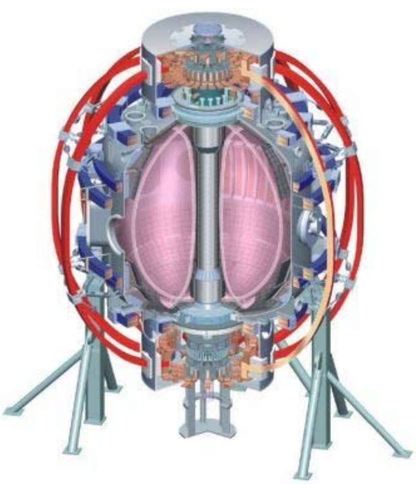
NSTX Supported by U.S. DEPARTMENT OF ENERGY Office of Science

Role of plasma edge in global stability and control*

J. Menard (PPPL), Y.Q. Liu (CCFE)
R. Bell, S. Gerhardt (PPPL)
S. Sabbagh (Columbia University)
and the NSTX Research Team

MHD Control Workshop
November 15-17
University of Wisconsin - Madison

*This work supported by US DoE contract DE-AC02-09CH11466



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Outline

1. Experimental motivation

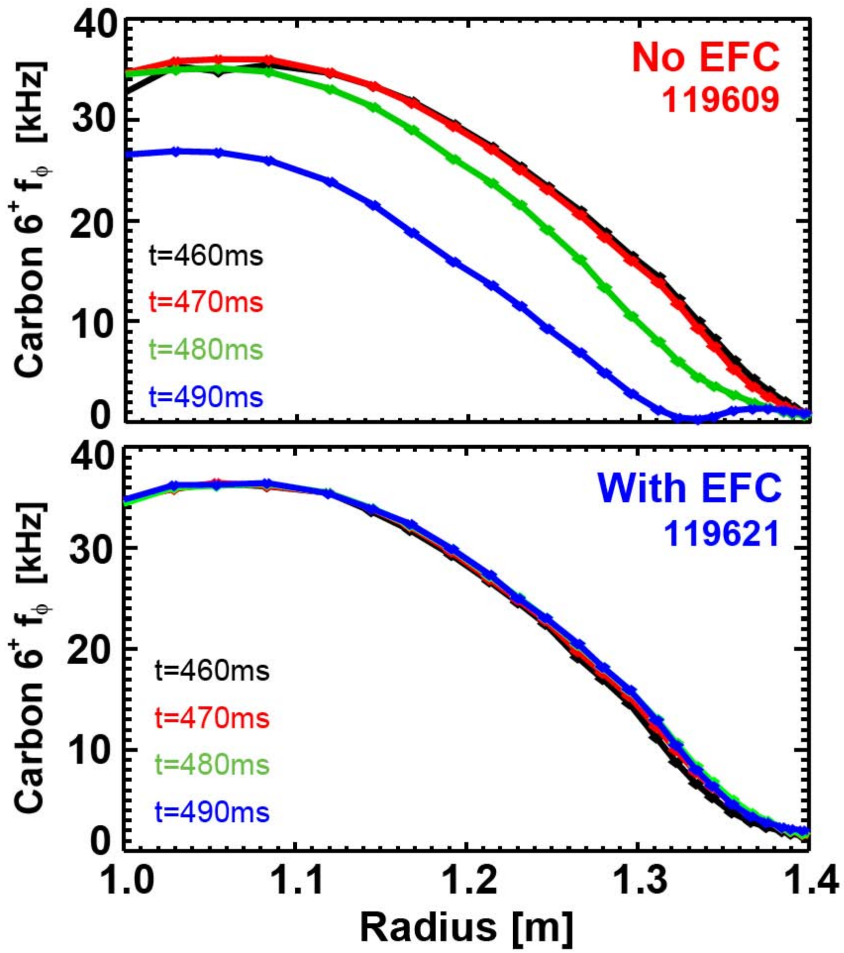
2. Role of E×B drift frequency profile

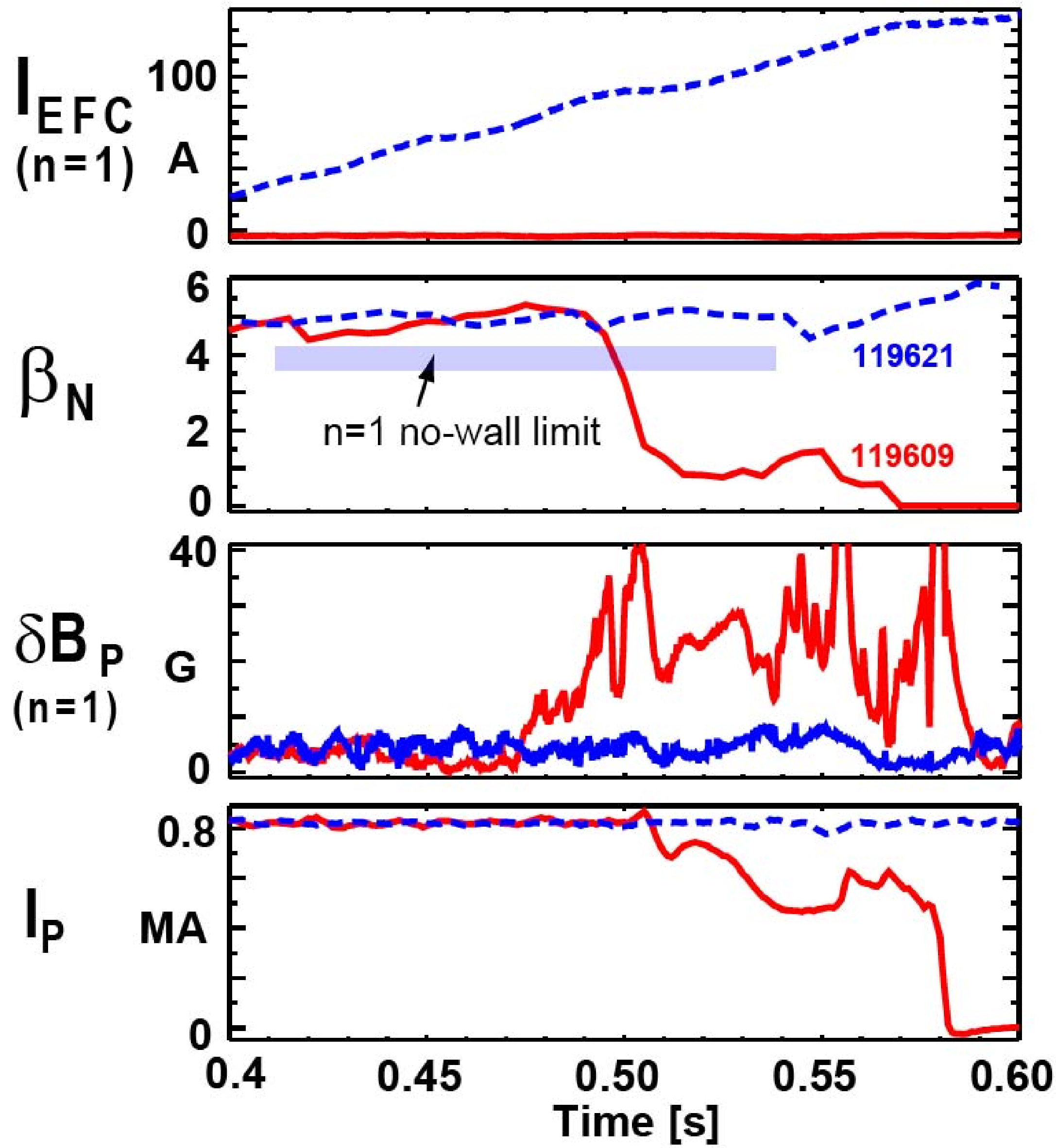
3. Kinetic stability analysis using MARS code
   - Comparisons with experiment
   - Some control considerations
   - Self-consistent vs. perturbative approach

4. Summary, future work, questions

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

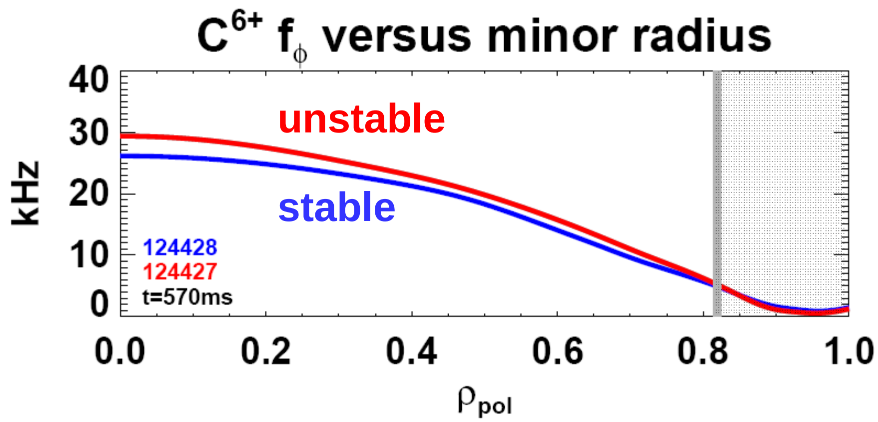


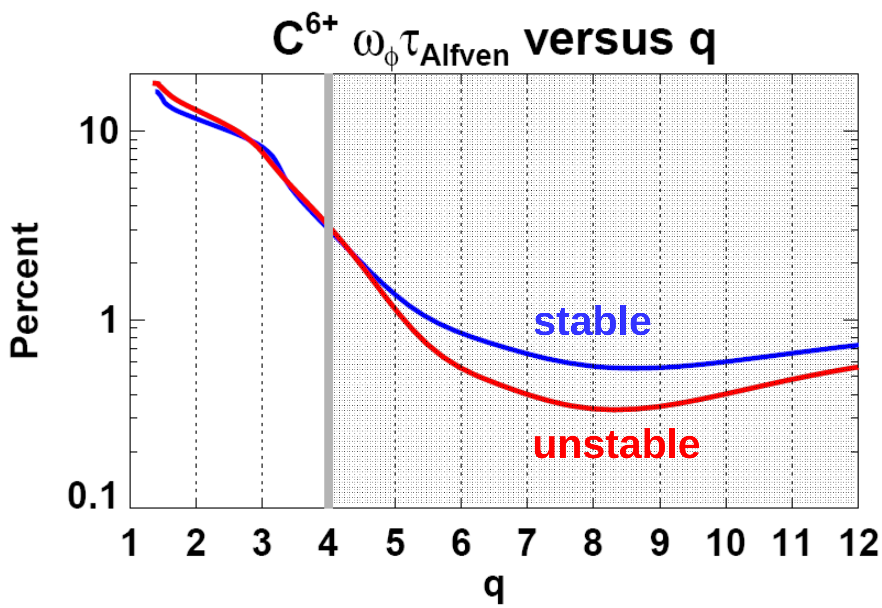


J.E. Menard et al, Nucl. Fusion 50 (2010) 045008

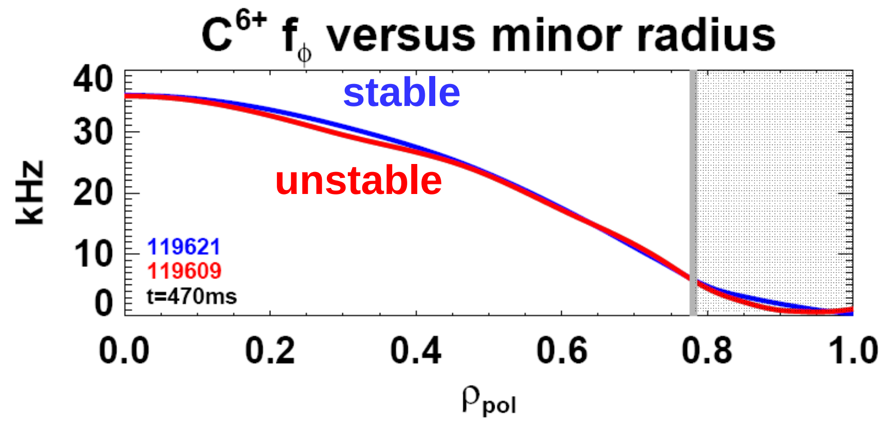
EFC experiments show edge region with $q \geq 4$ and $r/a \geq 0.8$ apparently determine stability

