The role of rotation and kinetic damping in high-β ST plasma stability*

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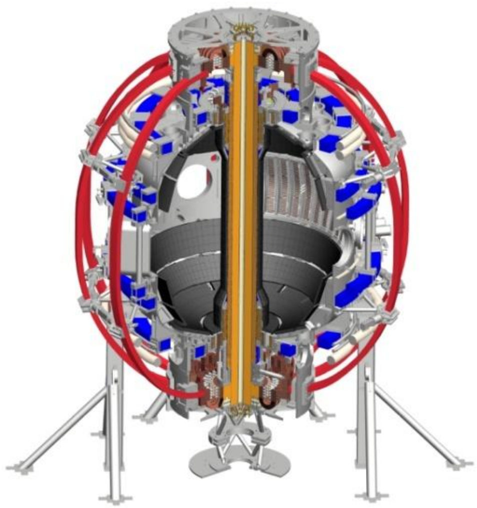

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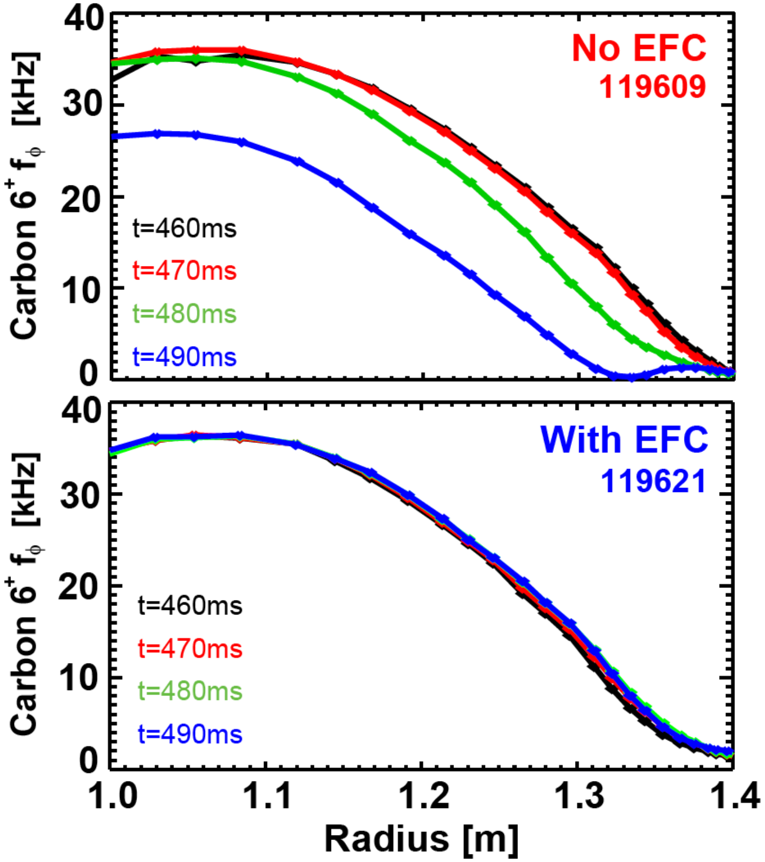
Overview

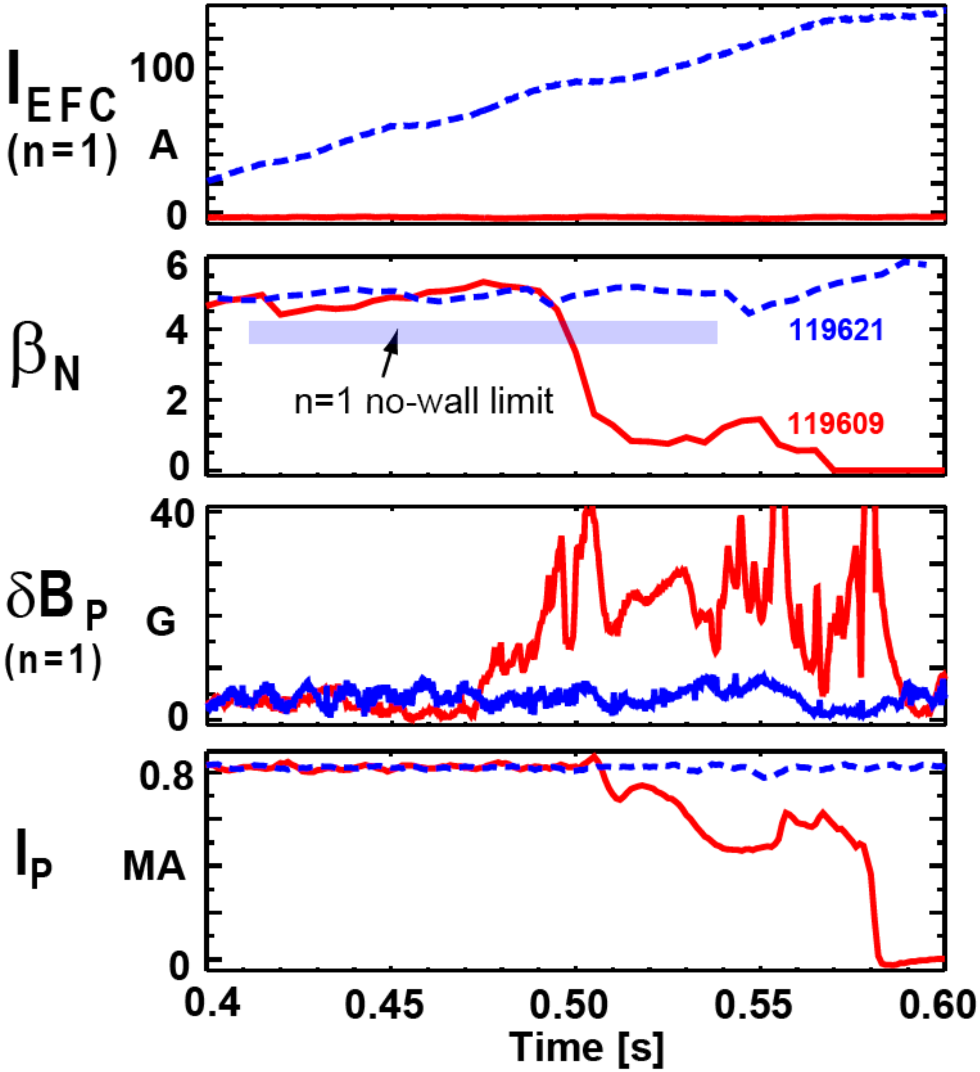
- Drift-kinetic effects have previously been included in RWM stability analysis for NSTX (see papers by Berkery, Sabbagh, Menard)
  - In this work, we briefly review result that RWM stability is sensitive function of edge rotation, and is consistent with MARS-F analysis
  - We then investigate how RWM eigenfunctions are modified by rotation and dissipation using MARS-K
    - Not previously documented for ST plasmas
    - Could impact 'perturbative' approach employed by codes such as MISK

- Drift-kinetic stability analyses have ***not*** previously been carried out for ideal-wall limit, aka the 'plasma mode'
  - Work here investigates impact of rotation, rotation shear, and kinetic damping on 'plasma mode' stability and eigenfunctions

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

Analysis of experiment uses MARS: 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*:**

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

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

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

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

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

- **Mode-particle resonance operator:**

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

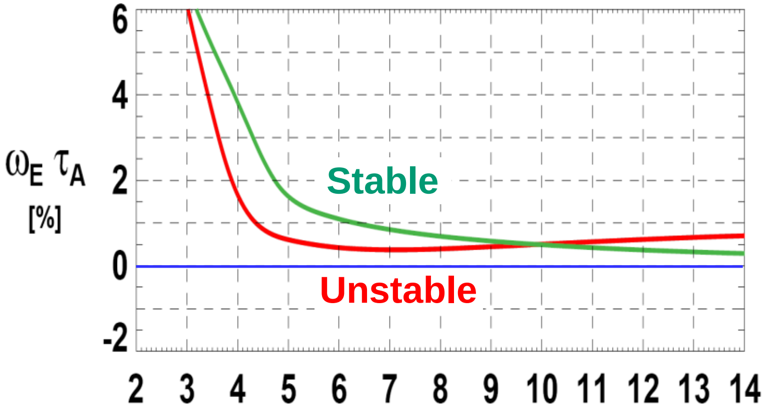
MARS-F: $$\lambda_{ml} = \frac{n[\cancel{\omega_{*N}} + (\hat{\epsilon}_k - 3/2)\cancel{\omega_{*T}} + \omega_E] - \omega}{n(\cancel{\langle\omega_d\rangle} + \omega_E) + [\alpha(m+nq) + l]\omega_b - \cancel{i\nu_{\text{eff}}} - \omega}$$

