Resistive plasma and RWM modeling for AT & ST plasmas using MARS

J. Menard, PPPL

9th Workshop on MHD Stability and Control

Princeton Plasma Physics Laboratory

November 21-23, 2004

Motivation

- Understand β-limiting modes in DIII-D AT
  - Tearing modes often observed near ideal-wall limits
    - No obvious precursor in many cases → classically unstable?
  - n=1 RWM also sometimes observed despite rotation values that typically stabilize mode

- Try to use MARS code to interpret observations - Attempt to understand interplay between:
  - Ideal wall limits and tearing activity
  - Plasma resistivity
  - Plasma rotation
  - RWM dissipation mechanisms
  - Wall resistivity

- Initial applications to NSTX

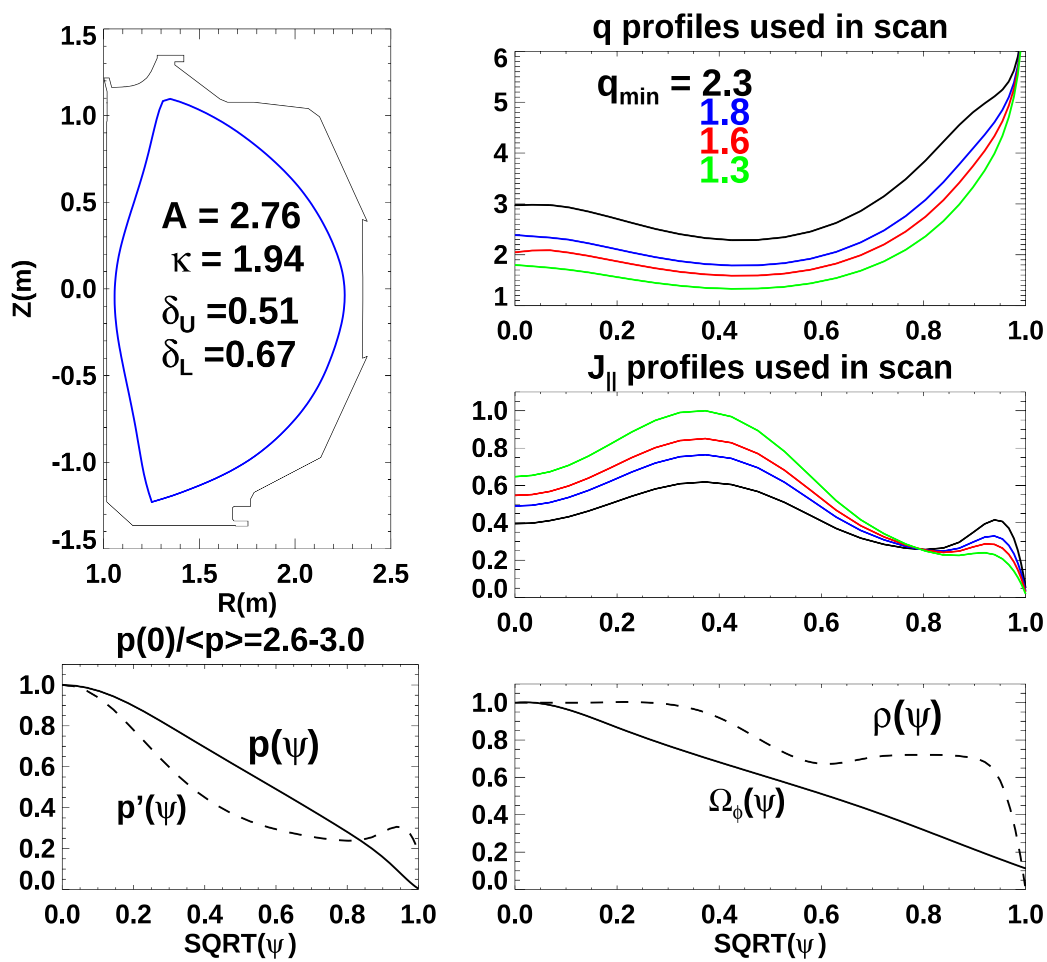
SYSTEMATIC STUDY INVESTIGATES DIII–D AT SCENARIO STABILITY

GOALS:

- Understand expt. instabilities
- Find stable J profile at $\beta_N \geq 4$
- Investigate non-ideal effects
  - — Tearing stability
  - — RWM stability