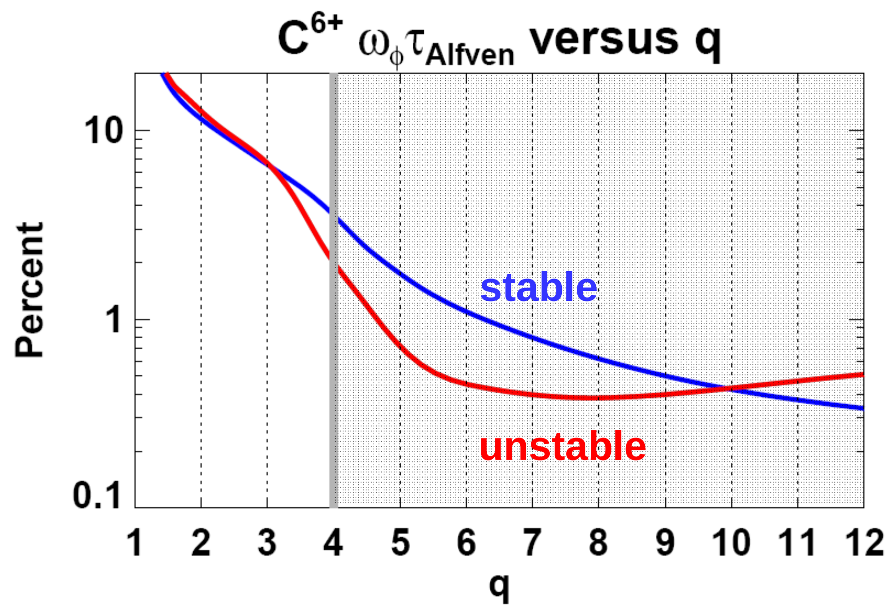
- n=3 EFC → stable
- No EFC → n=1 RWM unstable





- 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*:**

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

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

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

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

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

- **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:

$\langle X \rangle \equiv \oint JX d\theta / \oint J d\theta$

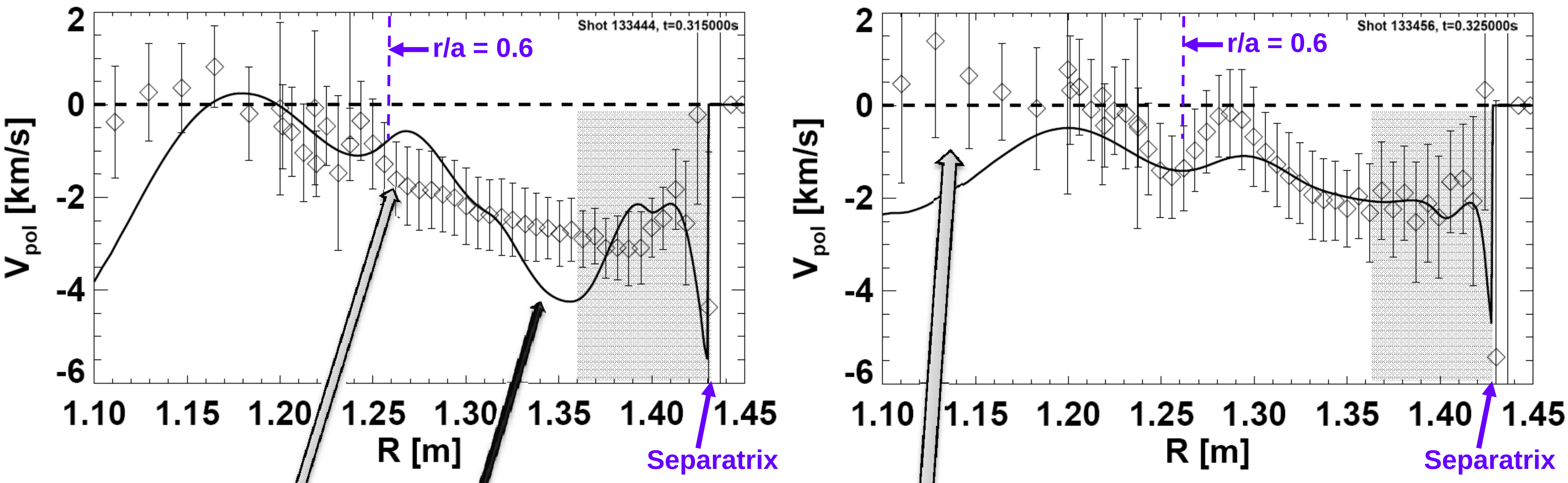
$F(\psi) \equiv RB_\phi$

NSTX edge v_{pol} ≈ neoclassical (within factor of ~2)

B_T = 0.34T

$V_{pol} \propto 1/B$ – trend consistent with neoclassical

B_T = 0.54T



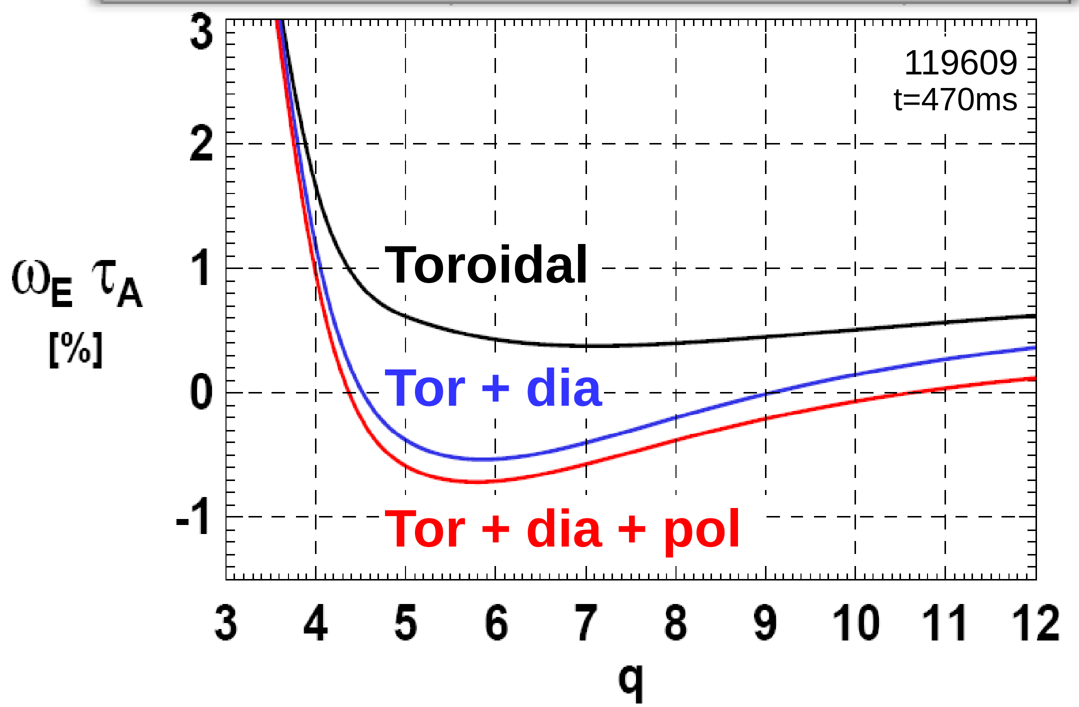
Measured v_{pol} neoclassical Largest deviation in core

Subsequent MARS calculations use neoclassical v_{pol}, but v_{pol} = 0 for r/a < 0.6

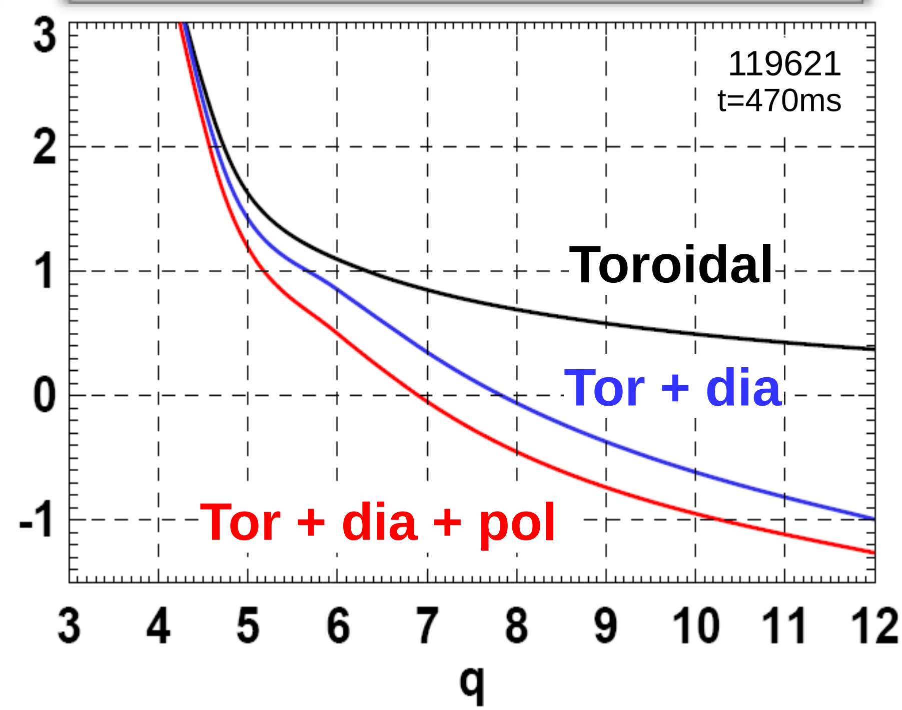
NSTX results: *R. E. Bell, et al., Phys. Plasmas **17**, 082507 (2010)*
Neoclassical: *W. Houlberg, et al., Phys. Plasmas **4**, 3230 (1997)*

