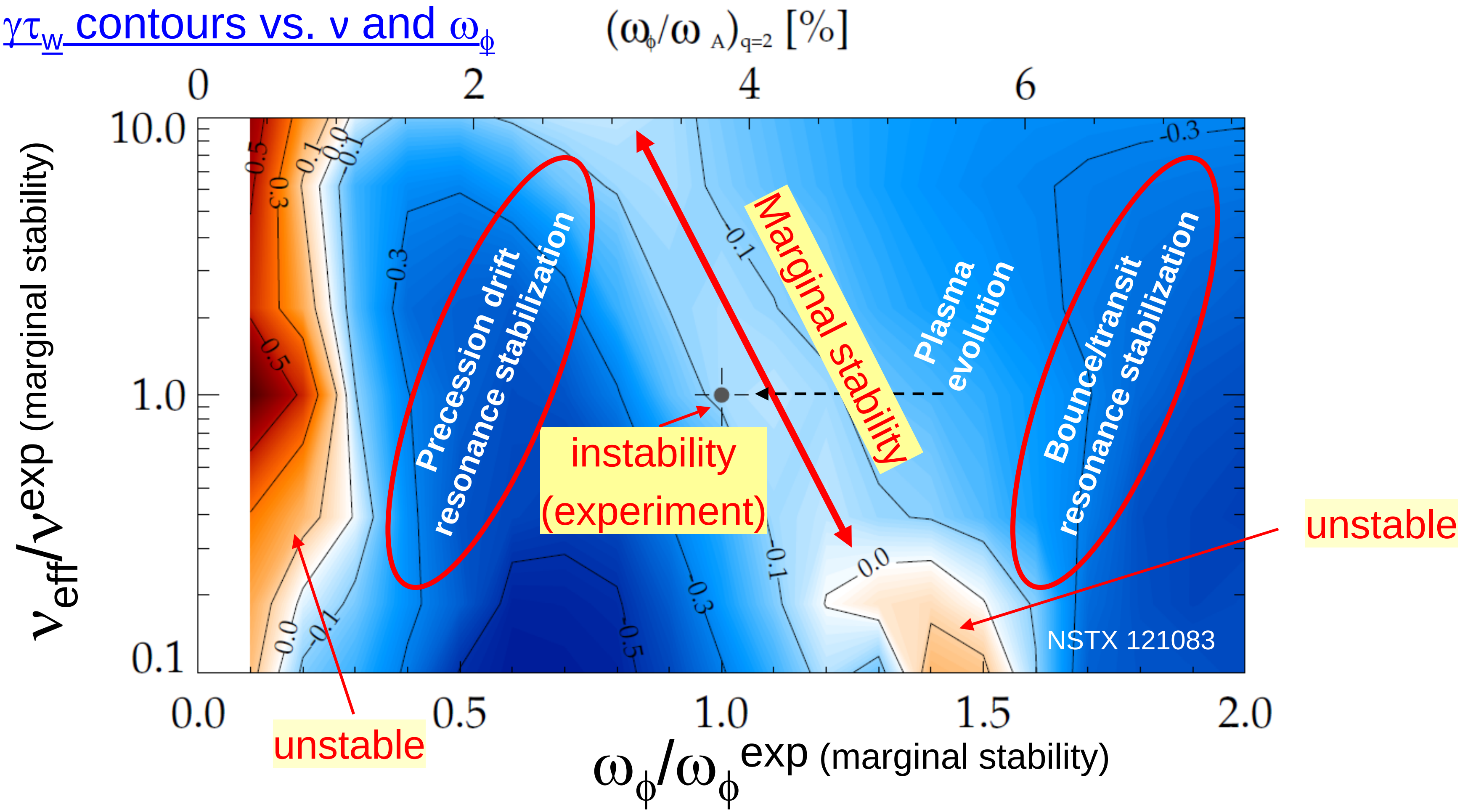
$\gamma\tau_w$ contours vs. ν and ω_ϕ

- Destabilization appears between precession drift resonance at low ω_ϕ, bounce/transit resonance at high ω_ϕ
- Destabilization moves to increased ω_ϕ as ν decreases

J.W. Berkery, et al., PRL **104** (2010) 035003
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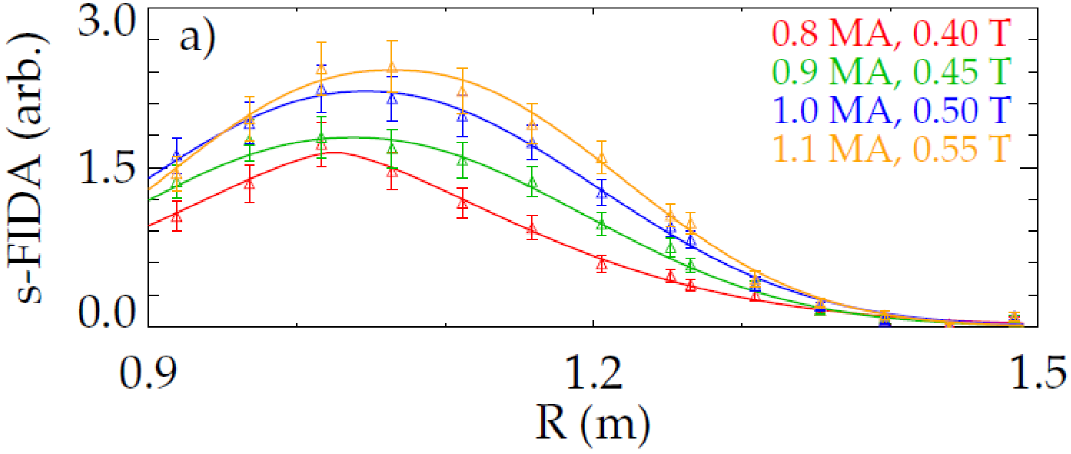
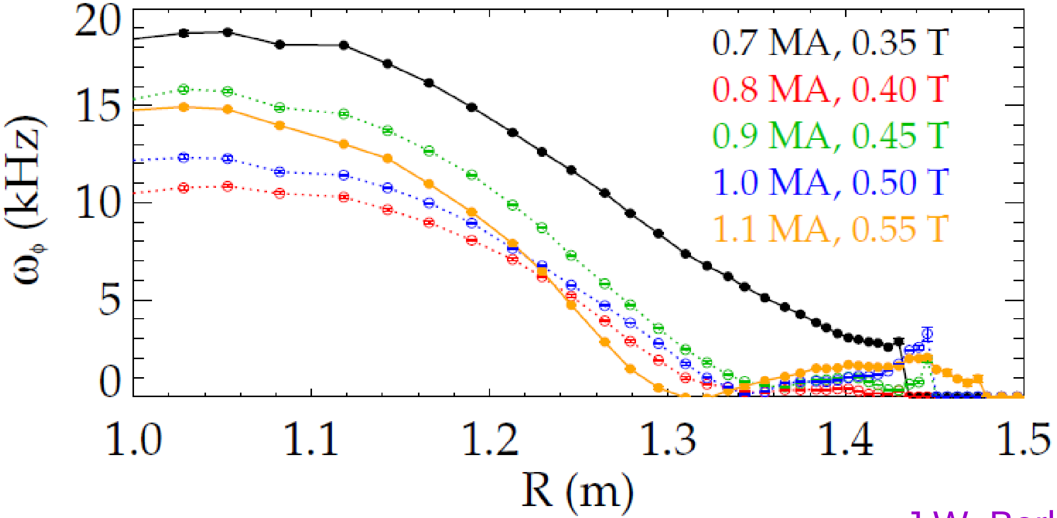
Rotation profile at RWM marginal stability altered by varying energetic particle content

