

MARS analysis of $n > 1$ RWM stability (+ update on role of $q=2$)

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(Thanks to Y. Liu and M. Chu)

Workshop on Active Control of MHD Stability 2005

University of Wisconsin, Madison, WI

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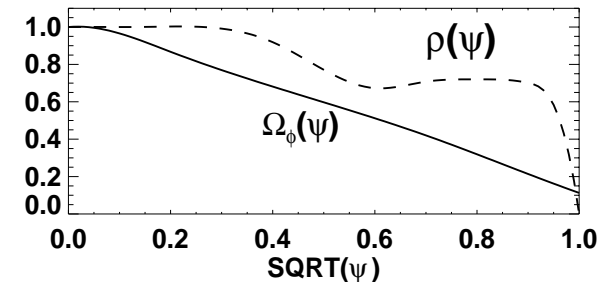
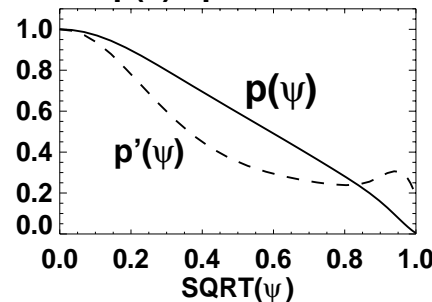
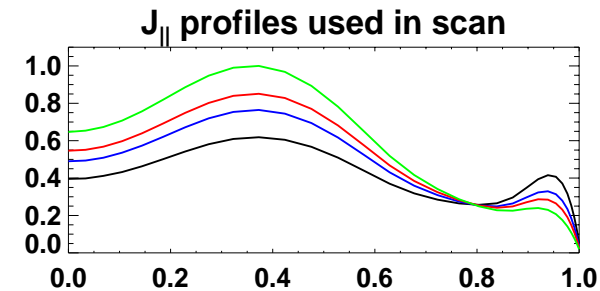
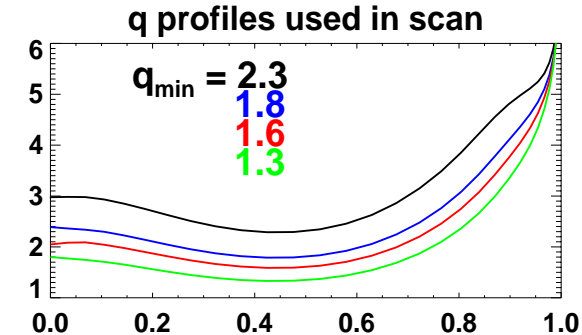
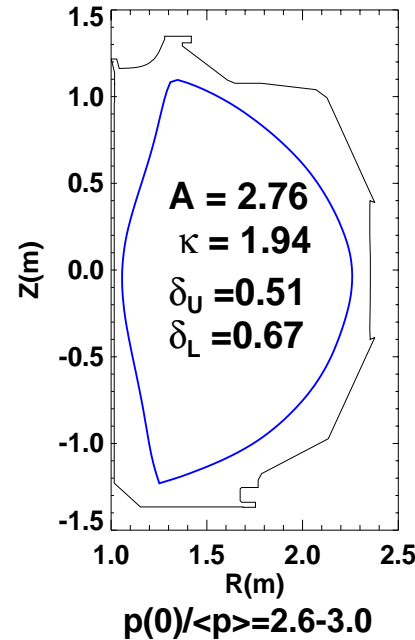


Motivation

- Understand role of $q=2$ surface in $n=1$ RWM stabilization via rotation + dissipation
 - Relevant to AT discharges with $q_{\text{MIN}} > 2$
- Compute stability of $n > 1$ RWMs stabilized with rotation + dissipation
 - Multiple unstable RWMs complicate feedback
- Look for theory predictions that can be compared to experiment
 - Test dissipation models for RWM damping

Present work is extension of systematic stability study of DIII-D AT scenario started last year

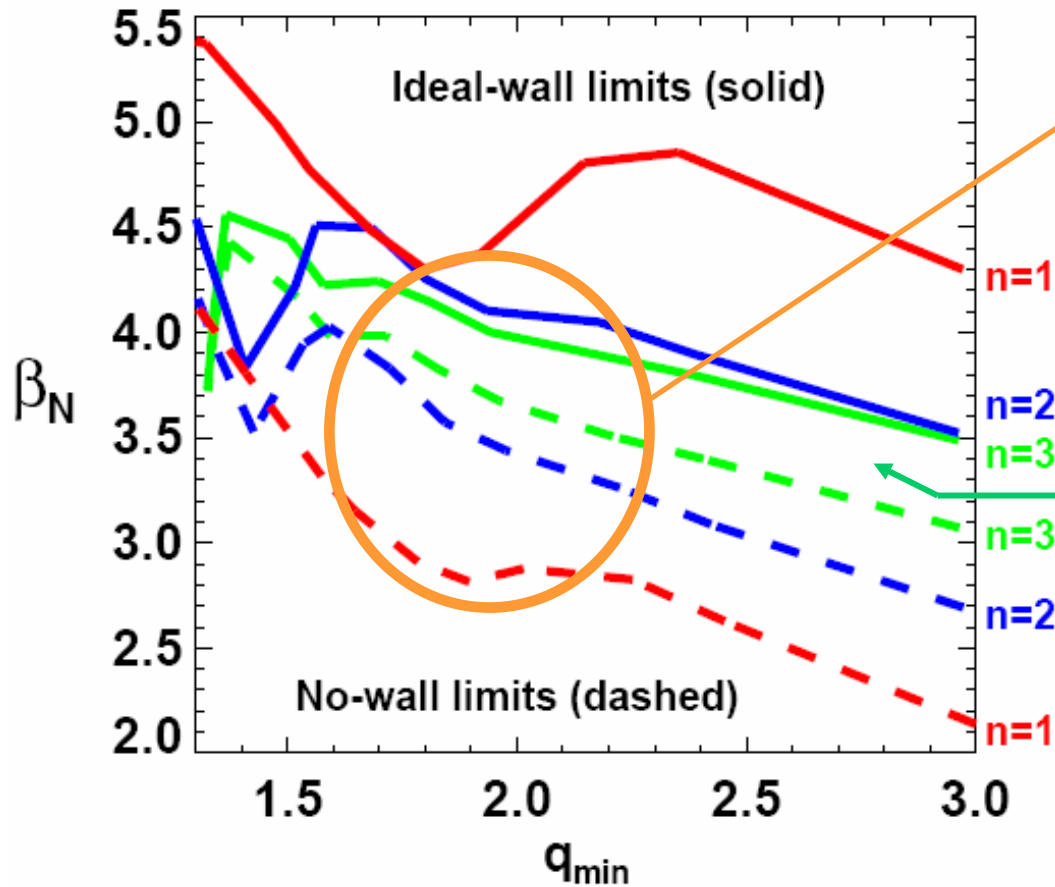
- Profiles from high $\beta_N = 4.1$ shots of AT shape expt.
 - $\beta_N > 4$ achieved transiently
 - High- κ DND (like modification)
- Vary J profile to scan q_{\min}
 - Weakly reversed, $q_0 - q_{\min} < 1$
 - $\rho_{q_{\min}} = 0.4 - 0.5$
 - $q_{95} = 5 - 5.5$
 - **$q_{99.7}$ fixed at 7.2**