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

n=1 RWM unstable (no n=1 EFC)



n=1 RWM stable (n=1 EFC)



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

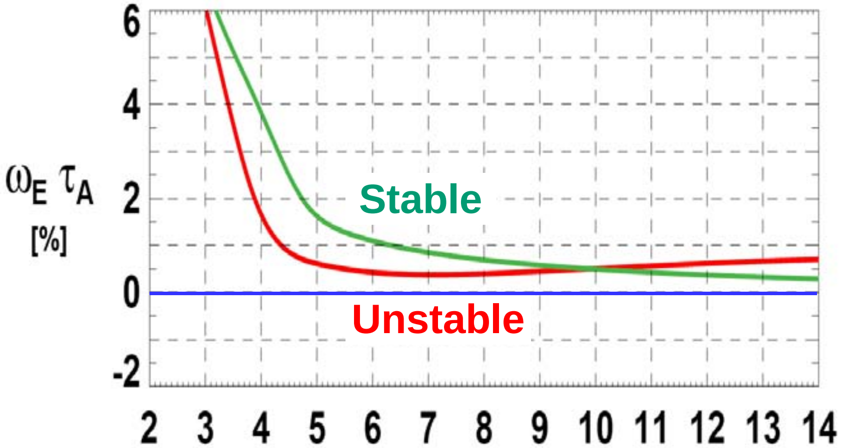
Toroidal + diamagnetic: $\omega_E = \Omega_{\phi\text{-}C}(\psi) - \omega_{*C}$

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

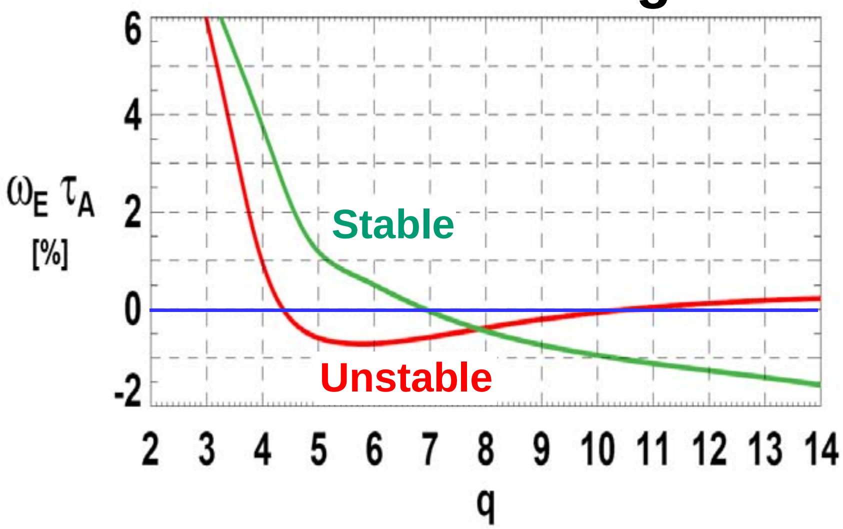
- Diamagnetic contribution to $\omega_E\tau_A$ ≈ -0.5 to -1.0%
- Neoclassical v_{pol} contribution to $\omega_E\tau_A$ ≈ -0.2 to -0.4%