Relative fast ion density profiles



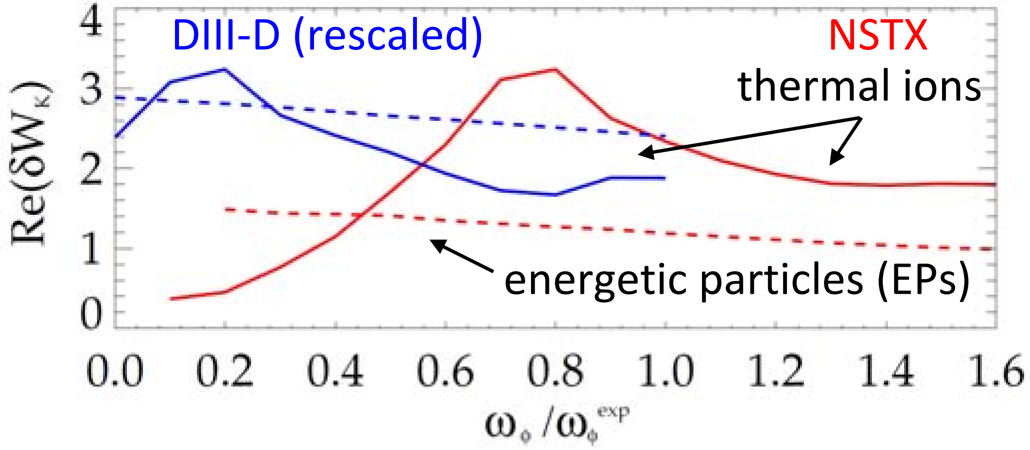
Rotation profiles at marginal stability

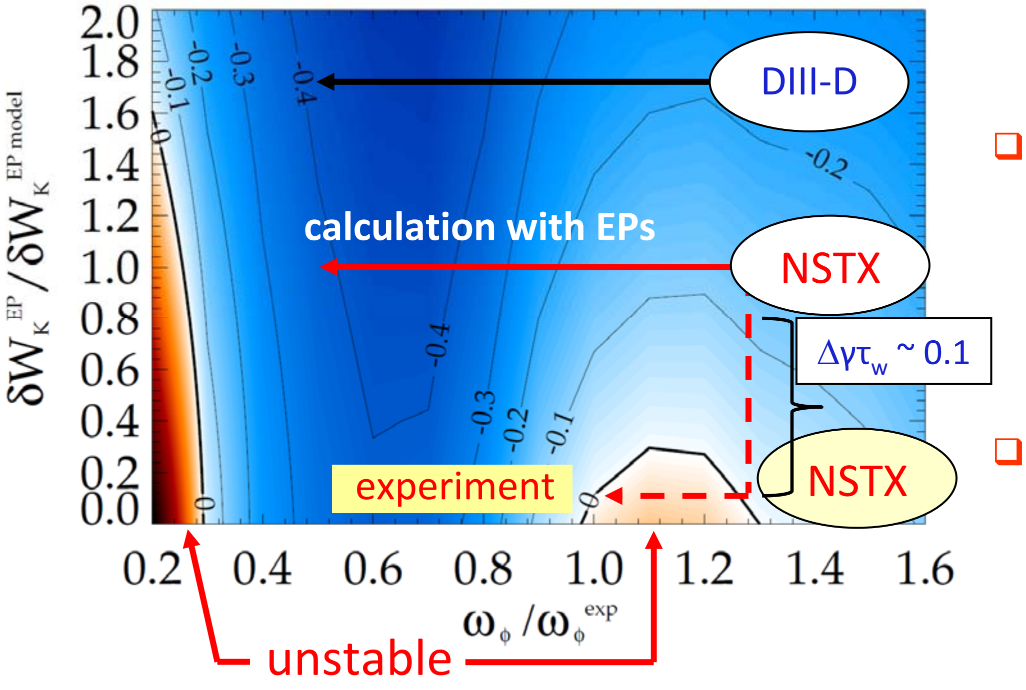


- I_p, B_t altered keeping q fixed in experiment
- Fast ion density increases with increased I_p
  - Indicated by fast ion D_α diagnostic
  - Range of TRANSP β_{fast}/β_{tot} 17% - 31%
- General reduction of RWM marginal ω_ϕ profile as I_p increased

J.W. Berkery, et al., Phys. Plasmas **17** (2010) 082504

Model of kinetic modifications to ideal stability can unify RWM stability results between devices