- **AT scenario above extended to somewhat higher β_N with larger $\rho_{q_{\min}}$ using I_p , B_T ramps by Garofalo, et. al this year – see his APS talk/paper**

DIII-D AT scenarios exhibit systematic decrease in ideal-wall (IW) β_N limit with increasing q_{MIN} and n

- Computed $n=1,2,3$ kink limits with and w/o DIII-D vessel (CHEASE + DCON)



- Focus on this region of stability space for this talk

- n=3 most unstable mode at the ideal wall limit
- Small gap between NW and IW limits for n=3

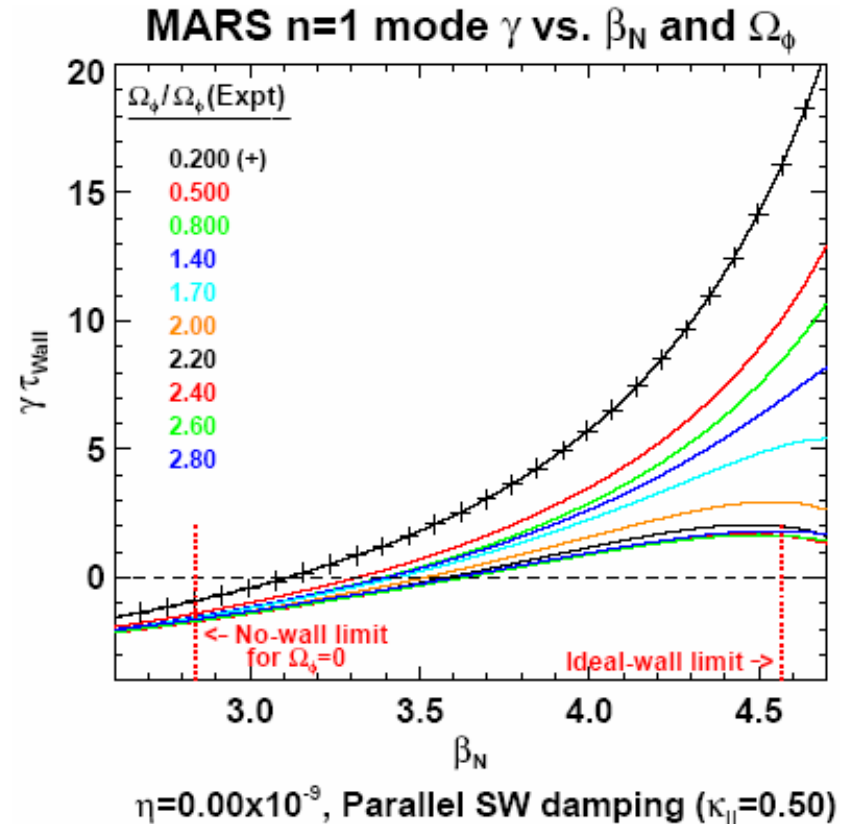
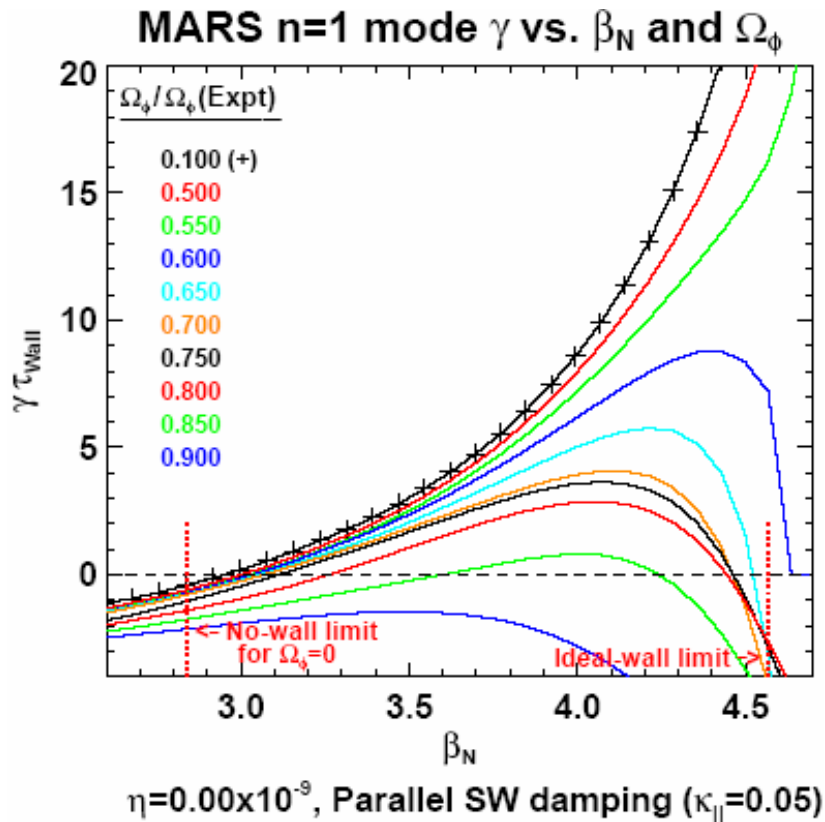
- Treat **n=1** and **n=2** where $\Delta\beta_N$ is ≥ 0.8

Sound wave damping model predicts $n=1$ critical rotation increases strongly with SW damping strength $\kappa_{||}$ when $q_{\text{MIN}} > 2$

Reminder: $\mathcal{F}_{SD} = -\kappa_{||} \sqrt{\pi} |k_{||} v_{\text{th}i}| \rho \mathbf{v}_1 \cdot \hat{\mathbf{b}} \hat{\mathbf{b}}$

$\kappa_{||} = 0.05$ $n=1$ $\Omega_{\text{crit}} \tau_A$ ($q=3$) = 2.3%

$\kappa_{||} = 0.5$ $n=1$ $\Omega_{\text{crit}} \tau_A$ ($q=3$) > 7%



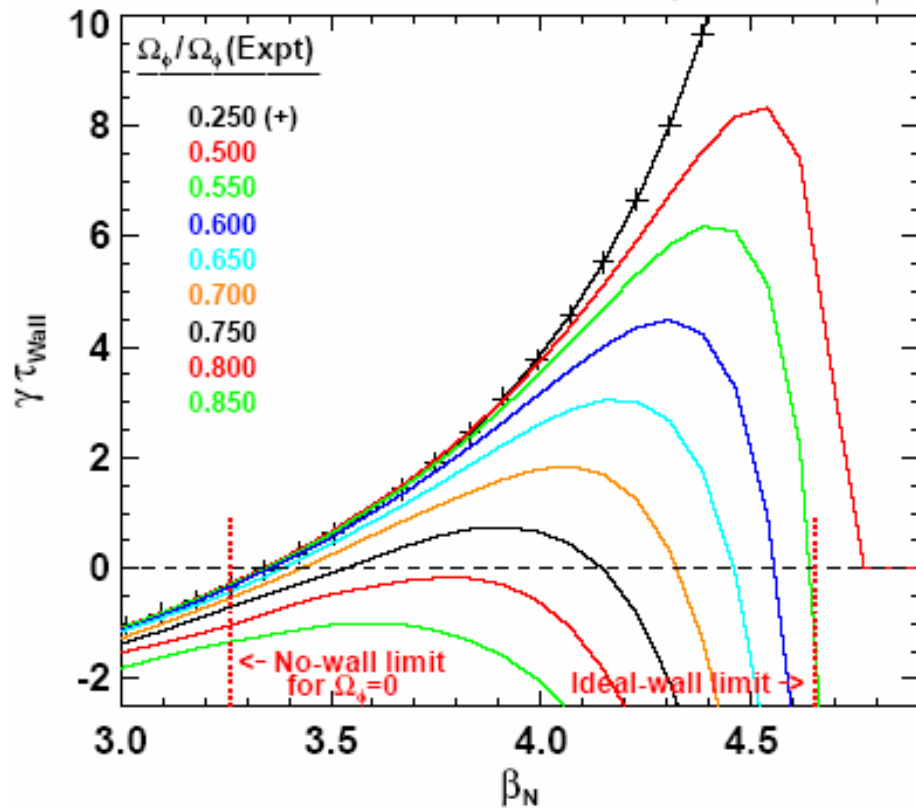
NOTE: $n=1$ RWM never fully stabilized at high rotation with larger $\kappa_{||}$...
→ Consider lower dissipation limit to assess role of q_{MIN}