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

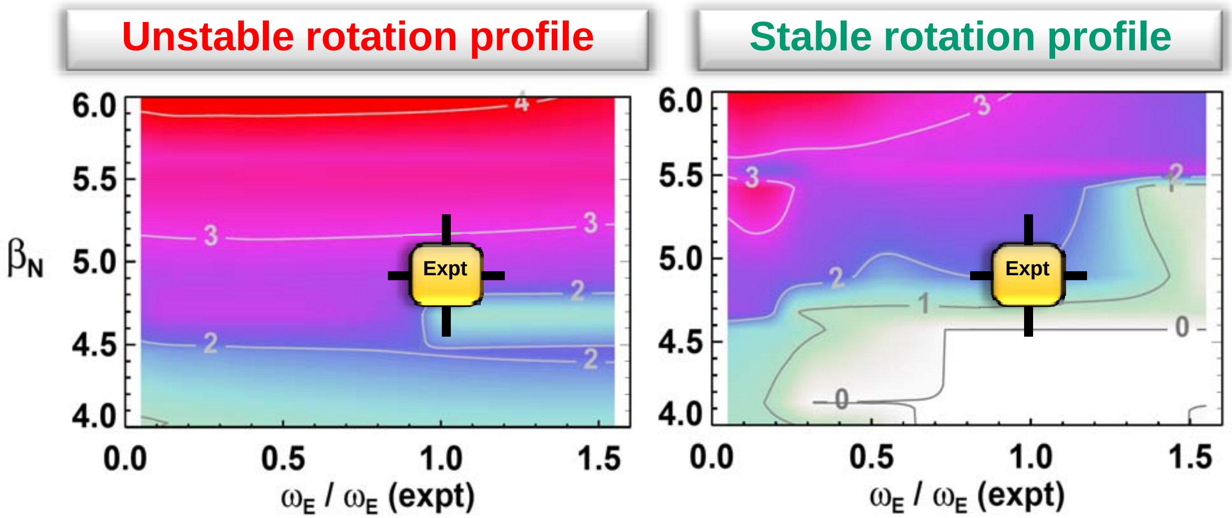
Toroidal rotation only



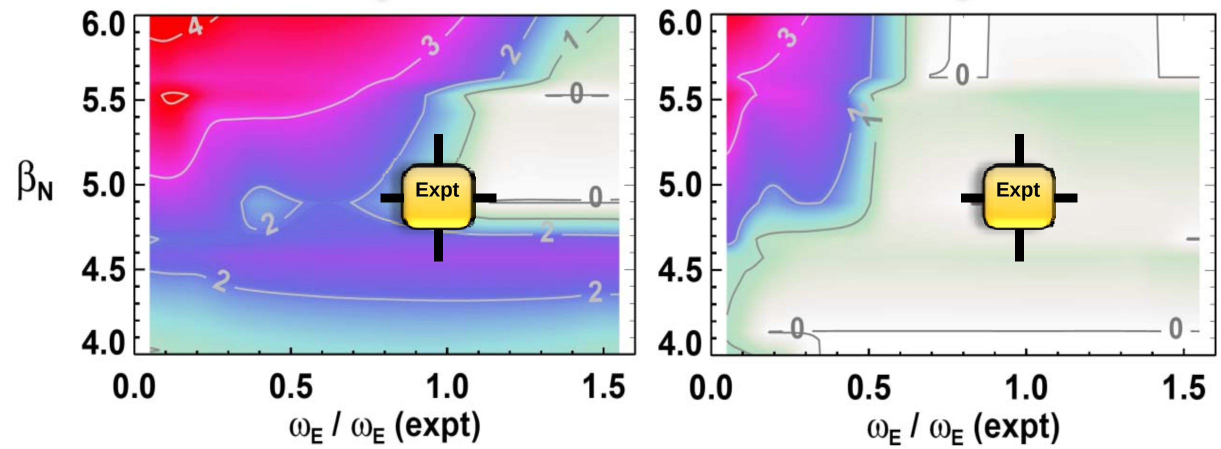
Toroidal + diamagnetic



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



Predictions inconsistent with experiment



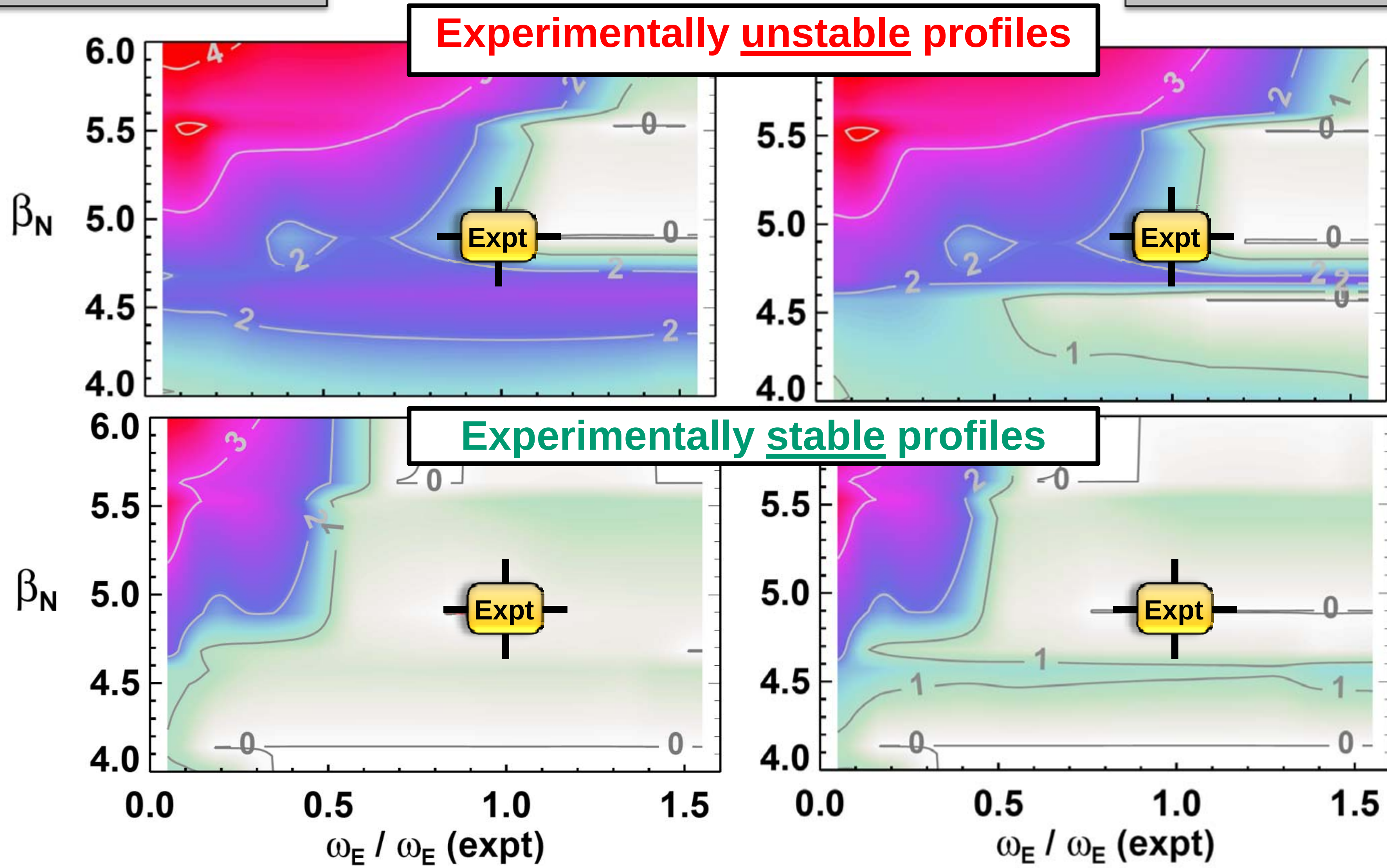
Predictions consistent with experiment

Addition of v_{pol} in ω_E modifies marginal stability

$\omega_{*C} / \omega_{*C}$ (expt) = 1
$u_\theta = 0$

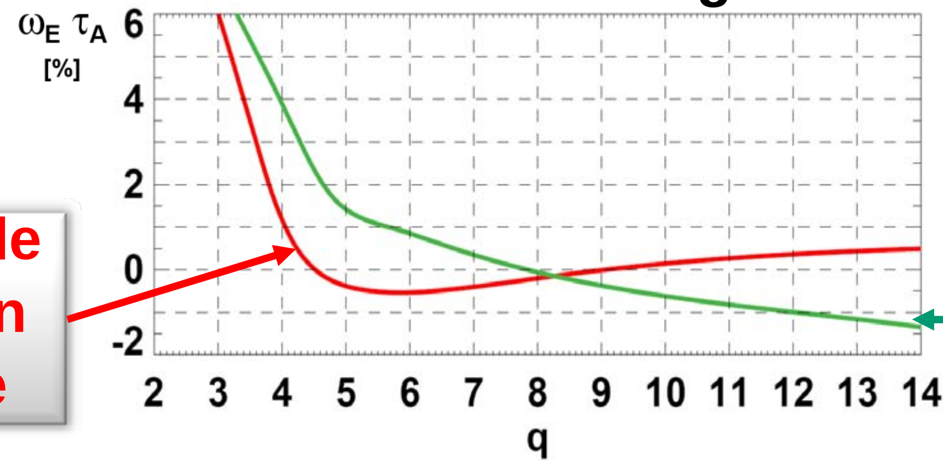
Calculated n=1 $\gamma\tau_{wall}$

$\omega_{*C} / \omega_{*C}$ (expt) = 1
u_θ = neoclassical



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

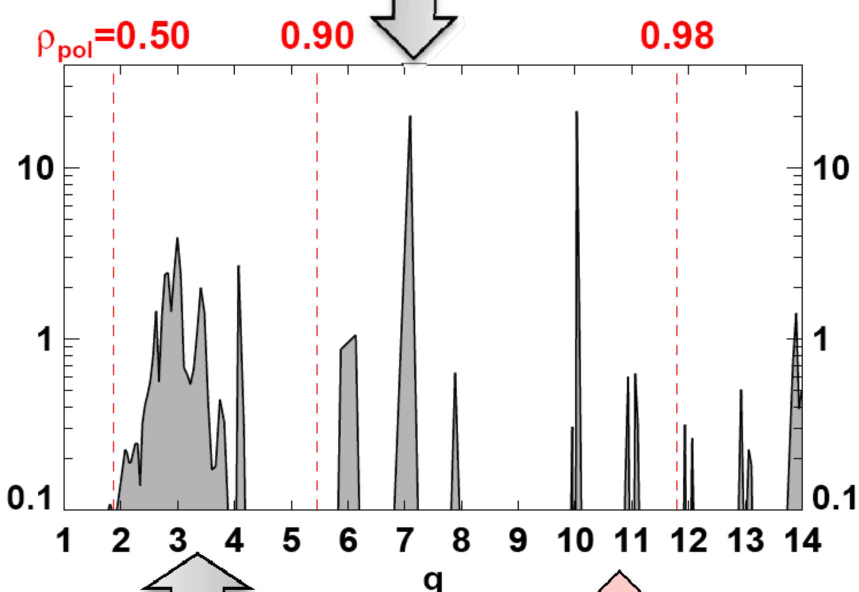
Toroidal + diamagnetic



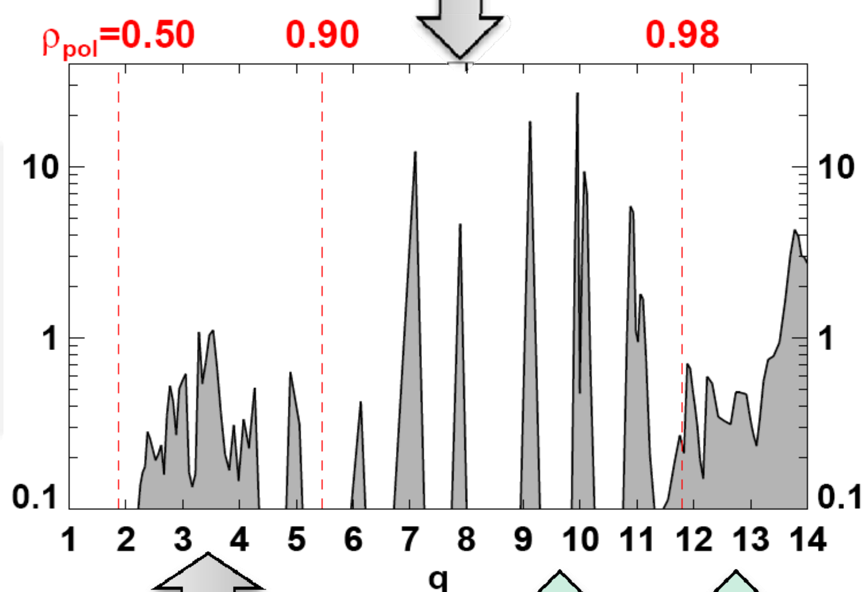
ω_E / ω_E (expt) = 0.5 used so unstable modes can be identified and local damping computed