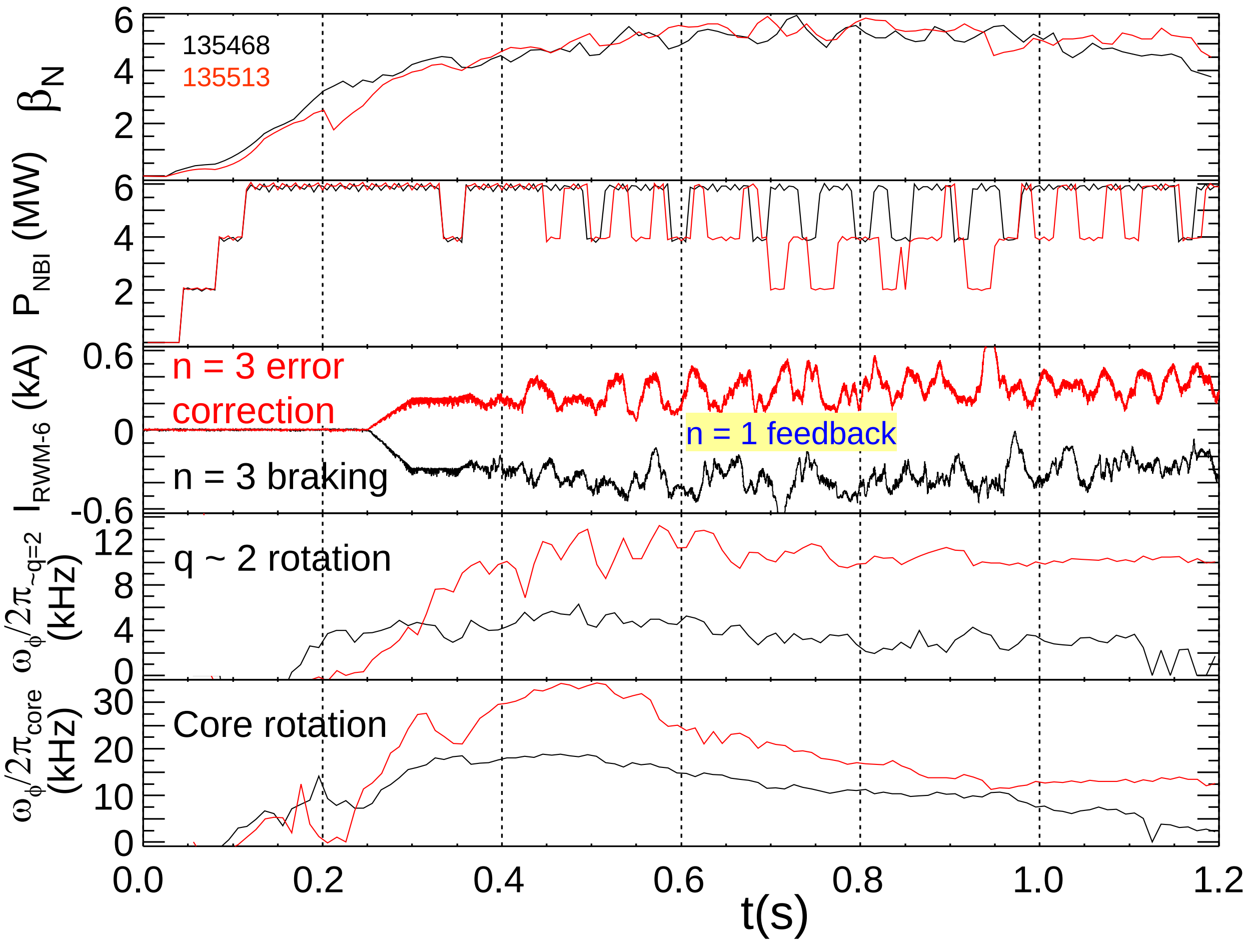


- NSTX
  - Less EP stability: RWM can cross marginal point as ω_ϕ is varied
- DIII-D
  - More EP stability (~ 2x NSTX): RWM stable at all ω_ϕ
  - RWM destabilized by events that reduce EP population

H. Reimerdes, et al., paper EXS/5-4

- ITER (advanced scenario IV)
  - RWM unstable at expected rotation
  - Only marginally stabilized by alphas at $\beta_N = 3$ See poster (EXS/5-5)
- Stability overpredicted with EPs – model development continues
  - Improve NBI anisotropic distribution
  - Examine effects originally thought small See poster (EXS/5-5)

β_N feedback combined with n = 1 RWM control to reduce β_N fluctuations at varied plasma rotation levels

