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The role of kinetic dissipation in modifying RWM eigenfunctions*

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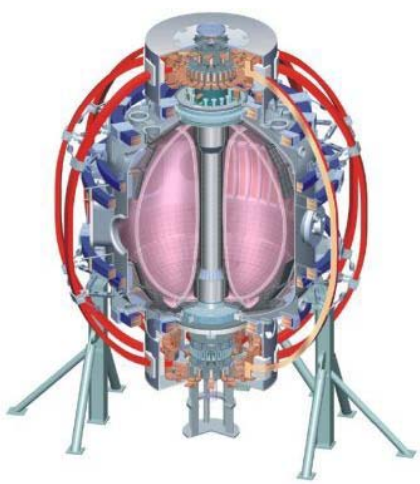

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Abstract

Kinetic resonances have been identified to play an important role in the stability of the resistive wall mode (RWM) in tokamaks. One approach to computing RWM stability is a ‘pertubative’ approach in which the mode stability is computed assuming the ideal kink eigenfunction is not modified by kinetic damping. The so-called ‘self-consistent’ approach includes the dissipation in the perturbed force balance and computation of the mode eigenfunction as embodied in the MARS-F and MARS-K codes. Initial MARS-F and MARS-K simulations for NSTX plasmas find that there can be substantial changes between the predicted fluid (non-kinetic) limit of the RWM eigenfunctions and the self-consistent eigenfunctions computed with full kinetic damping included. These changes can be most pronounced near the plasma edge where the dissipation can be large for NSTX plasmas. These comparisons and the possible implications for the perturbative and self-consistent approaches will be described.

Outline

1. Experimental motivation

2. Role of E×B drift frequency profile

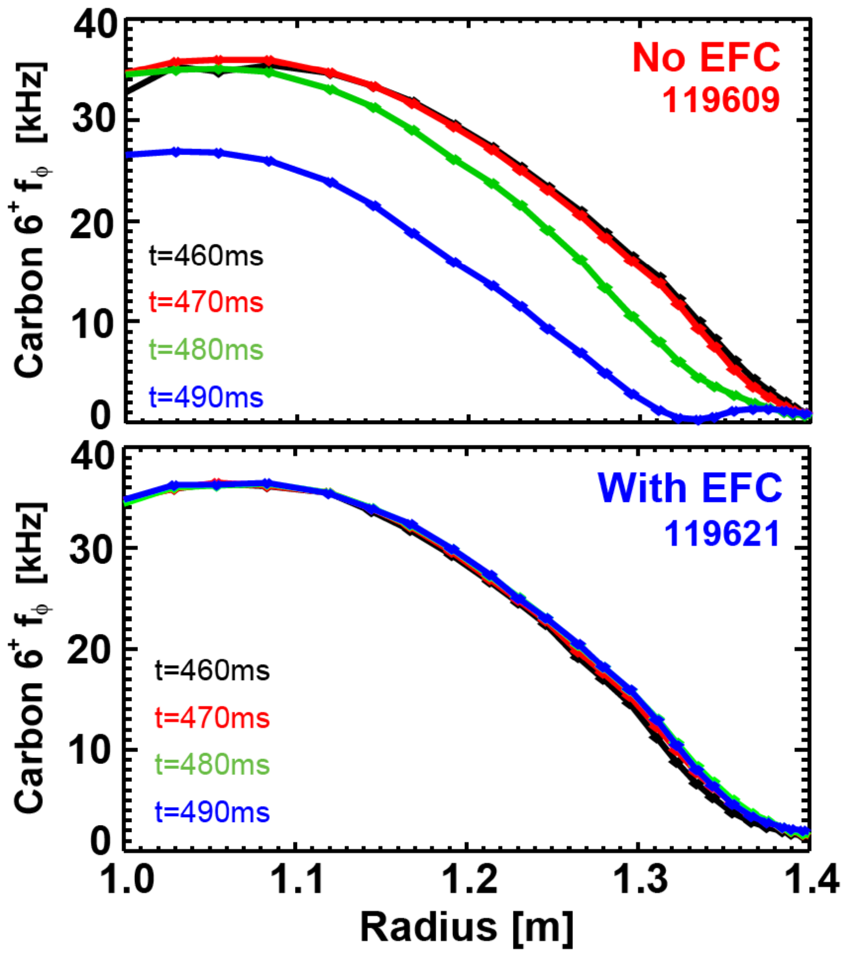
3. Kinetic stability analysis using MARS code
   - Comparisons with experiment
   - Self-consistent vs. perturbative approach

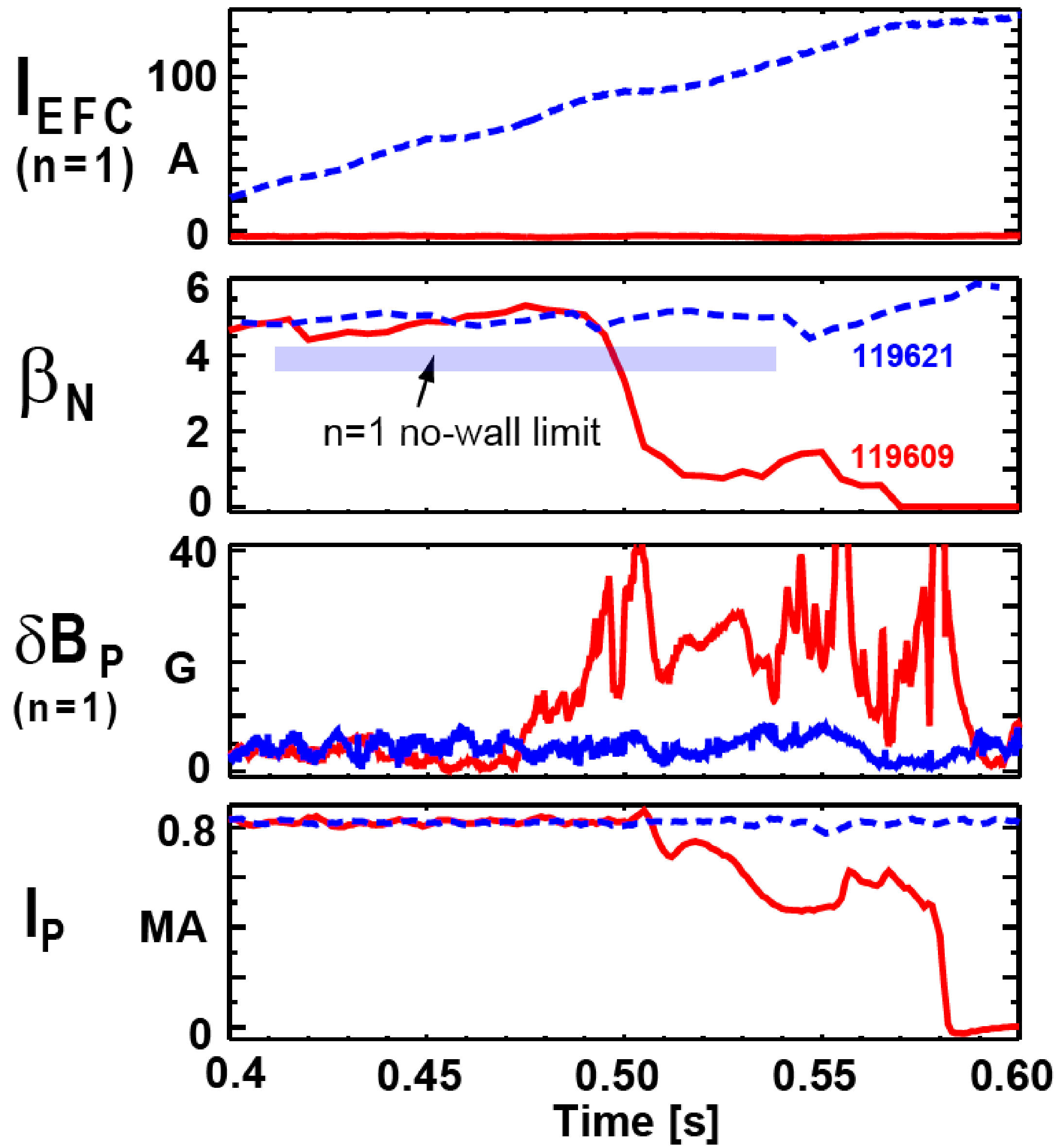
4. Eigenfunctions versus dissipation, rotation

5. Summary

Error field correction (EFC) often necessary to maintain rotation, stabilize n=1 resistive wall mode (RWM) at high β_N

- **No EFC → n=1 RWM unstable**
- **With EFC → n=1 RWM stable**

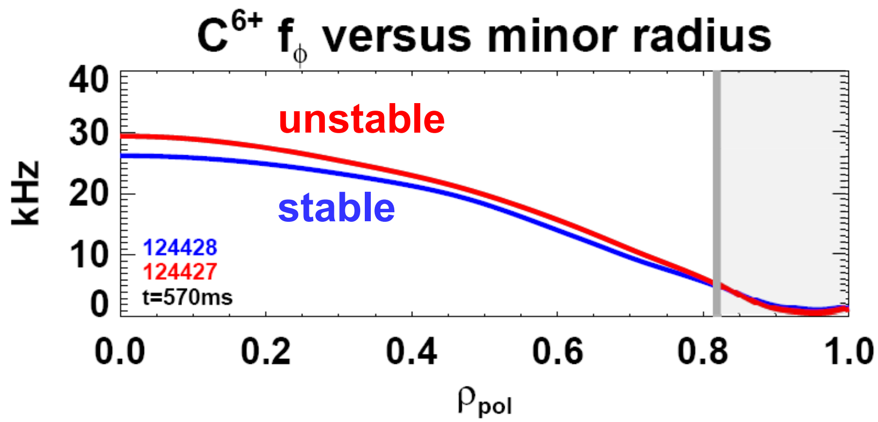


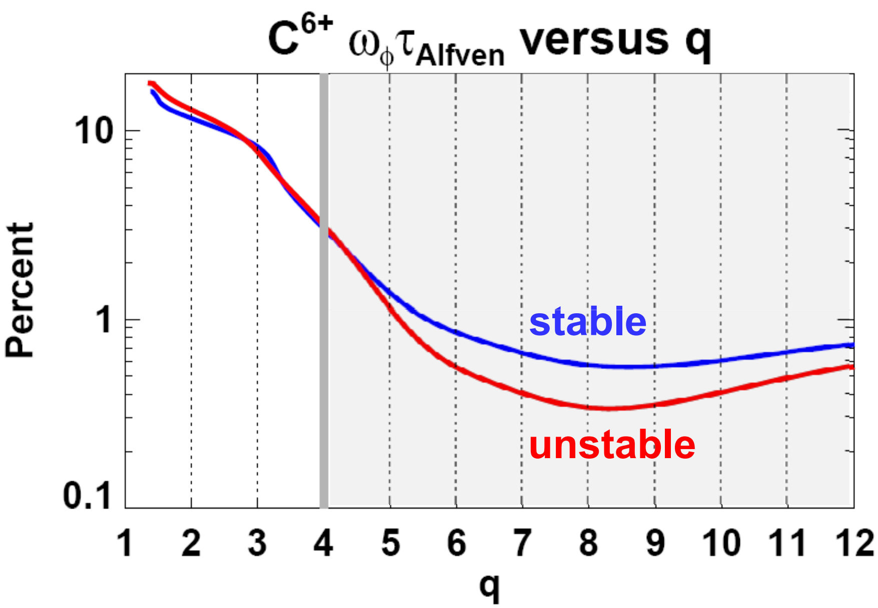


J.E. Menard et al, Nucl. Fusion 50 (2010) 045008

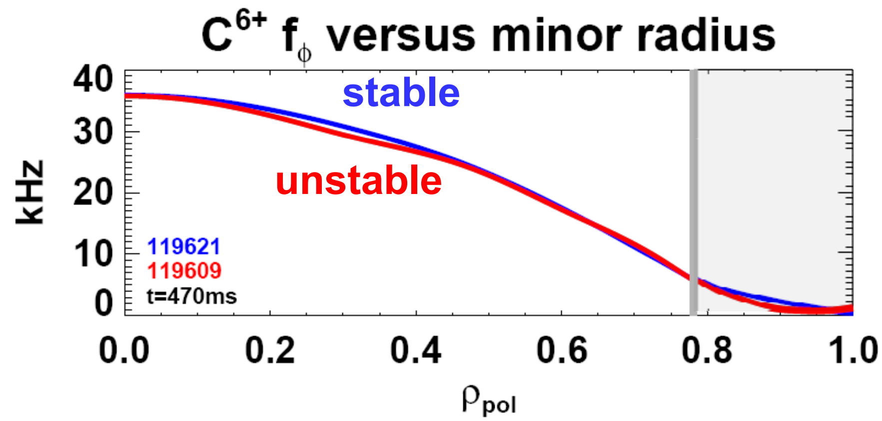
EFC experiments show edge region with $q \geq 4$ and $r/a \geq 0.8$ apparently determine stability

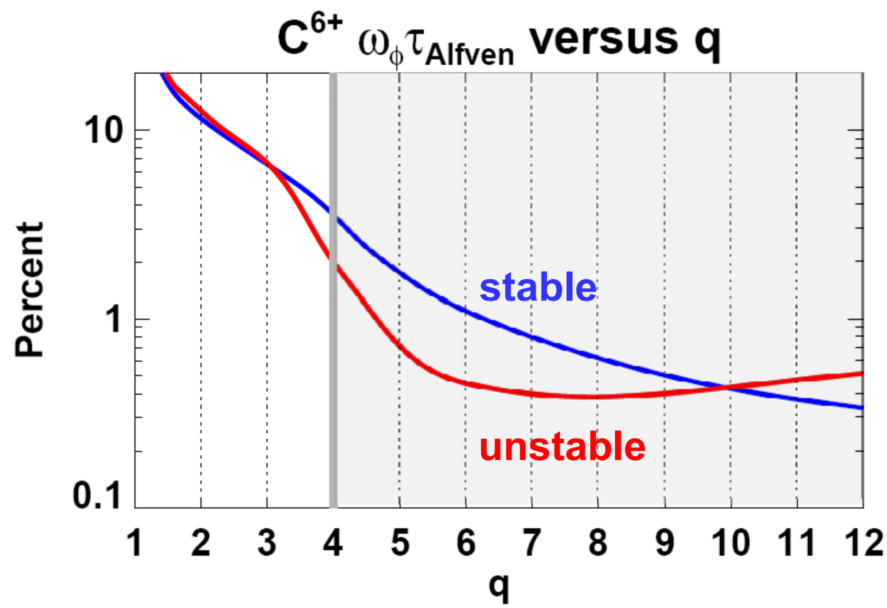
- n=3 EFC → stable
- No EFC → n=1 RWM unstable





- n=1 EFC →stable
- No EFC → n=1 RWM unstable





MARS is linear MHD stability code that includes toroidal rotation and drift-kinetic effects

- **Single-fluid linear MHD**

$$(\gamma + in\Omega)\boldsymbol{\xi} = \mathbf{v} + (\boldsymbol{\xi}\cdot\nabla\Omega)R^2\nabla\phi$$

$$\rho(\gamma + in\Omega)\mathbf{v} = -\nabla\cdot\mathbf{p} + \mathbf{j}\times\mathbf{B} + \mathbf{J}\times\mathbf{Q} - \rho[2\Omega\hat{\mathbf{Z}}\times\mathbf{v} + (\mathbf{v}\cdot\nabla\Omega)R^2\nabla\phi]$$

$$(\gamma + in\Omega)\mathbf{Q} = \nabla\times(\mathbf{v}\times\mathbf{B}) + (\mathbf{Q}\cdot\nabla\Omega)R^2\nabla\phi$$

$$(\gamma + in\Omega)p = -\mathbf{v}\cdot\nabla P, \qquad \mathbf{j} = \nabla\times\mathbf{Q}$$

