Resistive Wall Mode Observation and Control in ITER-Relevant Plasmas

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Outline

- Basic Resistive Wall Mode (RWM) model
- RWM stability, neglecting kinetic effects
  - Sufficient for machines without large energetic particle populations
- Extended RWM stability, including kinetic effects
  - Important for large machines like ITER
- Measuring RWMs
- Why RWMs are important
- Expected RWMs in ITER
  - Scenario-dependent
- RWM effects on bulk plasma properties
- Controlling RWMs
  - Passive stabilization
  - Active feedback

The Resistive Wall Mode (RWM) is a form of the ideal external kink whose growth rate has been slowed by a conducting wall

- Ideal MHD stability analysis of tokamak plasmas introduces the ideal *external kink*.

- A conducting wall near the edge of a tokamak plasma slows the growth rate of the external kink from an Alfvénic time scale to the *resistive time scale* (τ_w) of the wall.

Fig. 2.3: An $(m, n) = (3, 1)$ perturbation to a toroidal surface, such as might be observed during the onset of an external kink mode.

Hanson, *Thesis*, 2009

MHD stability analysis gives a straightforward estimate for RWM growth rate

$$\boxed{\gamma\tau_W = -\frac{\delta W_\infty}{\delta W_b}}$$

← No wall (or wall at infinity) $\quad \delta W_\infty = \delta W_F + \delta W_V^{(\infty)}$

← Ideal wall at position b $\quad \delta W_b = \delta W_F + \delta W_V^{(b)}$

(Neglecting δW_S)

Plasma contribution (same for both parts):

$$\delta W_F = \frac{1}{2}\int_{V_P}\left(\frac{|\delta \mathbf{B}|^2}{\mu_0} - \xi\cdot(\mathbf{J}\times\delta\mathbf{B}) + \Gamma p|\nabla\cdot\xi|^2 + (\xi\cdot\nabla p)\nabla\cdot\xi\right)dV$$

Vacuum contribution:

$$\delta W_V^{(\infty)} = \frac{1}{2\mu_0}\int_{S_p}(\mathbf{e}_n\times\delta\hat{\mathbf{A}}_\infty)\cdot\mathbf{e}_n\times(\mathbf{e}_n\times\nabla\times\delta\hat{\mathbf{A}}_\infty)dS$$

(from: $\delta W_V^{(\infty)} = \frac{1}{2}\int_V \frac{|\delta\hat{\mathbf{B}}_\infty|^2}{\mu_0}dV$)

$$\delta W_V^{(b)} = \frac{1}{2\mu_0}\int_{S_p}(\mathbf{e}_n\times\delta\hat{\mathbf{A}}_b)\cdot\mathbf{e}_n\times(\mathbf{e}_n\times\nabla\times\delta\hat{\mathbf{A}}_b)dS$$

Haney, *PFB*, 1989

Kinetic effects become important for plasmas with significant energetic particle content

- Including kinetic effects changes the growth rate and introduces rotation

Neglecting kinetic effects		Including kinetic effects
$\gamma\tau_w = -\delta W_\infty / \delta W_b$	$\Rightarrow$	$(\gamma - i\omega_r)\tau_w = -\dfrac{\delta W_\infty + \delta W_K}{\delta W_b + \delta W_K}$

- Kinetic contribution can have resonances:

$$\delta W_K = \frac{\sqrt{2}\pi^2}{m_j^{3/2}} \sum_{l=-\infty}^{\infty} \int d\varepsilon \int d\chi \int \frac{d\Psi}{B_0} \hat{\tau} \left(-2|\chi| \frac{B_0}{B} \right) \times \frac{(\omega_r + i\gamma - \omega_E)\dfrac{\partial f_j}{\partial \varepsilon} - \dfrac{1}{eZ_j}\dfrac{\partial f_j}{\partial \Psi}}{\langle \omega_D^j \rangle + l\omega_b^j - i\nu_{\mathrm{eff}}^j + \omega_E - \omega_r - i\gamma} \varepsilon^{5/2} |\langle H/\hat{\varepsilon} \rangle|^2$$

Berkery, *PoP*, 2010

RWM eigenfunctions have a global extent

NSTX

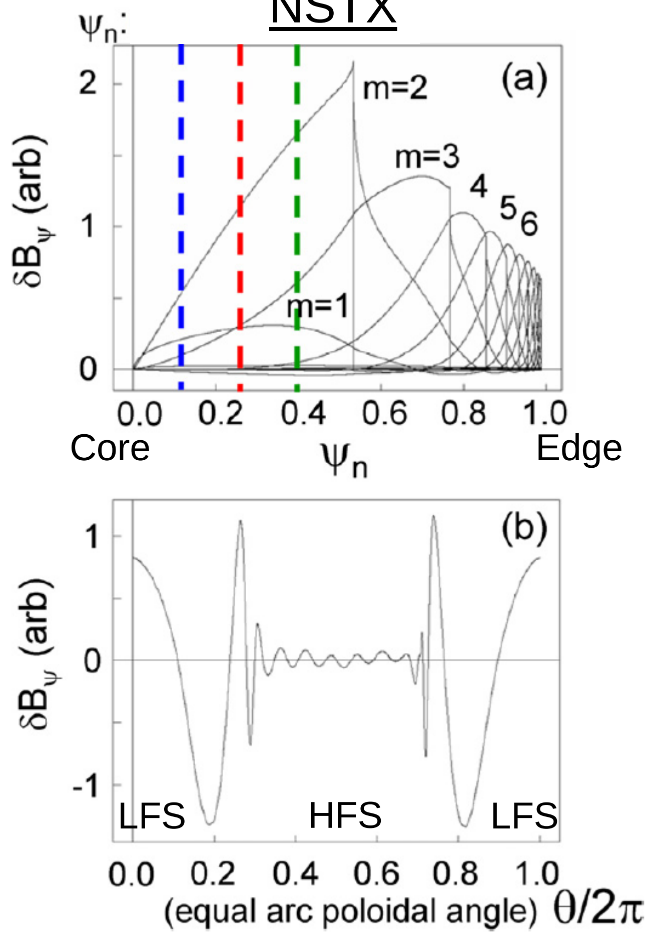
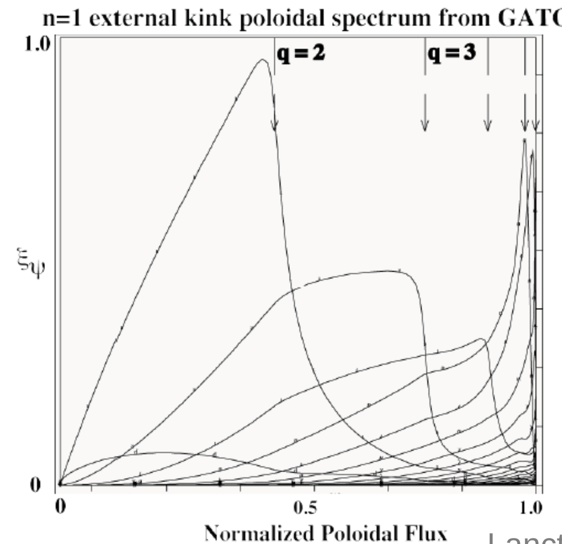


Figure 6. Theoretical computed $n = 1$ ideal mode field normal to the flux surface decomposed into poloidal harmonics as a function of normalized poloidal flux (frame (*a*)) and poloidal variation of the $n = 1$ RWM field at the plasma boundary as a function of poloidal angle (frame (*b*)).