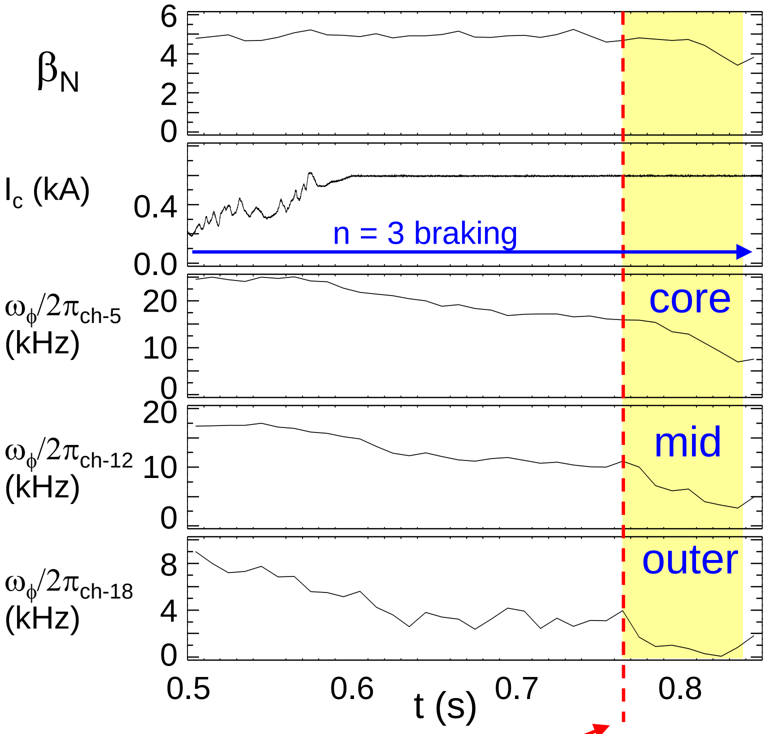


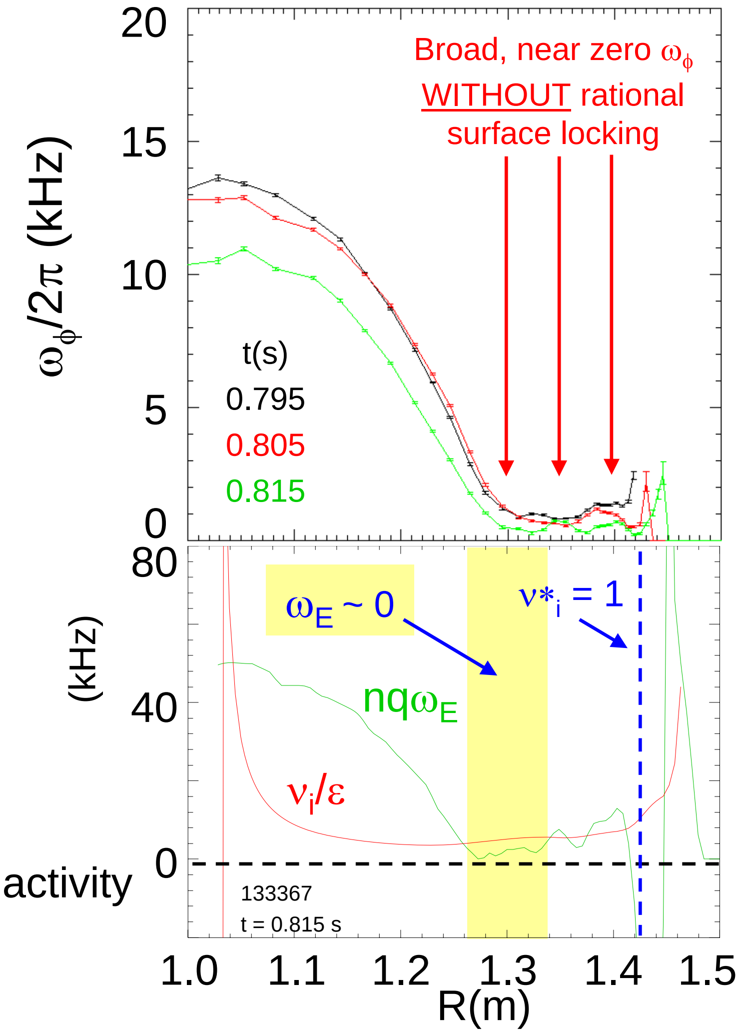
- ❑ Prelude to ω_ϕ control
  - ❑ Reduced ω_ϕ by n = 3 braking is compatible with β_N FB control

S. Gerhardt, EXS/P2-08

- ❑ Steady β_N established over long pulse
  - ❑ independent of ω_ϕ over a large range
- ❑ Radial field sensors added to n = 1 feedback (2010)
  - ❑ Full sensor set further reduces n = 1 amplitude, improves control

Stronger braking with constant n = 3 applied field and β_N as ω_E reduced – accessing superbanana plateau NTV regime

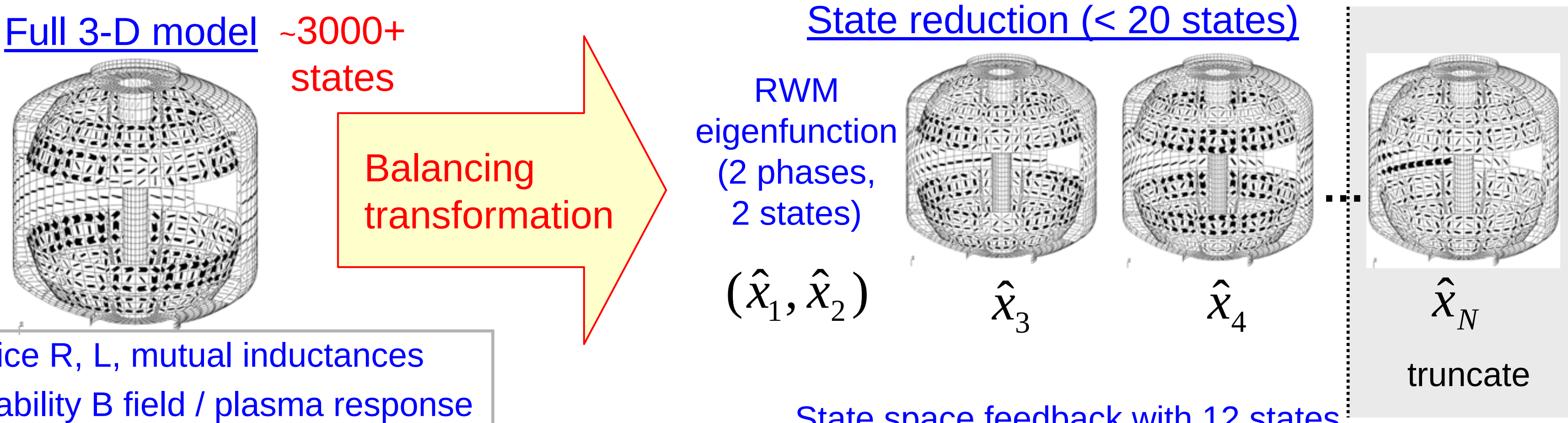




- Faster braking with
  - Constant applied n = 3 field, β_N; No mode activity
- Torque not $\propto 1/\omega_\phi$ (non-resonant)
  - NTV satisfies low collisionality "1/ν regime" criterion ($|nq\omega_E| < \nu_i/\varepsilon$ and $\nu^*_i < 1$) Callen OV/4-3
  - Stronger braking expected at low ω_E (superbanana plateau regime)

    (K.C. Shaing et al., PPFC **51** (2009) 035009)