Y.Q. Liu, et al., Phys. Plasmas 15, 112503 2008

- **Kinetic effects in perturbed *p*:**

$$\mathbf{p} = p\mathbf{I} + p_{\|}\hat{\mathbf{b}}\hat{\mathbf{b}} + p_{\perp}(\mathbf{I} - \hat{\mathbf{b}}\hat{\mathbf{b}})$$

$$p_{\|}e^{-i\omega t + in\phi} = \sum_{e,i}\int d\Gamma M v_{\|}^2 f_L^1$$

$$p_{\perp}e^{-i\omega t + in\phi} = \sum_{e,i}\int d\Gamma \frac{1}{2} M v_{\perp}^2 f_L^1$$

$$f_L^1 = -f_{\epsilon}^0 \epsilon_k e^{-i\omega t + in\phi}\sum X_m^u H_{ml}^u \lambda_{ml} e^{-in\tilde{\phi}(t) + im\langle\dot{\chi}\rangle t + il\omega_b t}$$

$$H_L = \frac{1}{\epsilon_k}[M v_{\|}^2 \vec{\kappa}\cdot\boldsymbol{\xi}_{\perp} + \mu(Q_{L\|} + \nabla B\cdot\boldsymbol{\xi}_{\perp})]$$

- **Mode-particle resonance operator:**

MARS-K:

$$\lambda_{ml} = \frac{n[\omega_{*N} + (\hat{\epsilon}_k - 3/2)\omega_{*T} + \omega_E] - \omega}{n(\langle\omega_d\rangle + \omega_E) + [\alpha(m+nq) + l]\omega_b - i\nu_{\text{eff}} - \omega}$$

MARS-F:

$$\lambda_{ml} = \frac{n[\cancel{\omega_{*N}} + (\hat{\epsilon}_k - 3/2)\cancel{\omega_{*T}} + \omega_E] - \omega}{n(\cancel{\langle\omega_d\rangle} + \omega_E) + [\alpha(m+nq) + l]\omega_b \cancel{- i\nu_{\text{eff}}} - \omega}$$

+ additional approximations/simplifications in f_L^1

- **Fast ions: MARS-K: slowing-down f(v), MARS-F: lumped with thermal**

Sensitivity of stability to rotation motivates study of all components of E×B drift frequency $\omega_E(\psi)$

- Decompose flow of species *j* into poloidal + toroidal components:

$$\vec{u}_j = u_{\theta j}(\psi)\vec{B}_P + \Omega_{\phi j}(\psi,\theta)R^2\nabla\phi \qquad \text{satisfying} \quad \nabla\cdot\vec{u}_j = 0$$

- Orbit-average E×B drift frequency: $\omega_E \equiv \langle\langle \vec{v}_E \cdot \nabla(\phi - q\theta)\rangle\rangle$

Bounce average: $\langle\langle X\rangle\rangle \equiv \frac{1}{\tau_b}\oint X d\tau$ $\qquad$ $\vec{v}_E$ = E×B drift velocity

F. Porcelli, et al., Phys. Plasmas 1 (1994) 470

- Ignoring centrifugal effects (ok in plasma edge), ω_E reduces to:

1. parallel/toroidal 2. diamagnetic 3. poloidal

$$\boxed{\omega_E(\psi) = \frac{\langle\vec{u}_j\cdot\vec{B}\rangle}{F} - \omega_{*j} - u_{\theta j}(\psi)\frac{\langle B^2\rangle}{F}}$$

measured $\qquad$ measured or neoclassical theory

$$\frac{\langle\vec{u}_j\cdot\vec{B}\rangle}{F} = \Omega_{\phi j}(\psi,\theta) + \frac{u_{\theta j}(\psi)}{F}\underbrace{\left[\langle B^2\rangle - \frac{F^2}{R^2}\right]}_{\text{reconstructions}}$$

flux function $\qquad$ measured

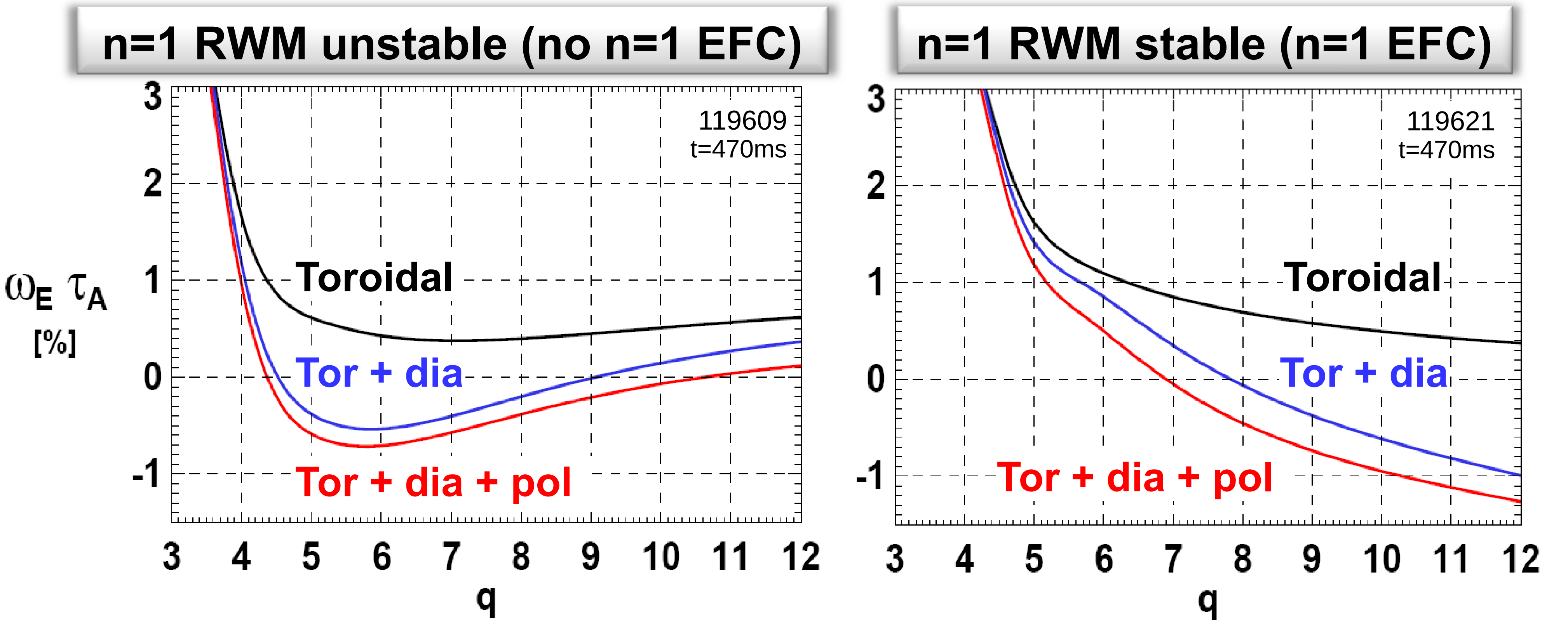
Y.B. Kim, et al., Phys. Fluids B 3 (1991) 2050

Flux-surface average:

$$\langle X\rangle \equiv \oint JXd\theta / \oint Jd\theta$$

$$F(\psi) \equiv RB_\phi$$

n=1 EFC profiles show impurity C diamagnetic and poloidal rotation modify $|\omega_E \tau_A| \sim 1\%$ in edge → potentially important



C^{6+} Toroidal rotation only: $\omega_E = \Omega_{\phi\text{-}C}(\psi)$

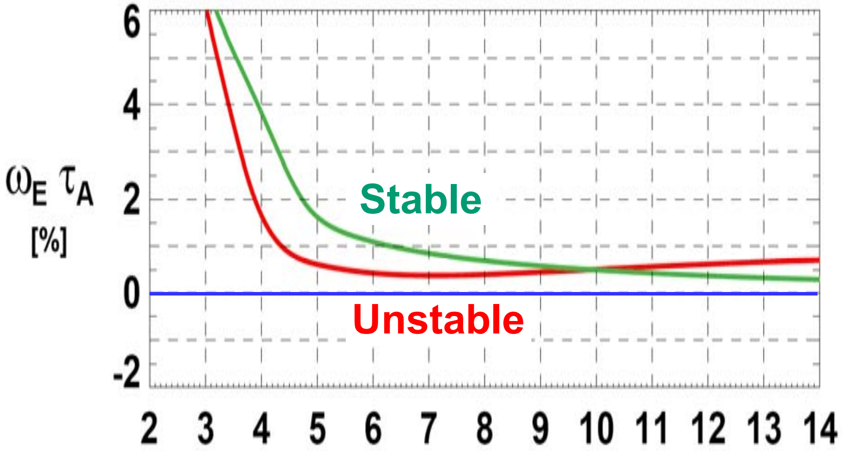
Toroidal + diamagnetic: $\omega_E = \Omega_{\phi\text{-}C}(\psi) - \omega_{*C}$

Toroidal + diamagnetic + poloidal: $\omega_E = \langle u_C \cdot B \rangle / F - \omega_{*C} - u_{\theta\text{-}C} \langle B^2 \rangle / F$

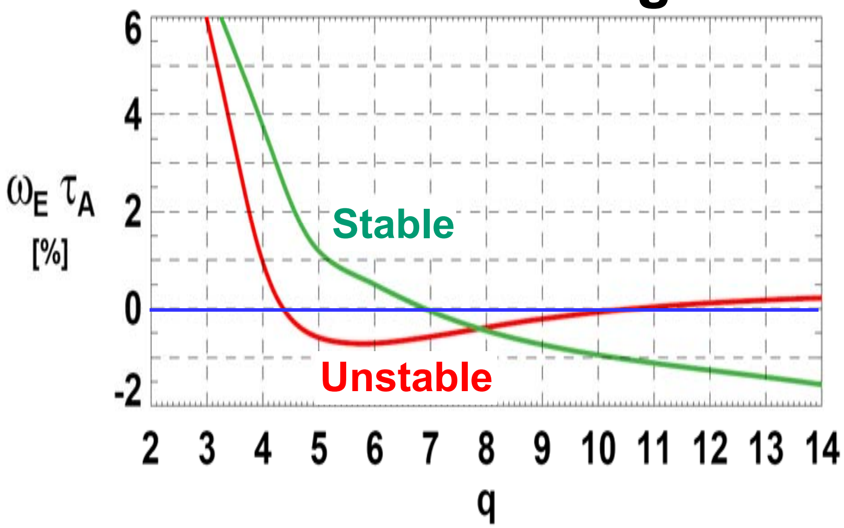
- Diamagnetic contribution to $\omega_E \tau_A$ ≈ -0.5 to -1.0%
- Neoclassical v_{pol} contribution to $\omega_E \tau_A$ ≈ -0.2 to -0.4%

Inclusion of ω_{*C} in ω_E increases separation between stable and unstable $\omega_E(\psi)$ and provides consistency w/ experiment

Toroidal rotation only

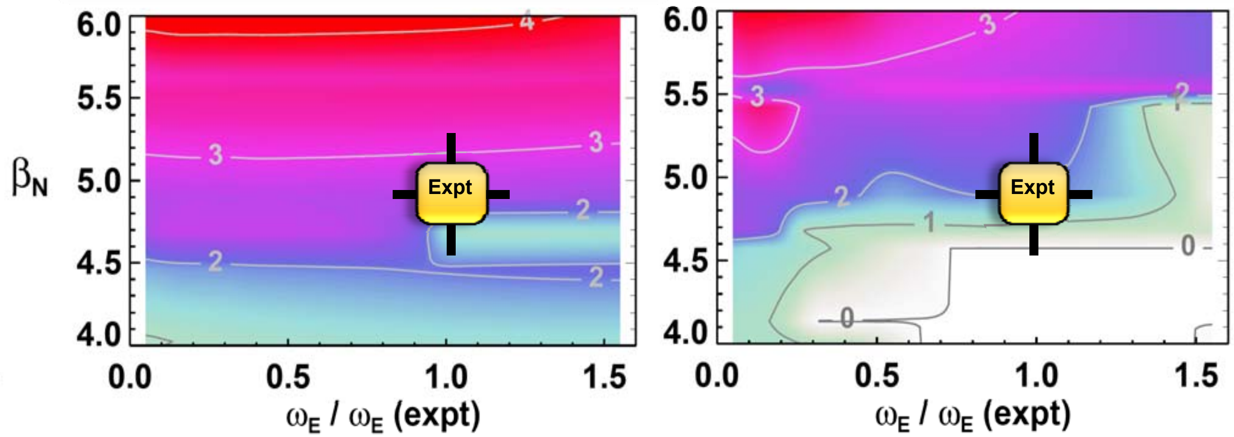


Toroidal + diamagnetic

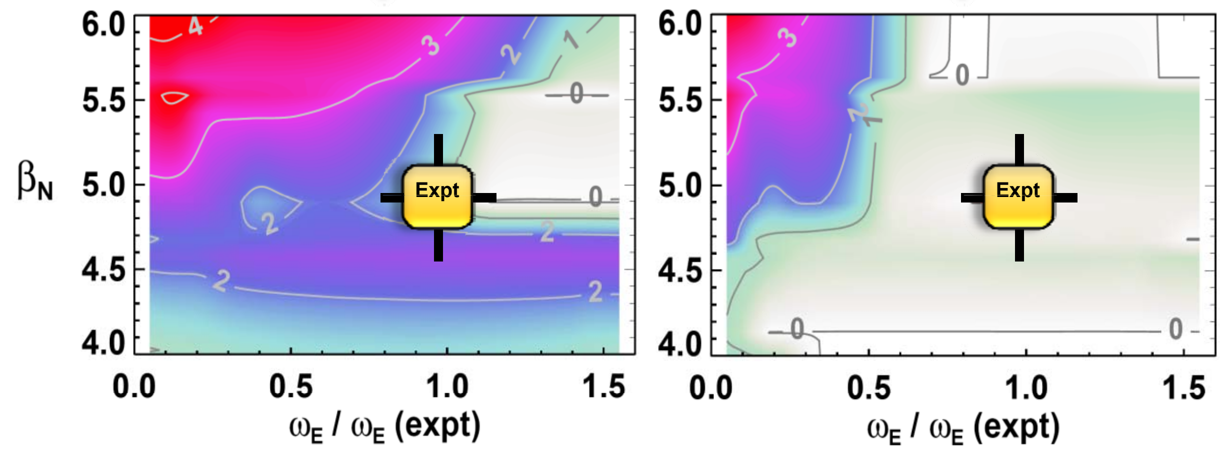


Calculated n=1 $\gamma\tau_{wall}$

Unstable rotation profile | **Stable rotation profile**



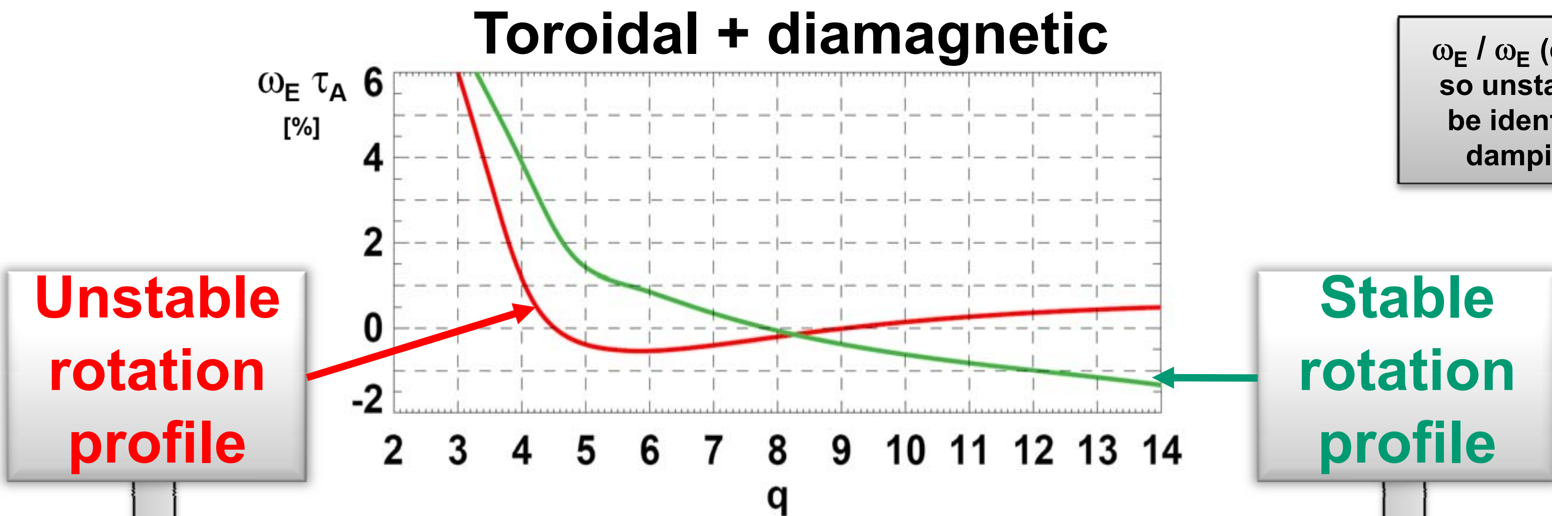
Predictions inconsistent with experiment