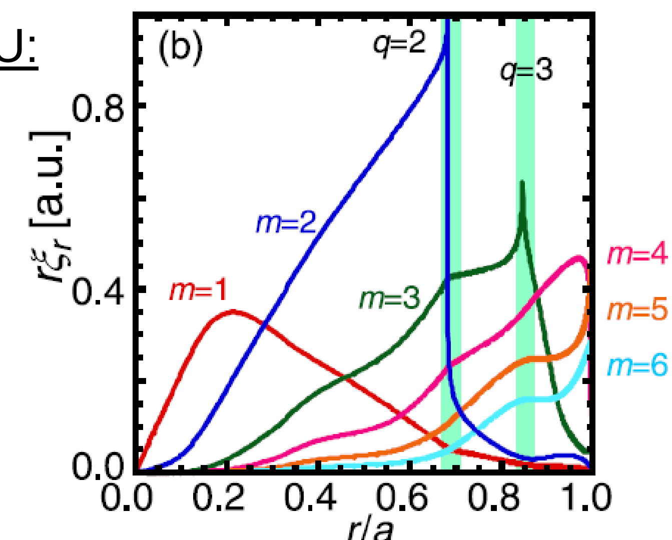
Sabbagh, *NF*, 2006

DIII-D:



Lanctot, *APS*, 2008

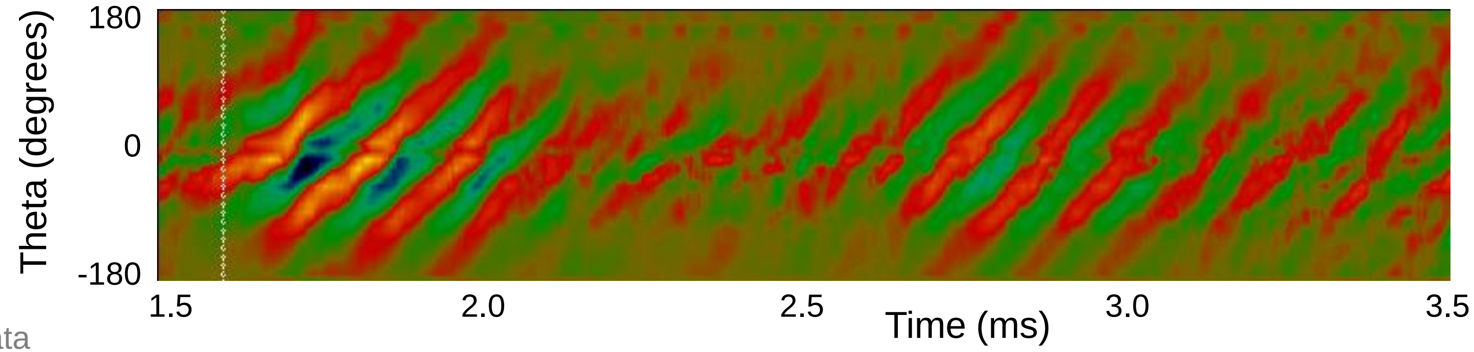
JT60-U:



Matsunaga, *PFR*, 2009

RWMs can be measured with external magnetic probes or with internal emission diagnostics

- External: Measuring magnetic field oscillations



HBT-EP data

- Internal: Measuring effects of the mode on plasma parameters

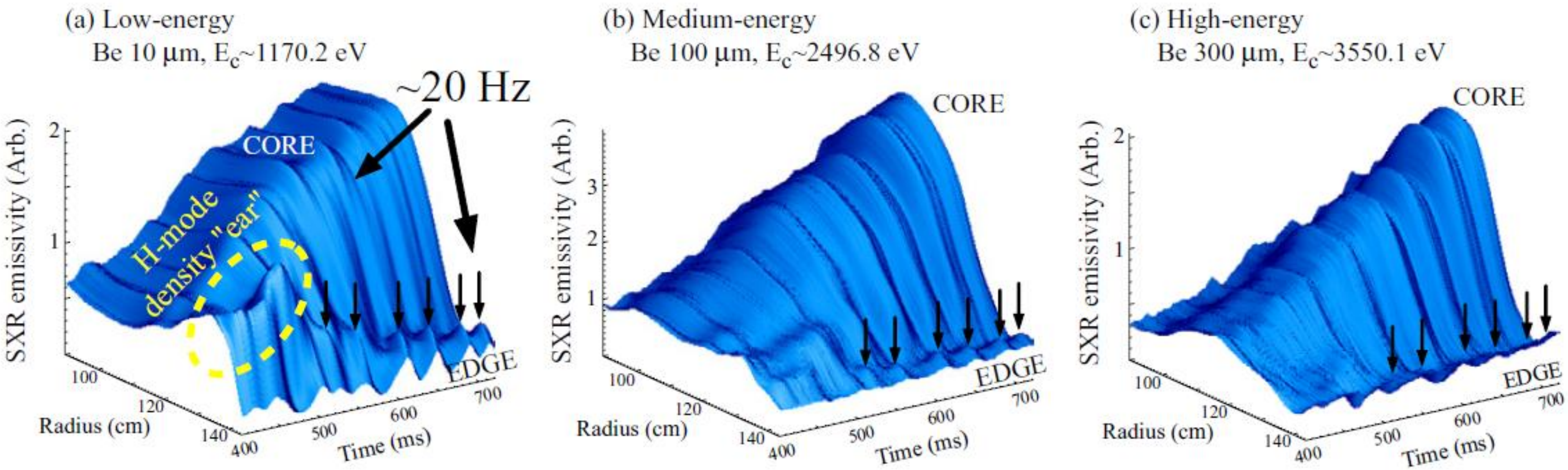


Figure 2. Plots of the three ME-SXR emissivities during the actively RWM control.