+ additional approximations/simplifications in f_L^1

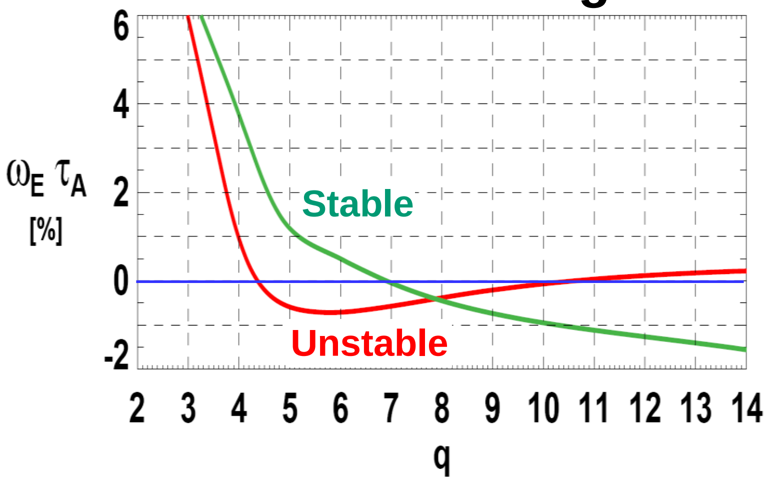
- **Fast ions: MARS-K: slowing-down f(v), MARS-F: lumped with thermal**

MARS-F: Inclusion of ω_{*C} in ω_E increases separation between stable and unstable $\omega_E(\psi)$, provides consistency w/ expt.

Toroidal rotation only



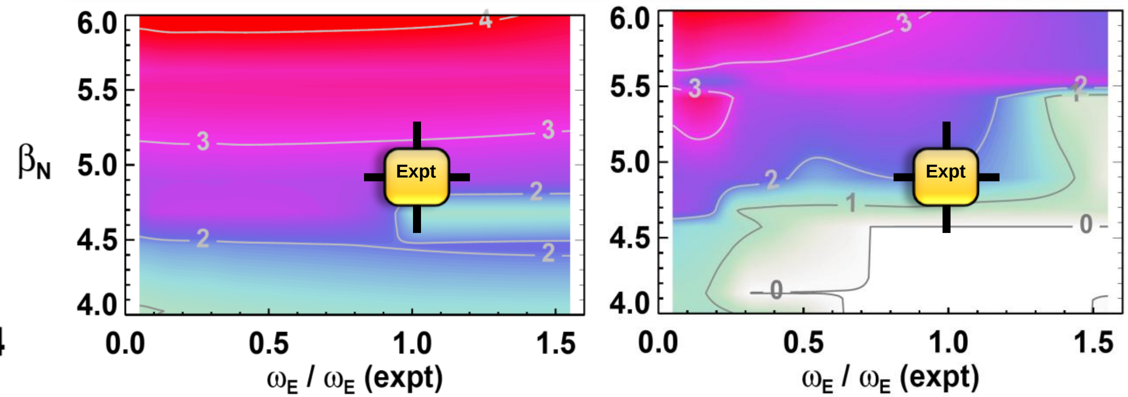
Toroidal + diamagnetic



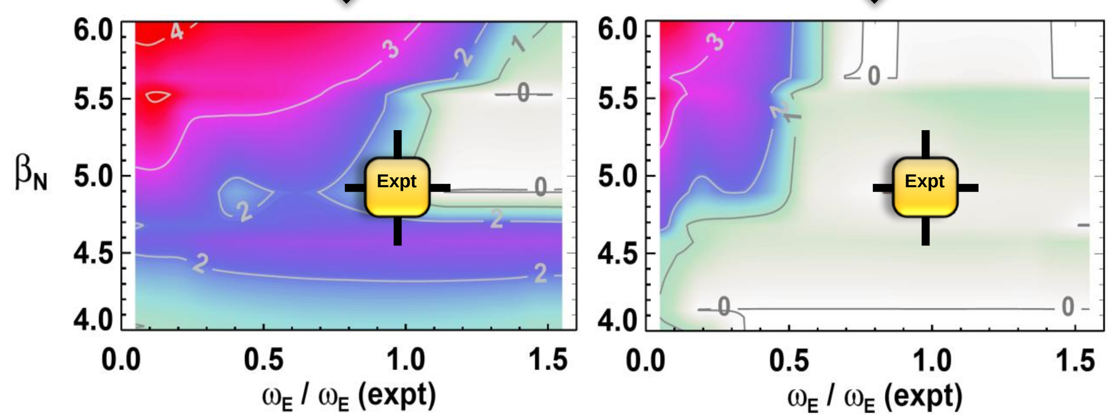
Calculated n=1 $\gamma\tau_{wall}$

Unstable rotation profile

Stable rotation profile



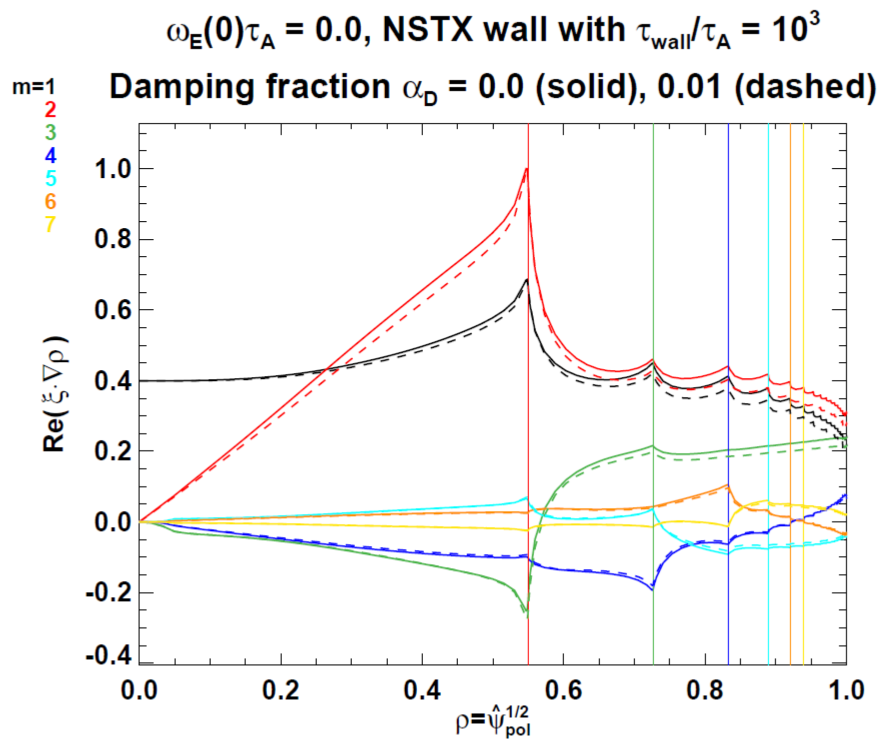
Predictions inconsistent with experiment