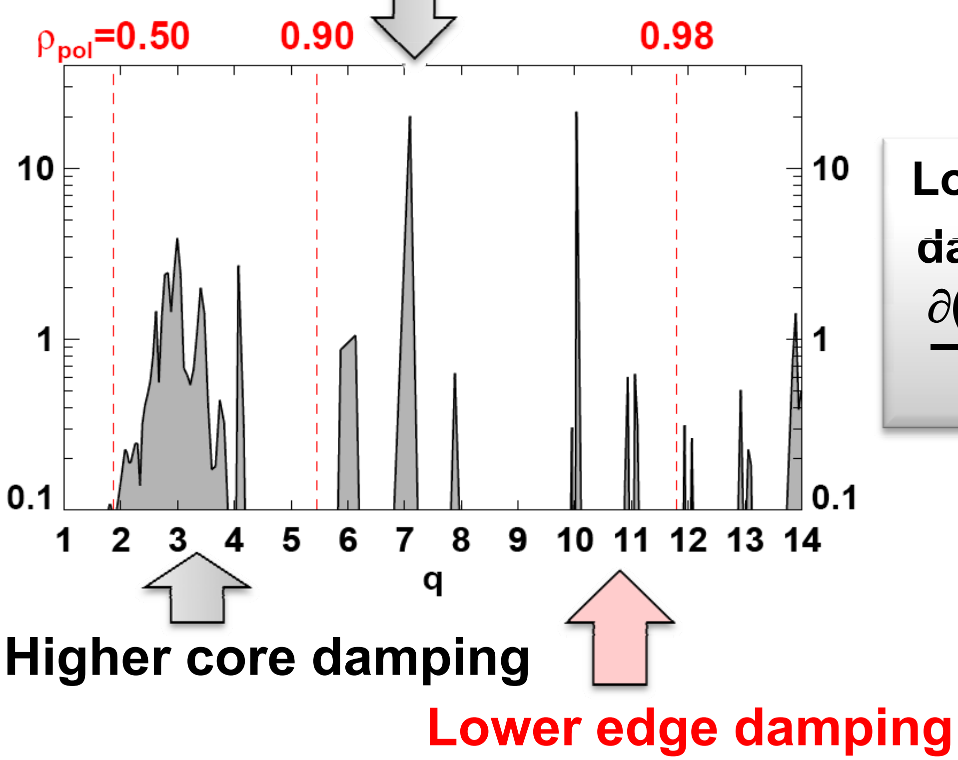


Predictions consistent with experiment

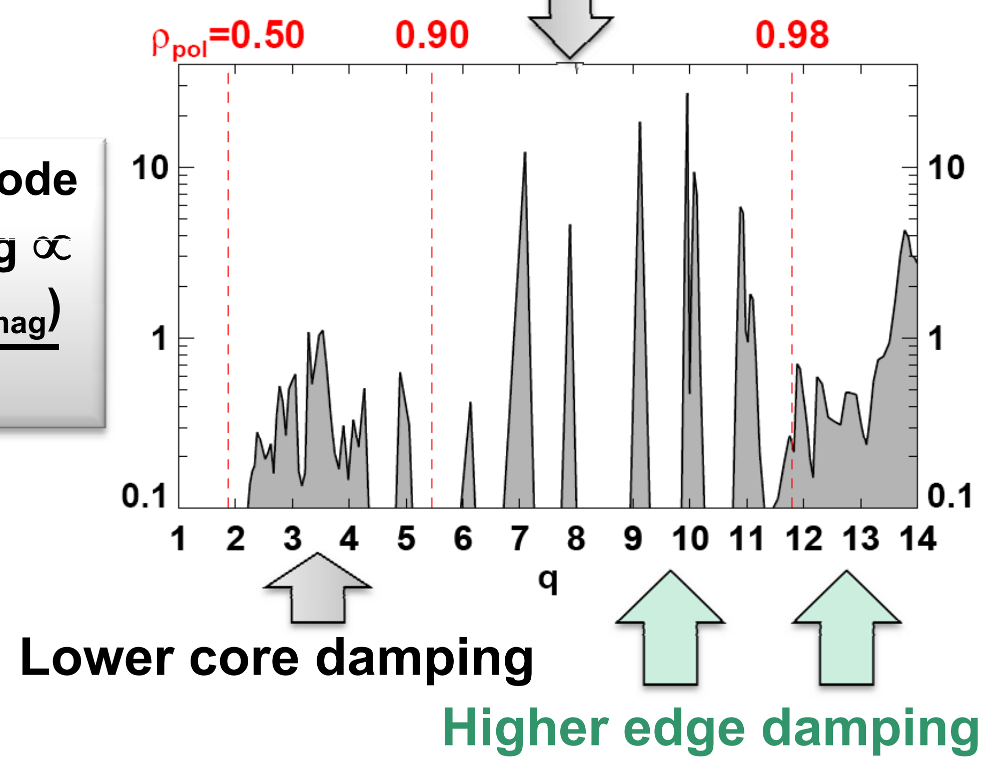
Mode damping in last 10% of minor radius calculated to determine stability of RWM in n=1 EFC experiments

ω_E / ω_E (expt) = 0.5 used so unstable modes can be identified and local damping computed





Local mode damping $\propto \frac{\partial(\delta W_{K\text{-}imag})}{\partial V}$



Kinetic stability analysis using MARS-K

- Comparison with experiment
- Self-consistent vs. perturbative approach
- Modifications of RWM eigenfunction

MARS-K consistent with EFC results and MARS-F trends

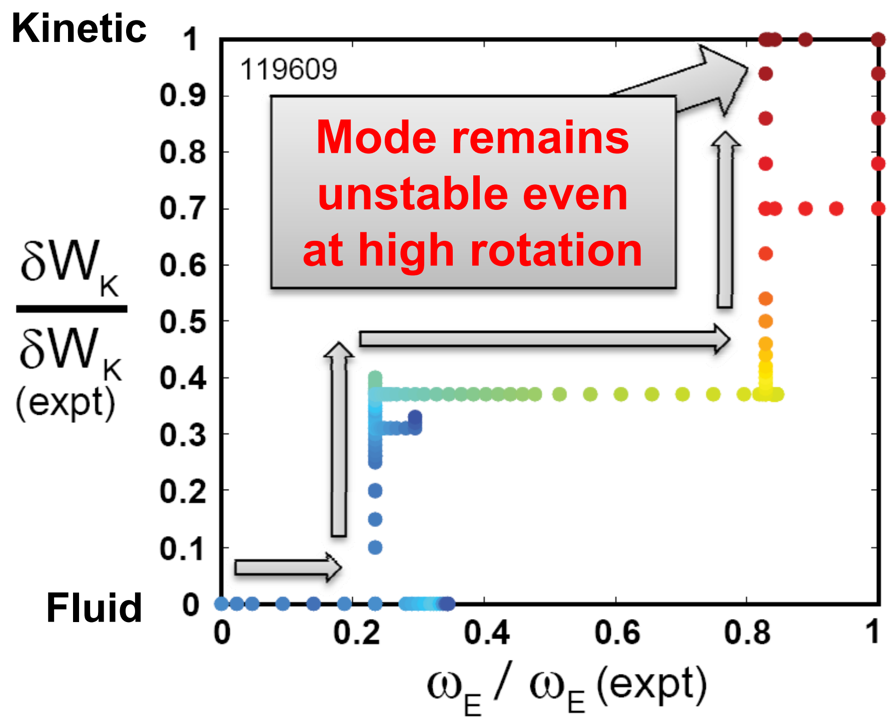
- MARS-K full kinetic δW_K → multiple modes can be present
  - Mode identification and eigenvalue tracking more challenging
- Track roots by scanning fractions of experimental ω_E and δW_K:

Experimentally unstable case

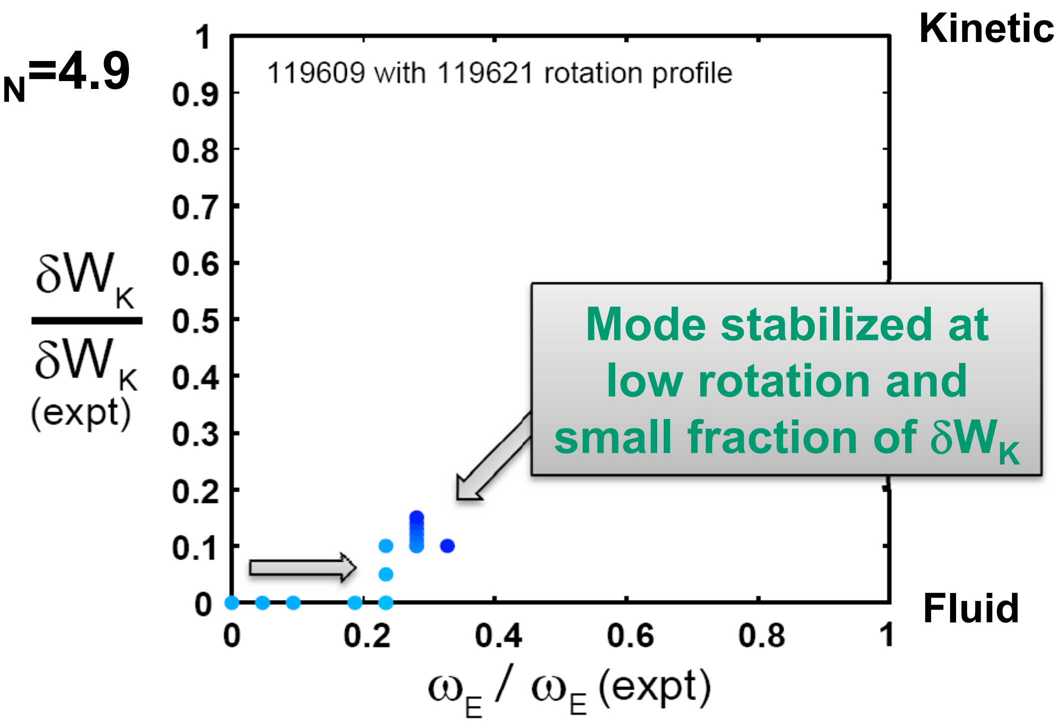
stable — unstable

$[Re(\gamma\tau_w)]^{1/3}$ 0 0.5 1 1.5 2 2.5 3

Experimentally stable case



β_N=4.9

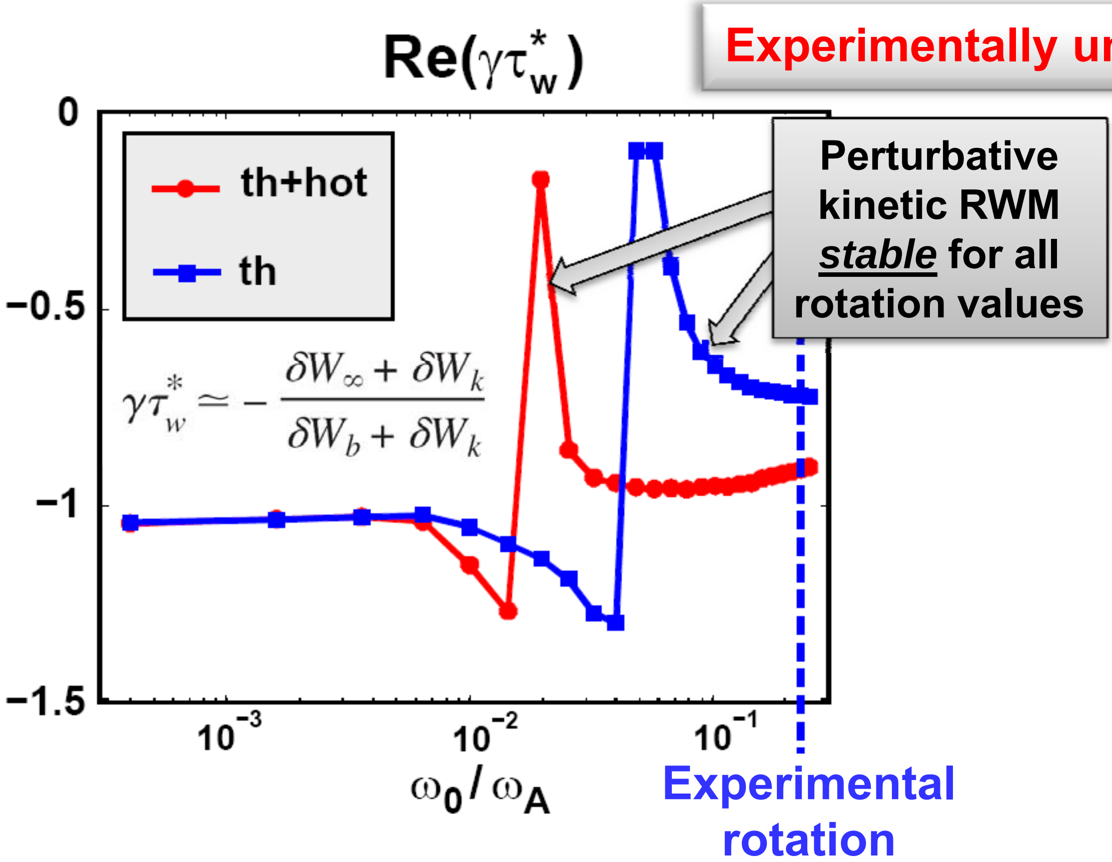


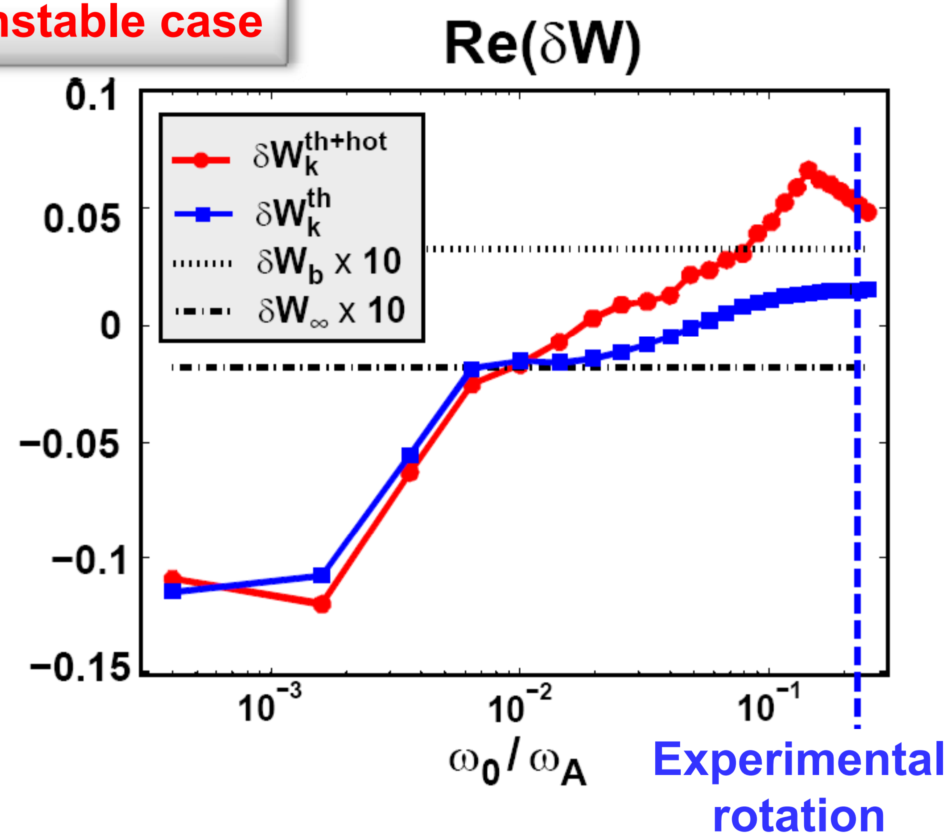
NOTE: NO collisions included

Perturbative approach predicts unstable case to be stable → inconsistent with self-consistent treatment and experiment