Delgado, *PPCF*, 2011

ITER steady-state scenarios are most susceptible to RWMs

Shimada, *NF*, 2007

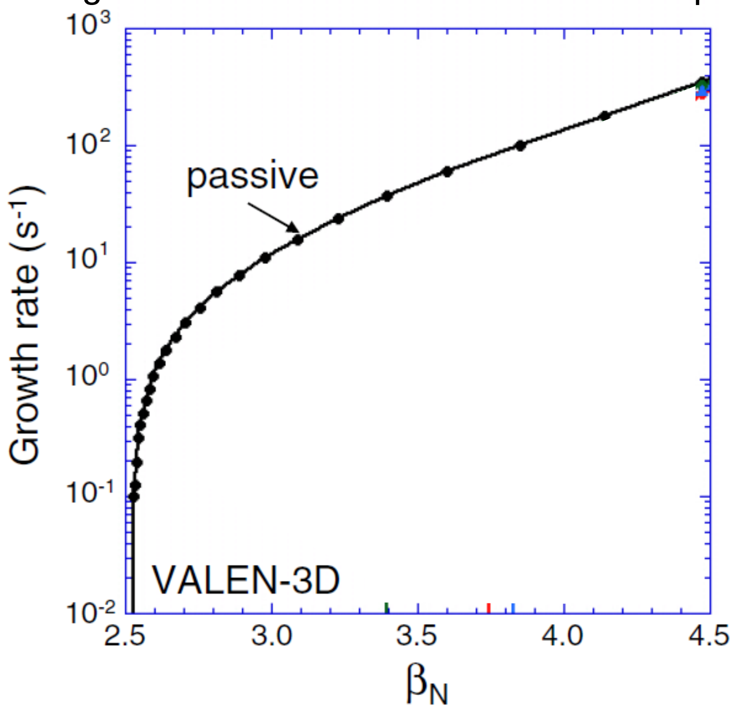
Table 3. ITER operation scenarios.

Scenario	Plasma current (MA)	Non-inductive fraction	H98(y,2)	li	β_N	Burn duration (s)
Inductive (Scenario 2)	15	0.15	1.0	0.8	1.8	~400
Hybrid (Scenario 3)	~12	~0.50	1–1.2	0.9	2–2.5	⩾1000
Steady-state (Scenario 4)	~ 9	1.00	⩾1.3	0.6	⩾2.6	3000[a]

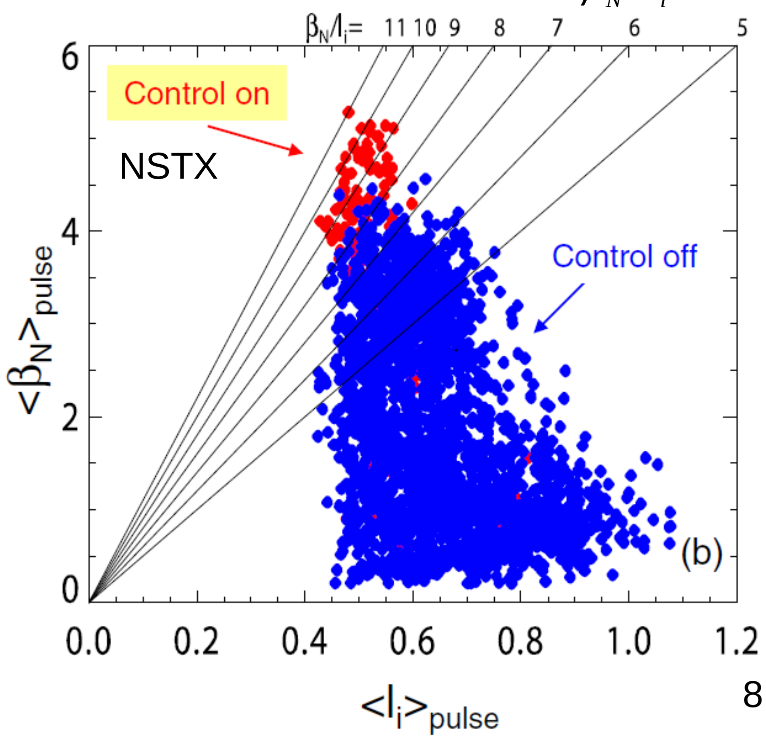
[a] 3000 s limit is imposed by the cooling system.

β_N / l_i gives an empirical stability limit...

RWM growth rate for an ITER scenario 4 equilibrium



...but NSTX doesn't have a clear β_N / l_i limit



Sabbagh, *NF*, 2010

The resistive wall mode prevents high β in steady-state scenarios unless it is stabilized

Degree of RWM instability:

$$C_\beta \equiv \frac{\beta_N - \beta_N^{no-wall}}{\beta_N^{ITER-wall} - \beta_N^{no-wall}}$$

With $\beta_N \sim \frac{\langle \beta_t \rangle}{I_p / aB_0}$

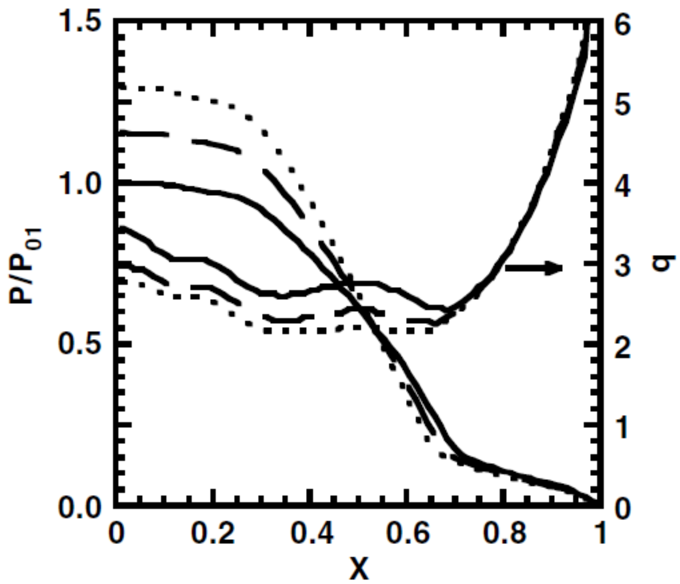


Figure 29. Normalized pressure and safety factor profiles for SS operational scenarios: solid line (N1): $q_{\min} = 2.43$, $\beta_N^{SS} = 2.56$, dashed line (N2): $q_{\min} = 2.25$, $\beta_N^{SS} = 2.7$, dotted line (N3): $q_{\min} = 2.12$, $\beta_N^{SS} = 2.82$; p_{01} corresponds to central pressure in the scenario N1 [203].