METHODOLOGY:

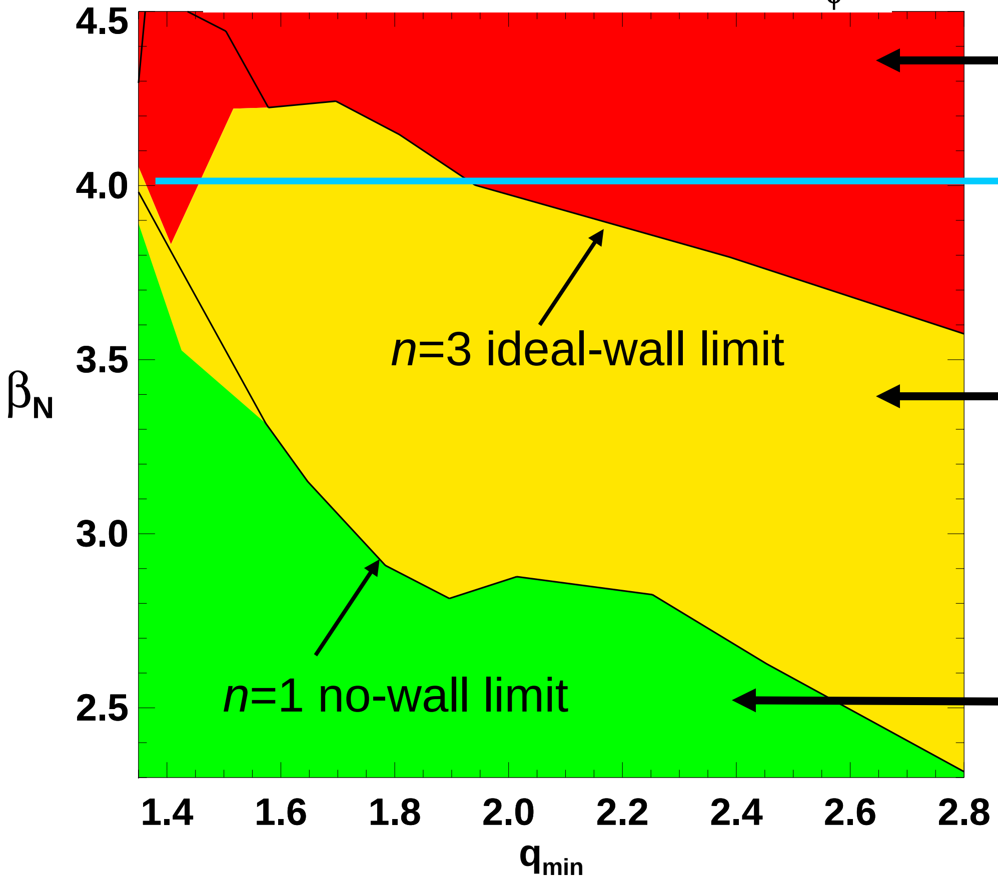
- Profiles from high $\beta_N = 4.1$ shots of AT shape expt.
  - — $\beta_N > 4$ achieved transiently
  - — High-κ DND (like modification)
- Vary J profile to scan q_{min}
  - — Weakly reversed, $q_0 - q_{min} < 1$
  - — $\rho_{qmin} = 0.4 - 0.5$
  - — $q_{95} = 5–5.5$
  - — $q_{99.7}$ fixed at 7.2



FIND β_N > 4 IDEALLY STABLE TO *n*=1–3 ONLY FOR q_{min}=1.5–1.9

- Computed *n*=1,2,3 kink limits with and without DIII–D vessel (CHEASE + DCON)

Kink Stability Space with Ω_ϕ=0



_n_ = 1–3 Stability Space:

Some *n* unstable w/ ideal wall

- β_N = 4 ⇒ near ideal wall limit
- β_N > 4 ⇒ q_{min}= 1.5-1.9

All *n* stable with ideal wall
Some *n* unstable without wall

- $\Delta\beta_N \approx 1$ for wide range of q_{min}

n=1-3 all stable without wall

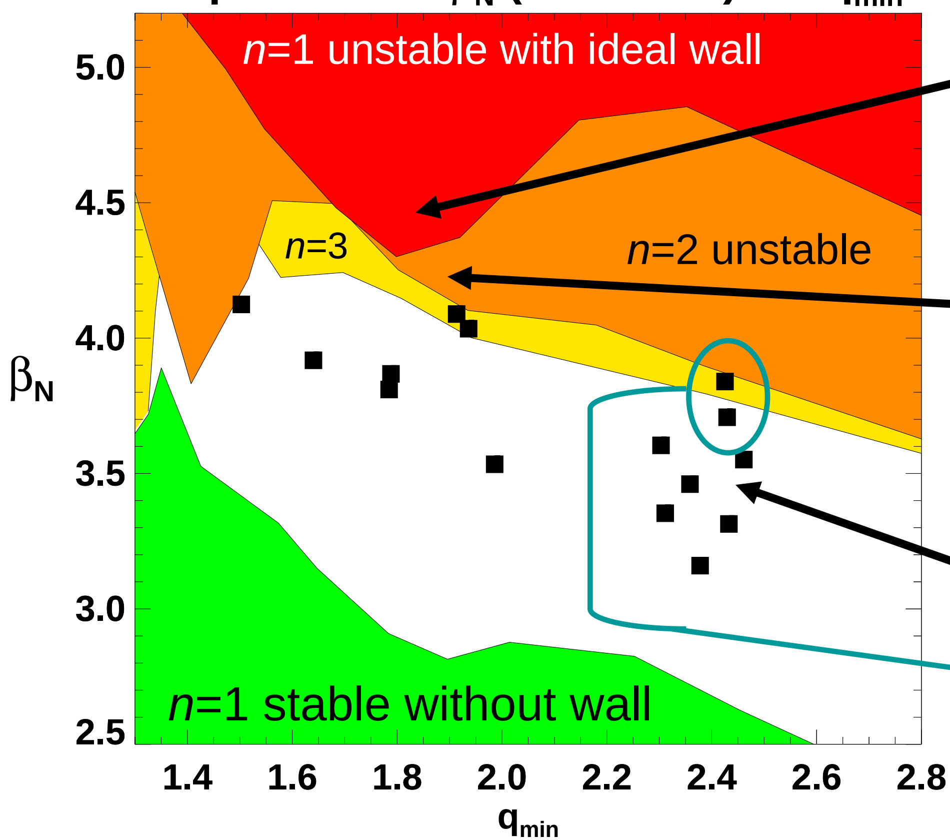
- High q_{min} has low no-wall limit

HIGH-β_N AT SHOTS EXCEED NO-WALL LIMITS AND APPROACH IDEAL-WALL LIMITS

$1.7 < \kappa < 1.9$, $\Delta R_{SEP} < 1cm$
$q_0 - q_{min} > 0.1$, $q_{95} > 4.5$

Discharges shown below have:
(from high q_{min}, AT shape, and flat-q experiments)