Removal of $q=2$ surface increases $n=1$ critical rotation by 35% at $q=3$ surface using low- κ_{\parallel} SW damping model

$q_{\text{MIN}} = 1.8$ $\Omega_{\text{crit}}\tau_A$ ($q=3$) = 1.7%

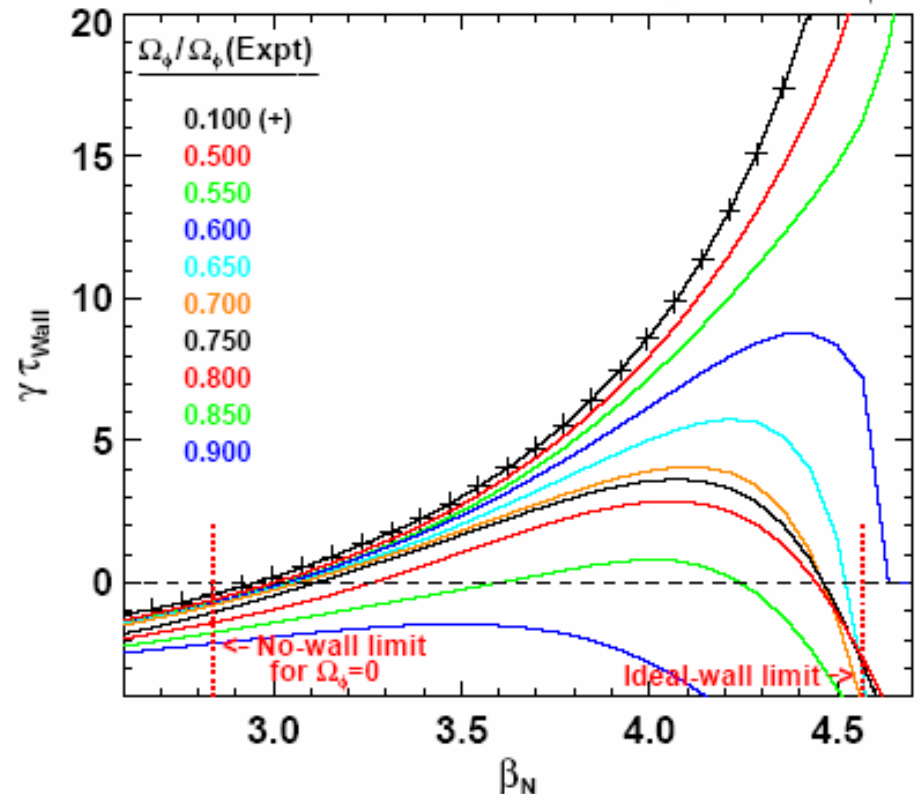
$q_{\text{MIN}} = 2.2$ $\Omega_{\text{crit}}\tau_A$ ($q=3$) = 2.3%

MARS $n=1$ mode γ vs. β_N and Ω_ϕ



$\eta=0.00 \times 10^{-9}$, Parallel SW damping ($\kappa_{\parallel}=0.05$)

MARS $n=1$ mode γ vs. β_N and Ω_ϕ



$\eta=0.00 \times 10^{-9}$, Parallel SW damping ($\kappa_{\parallel}=0.05$)

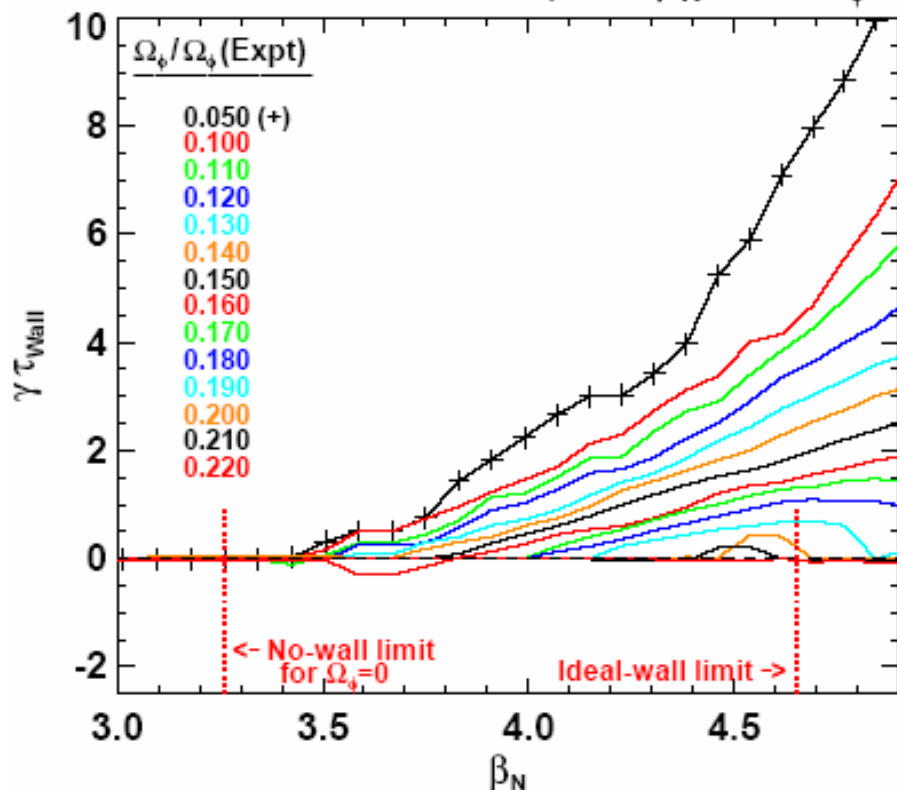
NOTE: These results only hold in the weak damping limit for SW damping

Using semi-kinetic damping model, removal of q=2 surface also increases n=1 critical rotation by 35% at q=3 surface