Unstable rotation profile

Stable rotation profile



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



Higher core damping

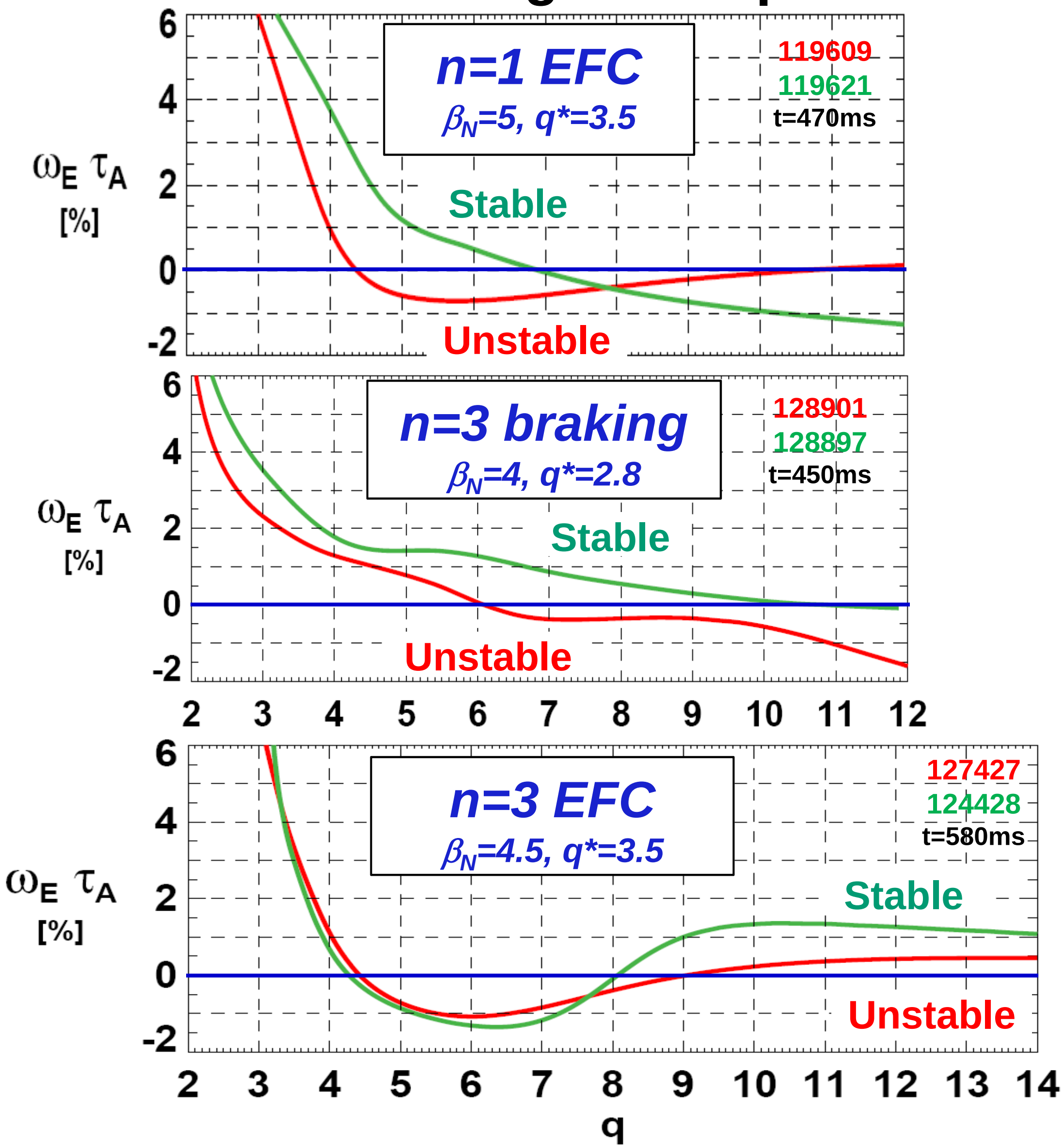
Lower edge damping

Lower core damping

Higher edge damping

Control of ω_E (r) could play important role in RWM stabilization

Toroidal + diamagnetic + poloidal



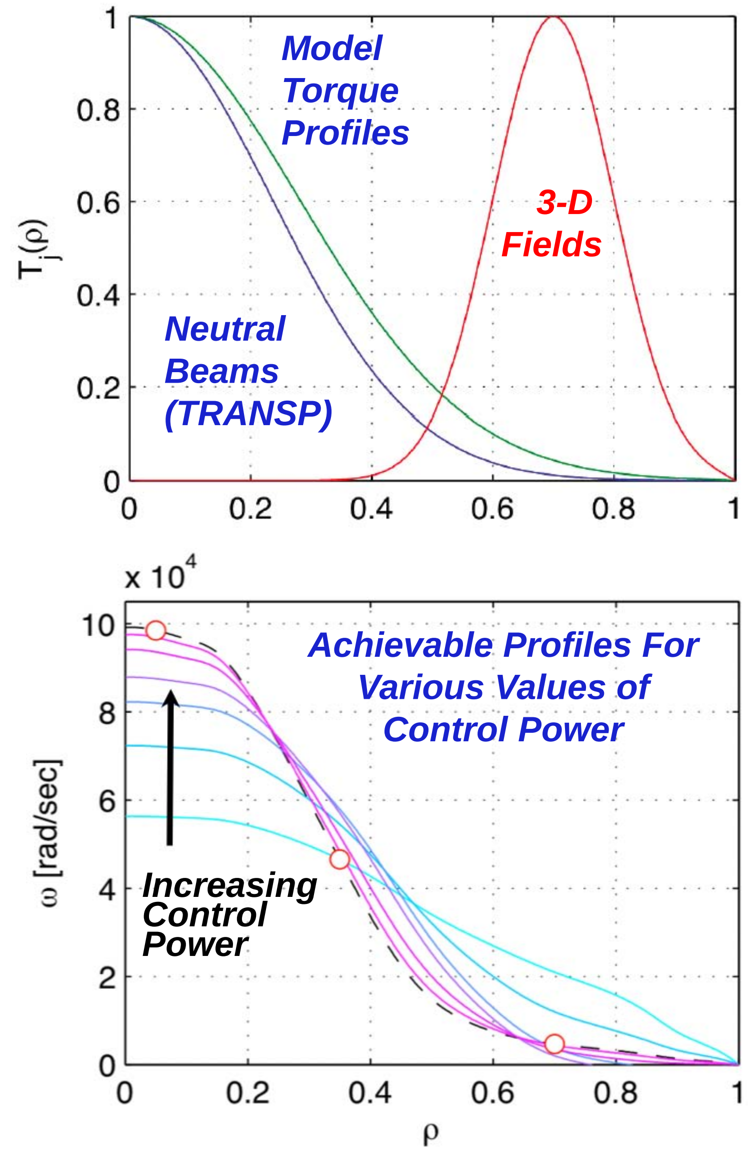
- Separation between **stable** and **unstable** profiles typically small:

$$\Delta(\omega_E \tau_A) \leq 1\%$$

- Instability may correlate with $\omega_E \approx 0$ occurring over most of edge region
  - If true, provides insight into which conditions to avoid
- Need for fast RWM active feedback control remains

NSTX preparing for real-time rotation control

- Physics studies enabled:
  - RWM & EF physics vs. rotation and β
  - Transport dynamics vs. rotation shear
  - Pedestal stability vs. edge rotation
  - **What is the optimal rotation profile for integrated plasma performance?**
- Plan: Use state-space controller based on momentum balance model
  - Real-time charge-exchange for v_ϕ
  - Neutral beams provide torque
  - 3-D fields provide braking
    - Vary toroidal mode number to vary magnetic braking profiles
    - Use 2nd Switching Power Amplifier for independent n=1,2,3 fields (2011)
- Goal: Test in 2012



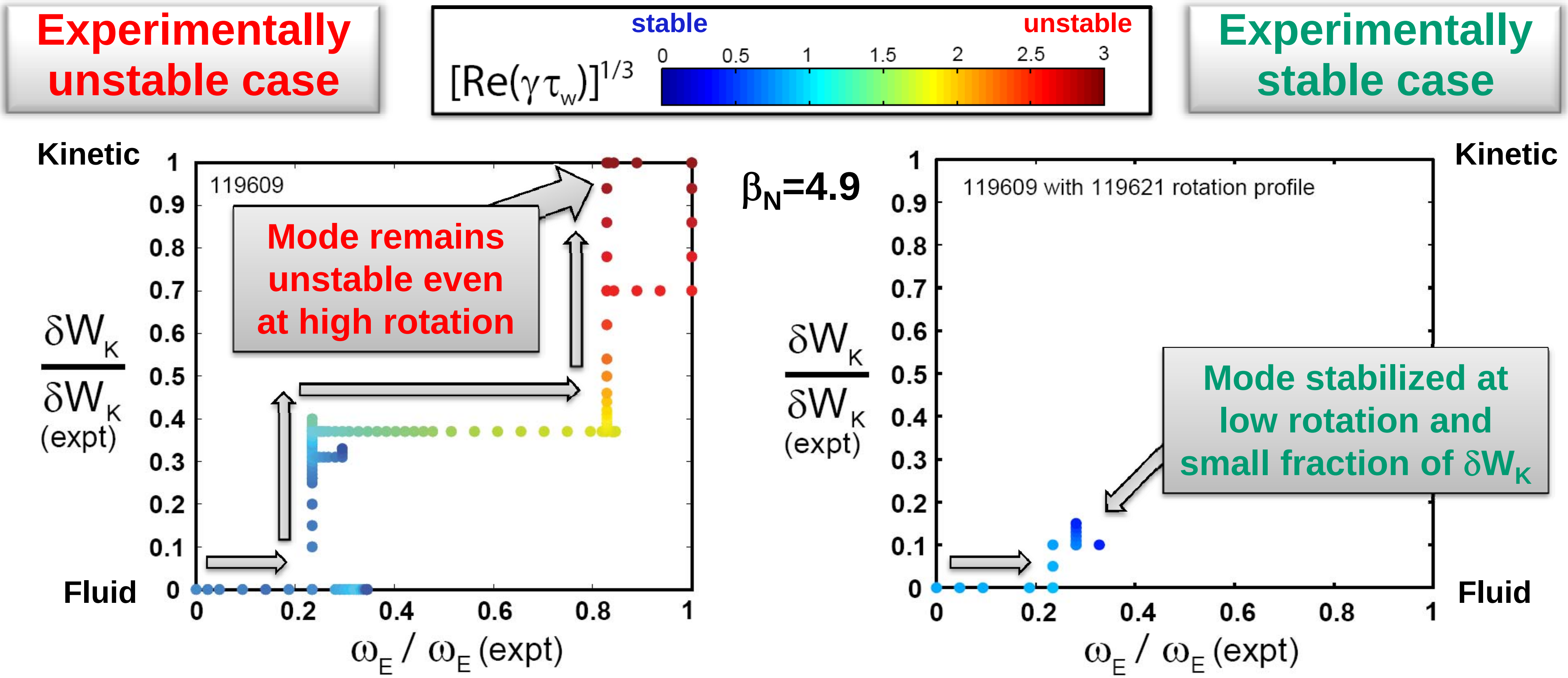
K. Taira, C.W. Rowley, N.J. Kasdin, (PU), M. Podesta, E. Kolemen, R. Bell, D. Gates (PPPL), S. Sabbagh (CU)

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

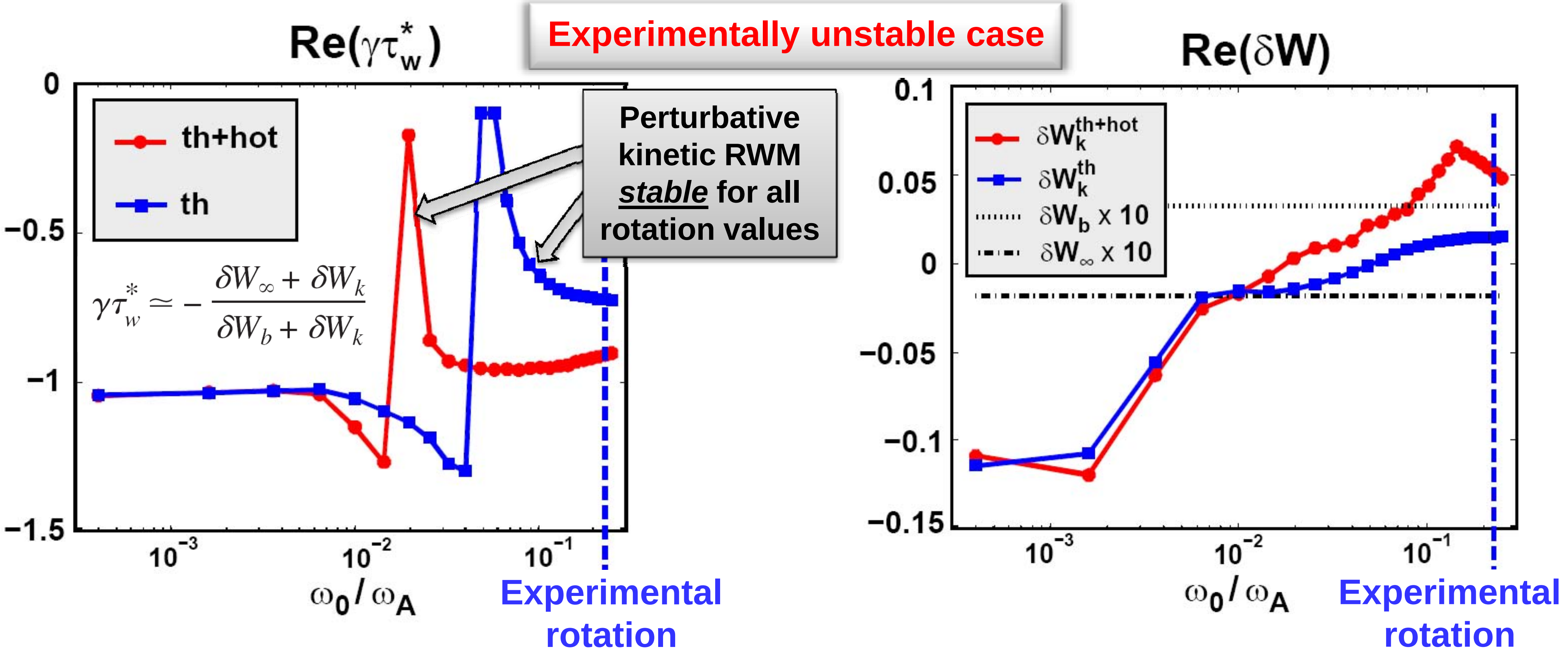
- MARS-K full kinetic δW_K → multiple modes can be present
  - Mode identification and eigenvalue tracking more challenging
- Track roots by scanning fractions of experimental ω_E and δW_K:



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

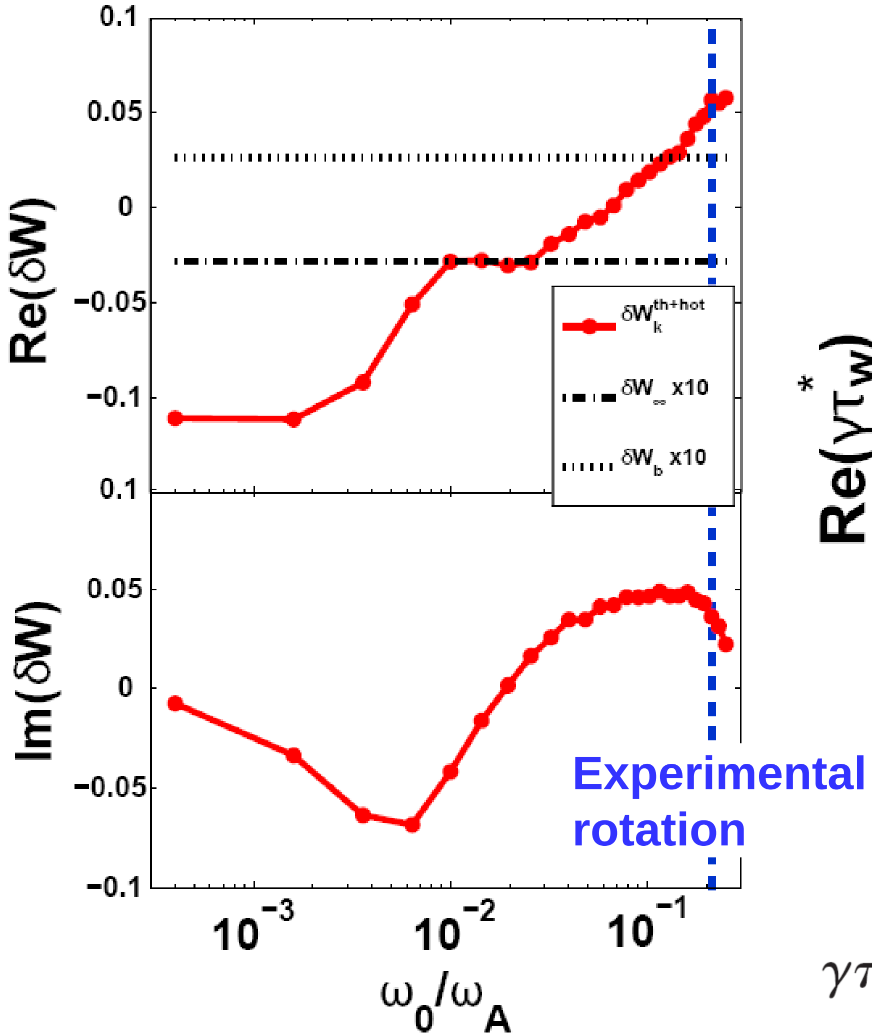
- Perturbative approach uses marginally unstable fluid eigenfunction at zero rotation in limit of no kinetic dissipation
- For cases treated here, $|\delta W_K|$ can be >> $|\delta W_\infty|$ and $|\delta W_b|$
  - Possibility that rotation/dissipation can modify eigenfunction & stability

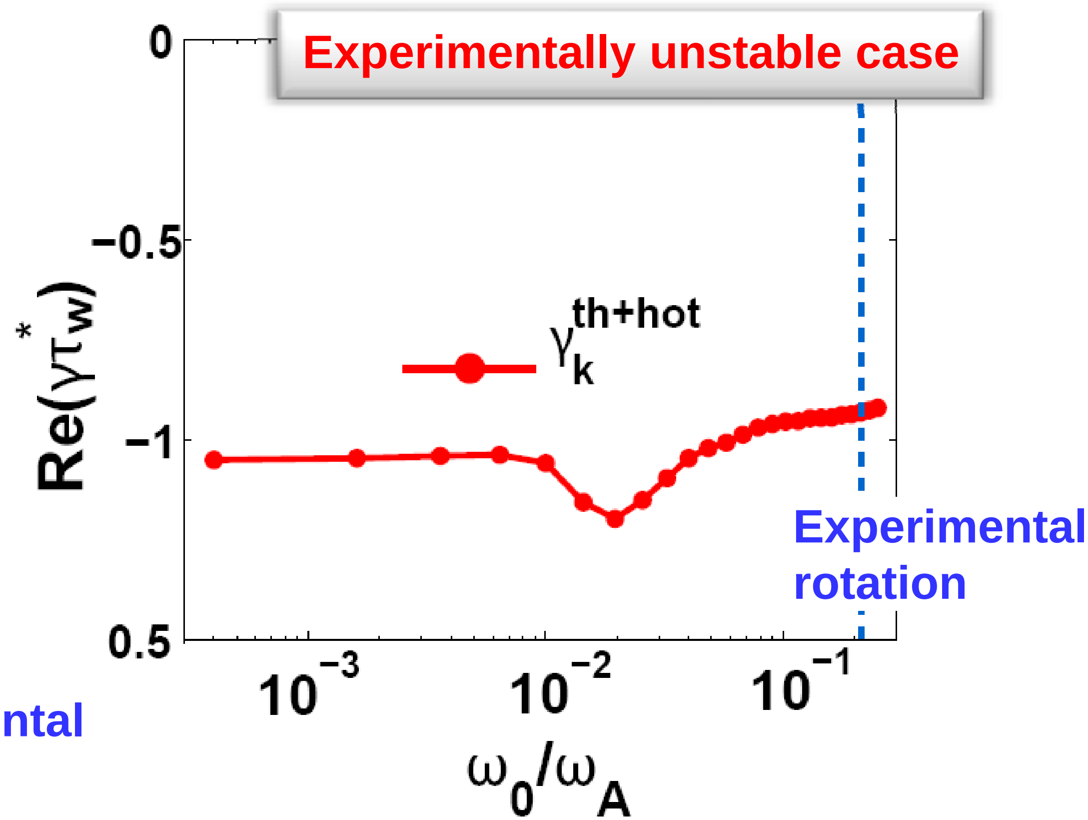
Experimentally unstable case



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

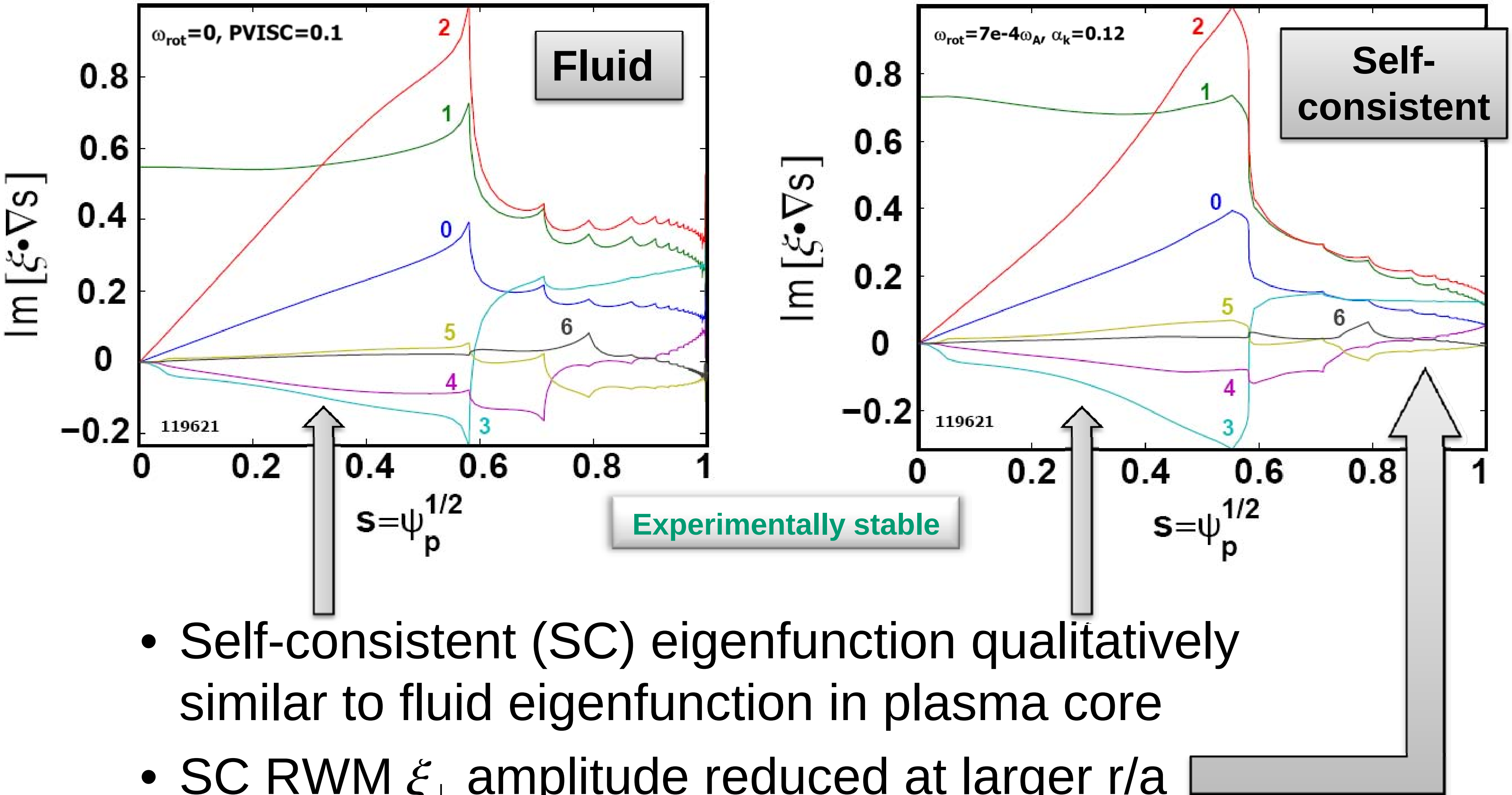
- Higher $\beta_N = 5.2$ does not exhibit approach to marginal stability
- $|\delta W_K|$ does not approach 0 → $\gamma\ \tau_w \approx -1$





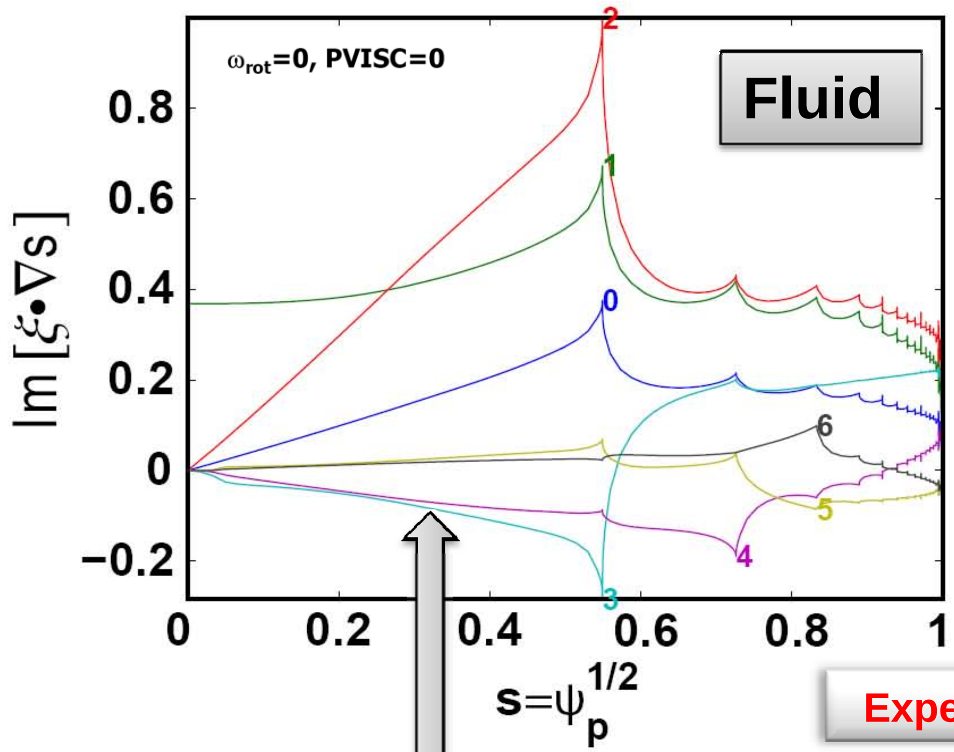
$$\gamma\tau_w^* \simeq -\frac{\delta W_\infty + \delta W_k}{\delta W_b + \delta W_k}$$