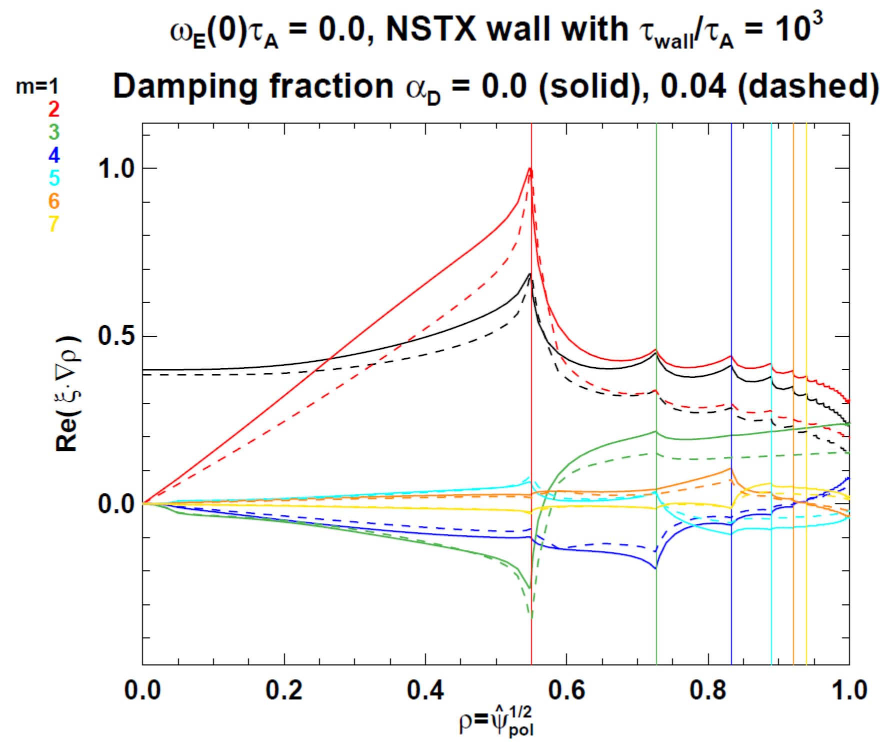


Predictions consistent with experiment

MARS-K studies of RWM eigenfunction: Dissipation alone can modify RWM eigenfunctions (1)

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

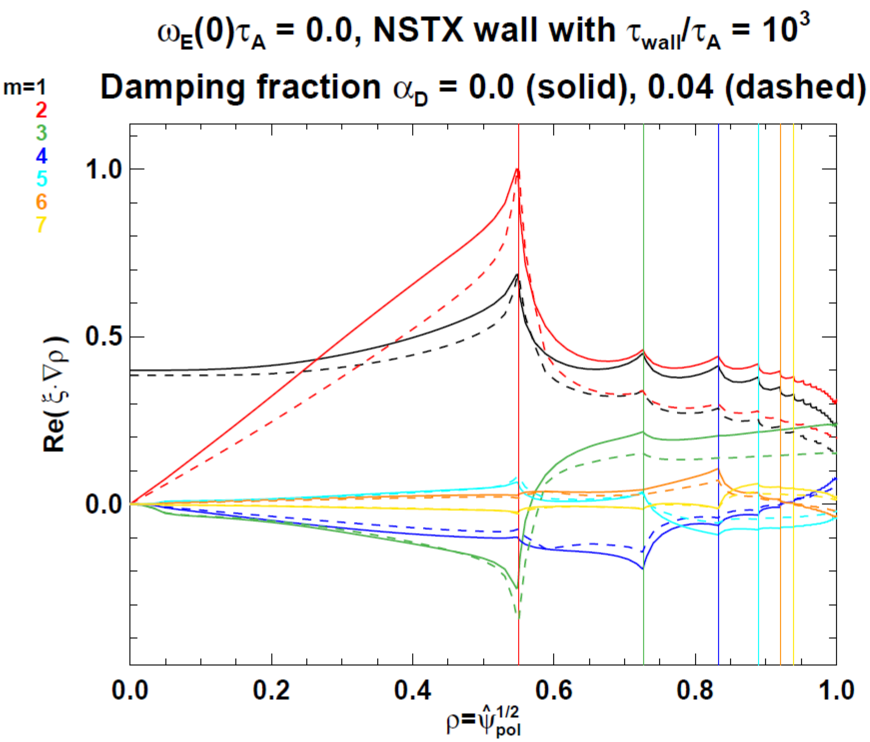


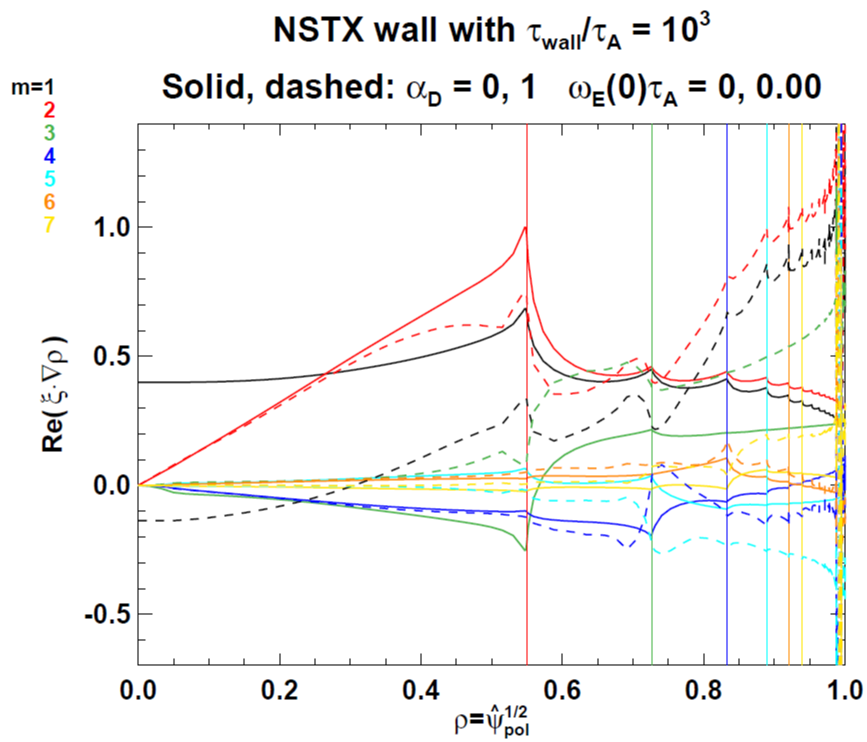


NOTE: collisions are included in this and subsequent calculations with energy independent collisionality with slowing-down ν evaluated at E = 5/2 T

MARS-K studies of RWM eigenfunction: Dissipation alone can modify RWM eigenfunctions (2)

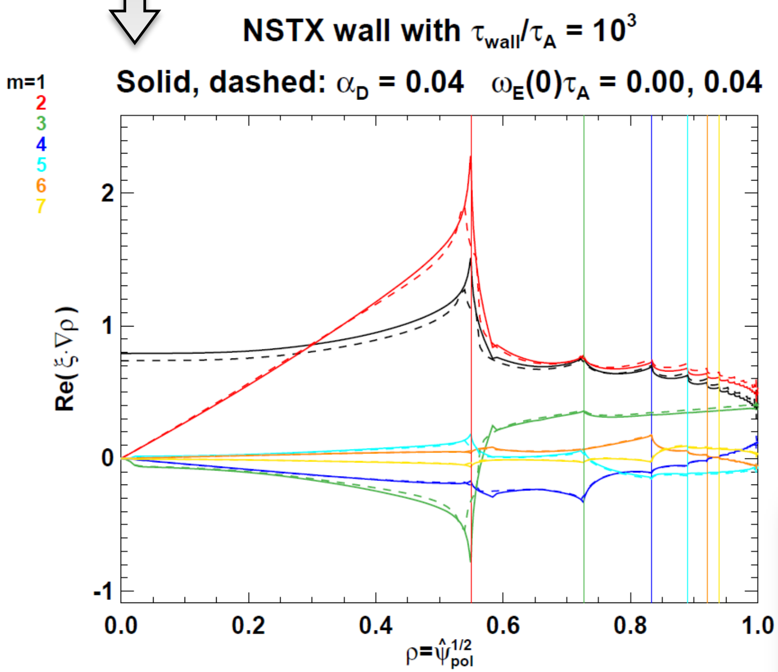
- Full kinetic damping can produce large changes in eigenmode structure near mode rational surfaces, and in edge region