$q_{\text{MIN}} = 1.8$ $\Omega_{\text{crit}}\tau_A (q=3) = 0.46\%$

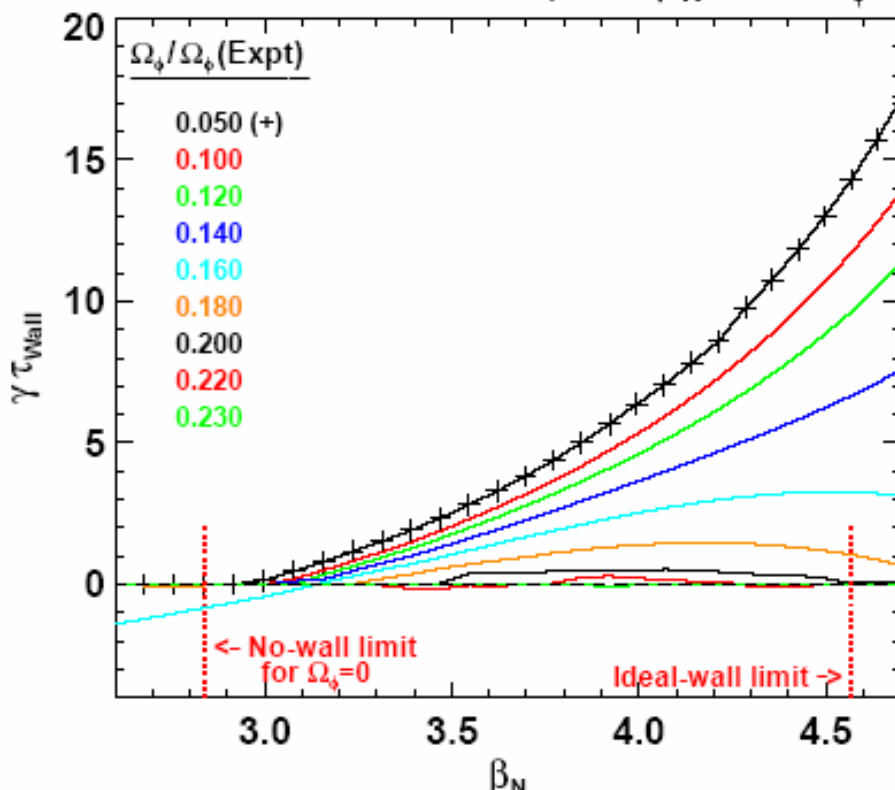
$q_{\text{MIN}} = 2.2$ $\Omega_{\text{crit}}\tau_A (q=3) = 0.62\%$

MARS n=1 mode γ vs. β_N and Ω_ϕ



$\eta=0.00 \times 10^{-9}$, Perpend. SK damping

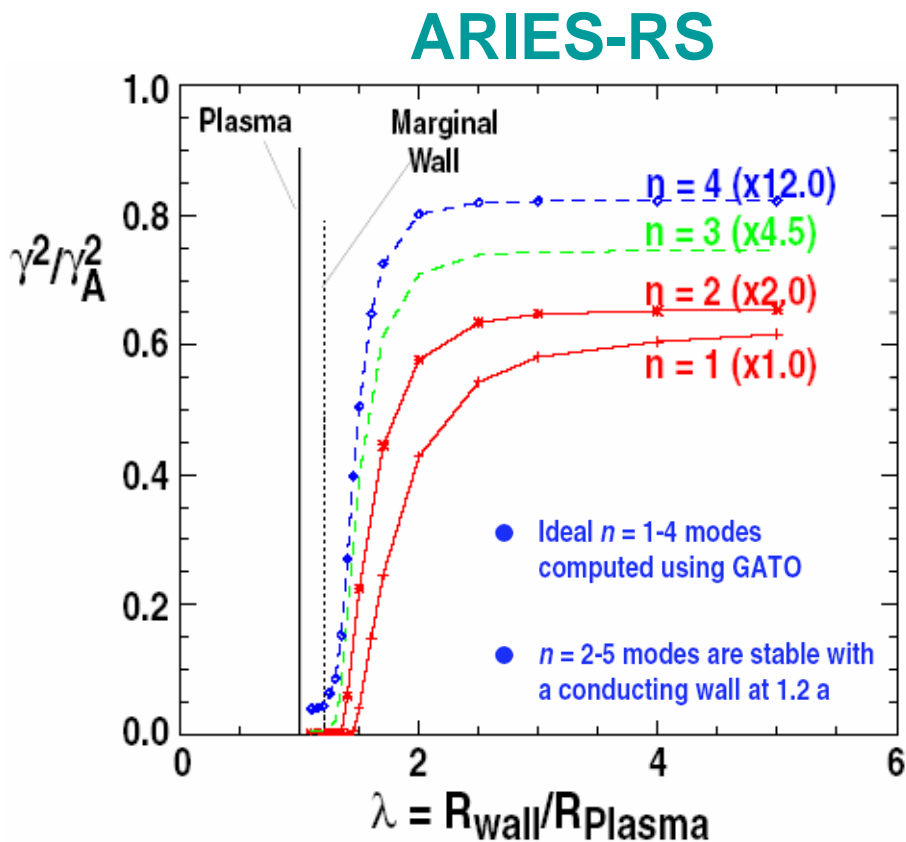
MARS n=1 mode γ vs. β_N and Ω_ϕ



$\eta=0.00 \times 10^{-9}$, Perpend. SK damping

NOTE: Abs. rotation value changes by only 5 % for SK and low κ_{\parallel} SW damping

As in DIII-D, AT reactor scenarios exhibit decreasing ideal-wall limits with increasing toroidal mode number



$A = 4.0, \beta_N = 5.3, q(0) = 2.8$

PHYSICS OPTIMIZATION OF THE ARIES-RS
FUSION POWER PLANT - V.S. CHAN, APS 1999

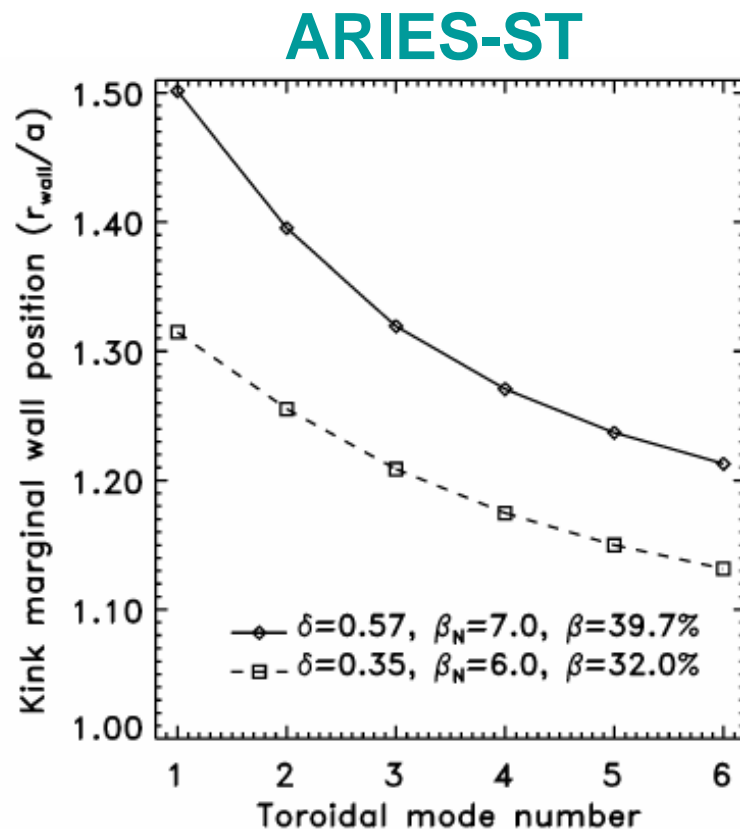


Fig. 4. Conformal wall separation which marginally stabilizes $n = 1-6$ kink modes as a function of toroidal mode number for ballooning stability optimized equilibria with $A = 1.6$, $\kappa = 3.2$, and triangularities 0.57 and 0.35.