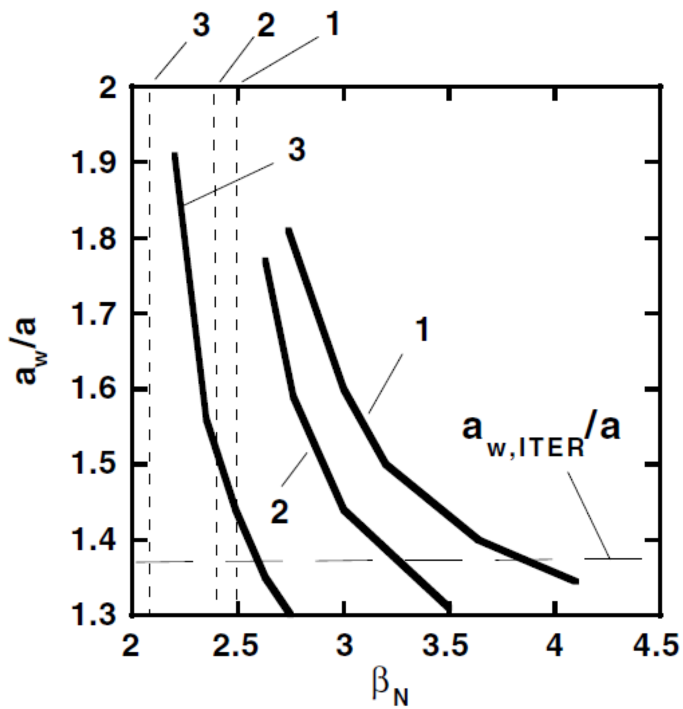


Figure 30. Stabilizing wall position a_w/a versus normalized beta β_N or q = const scan of SS operational points N1,2,3. The no-wall limits are shown by vertical dashed lines [286].

Hender, *NF*, 2007

ITER scenario 4 plasmas are expected to be marginally stable to RWMs for the predicted rotation and alpha particle content

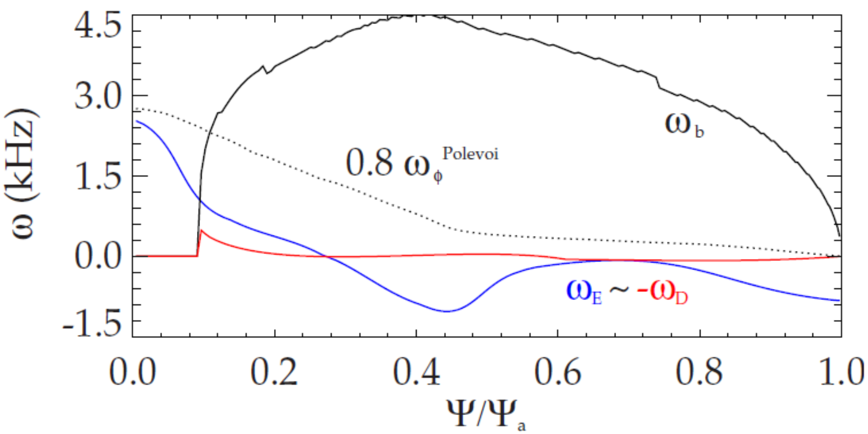


FIG. 4. (Color online) Profiles of 0.8 $\omega_\phi^{\text{Polevoi}}$, the resulting ω_E, ω_b with $\chi=0$ and $\hat{\varepsilon}=2$, and $-\langle\omega_D\rangle$ with $\chi=0$ and $\hat{\varepsilon}=\frac{3}{2}$ (see Ref. 9) vs Ψ for ITER scenario 4.

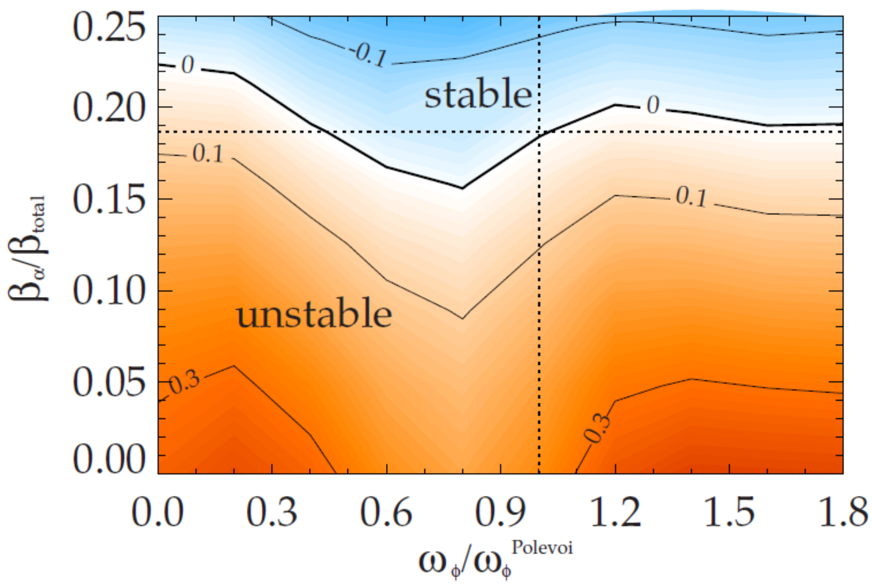


FIG. 5. (Color online) Contours of predicted $\gamma\tau_w$ vs the fraction of total β in α particles and scaled rotation for ITER scenario 4. The horizontal dashed line indicates the predicted $\beta_\alpha/\beta_{\text{tot}}$, while the vertical line indicates the $\omega_\phi^{\text{Polevoi}}$ profile.