- Perturbative approach uses marginally unstable fluid eigenfunction at zero rotation in limit of no kinetic dissipation
- For cases treated here, $|\delta W_K|$ can be >> $|\delta W_\infty|$ and $|\delta W_b|$
  - Possibility that rotation/dissipation can modify eigenfunction & stability

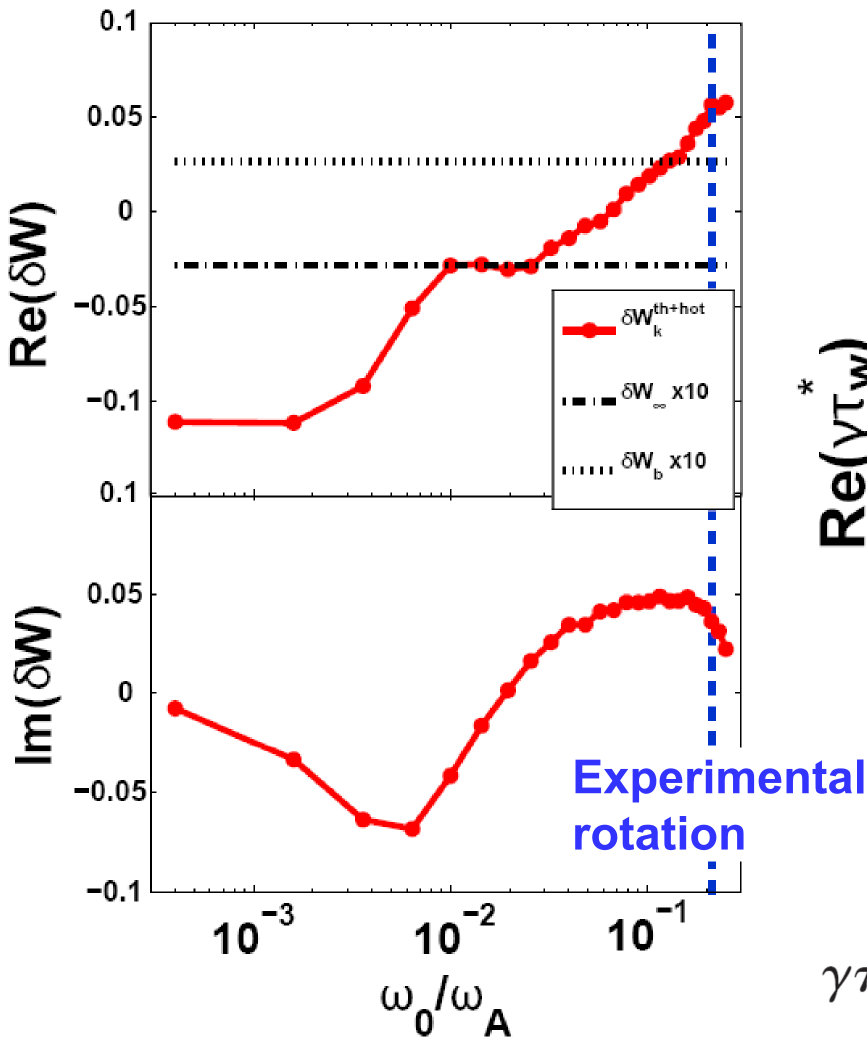
Experimentally unstable case

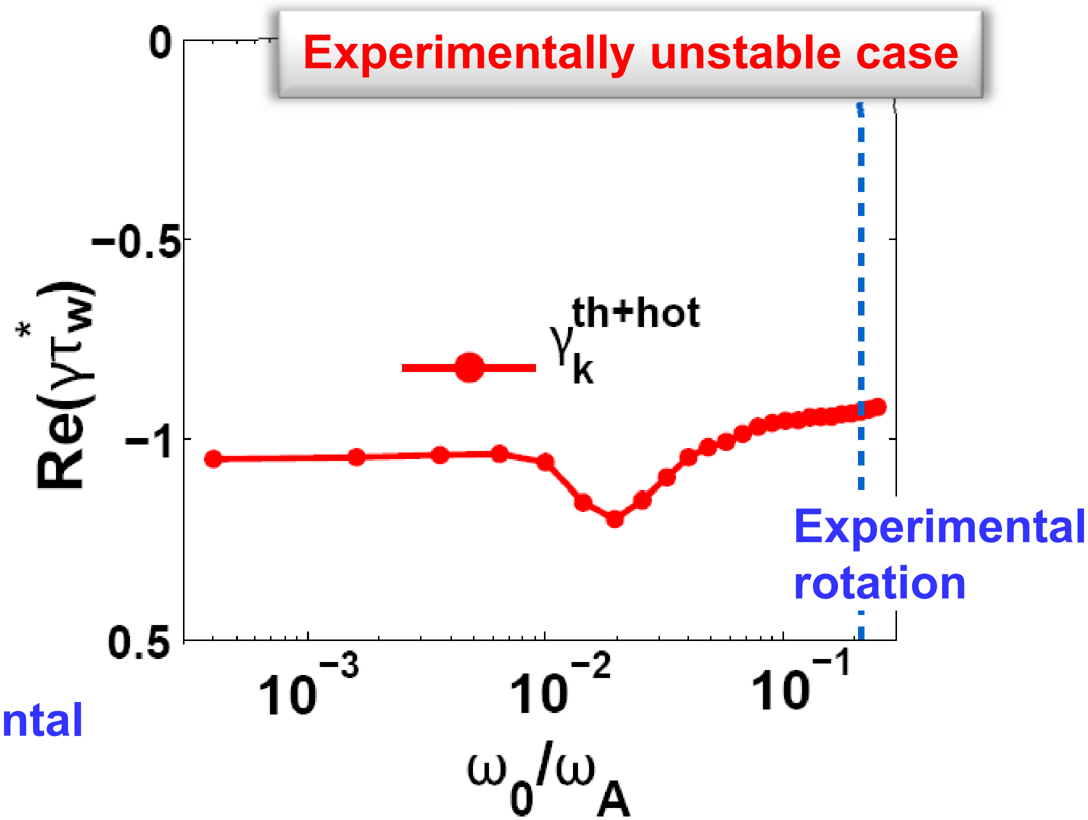




Perturbative approach results sensitive to β_N (but remain inconsistent with experiment)

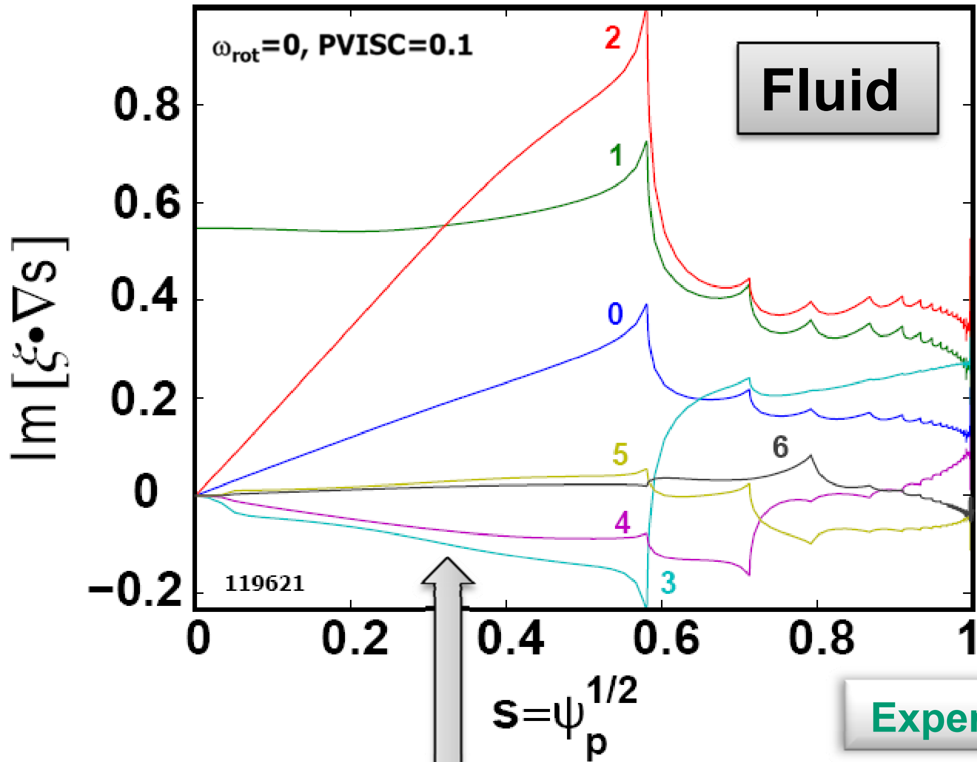
- Higher β_N = 5.2 does not exhibit approach to marginal stability
- $|\delta W_K|$ does not approach 0 → $\gamma\ \tau_w \approx -1$

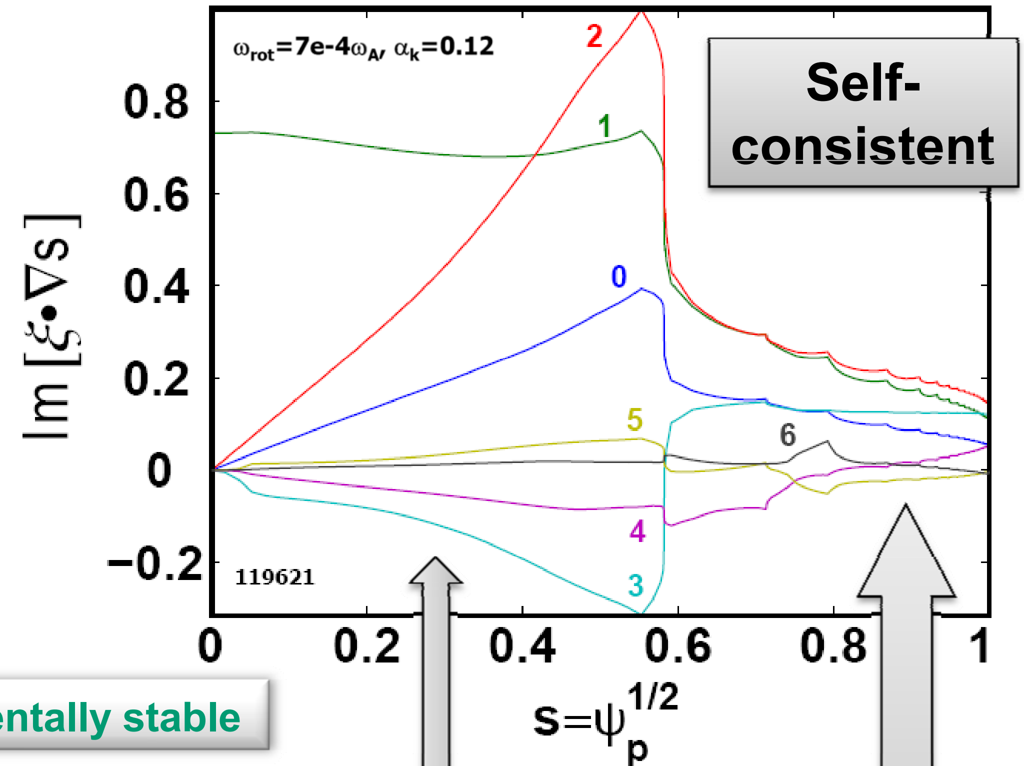




$$\gamma\tau_w^* \simeq -\frac{\delta W_\infty + \delta W_k}{\delta W_b + \delta W_k}$$

MARS-K self-consistent calculations for stable case indicate modifications to eigenfunction begin to occur at low rotation