Fusion Engineering and Design 65 (2003) 165/197

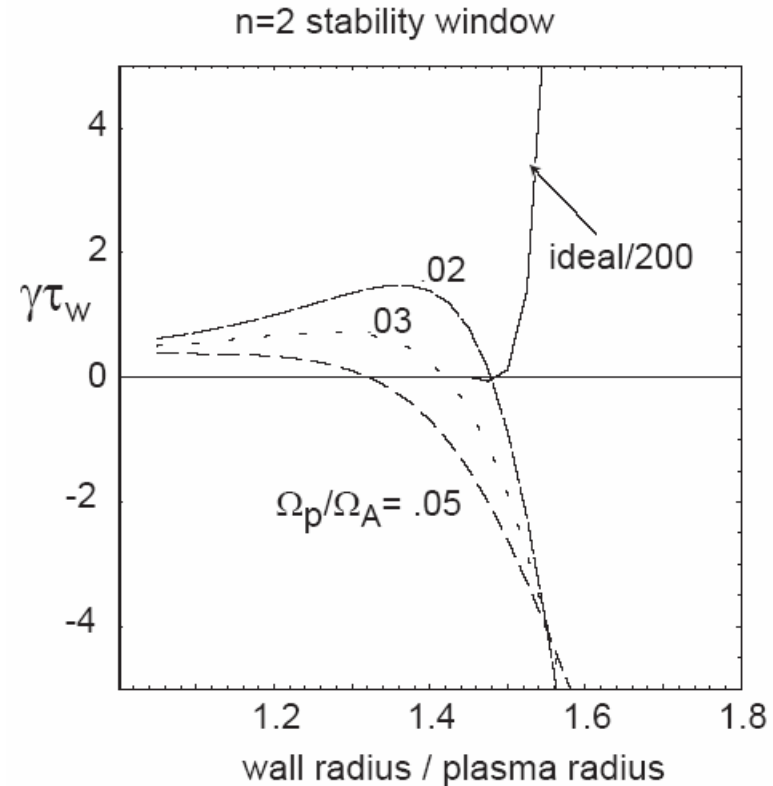
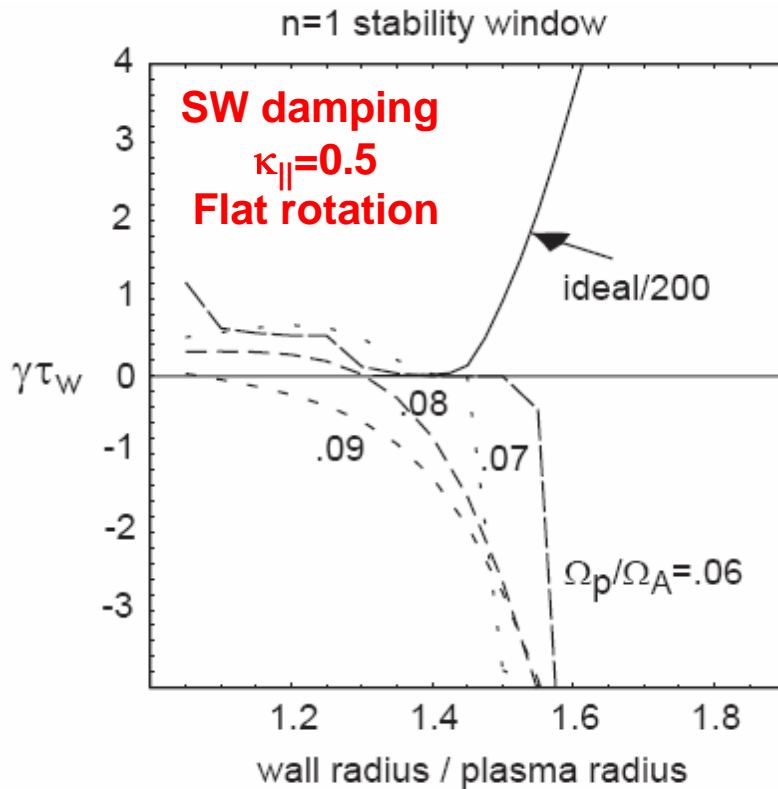
Rotation required for stabilizing $n > 1$ RWM largely unknown experimentally – very few calculations for $n > 1$

• ARIES-AT at limiting $\beta_N=5.9$

Physics Basis for the Advanced Tokamak
Fusion Power Plant ARIES-AT - PPPL-3878

Marginal wall position (r_{wall}/a)

$n = 1$	$n = 2$	$n = 3$
1.575	1.450	1.400

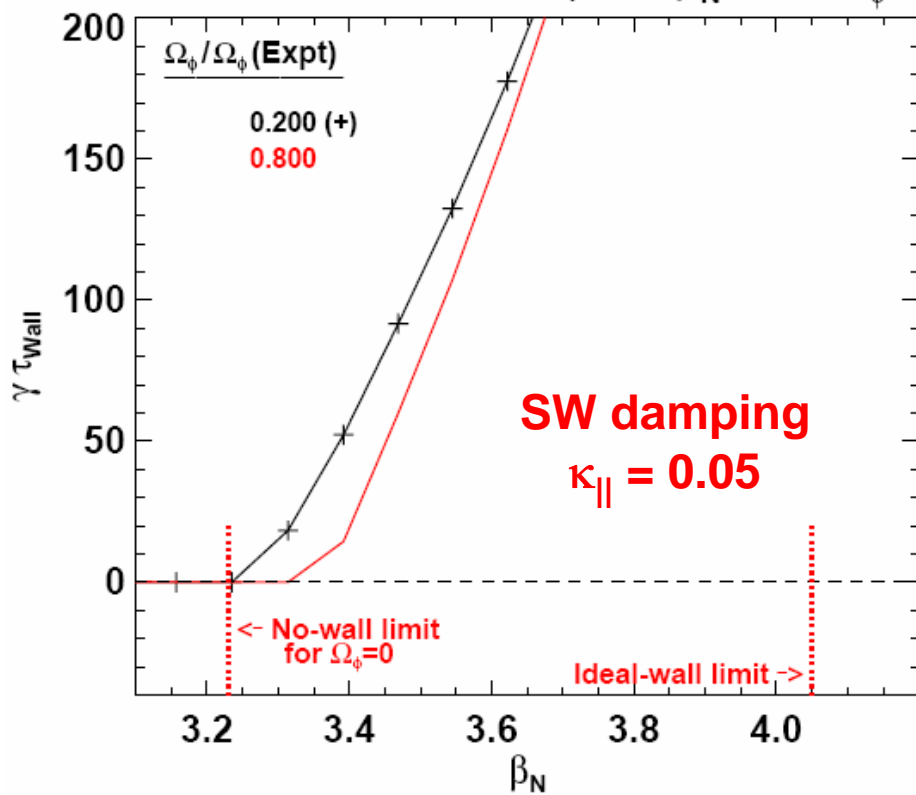


- Sound-wave (SW) damping model predicts $\times 2$ decrease in Ω_{crit} for $n=1 \rightarrow n=2$
- NOTE: MARS ideal mode $n=1$ marginal wall position $<$ $n=2$ marginal wall position