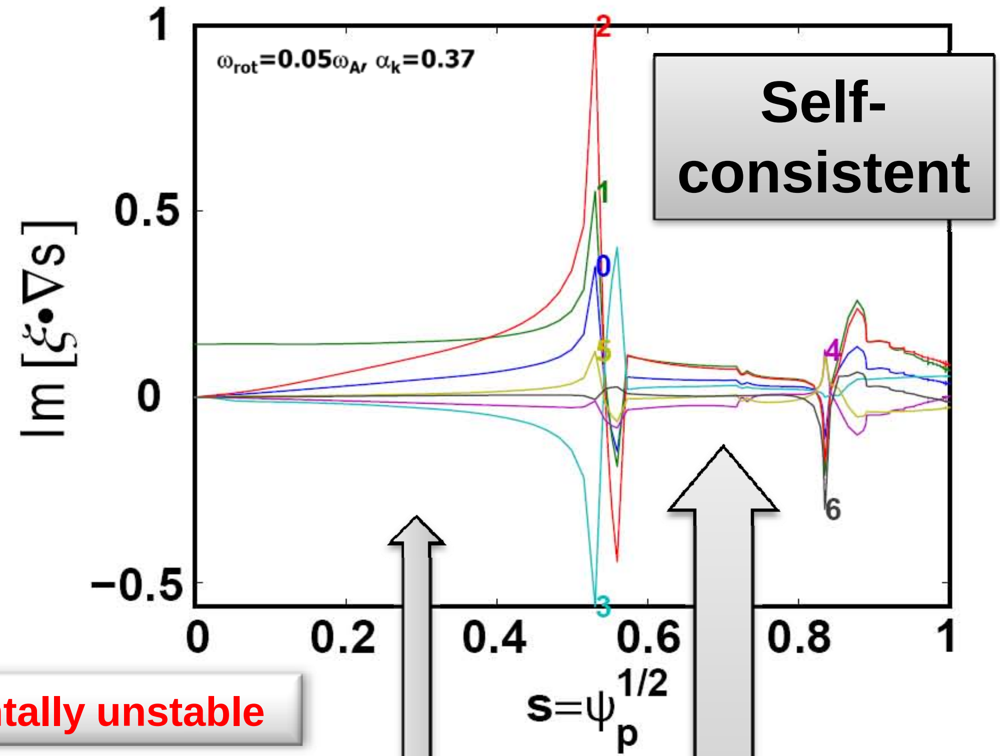
MARS-K self-consistent calculations for stable case indicate modifications to eigenfunction begin to occur at low rotation



- 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

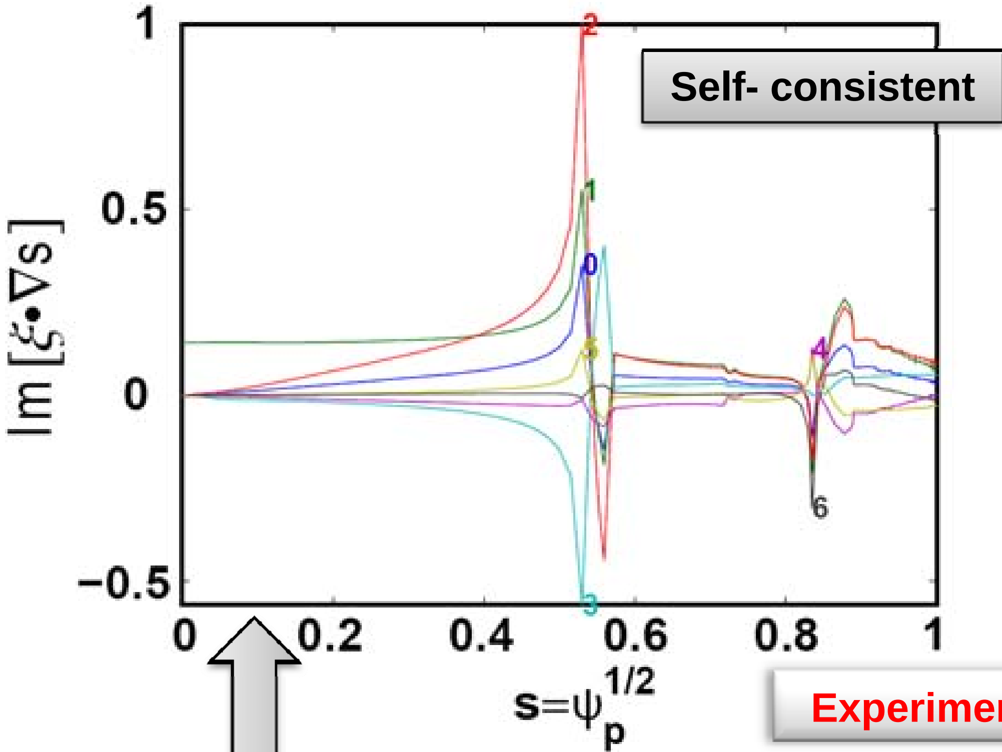




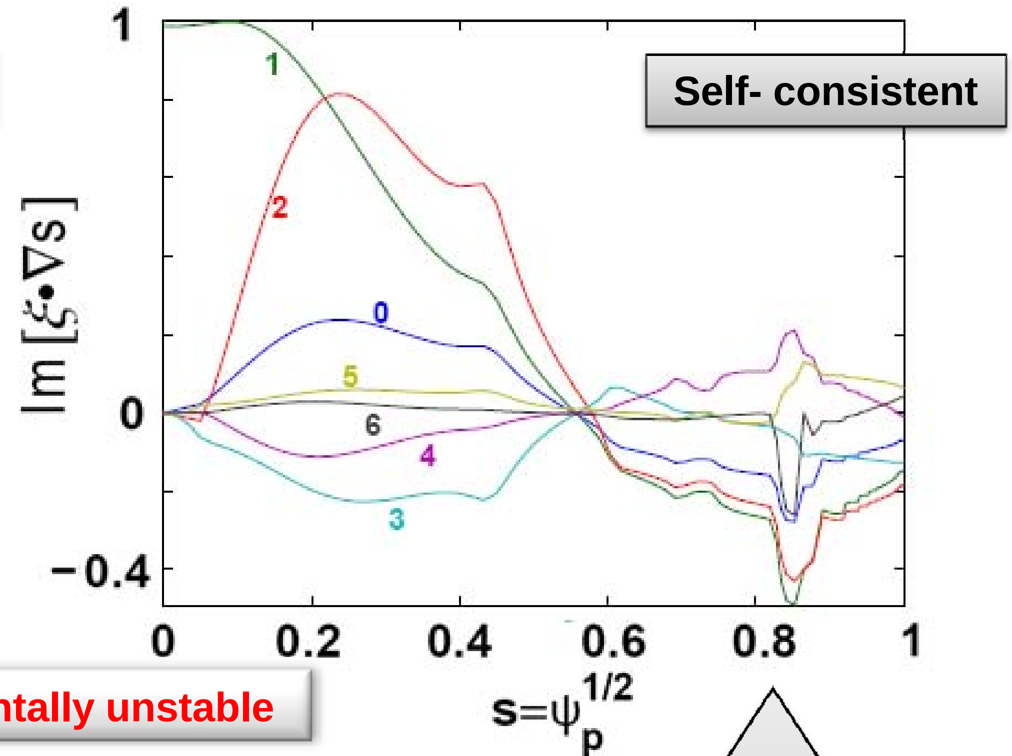
Experimentally unstable

- 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?

Summary

- Edge rotation ($q \geq 4$, $r/a \geq 0.8$) important for 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
  - Rotation control could assist RWM stabilization (planned)
- MARS-K (full kinetic) trends (stable/unstable) using self-consistent approach consistent with experiment
- Perturbative treatment inconsistent – overly stable
  - Edge eigenfunction strongly modified by rotation/dissipation
  - Reduction/modification of $\xi_\perp$ reduces kinetic stabilization

Future work, remaining questions

- Future work:
  - Collisions were not included in MARS-K analysis shown
    - Adding soon - will modify electron contribution to δW_K, other?
  - Need more systematic benchmarking of fluid and kinetic δW
  - More complete comparisons to experiment: γ, ω, ξ
- Questions:
  - Are differences between perturbative & SC unique to NSTX?
  - What determines range of validity of perturbative approach?
    - How large can δW_K and dissipation be?
    - What are effects of large ω_E on dispersion?

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

  - Is underlying single-fluid MHD treatment sufficient?
    - Eigenfunctions, dissipation can be highly localized near rationals
    - Is continuum damping computed accurately?