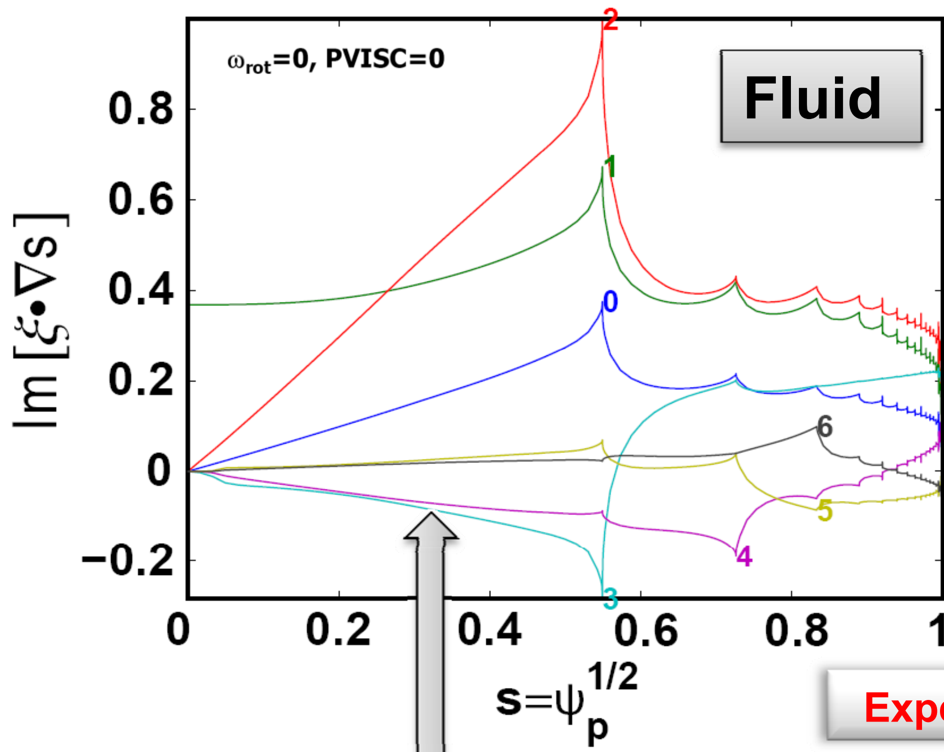


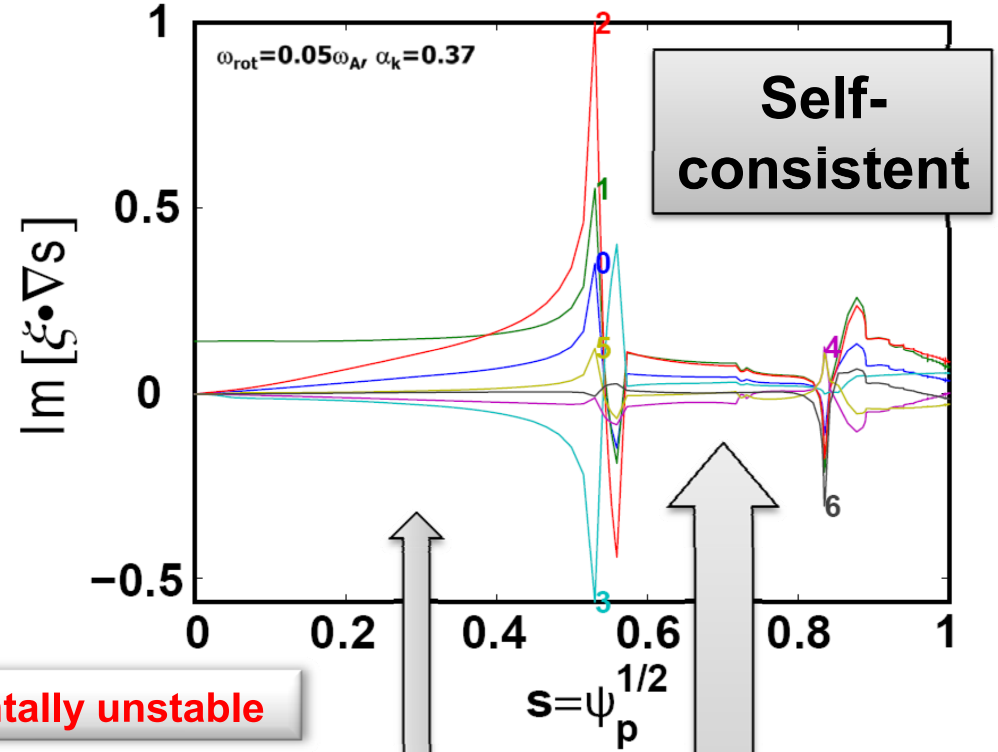


Experimentally stable

- Self-consistent (SC) eigenfunction qualitatively similar to fluid eigenfunction in plasma core
- SC RWM $\xi_\perp$ amplitude reduced at larger r/a
  - Low ω_E / ω_E (expt) = 0.3%, $\delta W_K / \delta W_K$ (expt) = 12%
  - Reduced amplitude could reduce dissipation, stability

MARS-K self-consistent calculations indicate rotation and dissipation can strongly modify RWM eigenfunction

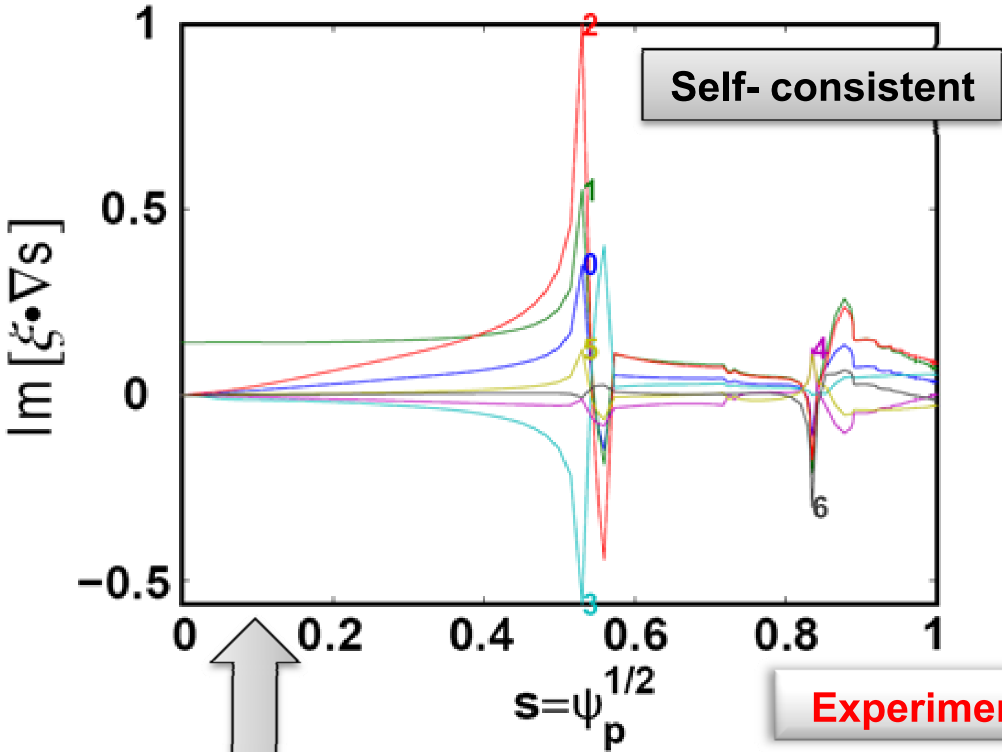




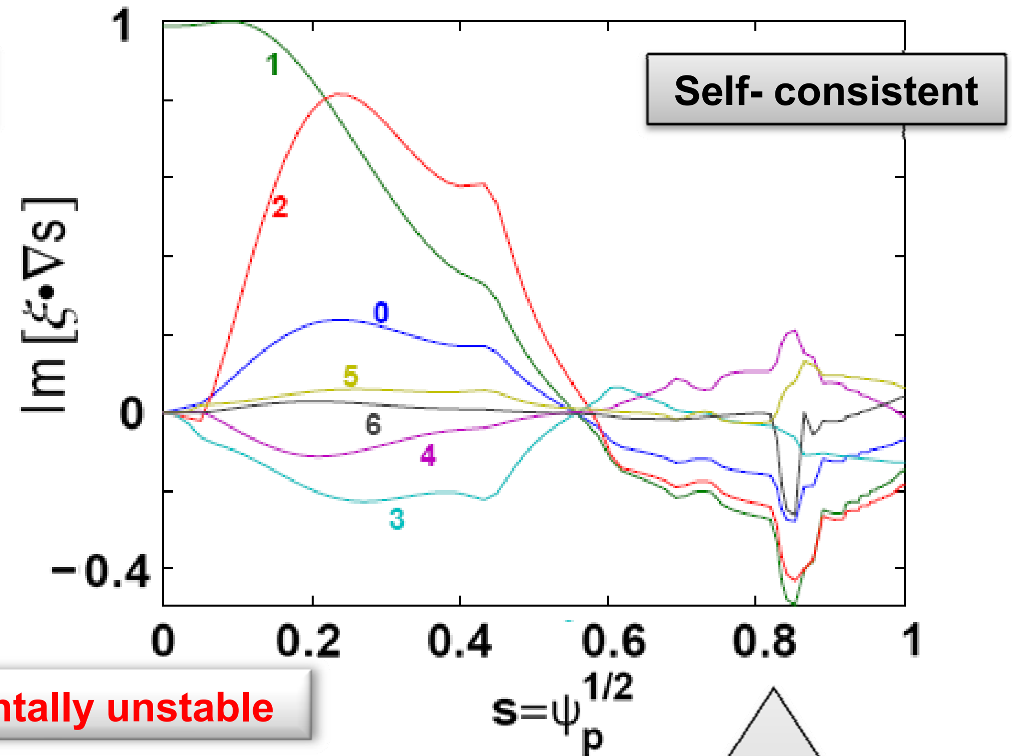
Experimentally unstable

- Self-consistent (SC) eigenfunction shape **differs** from fluid eigenfunction in plasma core
- SC RWM $\xi_\perp$ substantially different at larger r/a
  - Moderate ω_E / ω_E (expt) = 22%, $\delta W_K / \delta W_K$ (expt) = 37%
  - Differences could be even larger at full rotation and δW_K
  - **Does reduced edge $\xi_\perp$ amplitude explain reduced stability?**

At full rotation and kinetic effects in NSTX, MARS-K indicates likely transition to 2nd unstable eigenfunction



Experimentally unstable



- SC RWM $\xi_\perp$ at fraction of ω_E and δW_K
  - –Moderate ω_E / ω_E (expt) = 22%, $\delta W_K / \delta W_K$ (expt) = 37%
- SC RWM $\xi_\perp$ at **full experimental ω_E and δW_K**
  - Eigenfunction shape substantially modified → transition to 2nd mode?

Experimental analysis results motivate more systematic study of MARS eigenfunctions

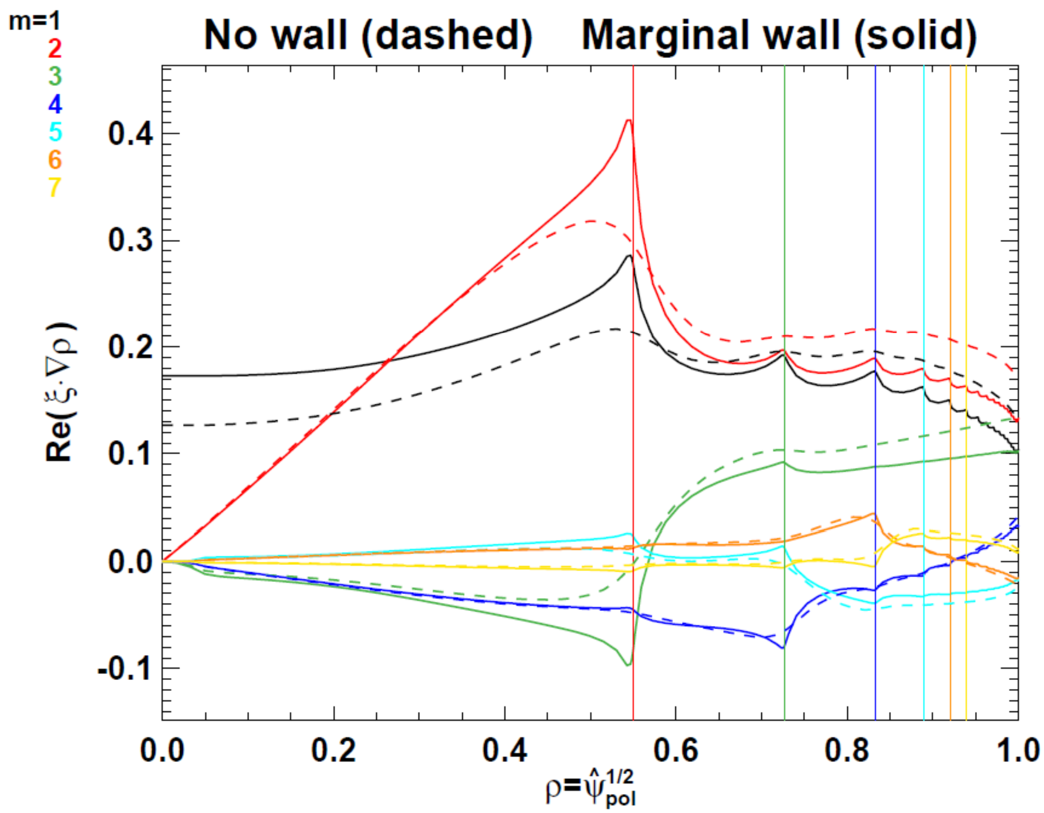
- Preliminary assessment of eigenfunction dependence on rotation and dissipation

- Where does perturbative approach break down?

Inclusion of wall excites expected discontinuities in radial derivative of displacement near mode rational surfaces

- Wall image currents excite resonant fields at plasma that must be shielded by singular currents in plasma to preserve topology of ideal plasma, i.e. to avoid island opening

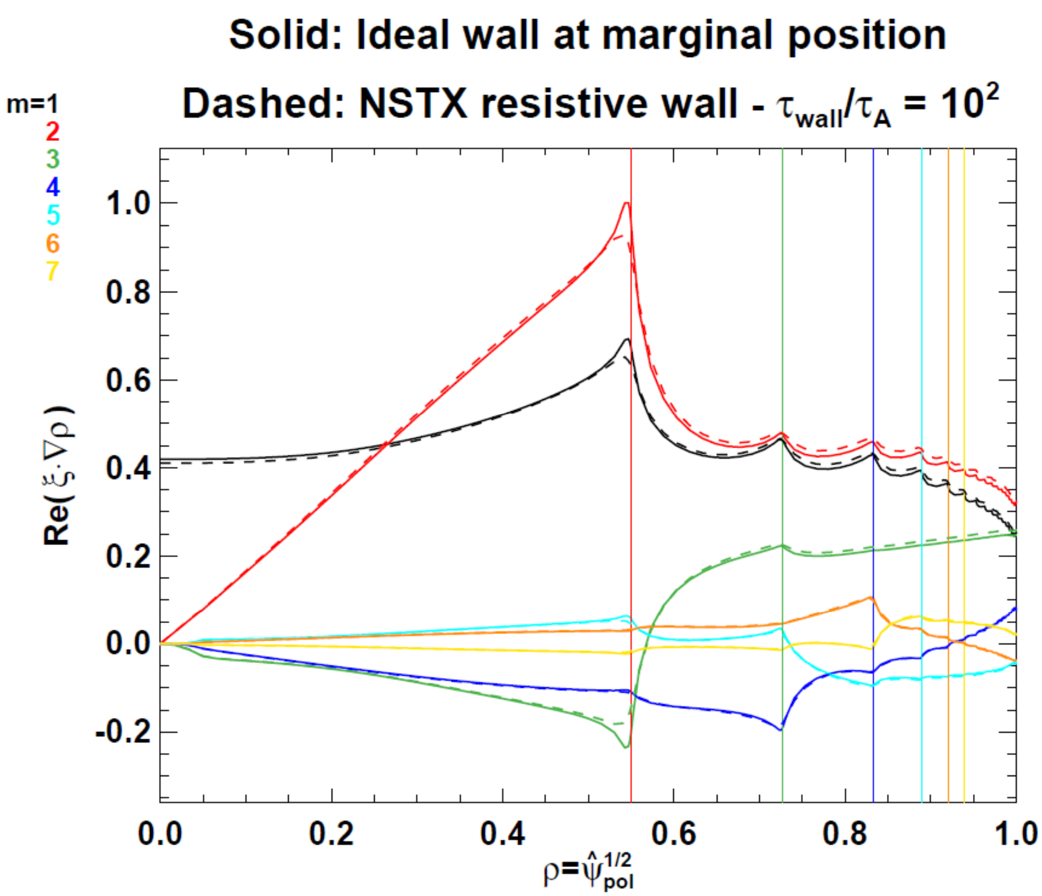
Ideal plasma, zero rotation, zero dissipation