Sanity check: MARS-F n=2 NW and IW limits match DCON values in the appropriate limits of dissipation and rotation

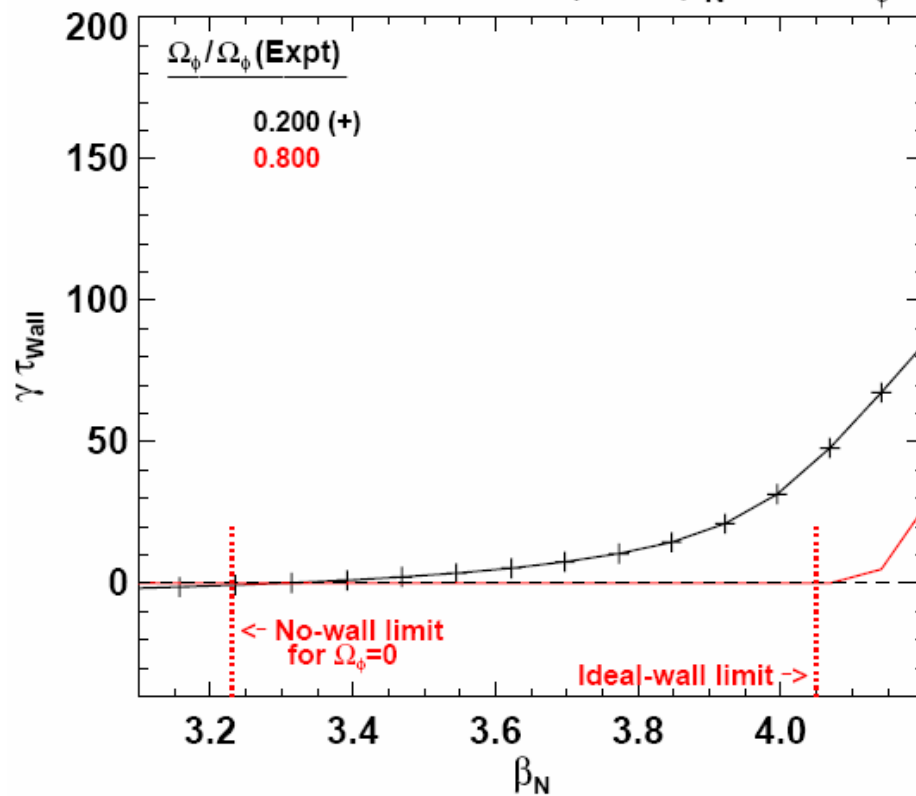
Weak damping, low rotation
reproduces DCON n=2 NW limit

MARS n=2 mode γ vs. β_N and Ω_ϕ



Weak damping, higher rotation
reproduces DCON n=2 IW limit

MARS n=2 mode γ vs. β_N and Ω_ϕ

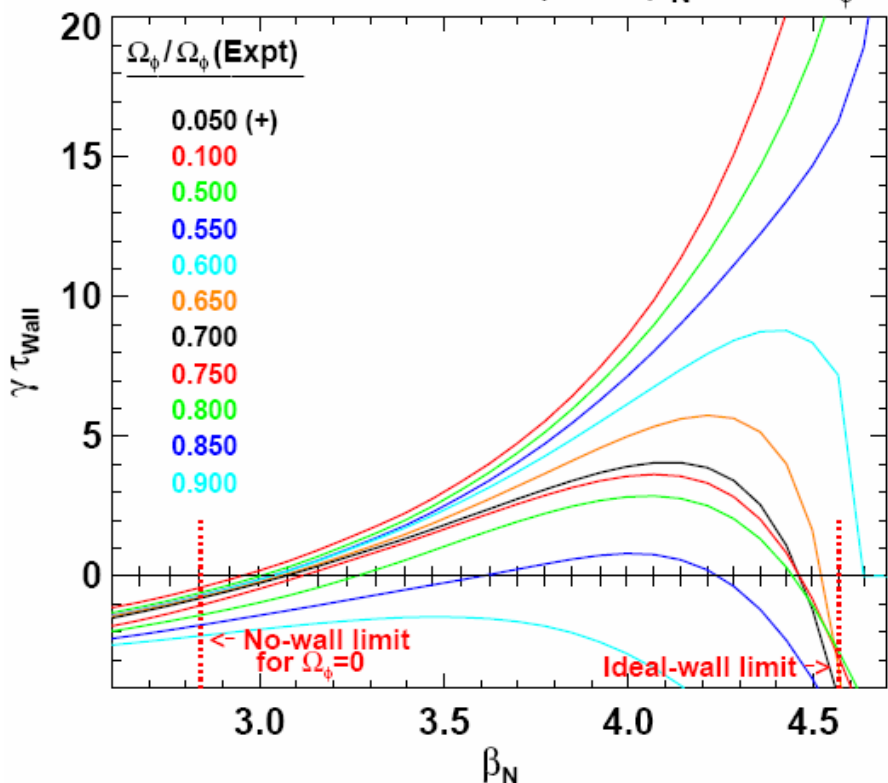


Sound wave damping model predicts $n=2$ critical rotation < half of value for $n=1$ in weak damping limit

$n=1$ $\Omega_{\text{crit}}\tau_A$ ($q=3$) = 2.3%

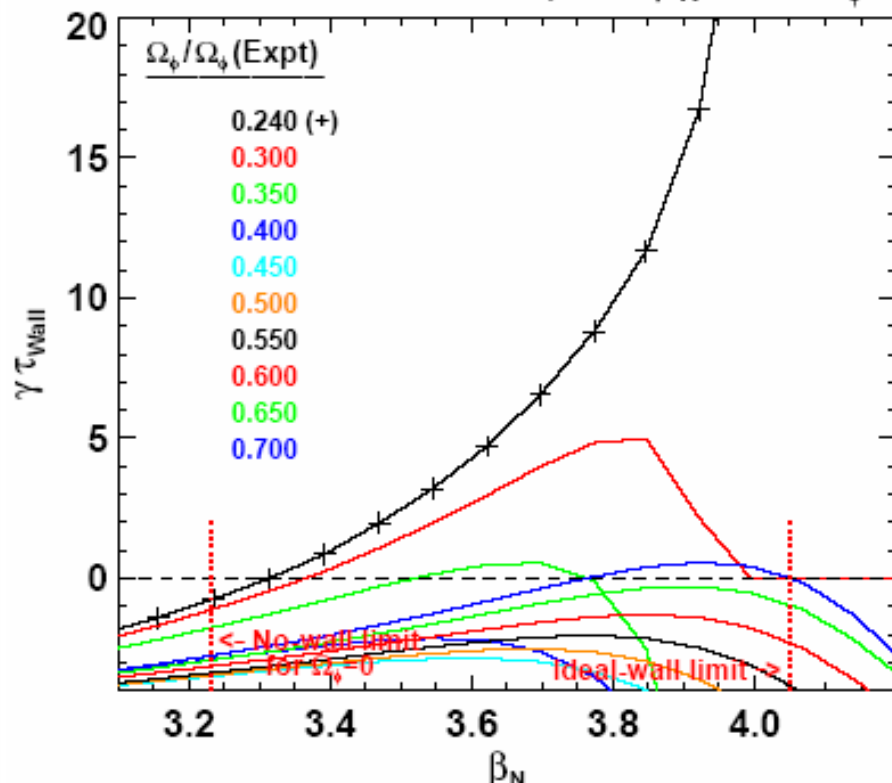
$n=2$ $\Omega_{\text{crit}}\tau_A$ ($q=3$) = 1.0%