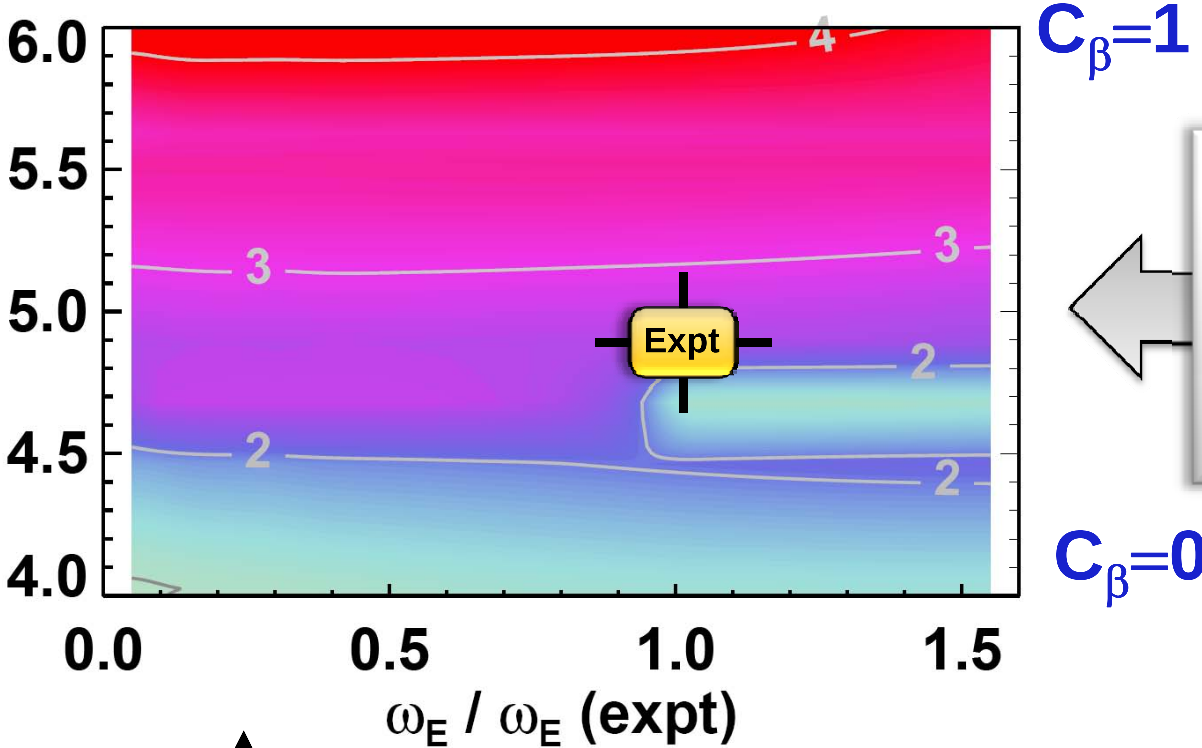
Backup

MARS-F using marginally unstable $\omega_E = \Omega_{\phi\text{-}C}$ predicts n=1 RWM to be robustly unstable → inconsistent with experiment

$$C_\beta \equiv \frac{\beta_N - \beta_N(\text{no-wall})}{\beta_N(\text{wall}) - \beta_N(\text{no-wall})}$$

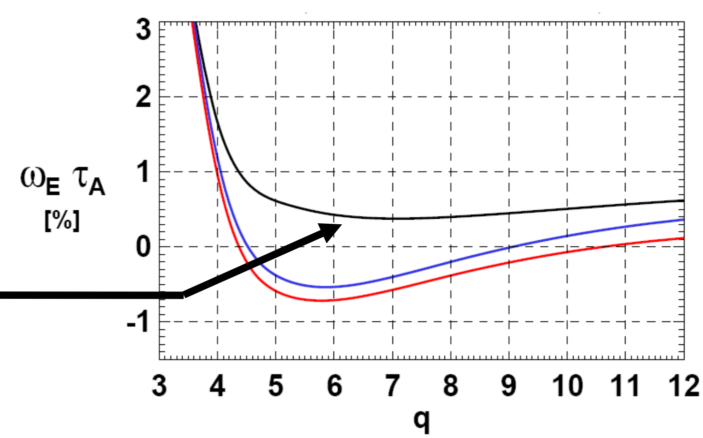
Calculated n=1 $\gamma\tau_{wall}$

Using experimentally marginally unstable profiles



- γ depends only weakly on rotation
- γ increases with β_N

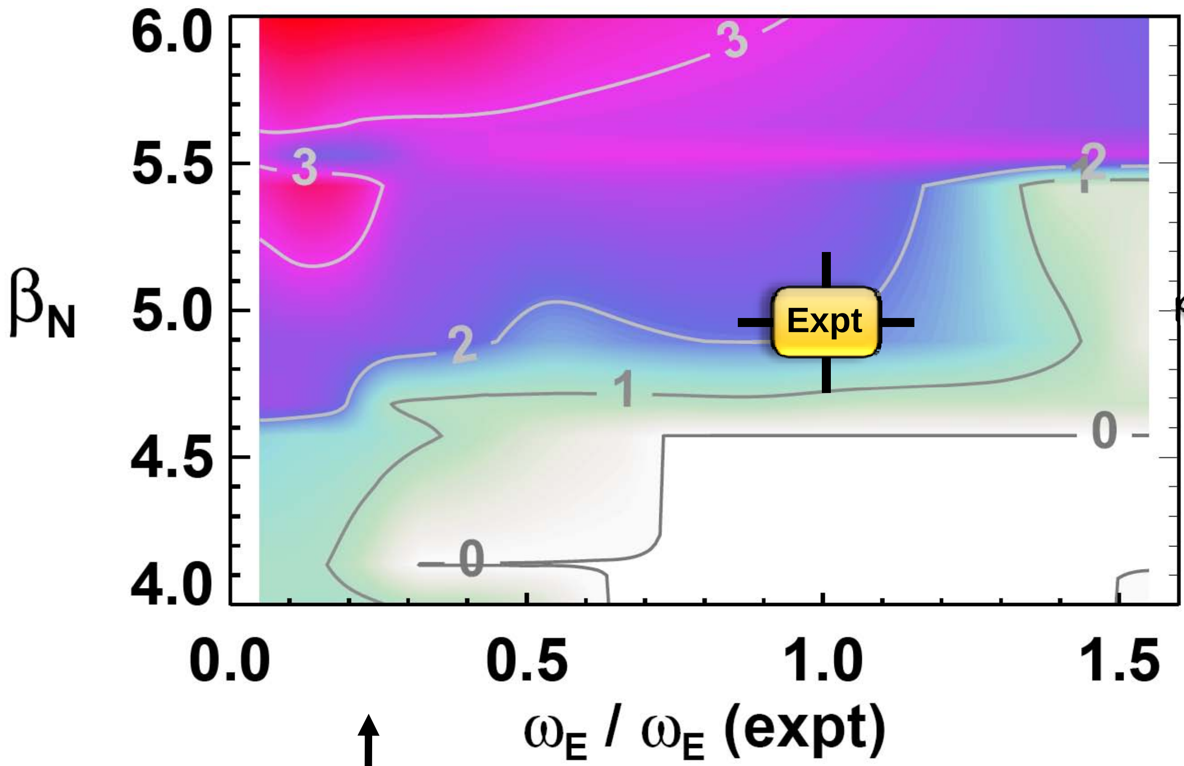
ω_{*C} / ω_{*C} (expt) = 0, u_θ = 0



MARS-F using stable $\omega_E = \Omega_{\phi\text{-}C}$ profile predicts n=1 RWM to be unstable → inconsistent with experiment

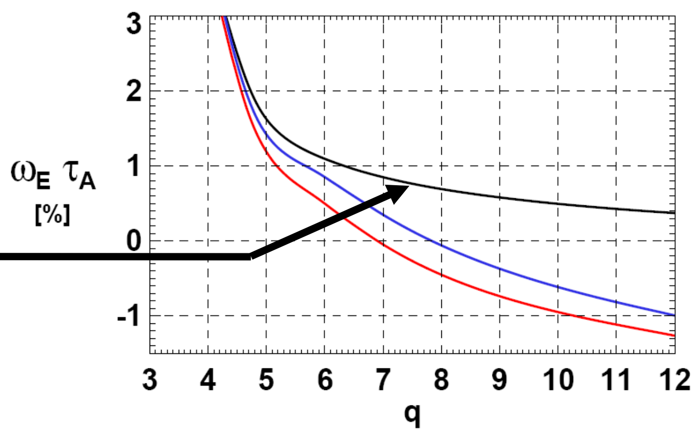
Calculated n=1 $\gamma\tau_{wall}$

using experimentally stable profiles



- **n=1 RWM predicted to be unstable for $\beta_N > 4.6$, but actual plasma operates stably at $\beta_N \geq 5$**

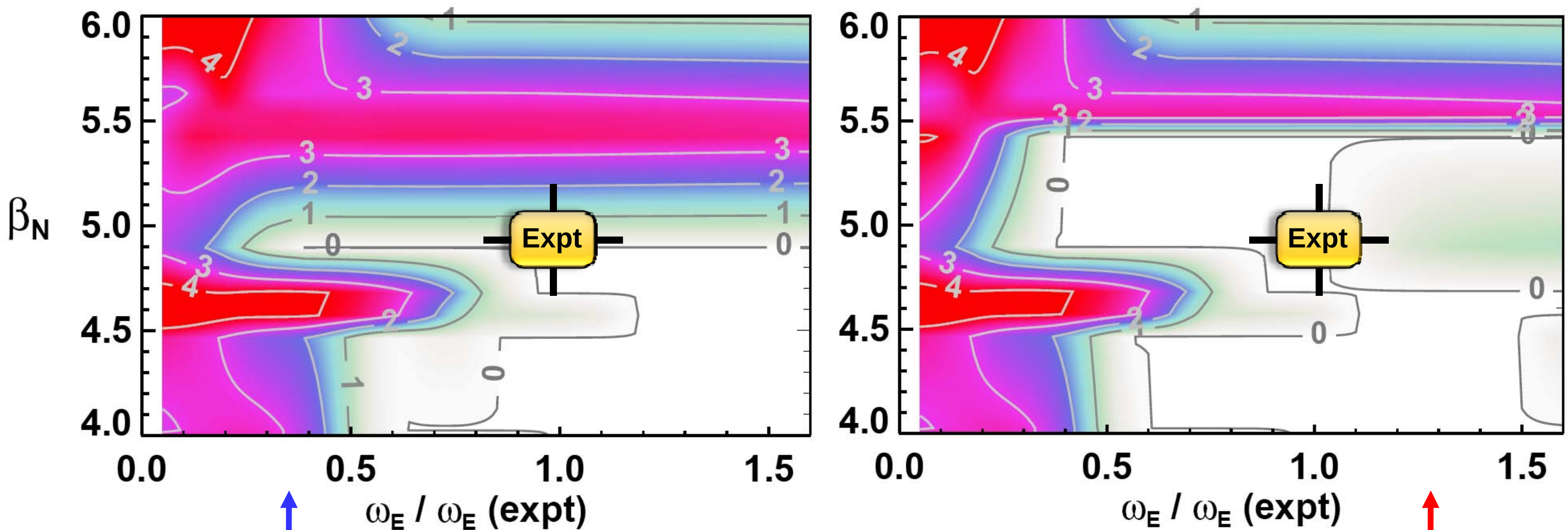
ω_{*C} / ω_{*C} (expt) = 0, u_θ = 0



Inclusion of v_{pol} in ω_E can sometimes modify marginal stability boundary – example: wall position variation

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

experimentally stable profiles and b_{wall} / a artificially increased × 1.1



ω_{*C} / ω_{*C} (expt) = 1
u_θ = 0

ω_{*C} / ω_{*C} (expt) = 1
u_θ = neoclassical

- Increased wall distance lowers with-wall limit to β_N ~ 5.5
- Case with u_θ=0 has lower marginal stability limit β_N ~ 5