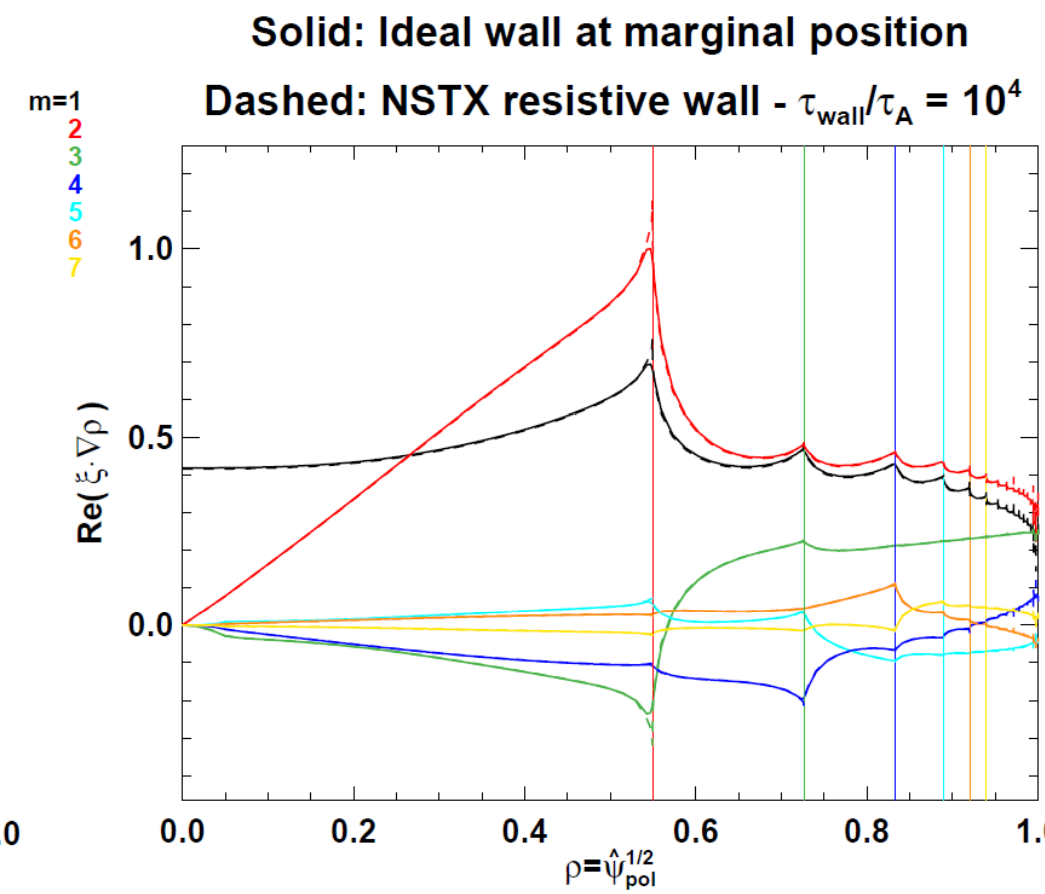


Ideal wall $\xi_\perp$ with wall at marginal position is very good approximation to $\xi_\perp$ with resistive wall at actual wall position

- Approximation holds for wide range of wall resistivity
- Only small differences in eigenfunction near rational surfaces

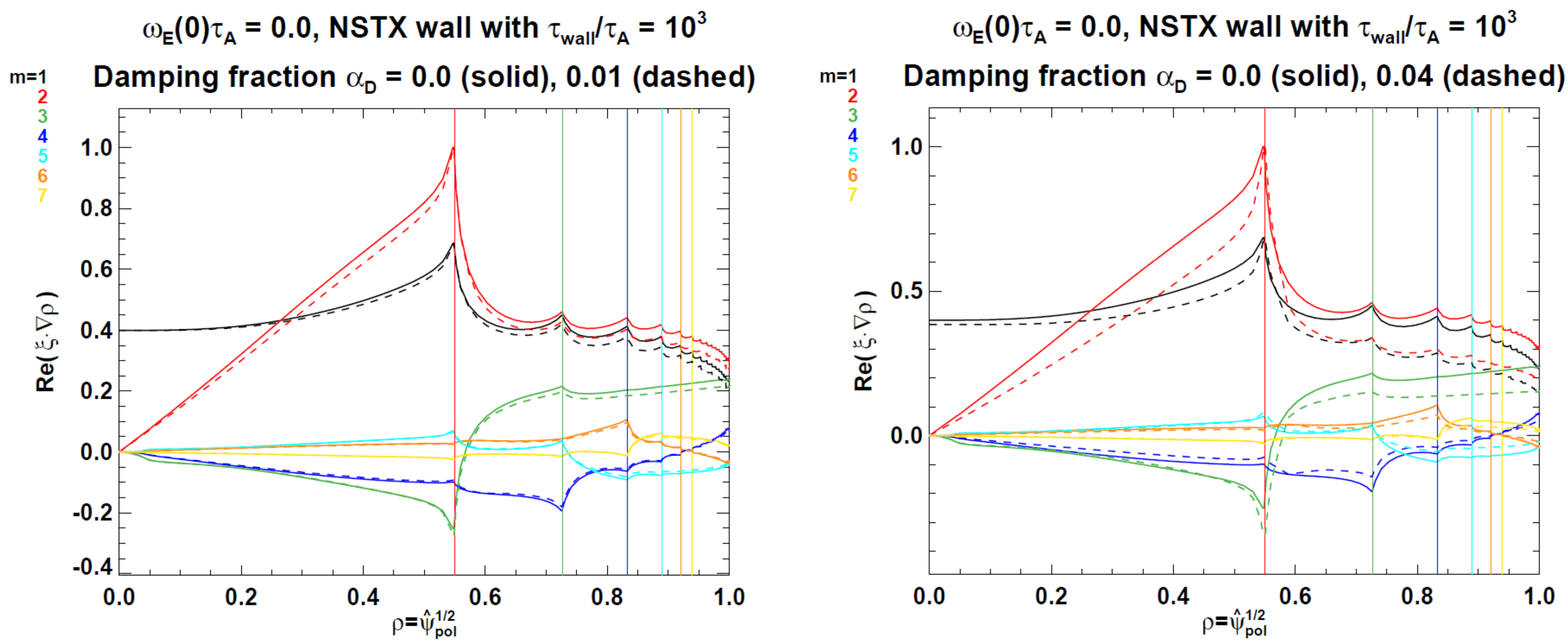
Ideal plasma, zero rotation, zero dissipation





Dissipation alone can modify RWM eigenfunctions (1)

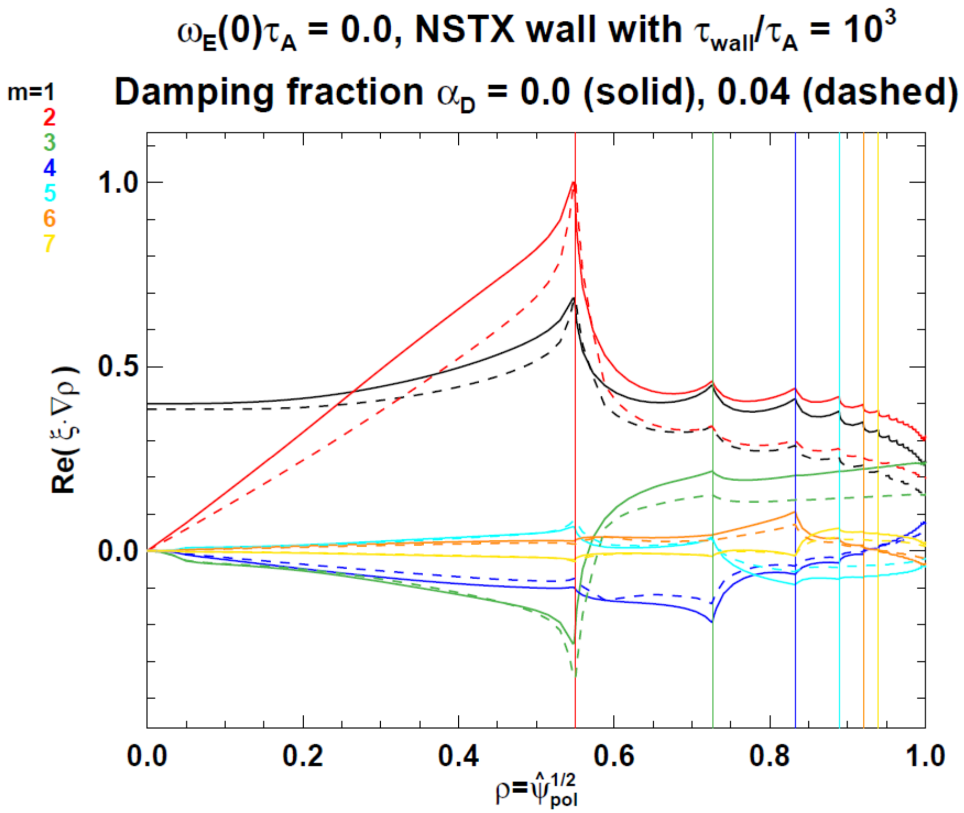
- 4% of full kinetic damping can reduce eigenfunction amplitude by 25-50% at large minor radii

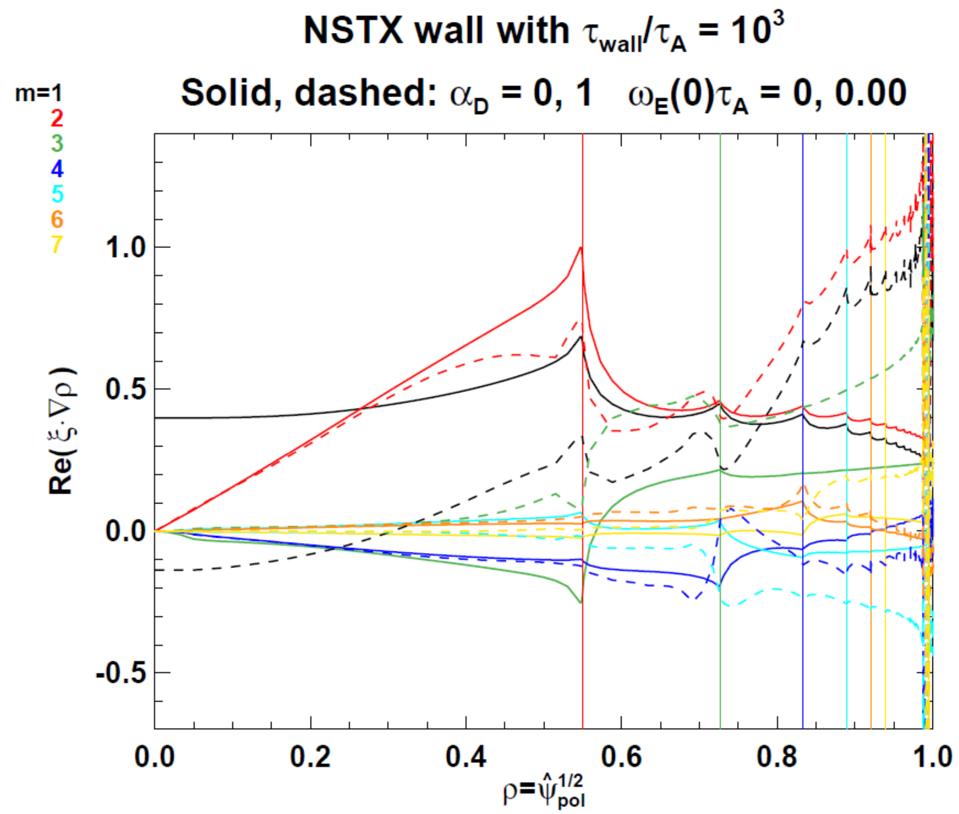


NOTE: collisions are included in this and subsequent calculations with energy independent collisionality with slowing-down v evaluated at E = 5/2 T

Dissipation alone can modify RWM eigenfunctions (2)

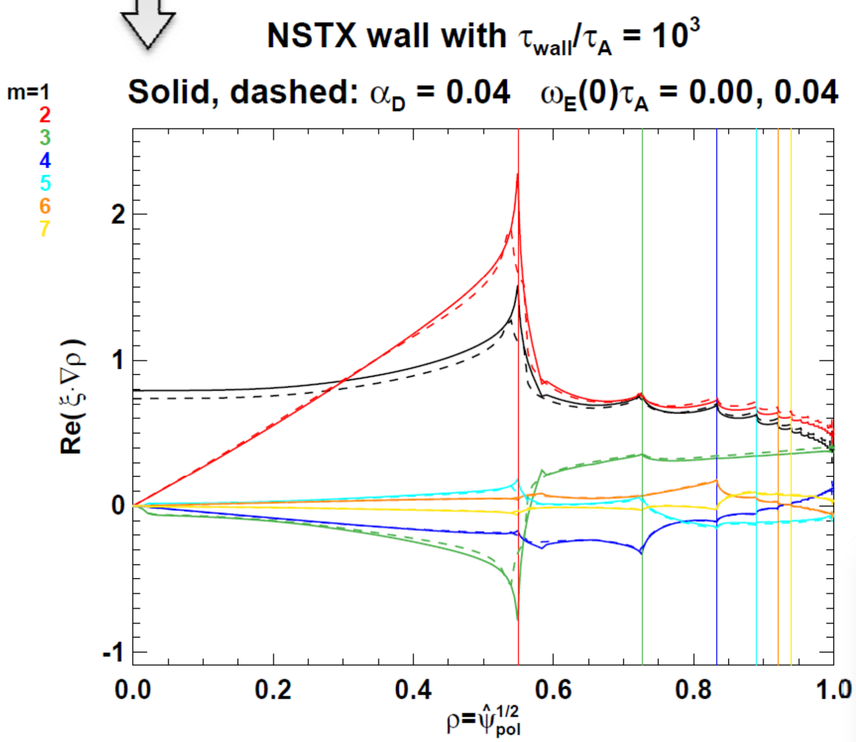
- Full kinetic damping can produce large changes in eigenmode structure near mode rational surfaces, and in edge region

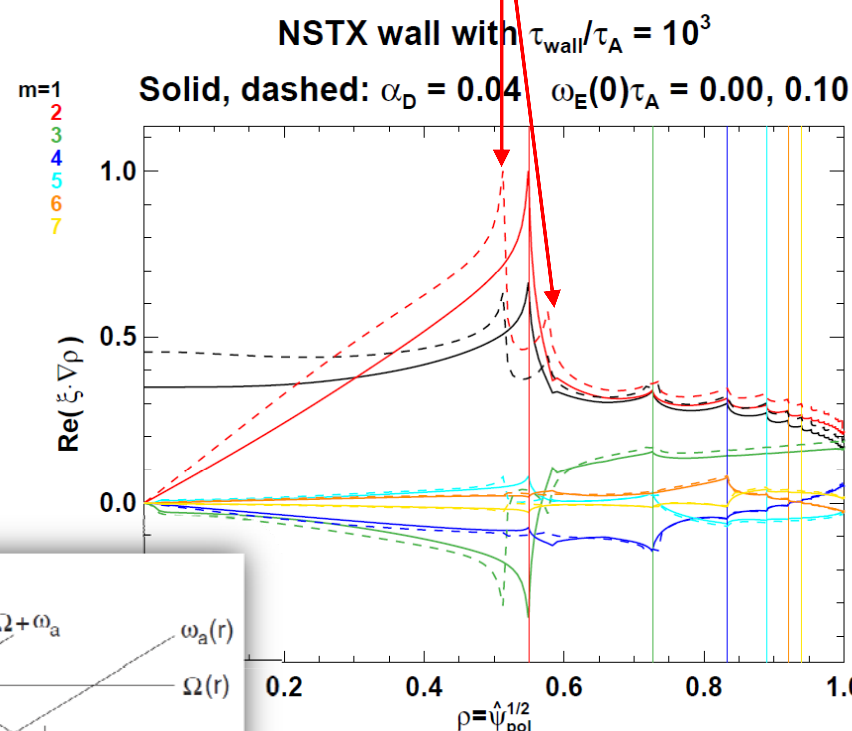


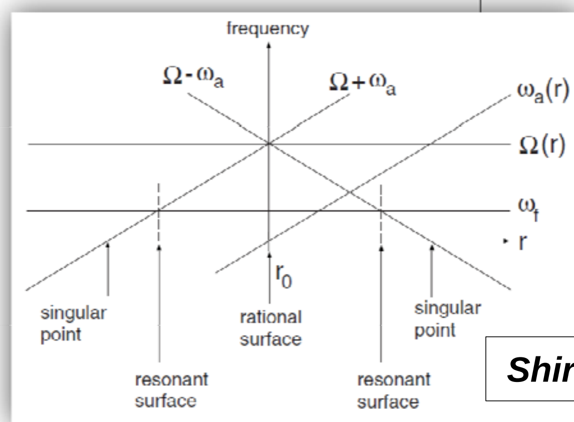


Rotation (with weak dissipation) can also modify RWM eigenfunctions

- Only small eigenfunction changes observed for $\omega_E(0)\tau_A = 0.04$
- Resonances appear on both sides of q=2 surface for $\omega_E(0)\tau_A = 0.1$
  - Alfvén singular points apparently split by Doppler shift