2. The effect of energetic particles

In addition to scaling the expected rotation level, we can now explore the effect of alpha particles on ITER RWM stability by using c_α to scale $\beta_\alpha/\beta_{\text{tot}}$ in MISK. Figure 5 indicates that a sufficient population of alpha particles is required to stabilize the RWM for this ITER equilibrium at plasma rotation speeds from 0 to 1.8 times that predicted by Polevoi *et al*. Without any alpha particles, the plasma is predicted to be unstable regardless of the rotation. As the alpha particle β …

Berkery, *PoP*, 2010

NTV braking torque can slow the plasma rotation during RWM activity

- Equilibrium plasma rotation decreases when RWM is MHD unstable

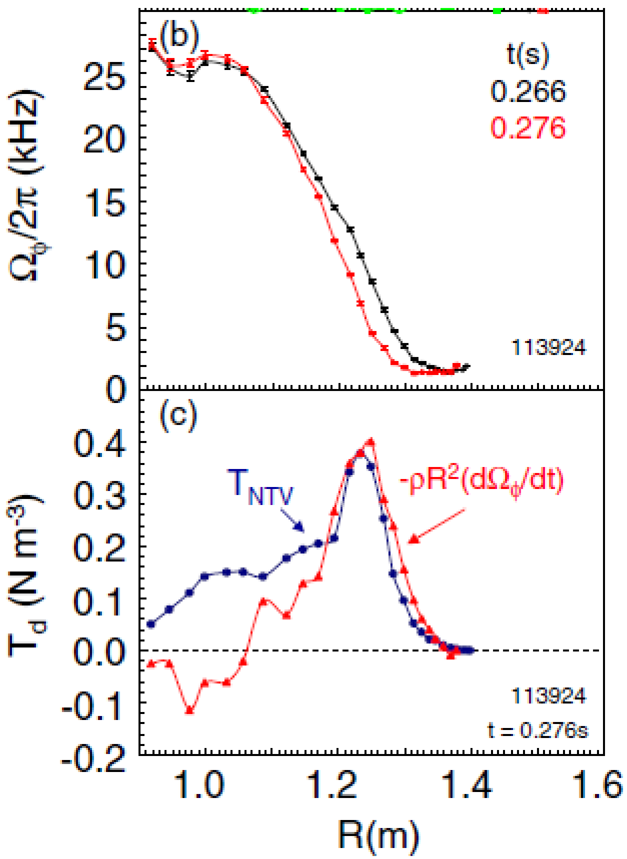
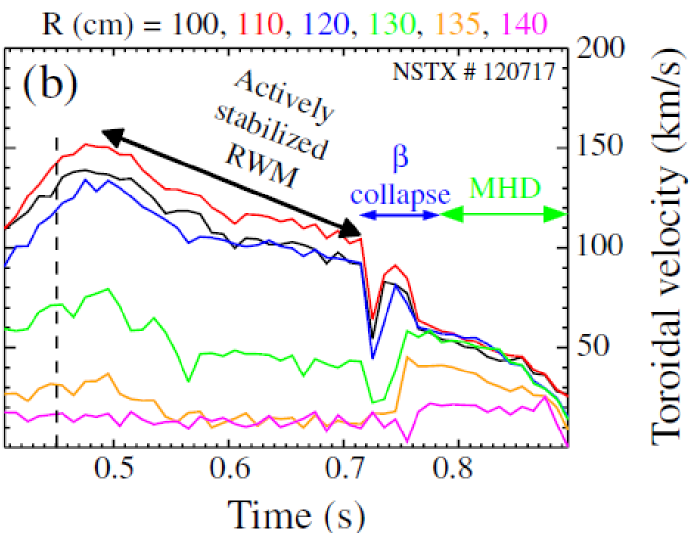
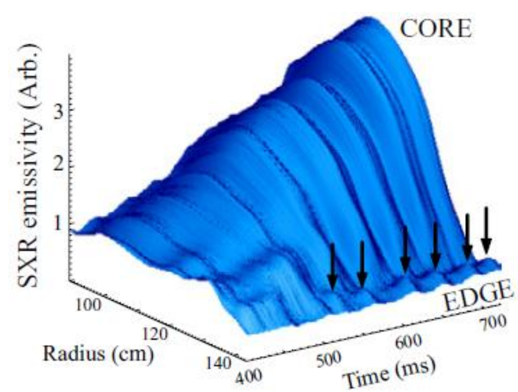


Figure 8. Plasma rotation damping during RWM (frames (*a*) and (*b*)) and the theoretical NTV damping torque profile (scaled) versus the measured plasma rotation damping at the onset of RWM growth (frame (*c*)).

Sabbagh, *NF*, 2006





Delgado, *PPCF*, 2011

RWM growth can cause a β collapse

- Rapid loss of plasma pressure occurs with RWM growth

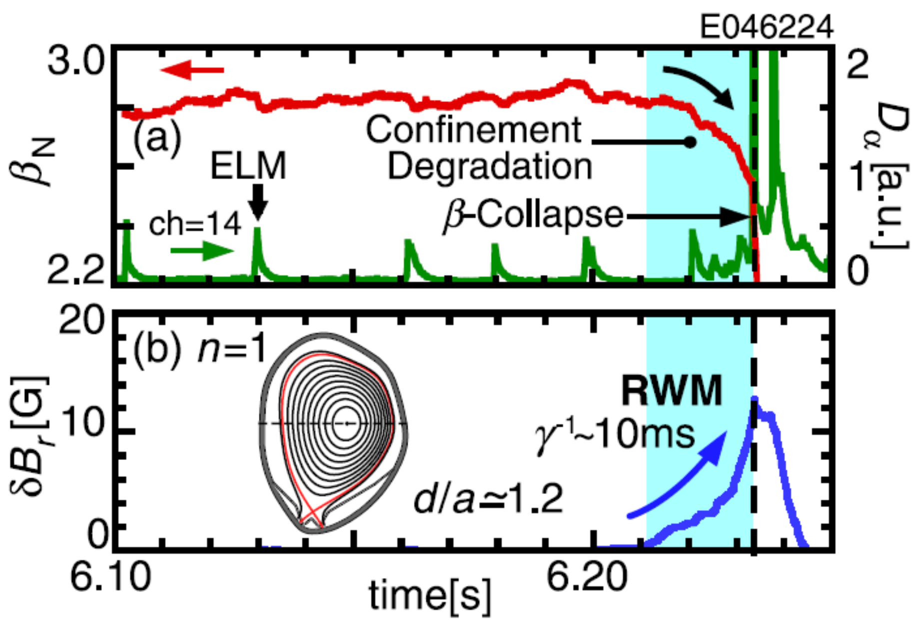
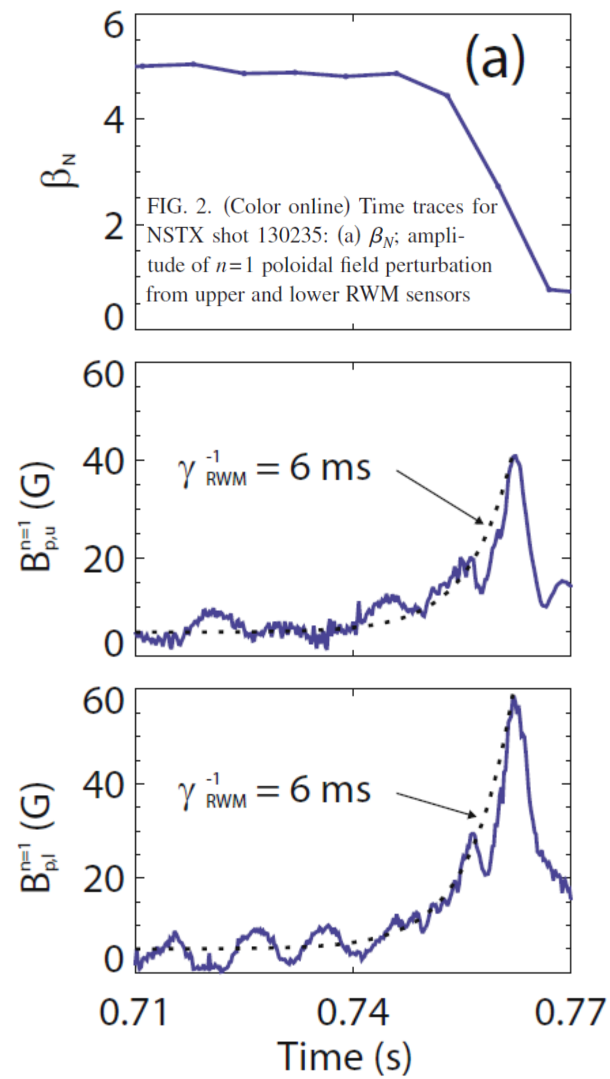