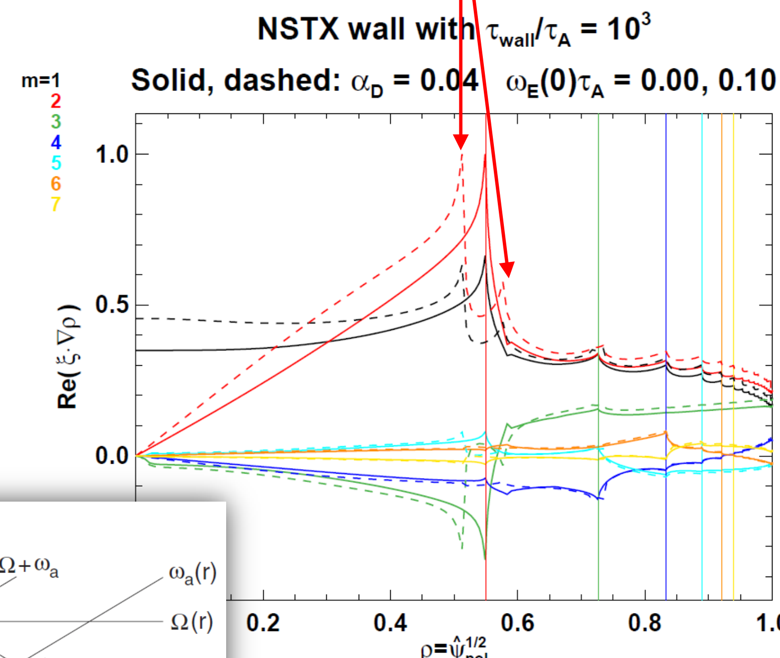


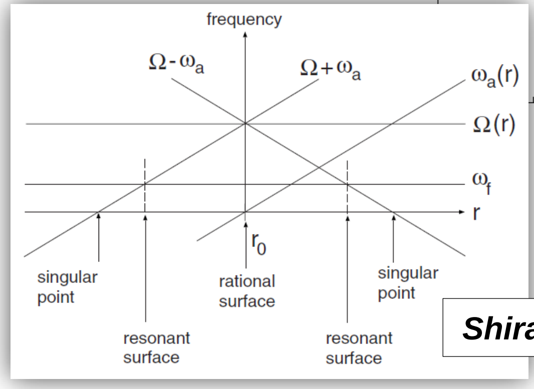


Rotation (with weak dissipation) can also modify RWM eigenfunctions

- 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



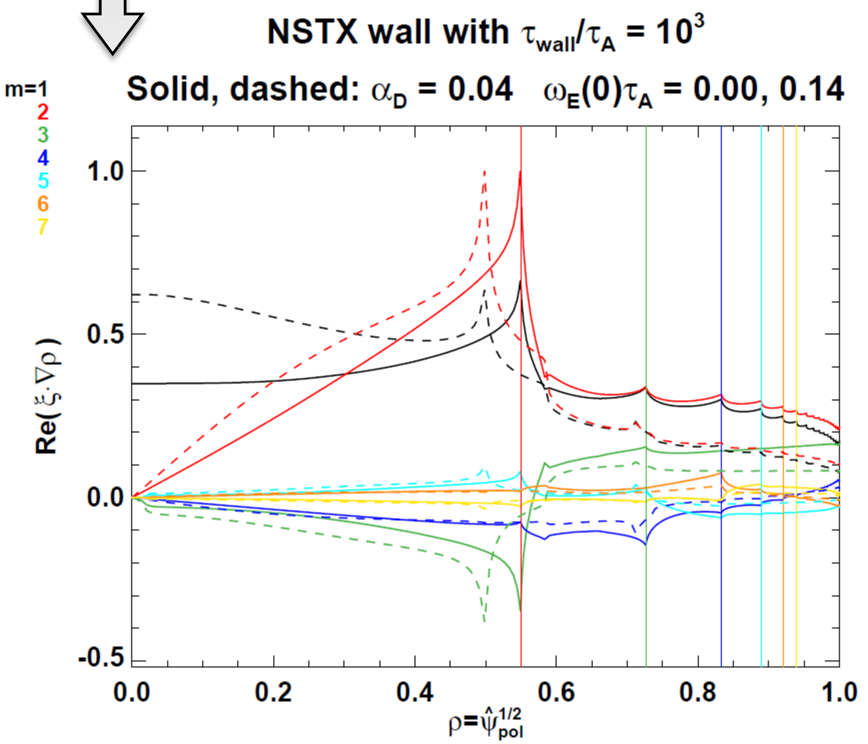


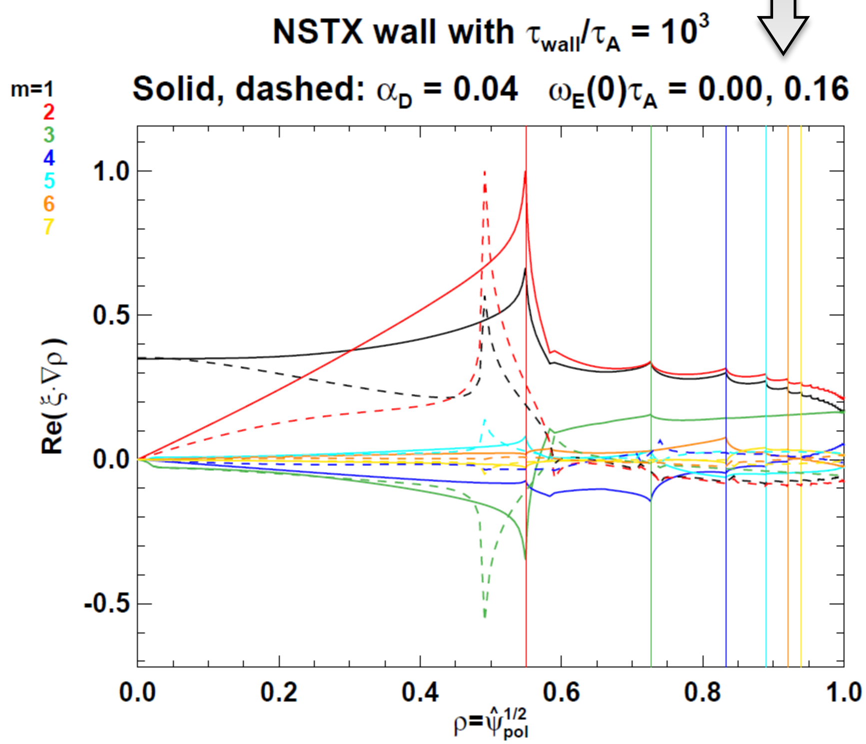


Shiraishi, PoP 2010

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

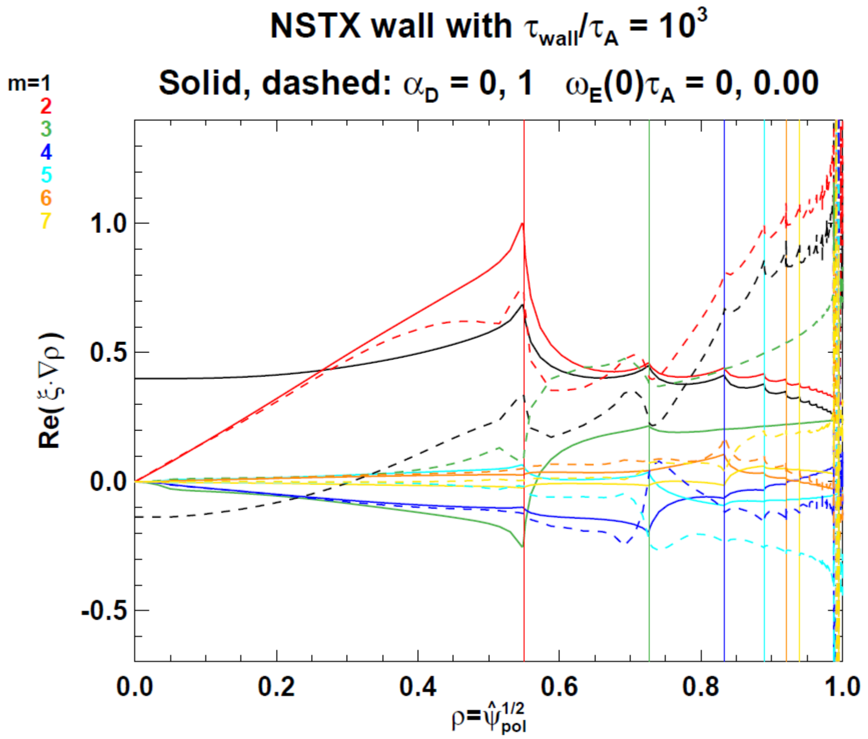
- Eigenfunction amplitude decreased by 25-50% at large minor radius for $\omega_E(0)\tau_A = 0.14$
- Eigenfunction strongly modified for $\omega_E(0)\tau_A = 0.16$
  - Rotation approaching marginal stability ($\omega_E(0)\tau_A \approx 0.22$)