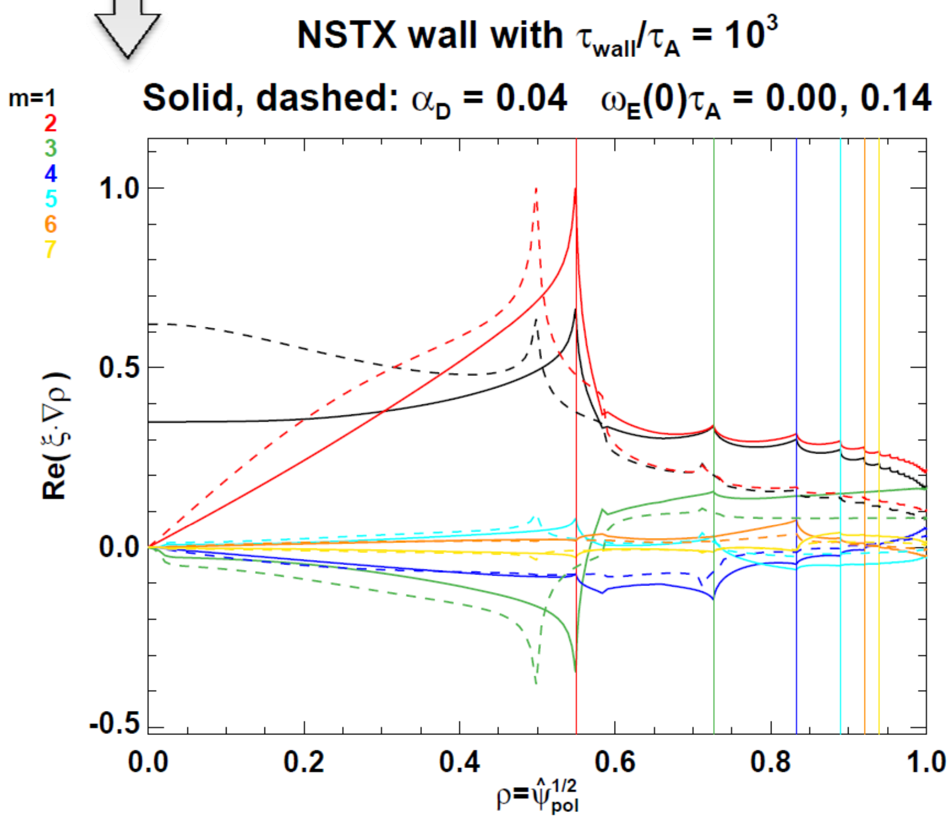


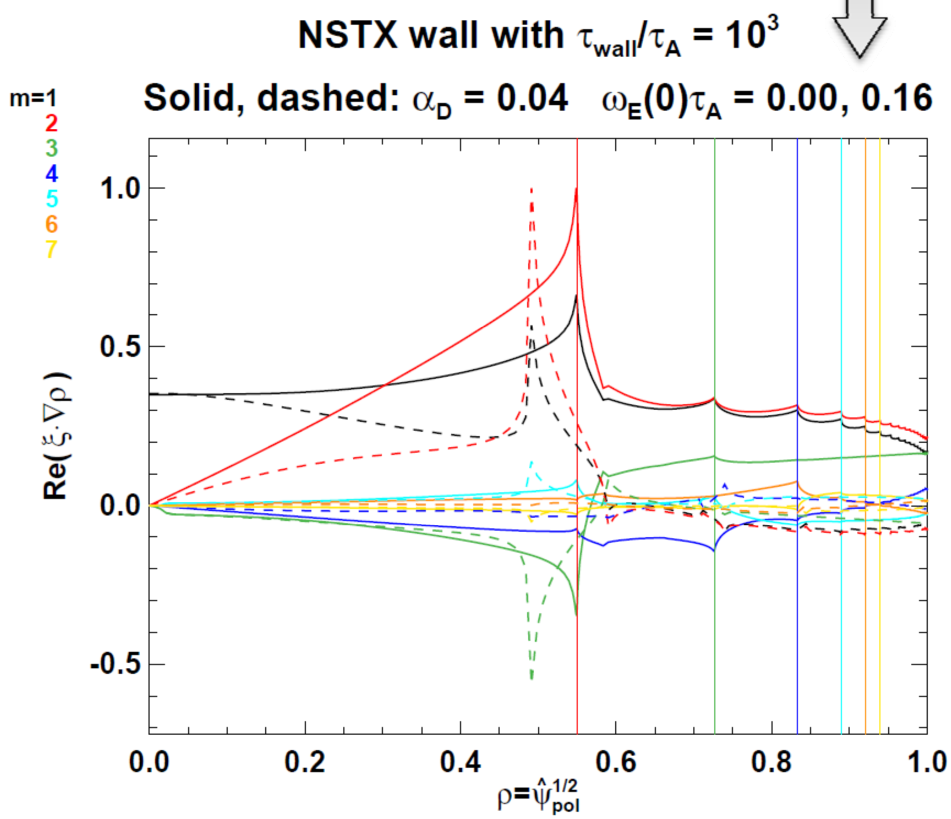


Shiraishi, PoP 2010

As rotation (with weak dissipation) increases toward experimental value, RWM eigenfunction is strongly modified

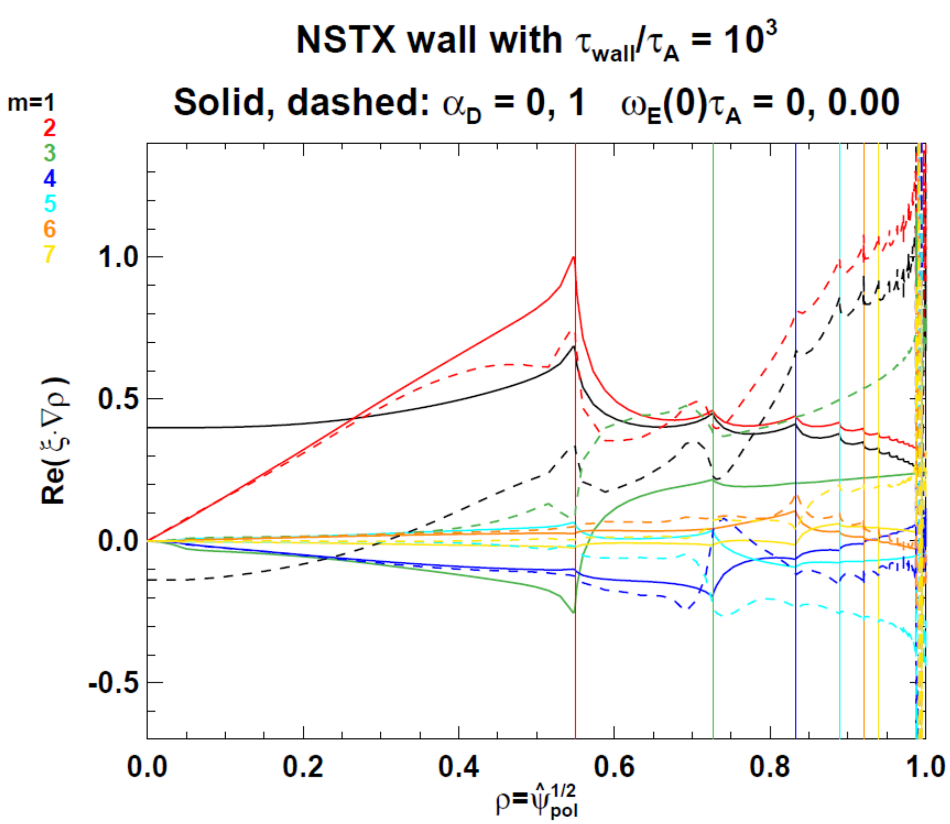
- Eigenfunction amplitude decreased by 25-50% at large minor radius for $\omega_E(0)\tau_A = 0.14$
- Eigenfunction strongly modified for $\omega_E(0)\tau_A = 0.16$
  - Rotation approaching marginal stability ($\omega_E(0)\tau_A \approx 0.22$)

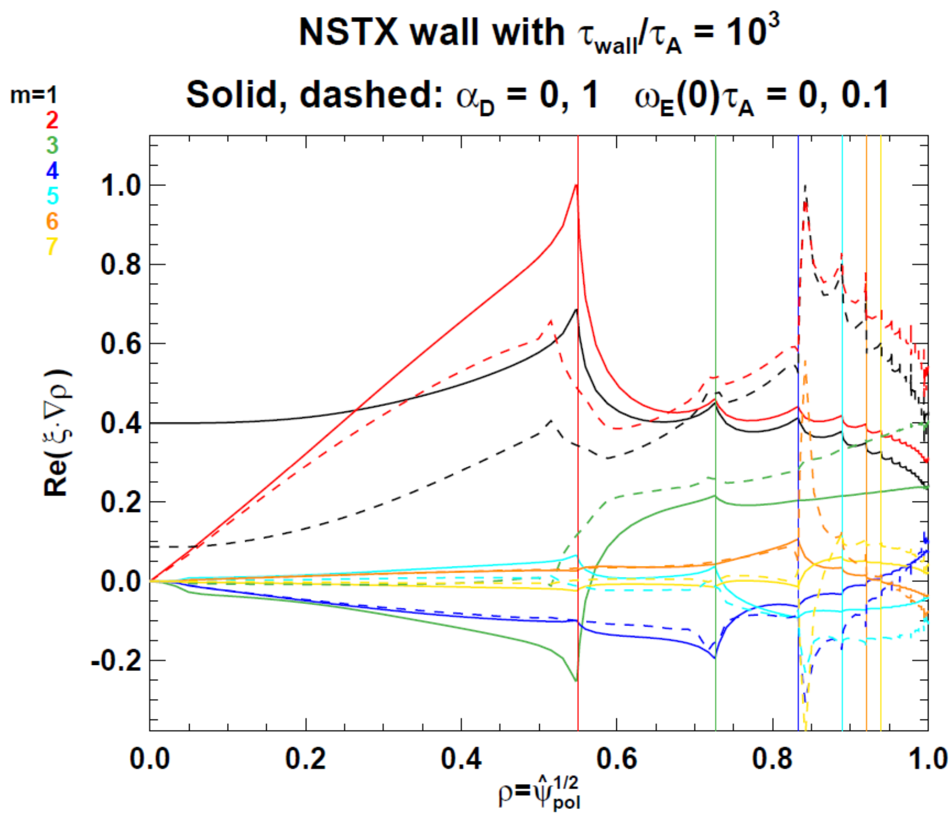




Rotation + dissipation strongly modifies RWM eigenfunctions

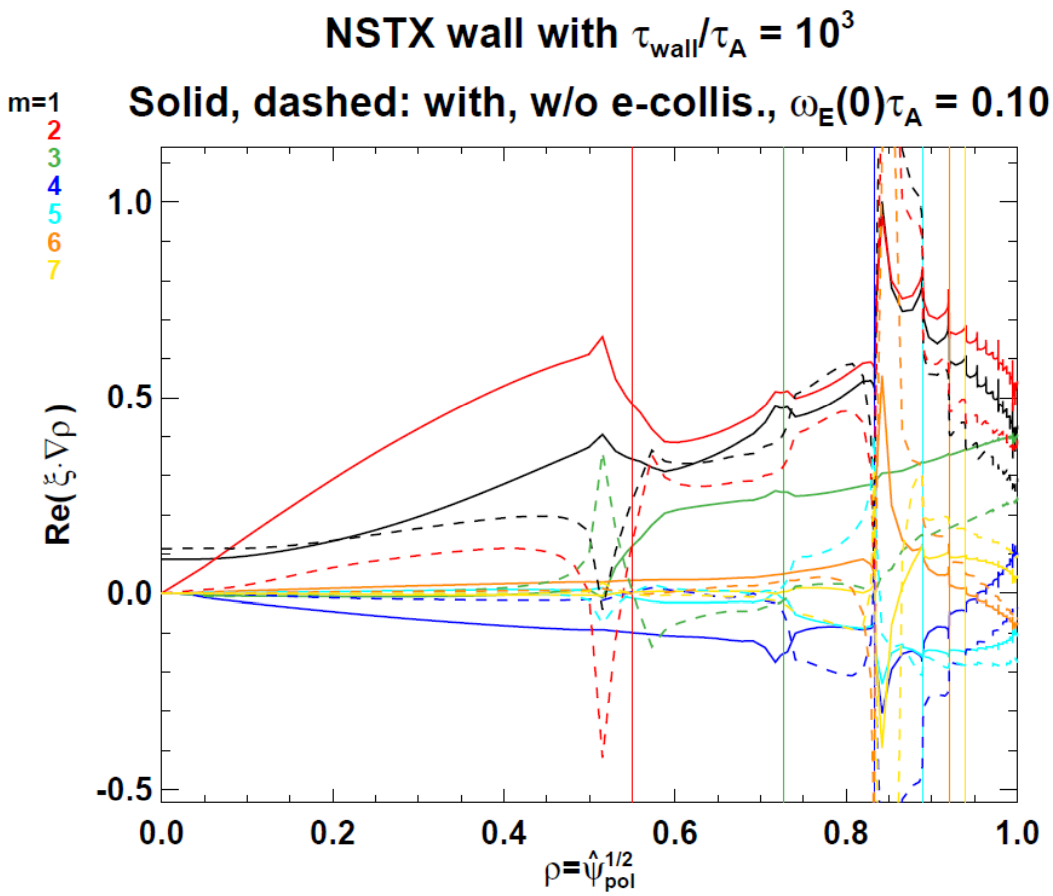
- Rotation added to full kinetic damping produces changes that deviate significantly from cases w/o rotation or dissipation





Inclusion of collisions can also modify eigenfunction

- Change due to electron collisions is largest, and including these collisions can result in less abrupt changes of eigenfunction across rational surfaces



Full kinetic damping

Toroidal rotation modifies no-wall ideal plasma eigenfunction in outer 1/3 of minor radius