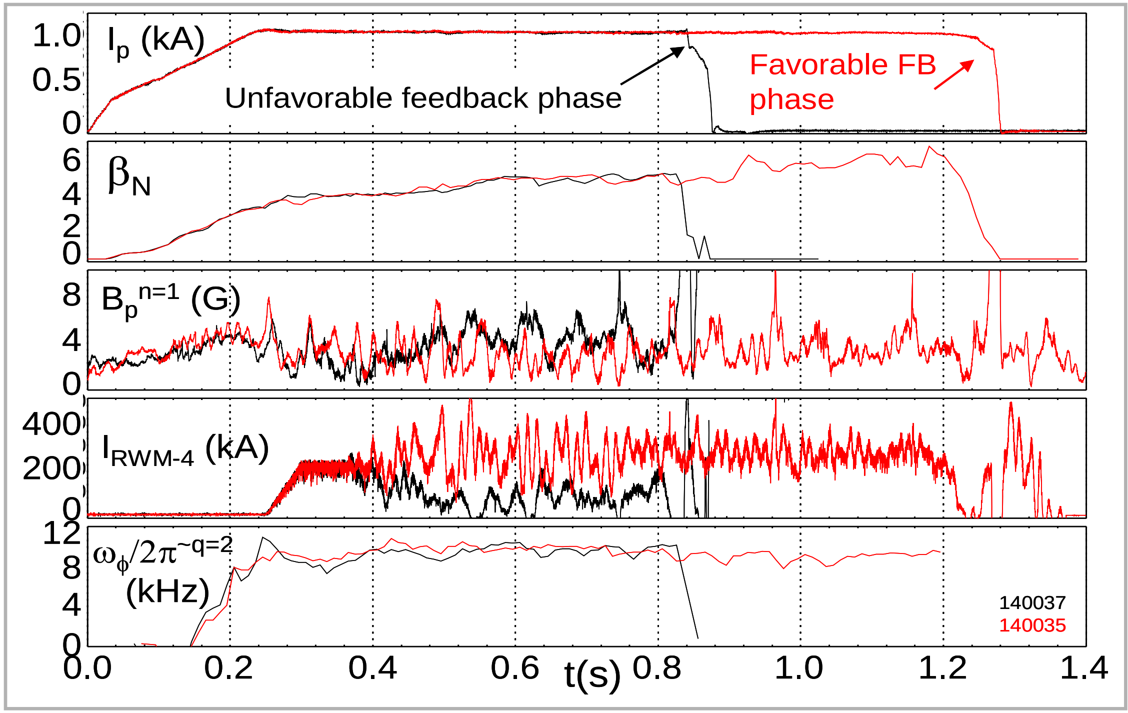
New RWM state space controller sustains high β_N plasma



- device R, L, mutual inductances
- instability B field / plasma response
- modeled sensor response

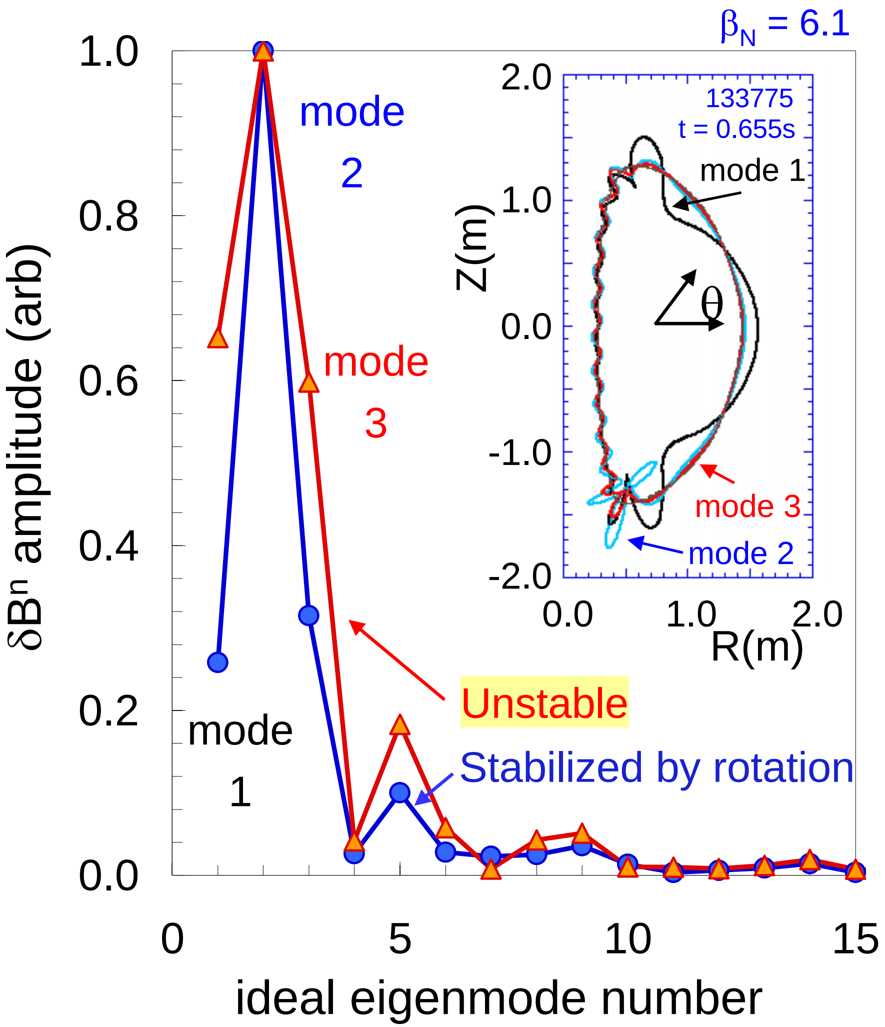
- Controller can compensate for wall currents
  - Including mode-induced current
  - Examined for ITER
    Katsuro-Hopkins, et al., NF (2007) 1157
- Successful initial experiments
  - Suppressed disruption due to n = 1 applied error field
  - Best feedback phase produced long pulse, $\beta_N = 6.4$, $\beta_N/l_i = 13$

State space feedback with 12 states



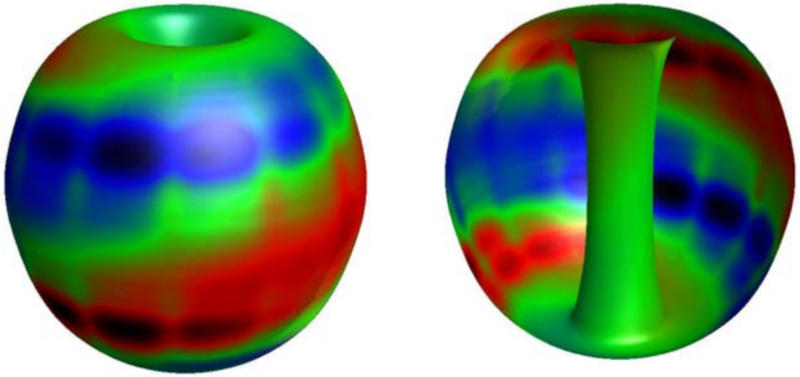
Multi-mode RWM computation shows 2nd eigenmode component has dominant amplitude at high β_N in NSTX stabilizing structure