MARS $n=1$ mode γ vs. β_N and Ω_ϕ



$\eta=0.00 \times 10^{-9}$, Parallel SW damping ($\kappa_{\parallel}=0.05$)

MARS $n=2$ mode γ vs. β_N and Ω_ϕ



$\eta=0.00 \times 10^{-9}$, Parallel SW damping ($\kappa_{\parallel}=0.05$)

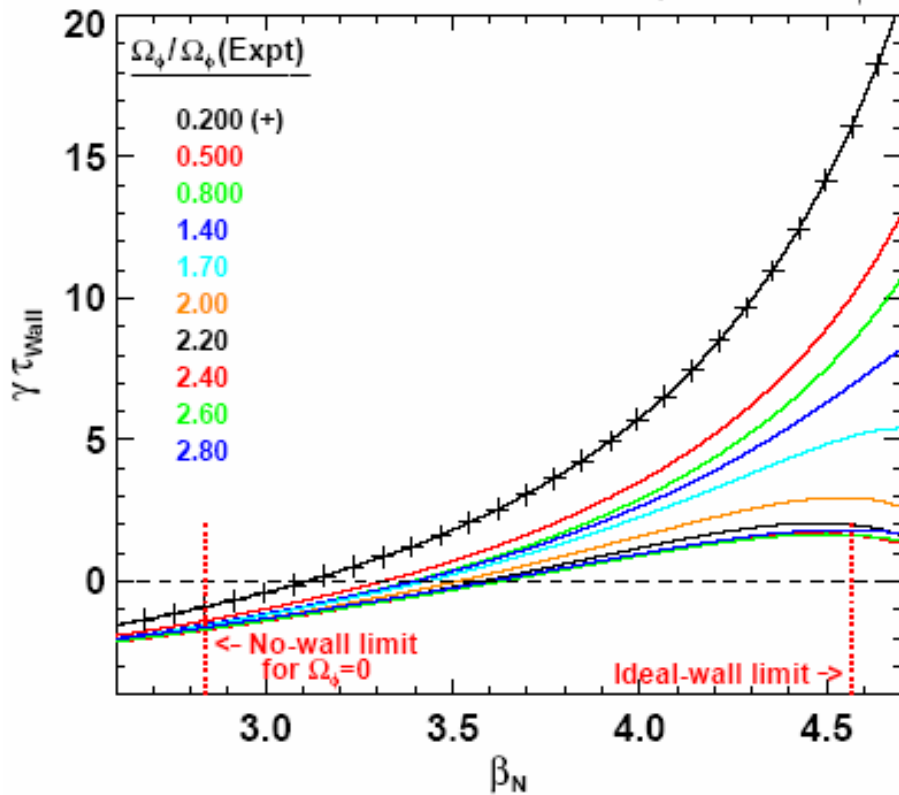
NOTE: $n=2$ Ω_{crit} increases with rotation at high rotation...

Sound wave damping model again predicts $n=2$ critical rotation $<$ half of value for $n=1$ in stronger damping limit

$n=1$ $\Omega_{\text{crit}}\tau_A$ ($q=3$) $>$ 7%

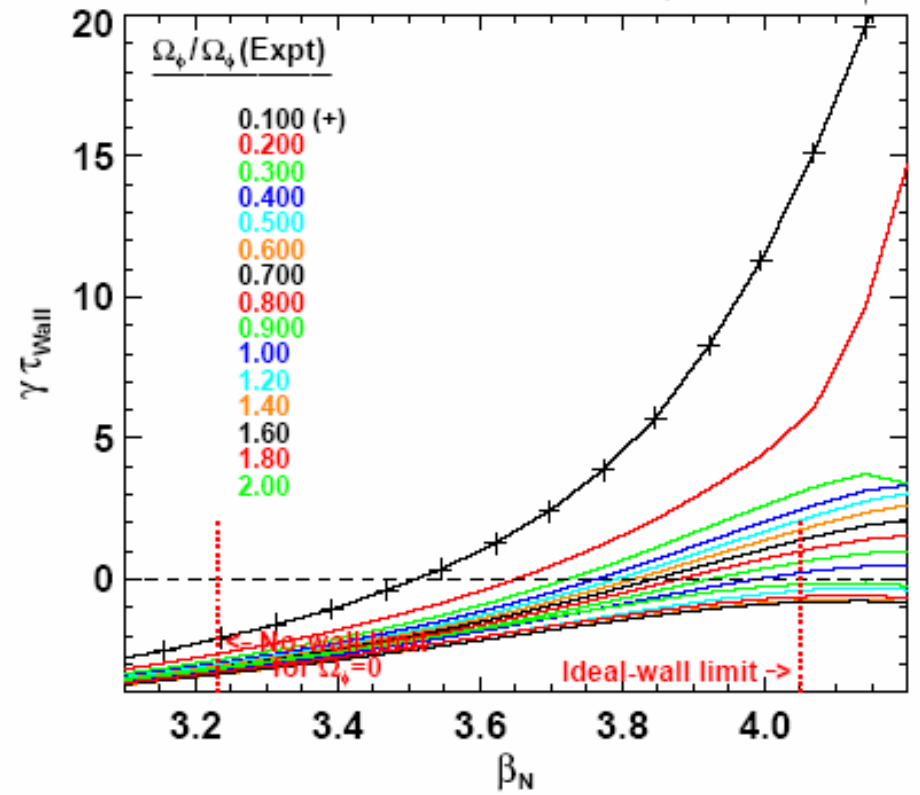
$n=2$ $\Omega_{\text{crit}}\tau_A$ ($q=3$) = 3%

MARS $n=1$ mode γ vs. β_N and Ω_ϕ



$\eta=0.00\times 10^{-9}$, Parallel SW damping ($\kappa_{\parallel}=0.50$)