Fig. 4 Expanded waveforms of high-β_N (Fig. 3) and high-β_p discharges just before collapse (disruption): (a) time evolution of β_N and D_α emission, (b) $n = 1$ integrated magnetic perturbation with the poloidal cross section. cf. (c) and



Matsunaga, *PFR*, 2009

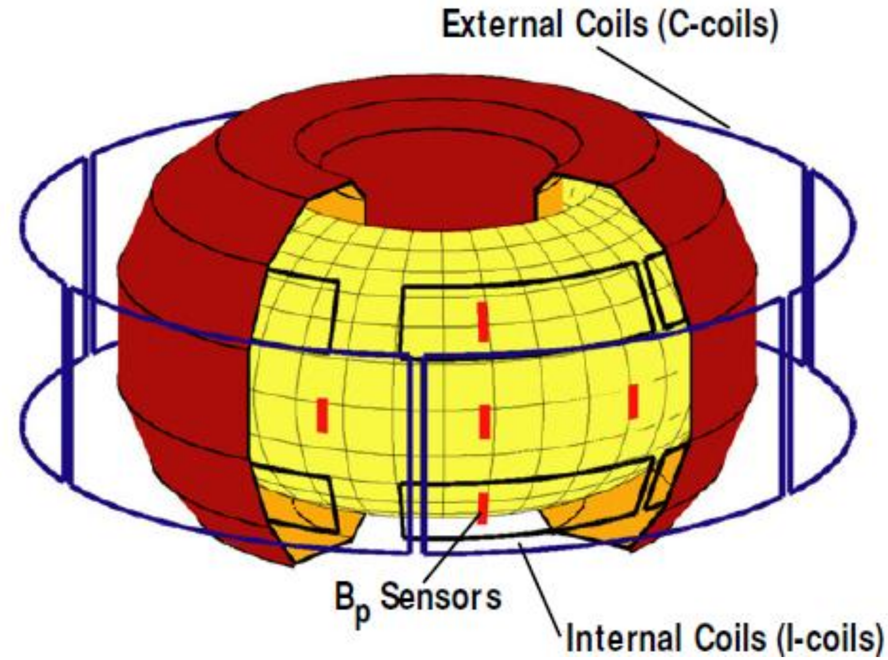
Berkery, *PoP*, 2010

RWMs can be *avoided* or *passively stabilized* in a variety of ways

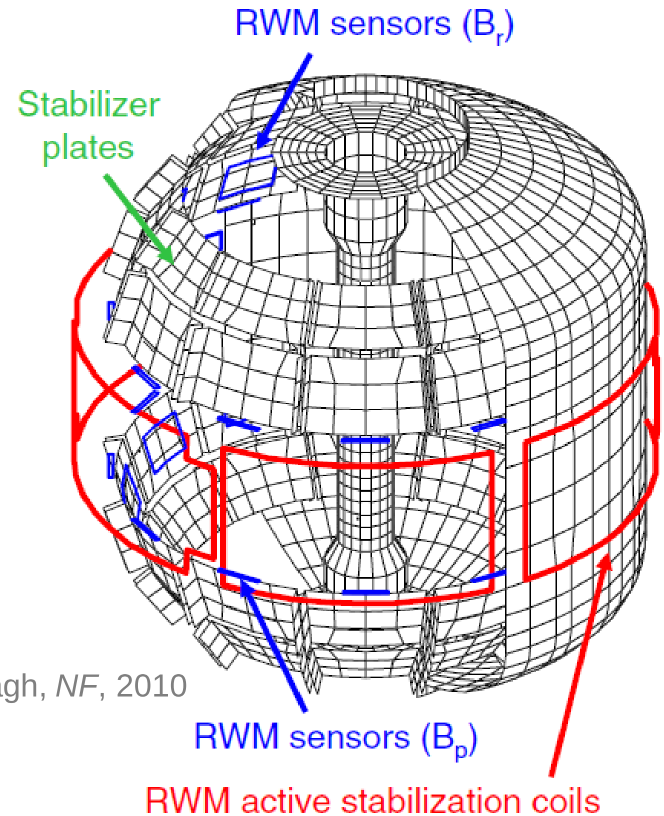
- Place a conducting wall near the plasma
  - Slows down the mode growth rate, and can stabilize quickly rotating modes
- β feedback/control
  - Feedback for heating mechanisms
    - Decrease β if it becomes too high
- Profile control
  - Modify current profile if l_i is too low
- Kinetic stabilization
  - Maintain appropriate plasma rotation
  - Raise energetic particle content
- Avoid RWM “triggers”
  - ELMs, sawteeth, Alfvén eigenmodes, etc., can cause a loss or redistribution of energetic particles, which can then reduce the RWM kinetic stabilization.