δB^n RWM multi-mode composition



mmVALEN code

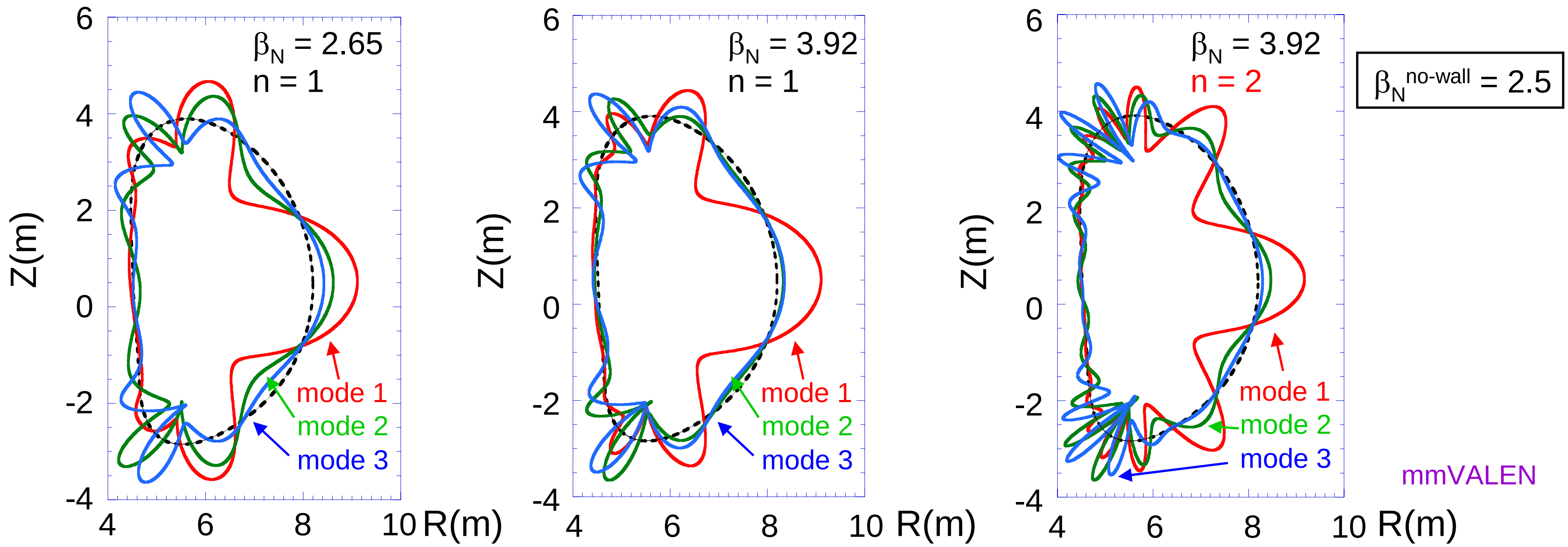
δB^n from wall, multi-mode response

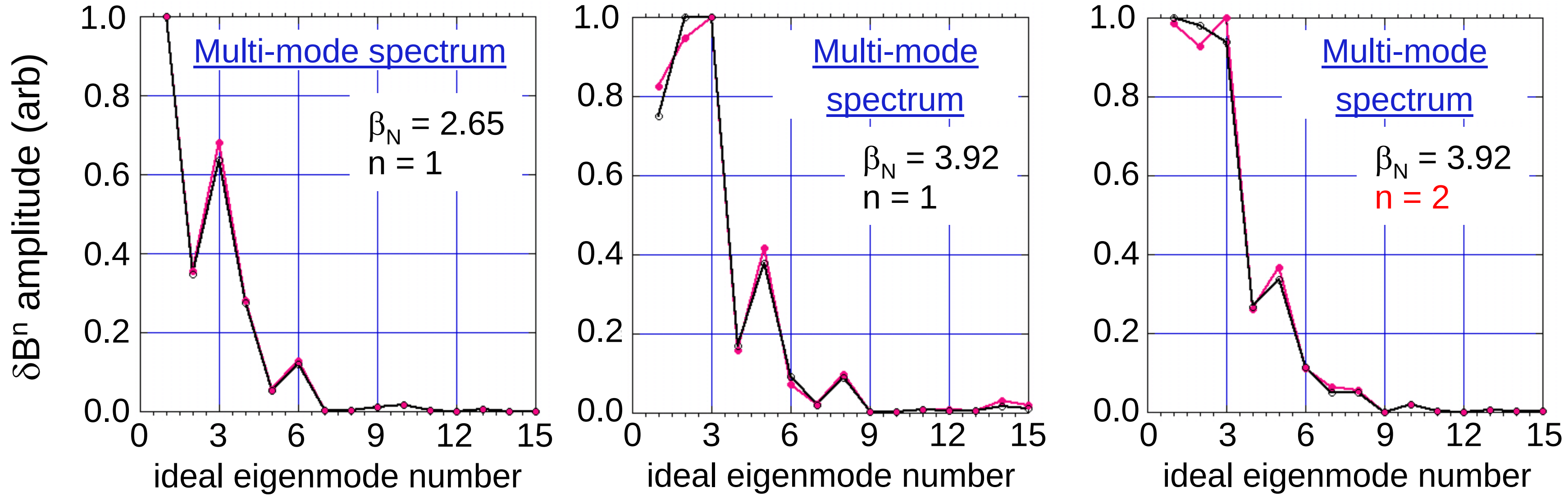


- NSTX unstable RWM
  - Computed growth time consistent with experiment
  - 2nd eigenmode ("divertor") has larger amplitude than ballooning eigenmode
- NSTX RWM stabilized by ω_ϕ
  - Ballooning eigenmode amplitude decreases relative to "divertor" mode
  - Computed RWM rotation ~ 41 Hz, close to experimental value ~ 30 kHz
- ITER scenario IV multi-mode spectrum
  - Significant spectrum for n = 1 and 2

See poster (EXS/5-5) for more detail

ITER Advanced Scenario IV: multi-mode RWM spectra computation shows significant ideal eigenfunction amplitude for several components





NSTX is Addressing Global Stability Needs Furthering Steady Operation of High Performance Plasmas