MARS $n=2$ mode γ vs. β_N and Ω_ϕ



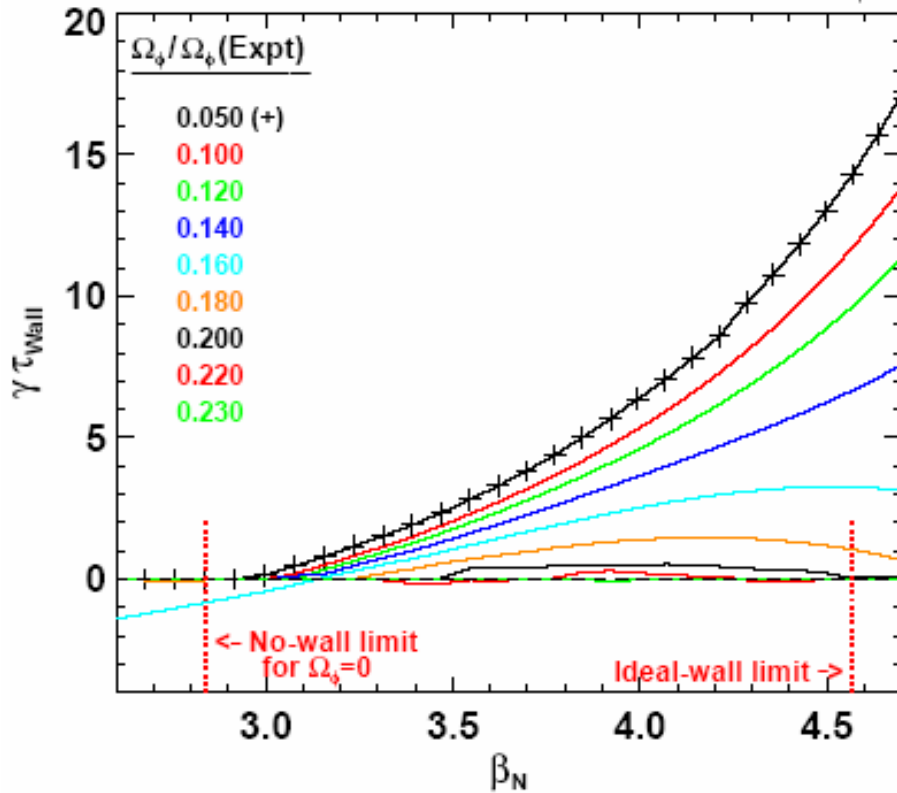
$\eta=0.00\times 10^{-9}$, Parallel SW damping ($\kappa_{\parallel}=0.50$)

NOTE: $n=2$ Ω_{crit} increases with rotation at high rotation as did $n=1$ in the strong damping limit

Unlike SW model, semi-kinetic damping model finds similar critical rotation values for n=1 and n=2 RWMs

n=1 $\Omega_{\text{crit}}\tau_A$ (q=3) = 0.61%

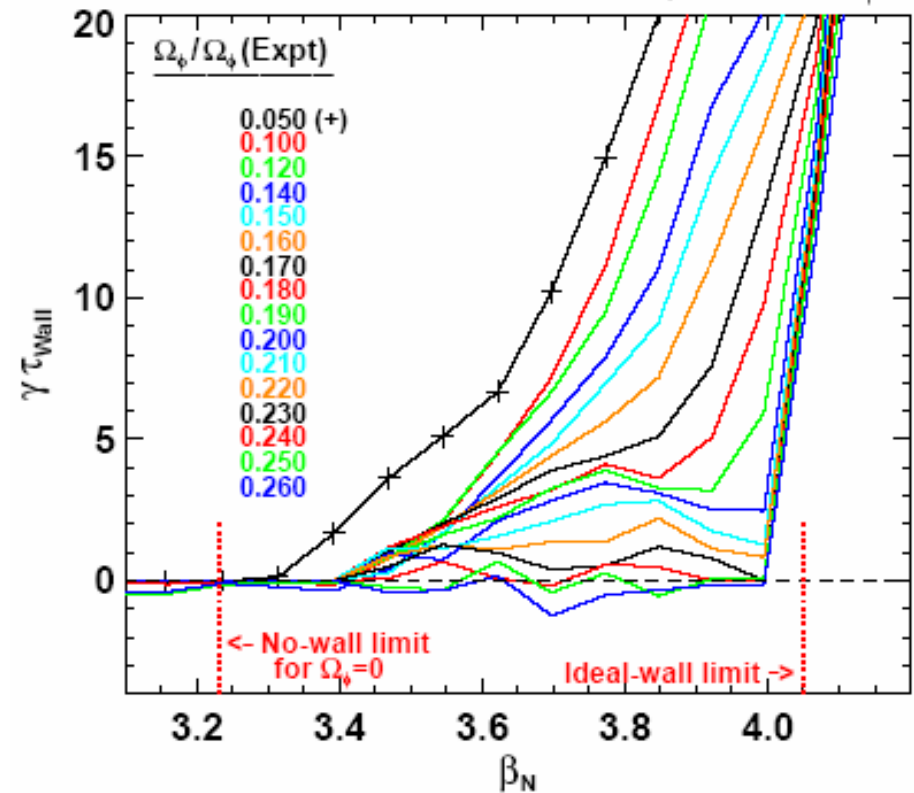
MARS n=1 mode γ vs. β_N and Ω_ϕ



$\eta=0.00 \times 10^{-9}$, Perpend. SK damping

n=2 $\Omega_{\text{crit}}\tau_A$ (q=3) = 0.68%

MARS n=2 mode γ vs. β_N and Ω_ϕ



$\eta=0.00 \times 10^{-9}$, Perpend. SK damping

NOTE: Ω_{CRIT} values from kinetic damping model systematically 3-4 \times LOWER than those obtained from sound wave damping model

Summary of Results (1)

- $n=1$ RWM
 - SW in strong damping limit → no access to IW limit w/ rotation alone
 - Recent DIII-D experiments marginally stable here...
 - Does this contradict SW damping in strong damping limit?
 - Lower κ_{\parallel} SW & kinetic models allow access to IW limit
 - Lower κ_{\parallel} SW and kinetic models predict 35% increase in Ω_{CRIT} when $q = 2$ surface is removed from the plasma
 - Increase consistent with DIII-D results
 - Kinetic damping model 3-4× lower critical rotation than SW
 - $\Omega_{\text{CRIT}}(n=1)$ ordering: Kinetic < experiment < SW

Summary of Results (2)

- $n=2$ RWM for $q_{\text{MIN}} > 2$
 - SW damping model predicts $\Omega_{\text{CRIT}}(n=2)/\Omega_{\text{CRIT}}(n=1) \leq 1/2$
 - Crudely expect $1/n$ scaling from # of sideband resonances
 - Kinetic damping model finds $\Omega_{\text{CRIT}}(n=2)/\Omega_{\text{CRIT}}(n=1) \approx 1$
 - Dissipation $\propto (\Omega/\omega_S)^6 \Rightarrow$ weaker scaling w/ # of resonances
 - Can we measure $n=2$ Ω_{CRIT} or RFA to distinguish between RWM damping models?
 - **What about $n=2$ in ITER AT scenario?**
 - **What is $n=2$ ideal-wall limit?**
 - **Is $n=2$ RWM unstable for ITER AT? (Impact on feedback?)**

RWM damping physics remains unclear

- Neither model in “agreement” with experimental Ω_{CRIT}
 - Presently within factor of 2 on DIII-D (SK works for JET)
 - SW damping model does not include particle trapping
 - Expect particle trapping to be strong effect
 - Trapping taken into account with kinetic model
 - Low energy particles near TP boundary dominate dissipation
 - MARS-F model derived in high-A circular cross-section limit
 - This limit over-predicts particle bounce-time by as much as factor of 2 near the edge of DIII-D plasmas
 - Dissipation $\propto (\Omega\tau_B)^6$ for trapped particles \Rightarrow correct bounce time tends to improve agreement between kinetic model and experiment
 - Using experimental $T_i/T_e > 1$ also improves agreement
 - ω^* effects also important in low $E \times B$ rotation limit
 - I’m not a theorist – please help!