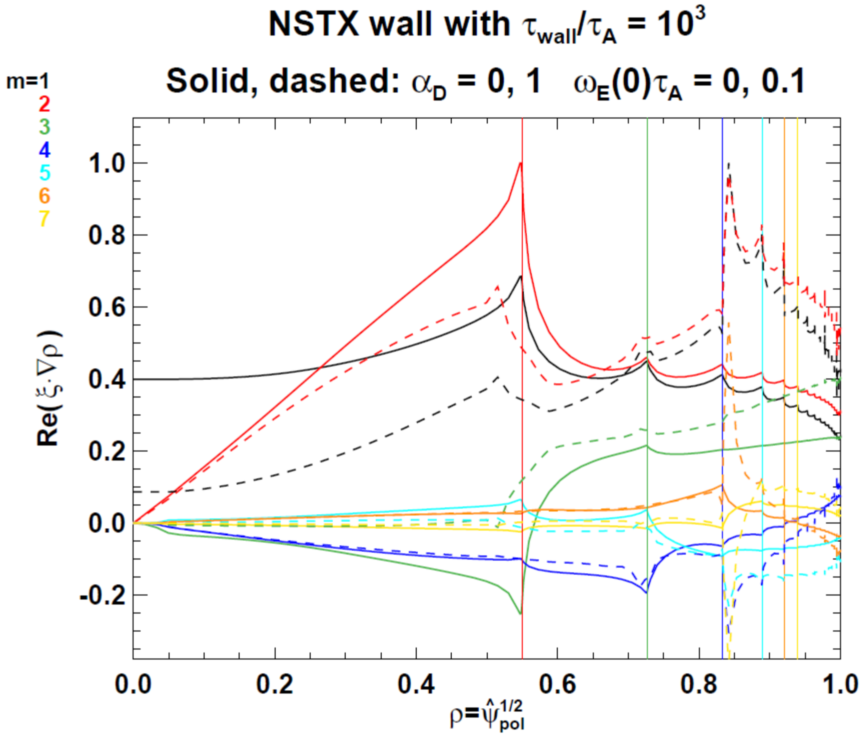




Rotation + dissipation strongly modifies RWM eigenfunctions

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



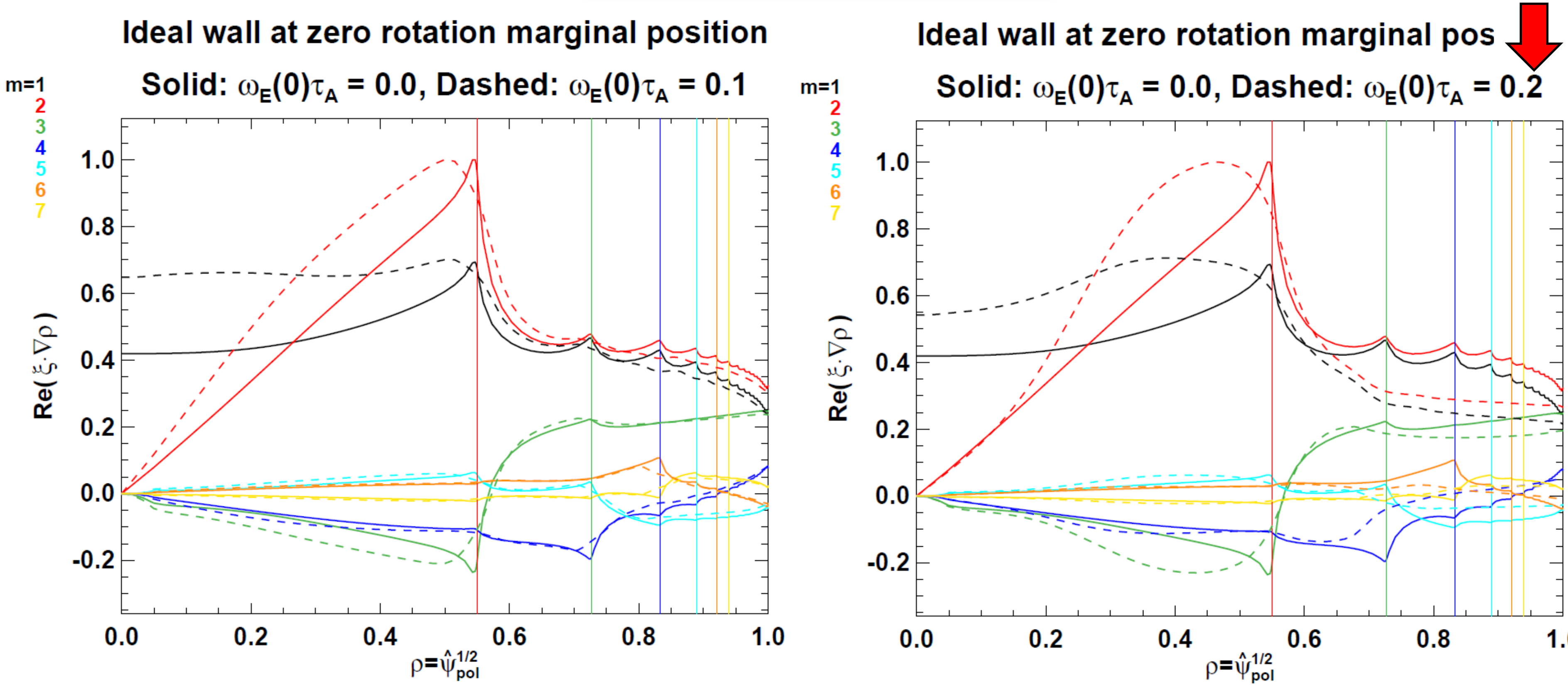


Toroidal rotation also modifies <u>with-wall</u> eigenfunction

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

Ideal plasma, zero dissipation

Experimental value



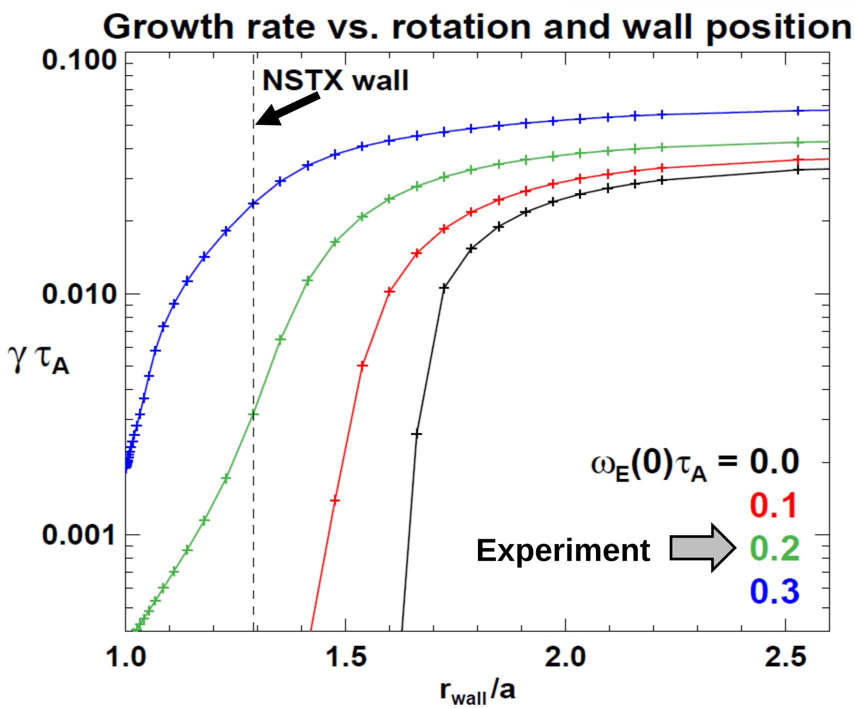
Increased toroidal rotation reduces 'plasma mode' stability