Physics addressed	Implications for	
	Future STs (NBI-driven, high ω_ϕ)	ITER advanced scenarios (low ω_ϕ)
❑ RWM instability observed at intermediate ω_ϕ correlates with kinetic stability theory	❑ ω_ϕ profile control ❑ Sufficient EP stabilization	❑ Sufficient EP stabilization needed at low ω_ϕ
❑ n = 1 RWM, β_N feedback control maintains high β_N at varied ω_ϕ using n = 3 NTV ω_ϕ profile modification	❑ Potential control compatibility	❑ Potential control at low ω_ϕ if EP stabilization insufficient
❑ Stronger NTV braking at reduced ω_E	❑ ω_ϕ profile control impact	❑ Further examine NTV at low ω_ϕ
❑ Initial success of RWM state space controller at high β_N	❑ More flexibility of control coil placement	❑ More flexibility of control coil placement
❑ Multi-mode RWM physics spectrum	❑ Determine RWM control impact	❑ Determine RWM control impact

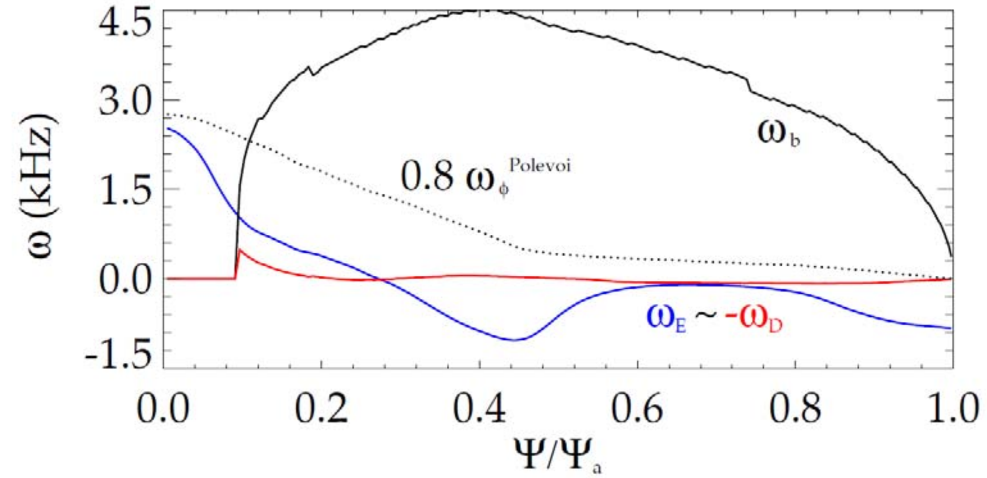
Additional Slides

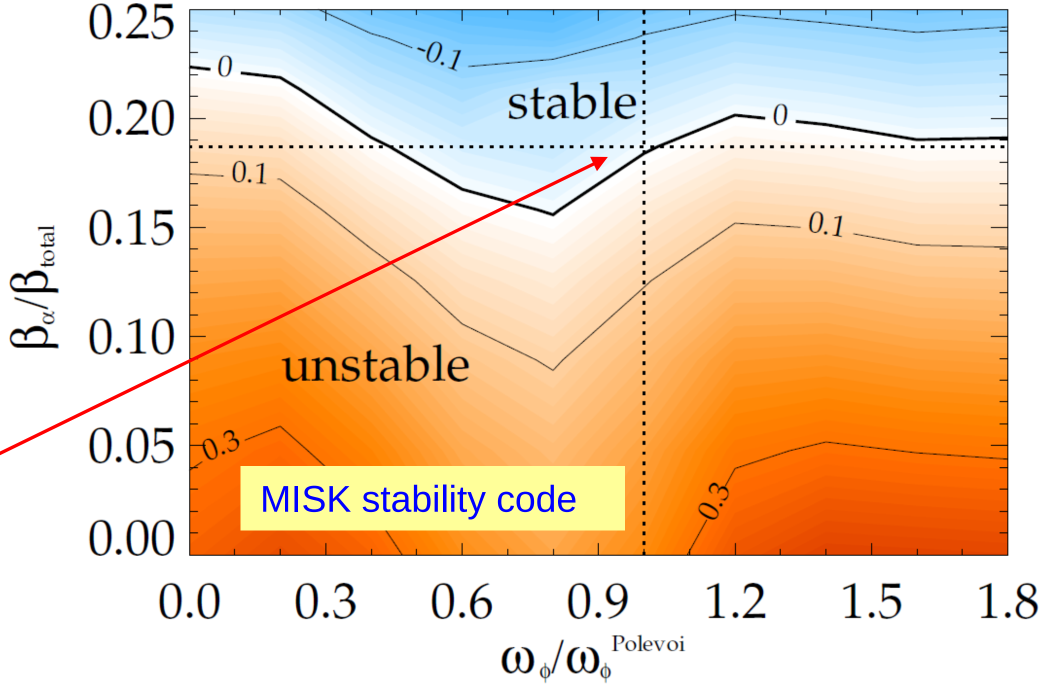
NSTX is Addressing Global Stability Needs Furthering Steady Operation of High Performance Plasmas

- RWM instability observed at intermediate plasma rotation correlates with kinetic stability theory
  - Theory of kinetic modifications to ideal stability may unify RWM stability results between devices
  - ITER advanced scenario 4 requires EP stabilization at expected ω_ϕ
- n = 1 RWM feedback control combined with new β_N feedback control shows regulation of high β_N at varied plasma rotation levels
  - Compatible with plasma rotation control by non-resonant 3D fields
- Stronger non-resonant NTV braking observed at reduced ω_E
  - Theoretically expected (superbanana plateau regime)
- New RWM state space controller sustains high β_N plasma
  - Potential for greater flexibility of RWM control coil placement for burning plasma devices
- Computed multi-mode RWM spectrum at high β_N shows significant amplitude in higher order modes