RWMs can be *actively suppressed* with internal or external magnetic feedback coils

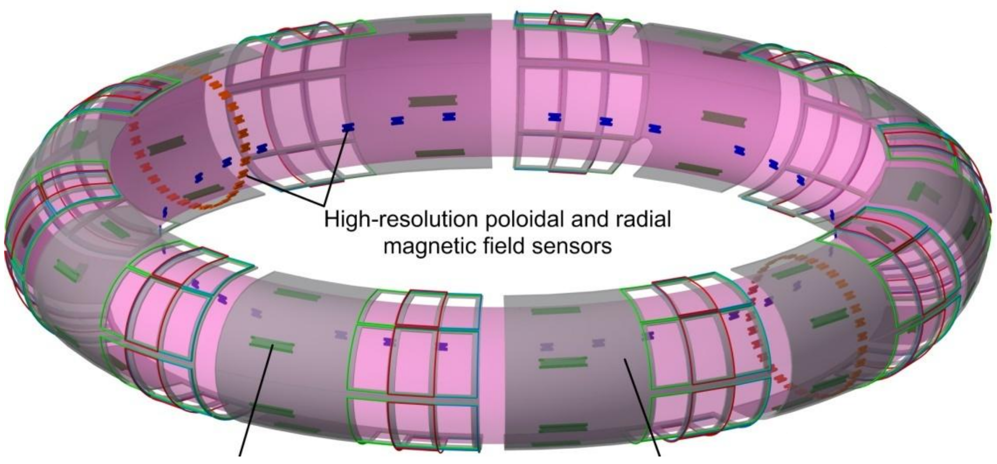
- External coils on NSTX
- Internal coils on HBT-EP
- Both types in DIII-D



Okabayashi, *NF*, 2005



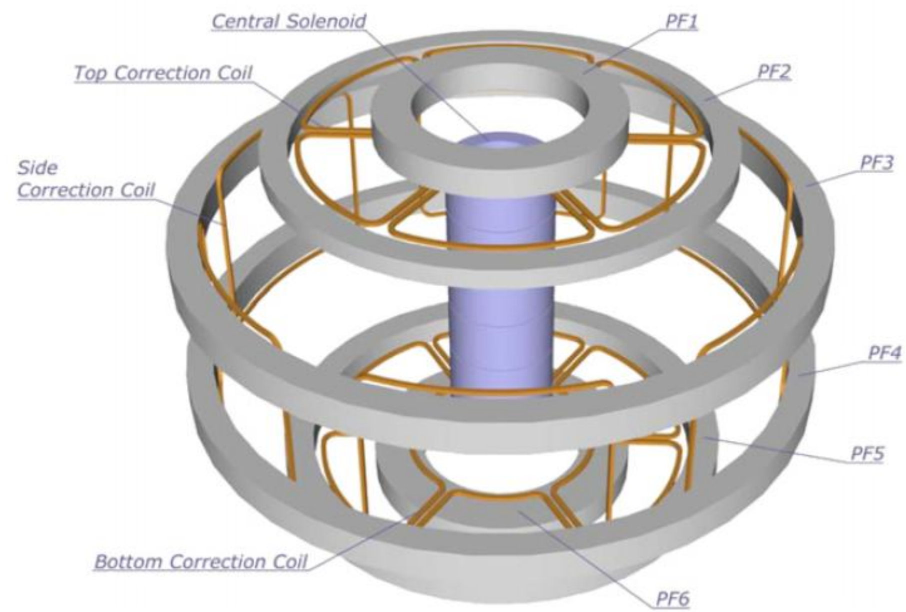
Sabbagh, *NF*, 2010



Ex-vessel "Side correction coils" in ITER can be used for slow magnetic feedback

- "Side correction coils" will be installed outside of the vacuum vessel
  - Mainly for static error field correction, but can also be used for slow RWM control
    - Circuit time constant of ~10s prevents fast feedback

- Internal coils are proposed for ITER, but not yet finalized
  - Also advertised as ELM mitigation coils



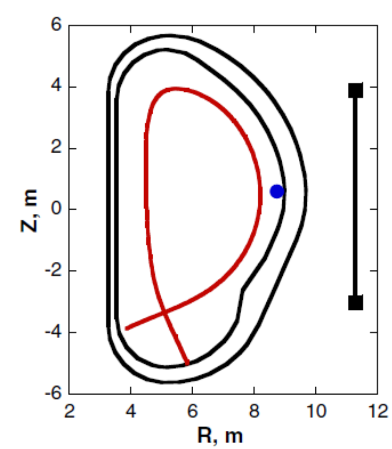


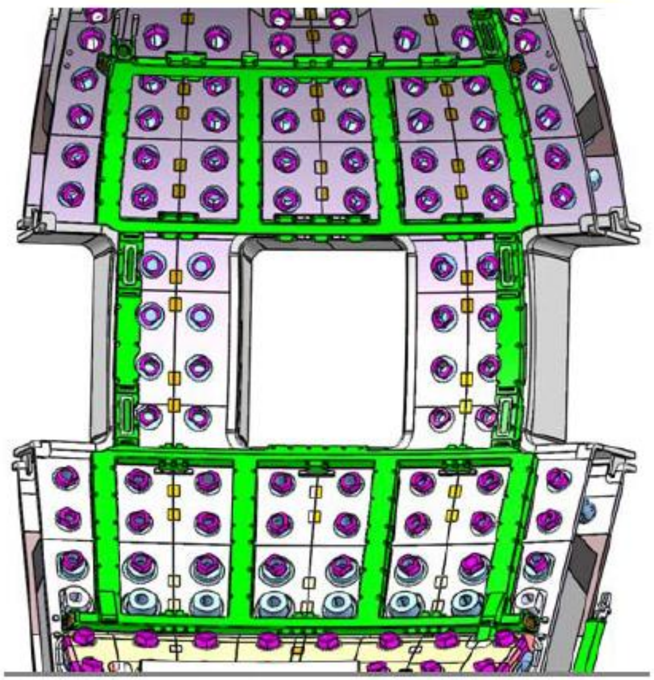
Figure 17. Plasma, vacuum vessel, magnetic sensor (circle) and coils(squares) used in the study of RWM control.

Hender, *NF*, 2007

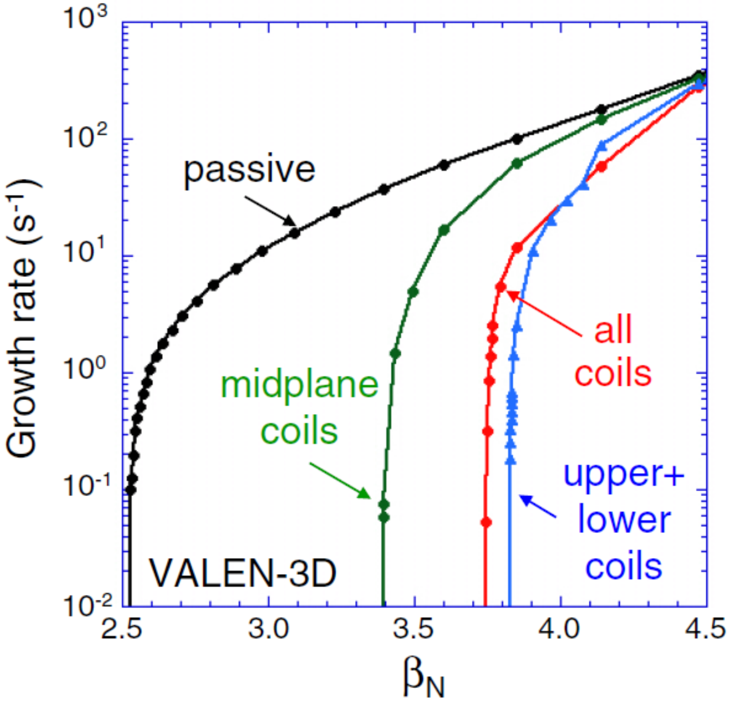
Internal control coils in ITER could significantly improve plasma performance