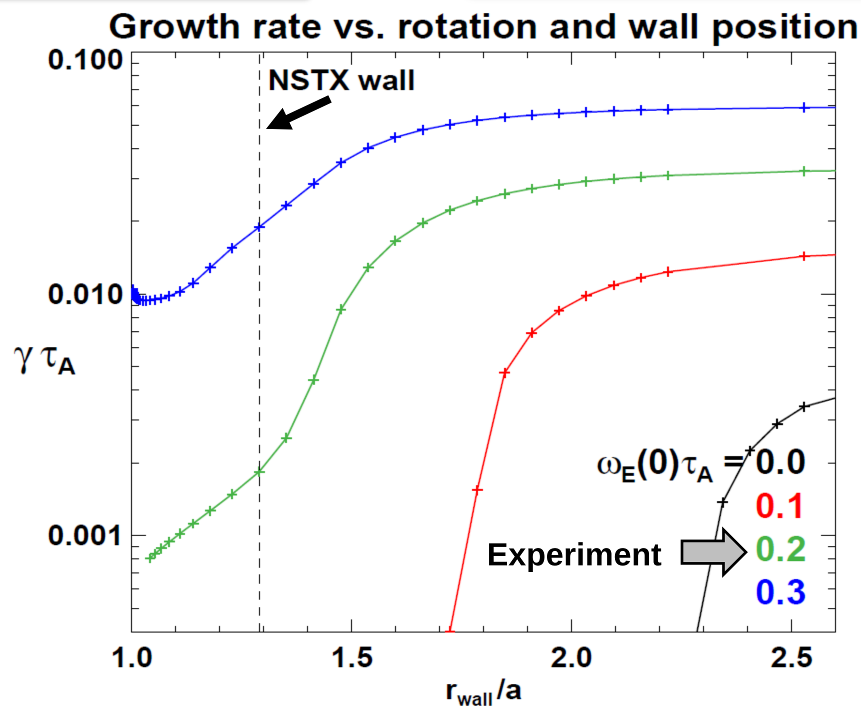
- Implication: 'ideal-wall limit' is function of rotation speed
- Plasma mode predicted to be unstable for NSTX wall and rotation, but experiment does not exhibit this fast rotating instability at this time

Experimentally unstable

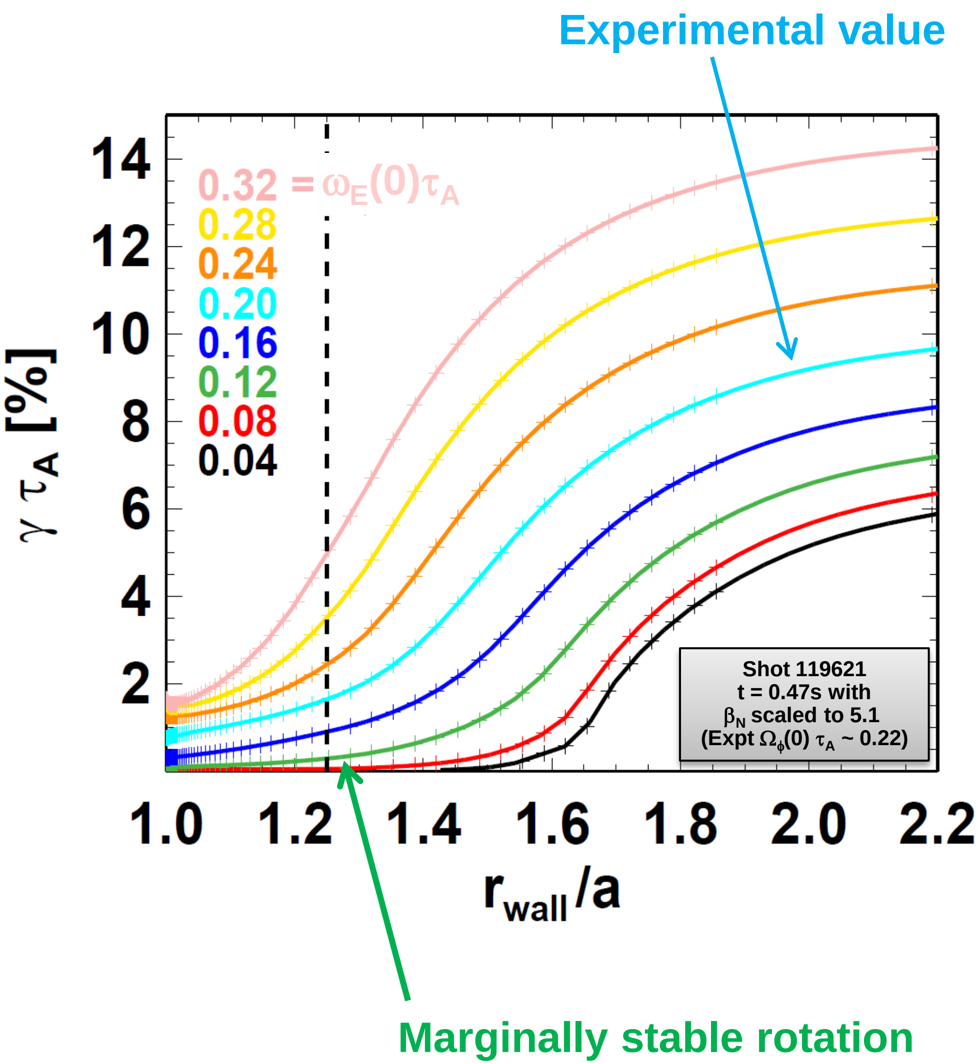
Ideal wall, ideal plasma, zero dissipation

Experimentally stable





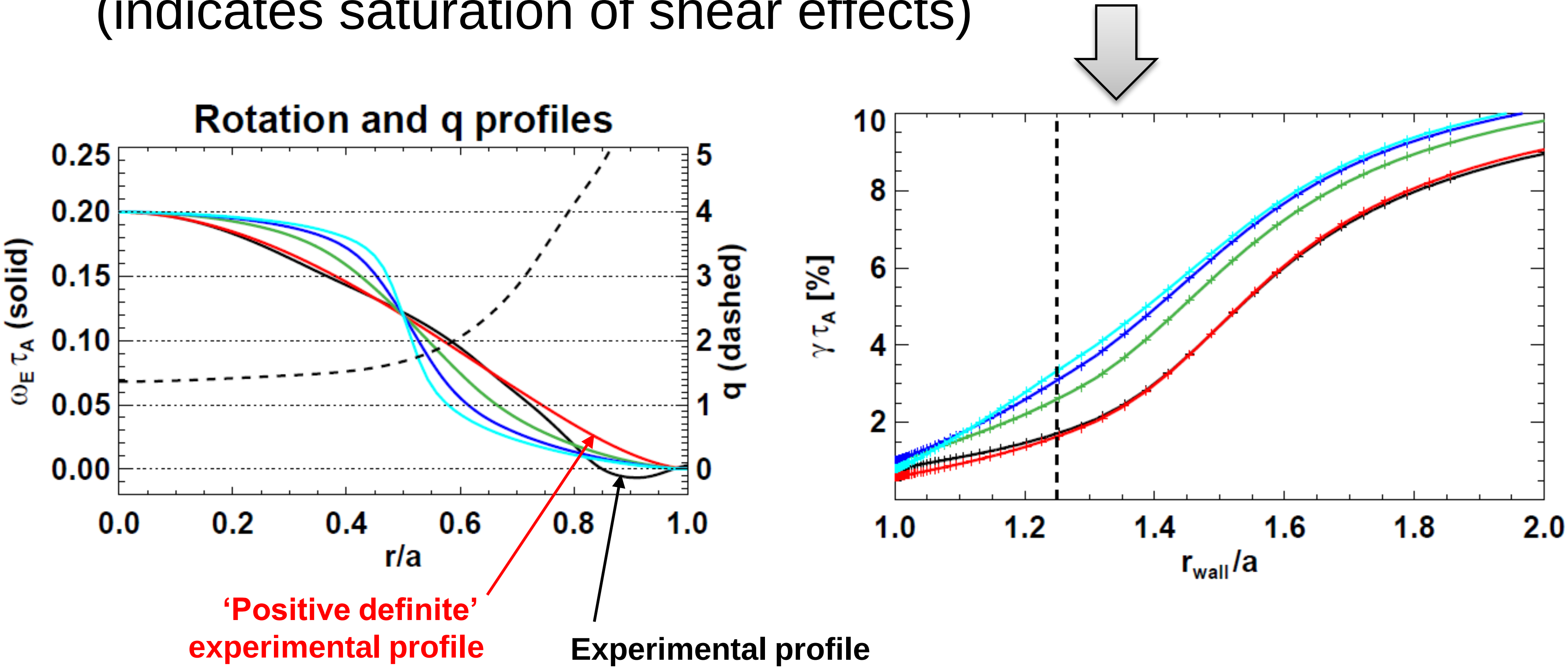
Higher-resolution rotation scan finds ideal 'plasma mode' marginally stability at ~50-60% of experimental rotation