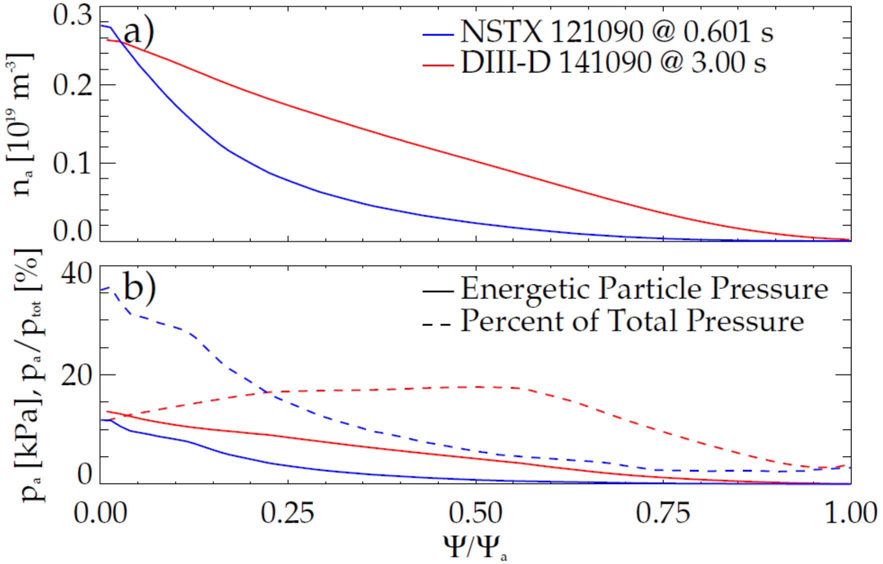
ITER Advanced Scenario IV: RWM just reaches marginal stability by energetic particles with $\beta_N = 3$

- **Equilibrium**
  - With $\beta_N = 3$ (20% above n = 1 no-wall limit)
  - Plasma rotation profile linear in normalized poloidal flux
- **Plasma rotation effect**
  - Stabilizing precession drift resonance weakly enhances stability near $\omega_\phi = 0.8\ \omega_\phi^{\text{Polevoi}}$
- **Energetic particle (EP) effect**
  - Alpha particles are required for RWM stabilization at all ω_ϕ
  - Near RWM marginal stability at ITER expected $\beta_\alpha/\beta_{\text{total}} = 0.19$ at $\omega_\phi = \omega_\phi^{\text{Polevoi}}$

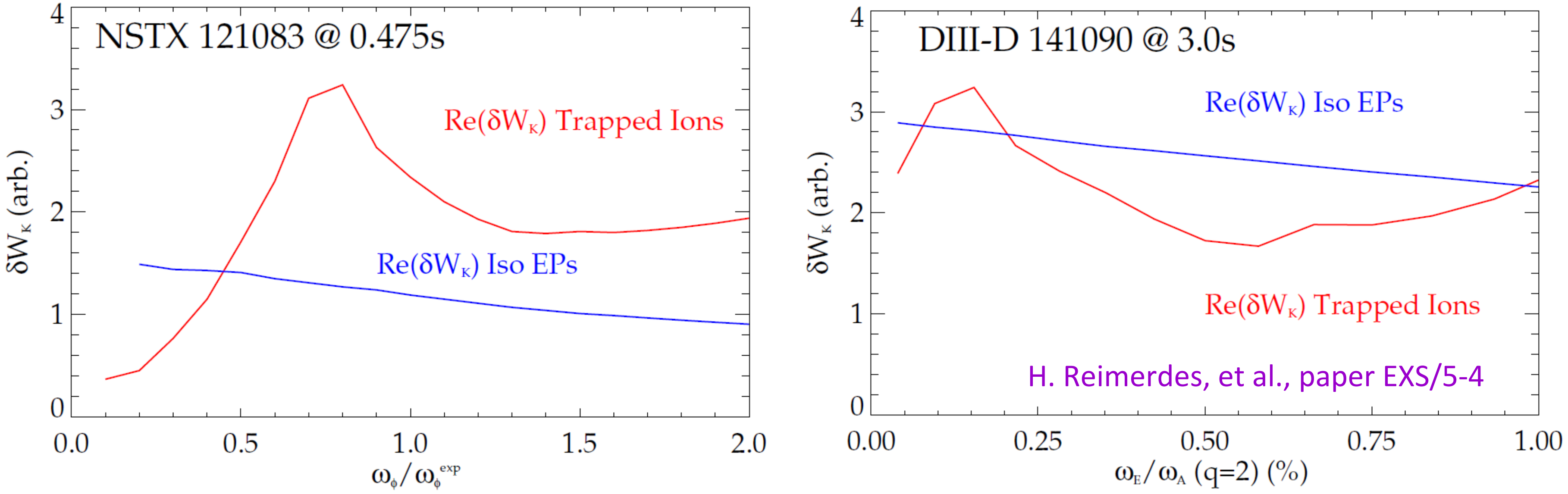




Energetic particles are stabilizing to RWM; computed effect is smaller in NSTX when compared to DIII-D



- Smaller energetic particle (EP) fraction in NSTX
  - Less stability due to EPs
- Scaled δW_k from MISK shows larger stabilization effect due to EPs in DIII-D



H. Reimerdes, et al., paper EXS/5-4

Advancements in MISK stability model continue

Electrostatic effect

The electrostatic component of the perturbed distribution function contributes to δW. (expected to be small).

$$\delta W_{\Phi} = -\frac{1}{2}\int e^2 \left|\tilde{\Phi} + \xi_{\perp}\cdot\nabla\Phi_0\right|^2 \sum_j Z_j^2 \frac{n_j}{T_j} dV$$

[B. Hu *et al.*, Phys. Plasmas **12**, 057301 (2005)]

Additional anisotropic term

In addition to present anisotropy effects on δW_K, when *f* is anisotropic an additional term arises that is proportional $\tilde{\mathbf{B}}_{\|}$:

$$\delta W_{\tilde{B}} = \sum_j \frac{1}{2}\int\int \langle HT_j\rangle^* \mu \frac{\tilde{\mathbf{B}}_{\|}}{B}\frac{\partial f_j}{\partial \mu} d^3\mathbf{v}dV.$$

Centrifugal destabilization

This fluid force term is usually neglected, but it is always destabilizing, and could be important if the plasma rotation Mach number is significant, or for alpha particles rotating at higher frequency ~ $\omega_{*\alpha}$. (significant for NSTX in core, not edge)

$$\delta W_C = -\frac{1}{2}\sum_j \int \xi_{\perp}^{*}\cdot[\tilde{\rho}\mathbf{v_0}\cdot\nabla\mathbf{v_0}]\, dV$$

Other possibilities:

- Inclusion of plasma inertia term in the dispersion relation
- Effect of poloidal rotation on ω_E (small)
- Use of a Lorentz collisionality model instead of current ad-hoc inclusion of collisionality

$$C\left(\tilde{f}\right) = \frac{1}{2}\nu\Pi_e \frac{\partial}{\partial \chi}(1-\chi)^2\frac{\partial \tilde{f}}{\partial \chi}$$