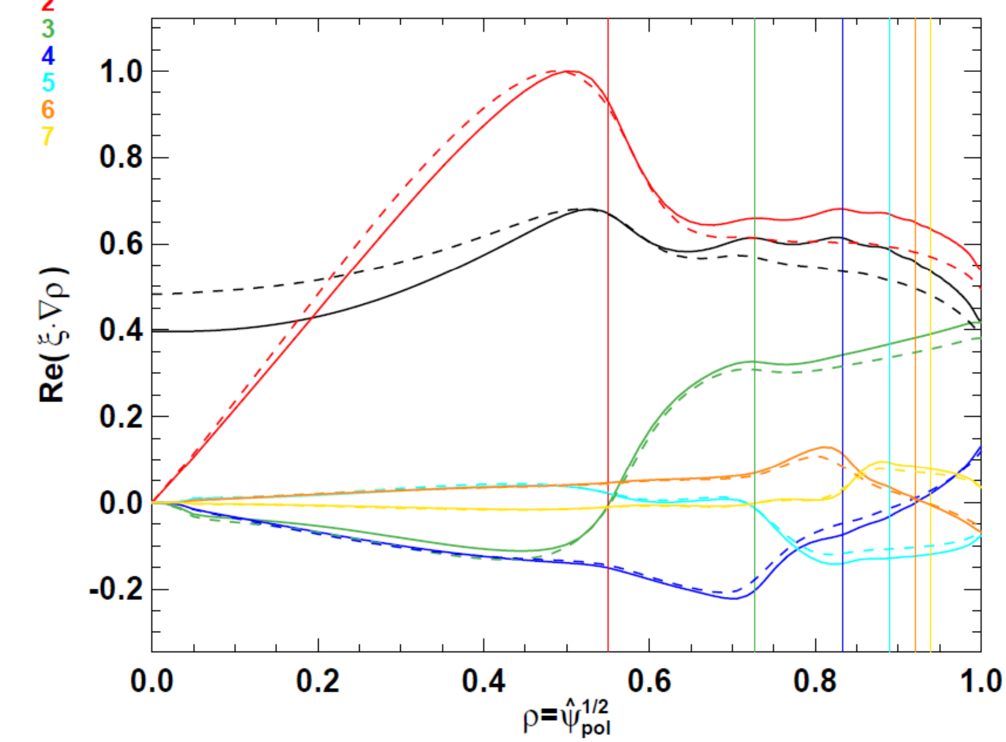
- 1/1 component modified in both core and edge
- Poloidal harmonics m=1-7 reduced at large minor radius

Ideal plasma, zero dissipation

Experimental value

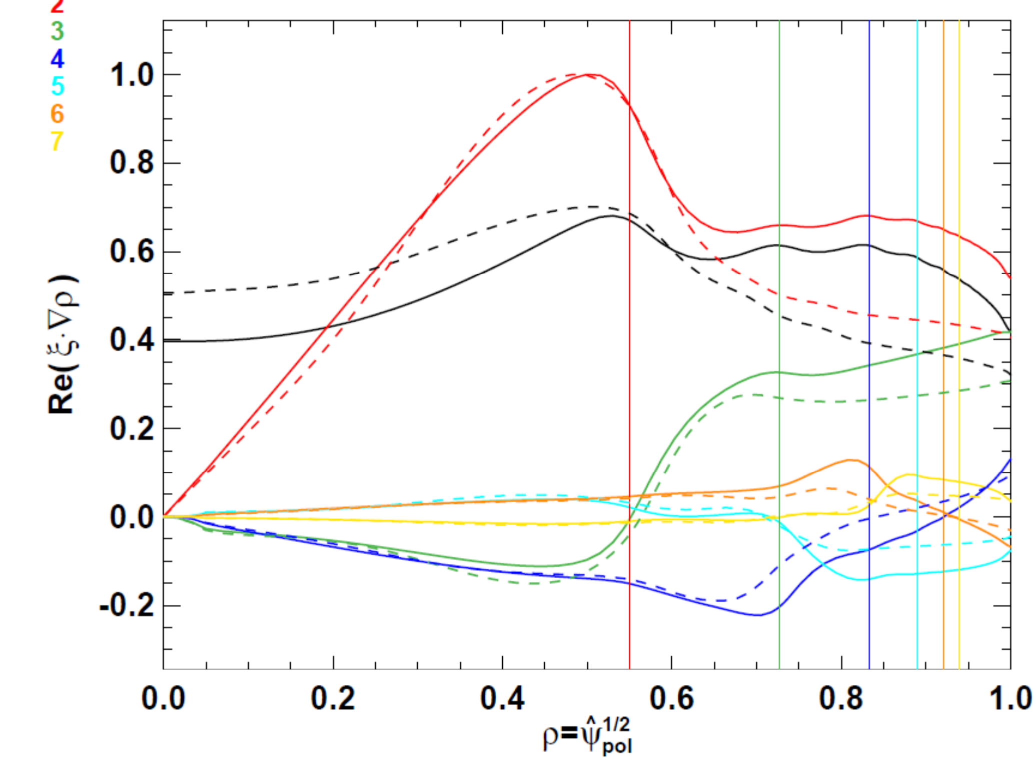
Ideal wall at infinity

Solid: $\omega_E(0)\tau_A$ = 0.0, Dashed: $\omega_E(0)\tau_A$ = 0.1



Ideal wall at infinity

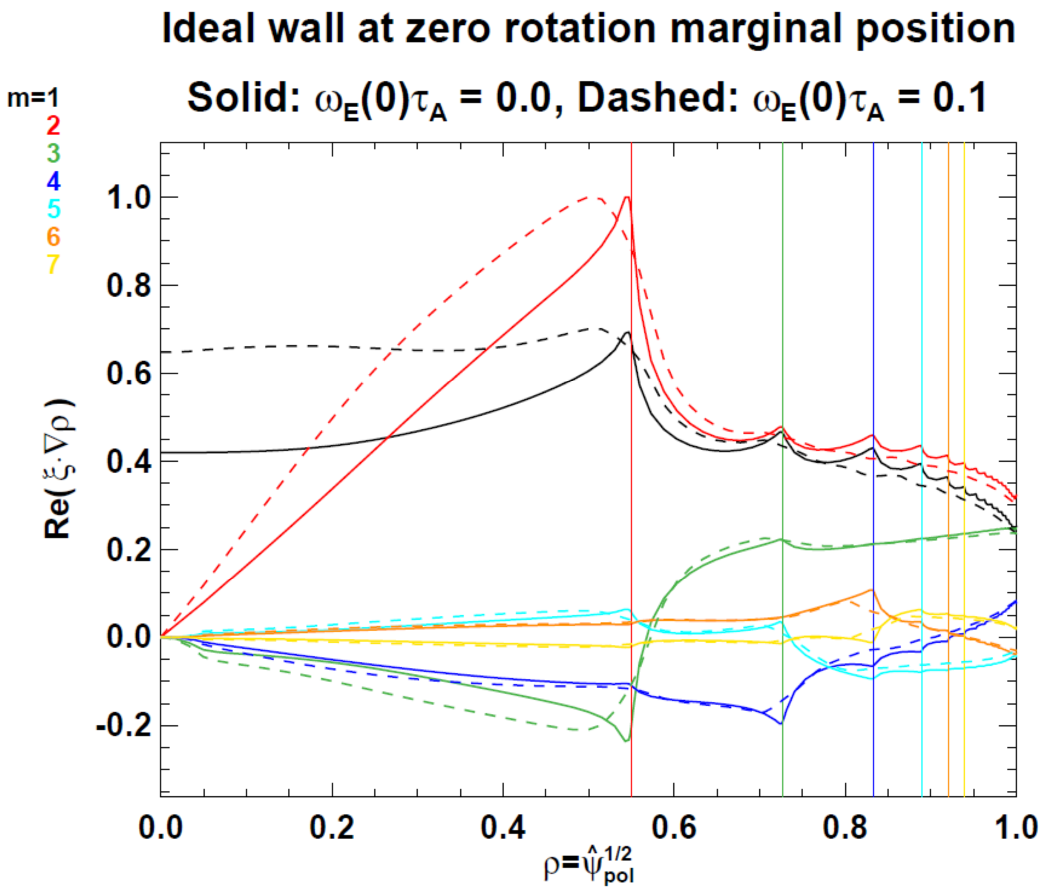
Solid: $\omega_E(0)\tau_A$ = 0.0, Dashed: $\omega_E(0)\tau_A$ = 0.2

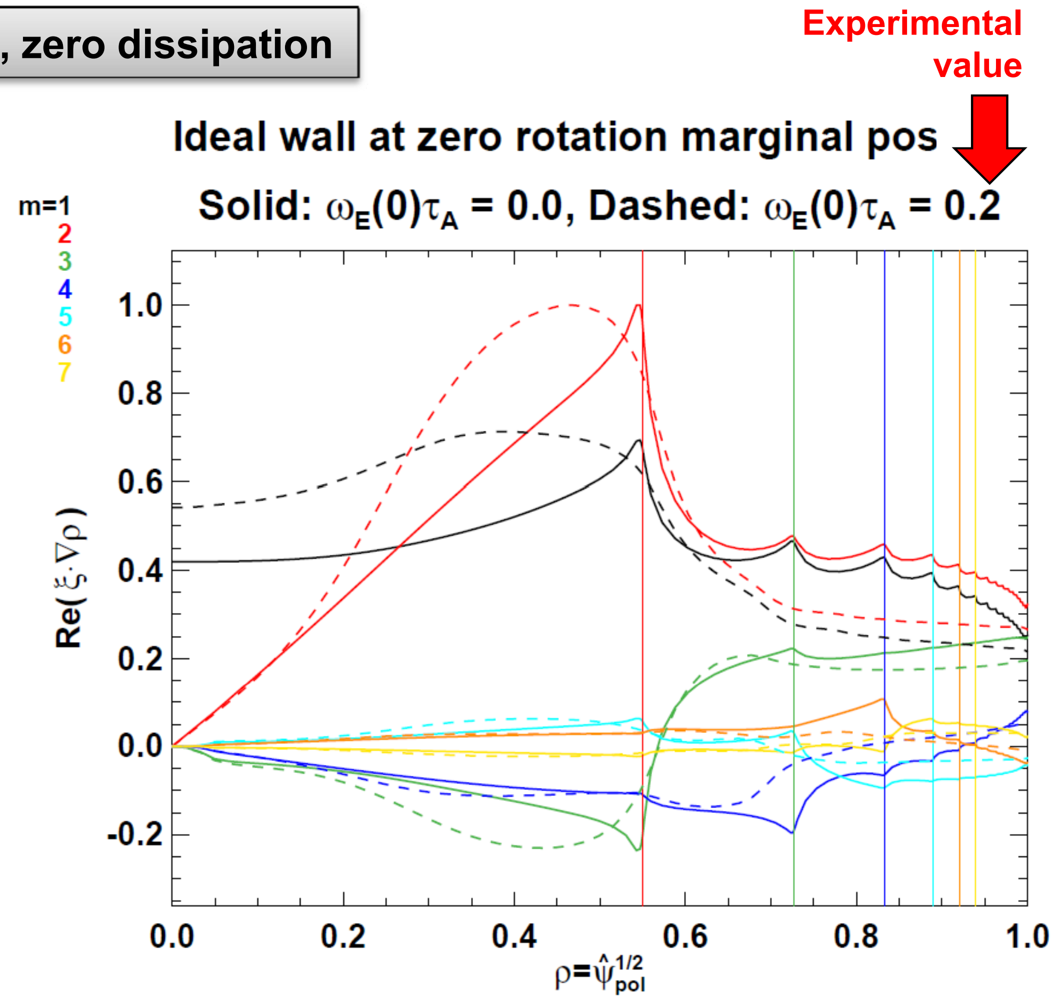


Toroidal rotation also modifies <u>with-wall</u> eigenfunction

- With wall present, eigenfunction modified in both core and edge
- Note – this is 'plasma mode' with ω_r ~ rotation frequency

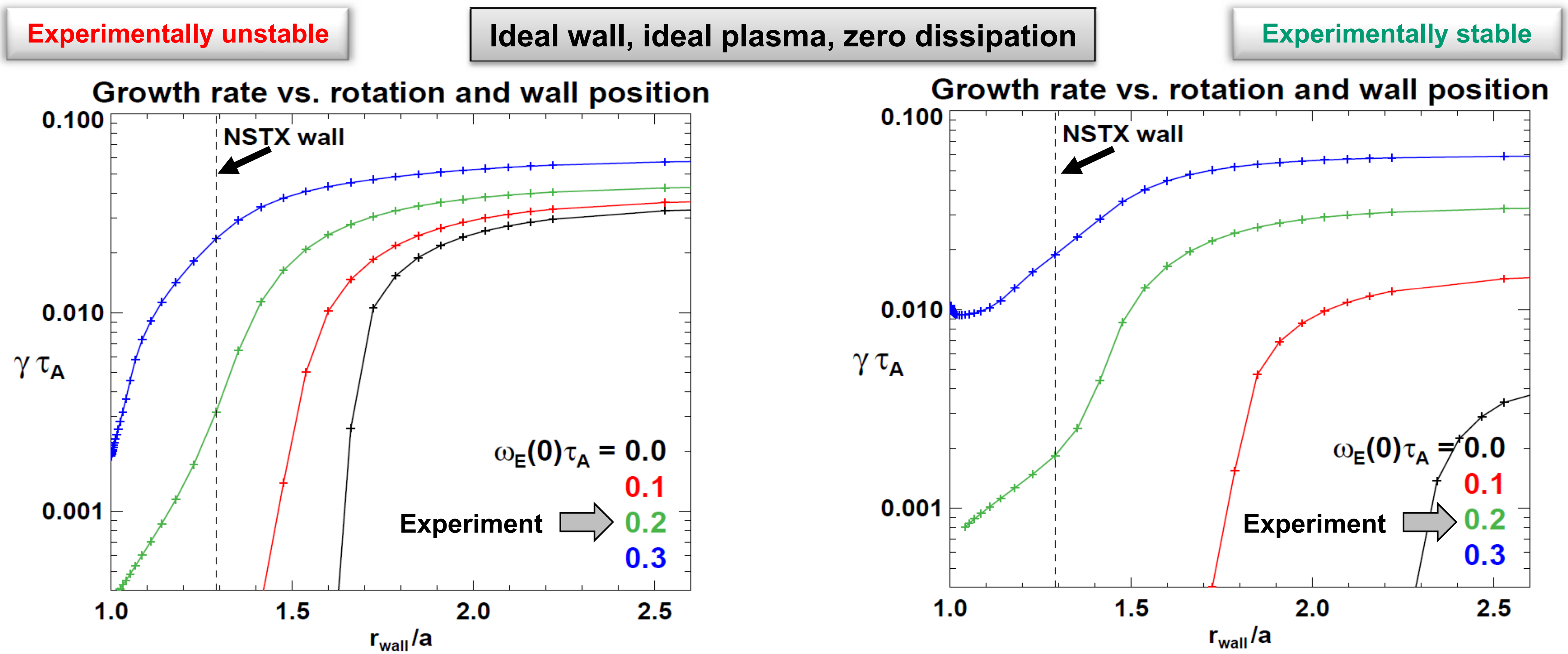
Ideal plasma, zero dissipation





Increased toroidal rotation reduces 'plasma mode' stability

- Implication: 'ideal-wall limit' is function of rotation speed
- Plasma mode predicted to be unstable for NSTX wall and rotation, but experiment does not exhibit this fast rotating instability
- Future: include dissipation in plasma mode calculation – stabilizing?



Summary

- Edge rotation ($q \geq 4$, $r/a \geq 0.8$) important for NSTX RWM
  - Trends consistent with stability calculations using MARS-F
- Stability quite sensitive to edge ω_E profile
  - Essential to include accurate edge ∇p in E_r profile
  - Poloidal rotation can also influence marginal stability
- MARS-K (full kinetic) trends (stable/unstable) using self-consistent approach consistent with experiment
  - Perturbative treatment inconsistent – overly stable
- RWM eigenfunctions are modified by dissipation, rotation
  - Reduction/modification of $\xi_\perp$ will modify kinetic stabilization
- 'Plasma mode' also modified/destabilized by rotation
  - Future: assess whether dissipation modifies plasma mode stability

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