- **Ideal NSTX plasma: β_N = 5.1, wall position r_{wall} / a ~ 1.25**
  - Low rotation → marginal r_{wall} / a ~ 1.65
  - As $\omega_E(0)\tau_A$ → 0.1-0.12 (no dissipation), n=1 becomes unstable
  - For $\omega_E(0)\ \tau_A$ ~ 0.2-0.3, n=1 mode is unstable even with the wall on the plasma boundary
- **Instability tentatively identified as Kelvin-Helmholtz**

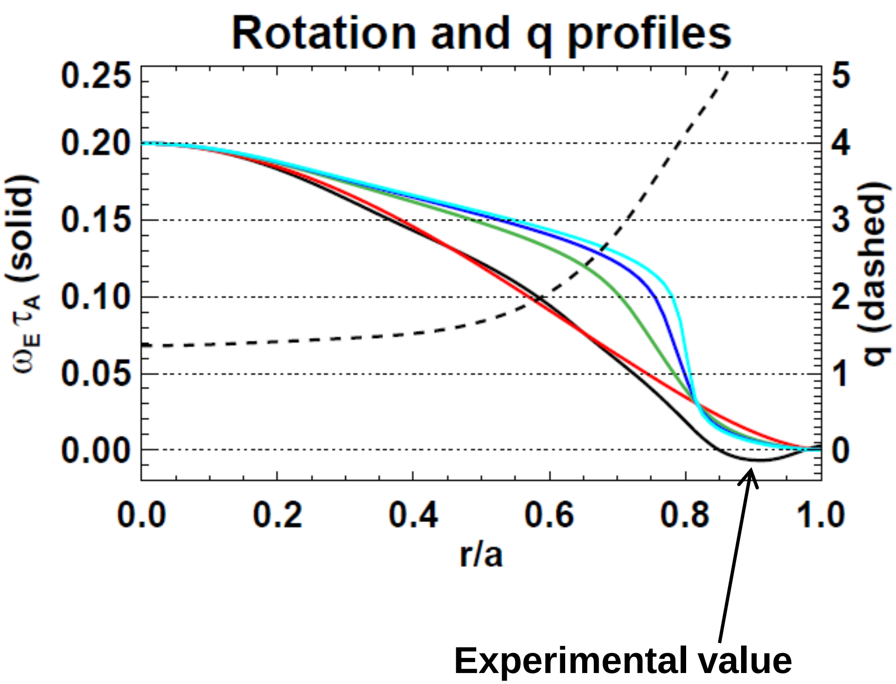
Increased rotation shear in plasma core is destabilizing
(consistent with expectation for Kelvin-Helmholtz)

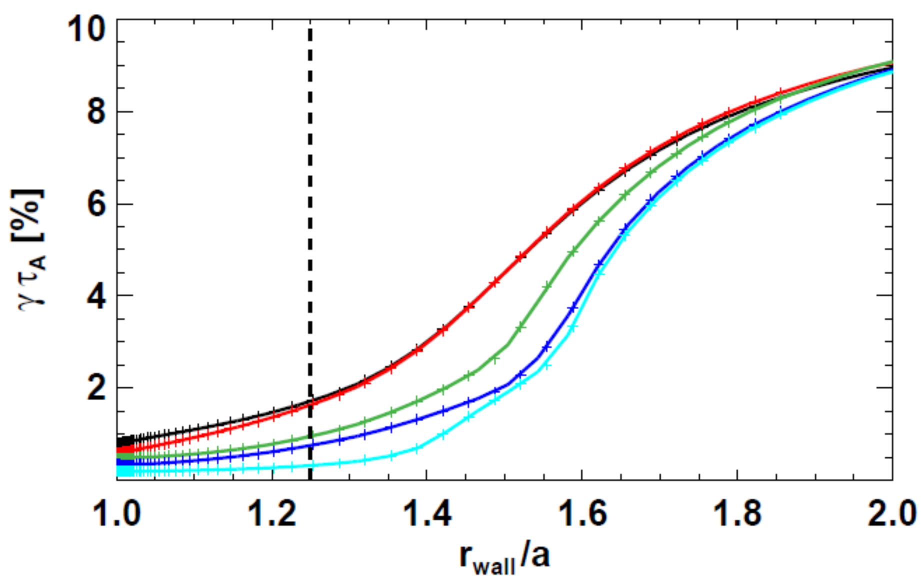
- Rotation variations in edge region change γ very little
  - Compare **experiment** and modified **'positive-definite'** profiles below
- γ independent of shear for 'medium' and 'high' shear cases (indicates saturation of shear effects)



However, increased rotation shear in plasma edge region can be <u>stabilizing</u>

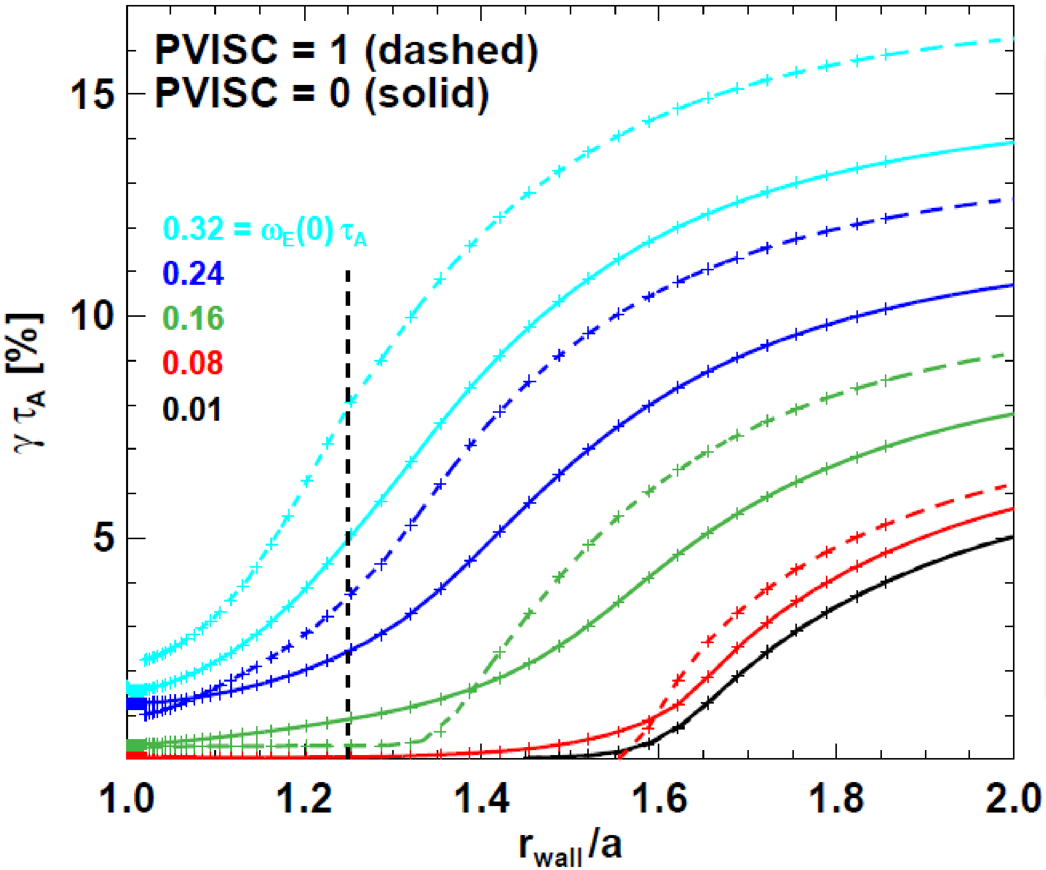
- For near-edge rotation shear, both the shear magnitude and the wall position influence the mode growth rate
- ‘high’ edge-shear case is nearly stable at experimental r_{wall} / a