- Large increase in achievable β_N with proportional gain feedback using internal control coils

ITER VAC02 design (40° sector)



RWM growth rate for an ITER scenario 4 equilibrium



Sabbagh, *NF*, 2010

References

- J. W. Berkery et al., “The role of kinetic effects, including plasma rotation and energetic particles, in resistive wall mode stability.” *Physics of Plasmas* **17**, 082504 (2010)
- L. Delgado-Aparicio et al., “Soft x-ray measurements of resistive wall mode behavior in NSTX.” *Plasma Phys. Control. Fusion* **53** 035005 (2011)
- R. Fitzpatrick and A.Y. Aydemir, “Stabilization of the resistive shell mode in tokamaks.” *Nuclear Fusion* **36**, 11 (1996)
- S. W. Haney and J. P. Freidberg, “Variational methods for studying tokamak stability in the presence of a thin resistive wall.” *Phys. Fluids B* **1**, 1637 (1989)
- J. M. Hanson, “A Kalman Filter for Active Feedback on Rotating External Kink Instabilities in a Tokamak Plasma.” *Thesis* (2009)
- T. C. Hender et al., “Chapter 3: MHD stability, operational limits and disruptions.” *Nuclear Fusion* **47**, S128 (2007)
- M. J. Lanctot et al., “Internal Mode Structure of Resonant Field Amplification in DIII-D.” *Poster at APS DPP Conference* (2008)
- G. Matsunaga et al., “Rotational Stabilization of Resistive Wall Mode on JT-60U.” *Plasma and Fusion Research* **4**, 051 (2009)
- M. Okabayashi et al., “Comprehensive control of resistive wall modes in DIII-D advanced tokamak plasmas.” *Nuclear Fusion* **49**, 125003 (2009)
- M. Okabayashi et al., “Control of the resistive wall mode with internal coils in the DIII-D tokamak.” *Nuclear Fusion* **45**, 1715 (2005)
- T. S. Pedersen et al., “Experiments and modeling of external kink mode control using modular internal feedback coils.” *Nuclear Fusion* **47**, 1293 (2007)
- S. A. Sabbagh et al., “Advances in global MHD mode stabilization research on NSTX.” *Nuclear Fusion* **50**, 025020 (2010)
- S. A. Sabbagh et al., “Resistive wall stabilized operation in rotating high beta NSTX plasmas.” *Nuclear Fusion* **46**, 635 (2006)

EXTRA SLIDES

Kinetic resonances

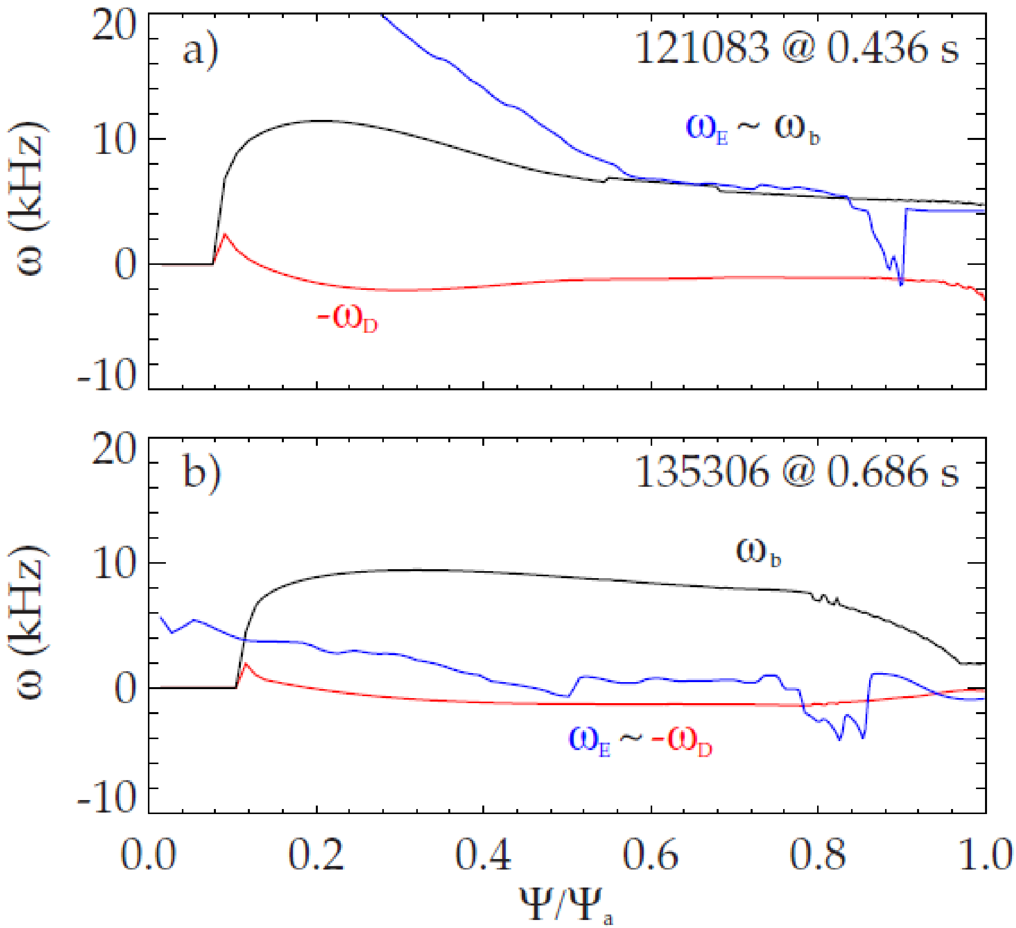


FIG. 6. (Color online) Comparison of frequency profiles vs normalized Ψ for two shots from NSTX: (a) with high rotation stability and (b) low rotation stability.

Berkery, *PoP*, 2010