Plasma mode destabilization by rotation/rotation shear is still predicted when parallel sound-wave damping is included

- For larger r_{wall} / a, parallel damping systematically increases growth rate
- For smaller r_{wall} / a, growth rate can be reduced relative to ideal case



Sound wave damping model:

$$\nabla\cdot\Pi_1 = \kappa_{||}\,\pi^{1/2}\,|k_{||}v_{thi}|\,\rho\mathbf{v}_1\cdot\mathbf{bb}$$

$\kappa_{||} \equiv$ Damping strength

$\kappa_{||} = 1 \rightarrow$ classic ion Landau damping

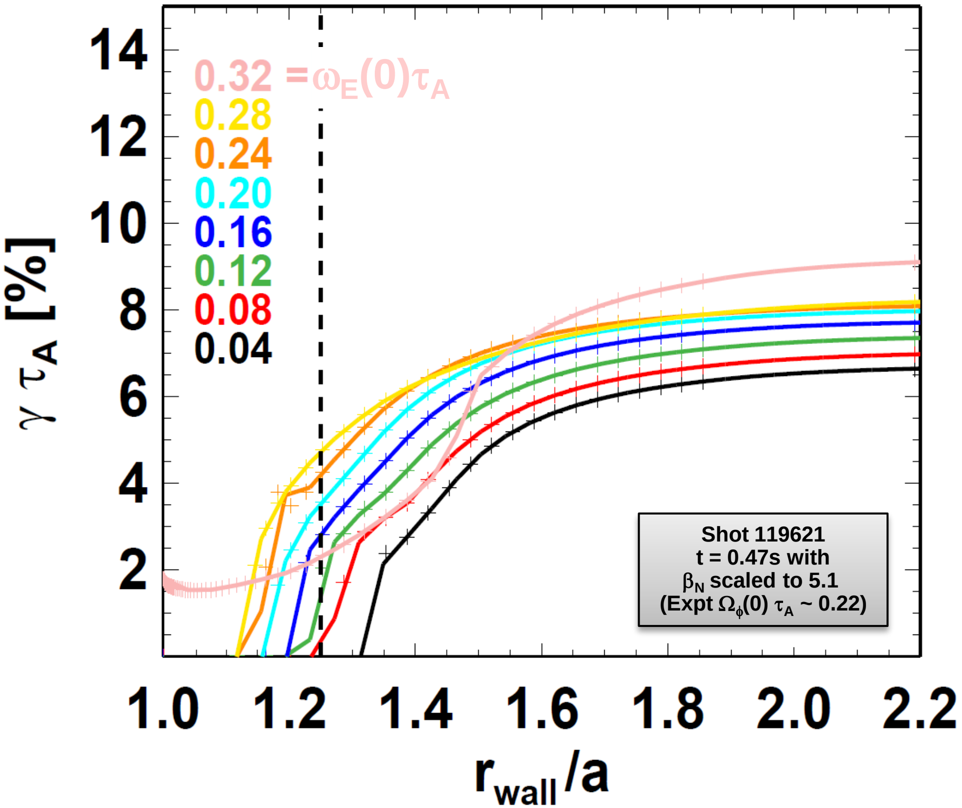
$$k_{||} \equiv (n-m/q)(1/R)$$

PVISC in MARS $\equiv \kappa_{||}\,\pi^{1/2}$

PVISC = 1 $\rightarrow$ $\kappa_{||} = 0.56$

(Perpendicular) kinetic damping stabilizes 'plasma mode' over a wider range of rotation, but only at reduced r_{wall} / a

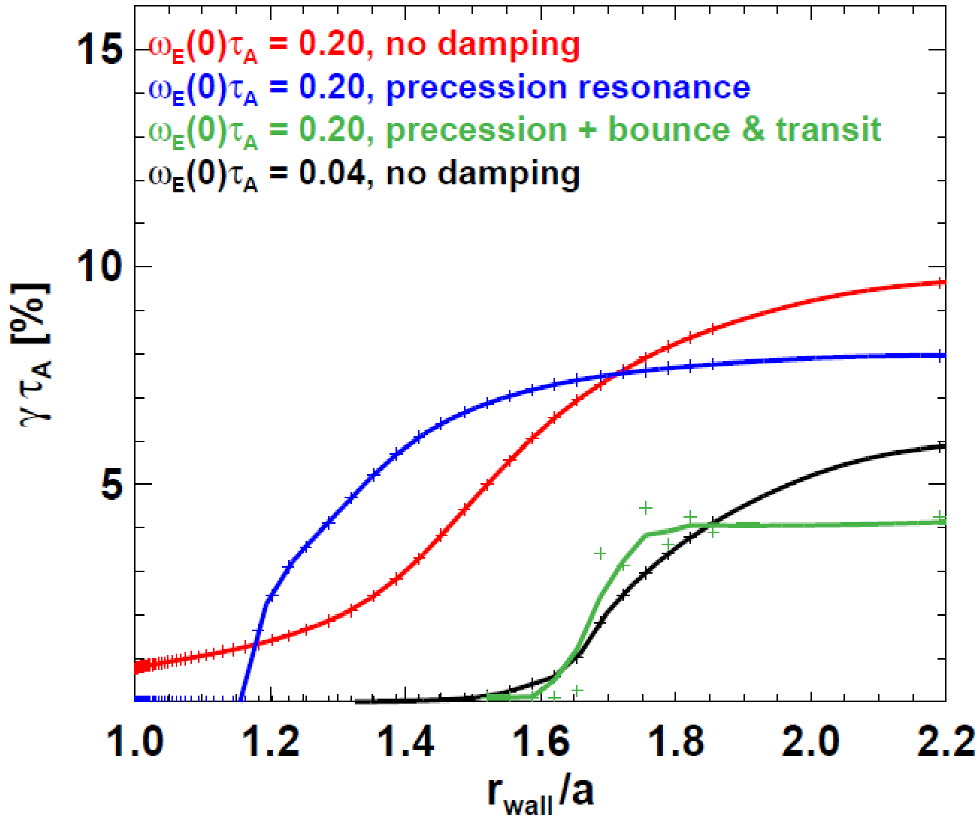
Kinetic damping from drift precession resonance included



- Mode γ generally reduced for large r_{wall} / a relative to ideal plasma predictions
- Mode can remain stable for high $\omega_E(0)\tau_A$ at small r_{wall} / a
- At sufficiently high $\omega_E(0)\tau_A$ ~ 0.3, plasma unstable even for r_{wall} / a = 1

Results imply both rotation and dissipation influence ideal-wall stability limit (plasma mode)

Initial calculations indicate bounce/transit resonances provide increased stability of 'plasma mode'



- Precession resonance provides stabilization for small r_{wall} / a
- Stabilization strongly enhanced by including bounce & transit resonances in damping
  - Marginal wall position similar to low-rotation ideal plasma limit
    - Coincidence?
- Future work: explore impact of beta & rotation on these trends

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

<u>Challenge</u>: simulations computationally expensive due to large m=30-40 needed to resolve high edge-q of ST (~1 day per eigenvalue)

Summary

- Edge rotation ($q \geq 4$, $r/a \geq 0.8$) important for NSTX RWM
  - Trends consistent with stability calculations using MARS-F
- RWM eigenfunctions are modified by dissipation, rotation
  - Reduction/modification of $\xi_\perp$ will modify kinetic stabilization
- Ideal-wall limit ('plasma mode') modified by rotation, dissipation
  - With no dissipation, plasma is predicted to be unstable at rotation ½ the experimental value, but no instability is observed in experiment
  - Rotation shear can be stabilizing or destabilizing, depending on where the maximum shear is located in minor radius
  - Parallel (SW) damping destabilizing/stabilizing at large/small r_{wall} / a
  - Perpendicular kinetic damping stabilizes plasma mode at high rotation
  - Bounce/transit resonances significantly increase plasma mode stability
  - Future: compare experiment to predicted ideal-wall limit and mode frequency including all kinetic resonances and at increased beta