Experimental β_N (with MSE) vs. q_{min}

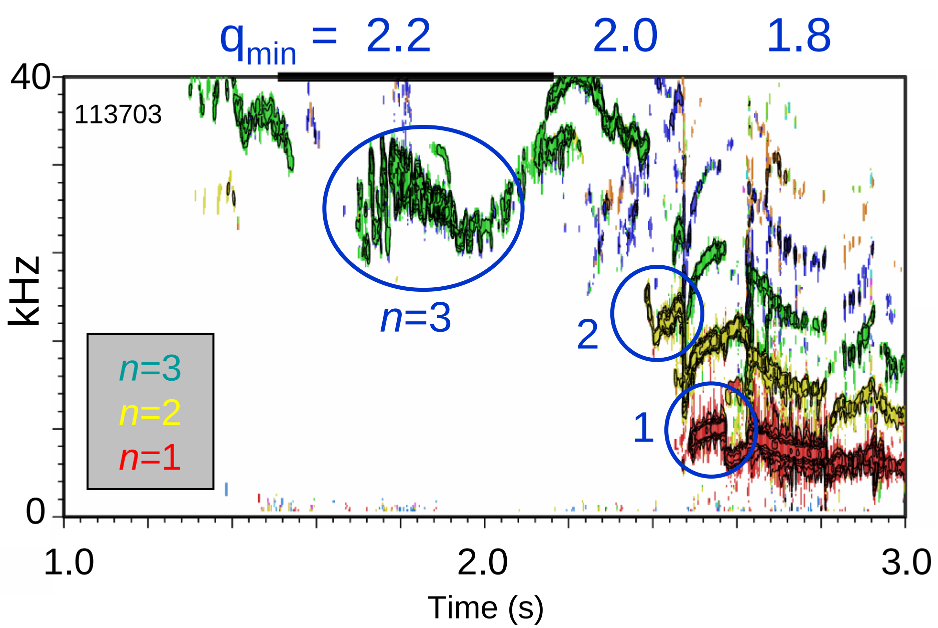


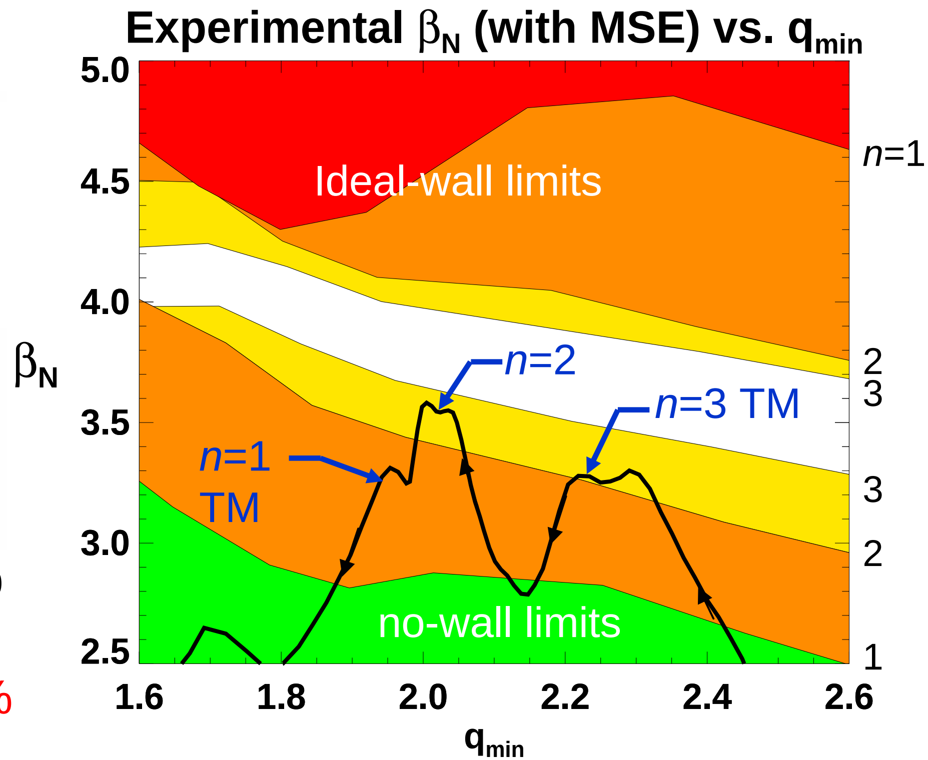
(EFIT02 – no E_r correction)

- *n*=1 ideal-wall limit locally minimum near q_{min}=1.6–2
  - — *n*=1 fast disruptions
  - — 2/1 modes excited near limit
- *n*=1,2,3 ideal-wall limits similar in highest β_N shots
  - — β saturation with *n*=2,3
  - — *n*=3 “X-events”
- Experimental β_N limits are generally lower at high q_{min}
  - — High β_N’s have broader p
  - ***J. Ferron APS RI1.005***
  - **— Increased *n*=2,3 tearing**
  - **— *n*=1 RWM more unstable?**

PROXIMITY TO IDEAL-WALL LIMIT CAN DESTABILIZE TEARING MODES

- Positive pole in Δ' near ideal-wall limit can classically destabilize tearing modes (D. Brennan – Poster NP1.010 DPP-2004 + other papers)
  - Kink vs. tearing mode excitation function of heating rate through ideal β-limit
- 2/1 tearing mode often observed at high β_N as $q_{min} \rightarrow 1.5$ from above
- *n* >1 tearing mode (TM) more commonly observed when $q_{min} > 2$





n=3 mode → 15% drop in β_N , *n*=1 → 25%

Resistive kink-tearing mode investigated with MARS

- Simple slab model of Δ' driven by dJ/dr illustrates separation of tearing and kink marginal stability boundaries with ideal wall.
- In MARS, a similar separation is evident when sufficiently large resistivity is used, and a resistive kink-tearing mode is excited
  - Separation of marginal β_N values increases with resistivity, as expected

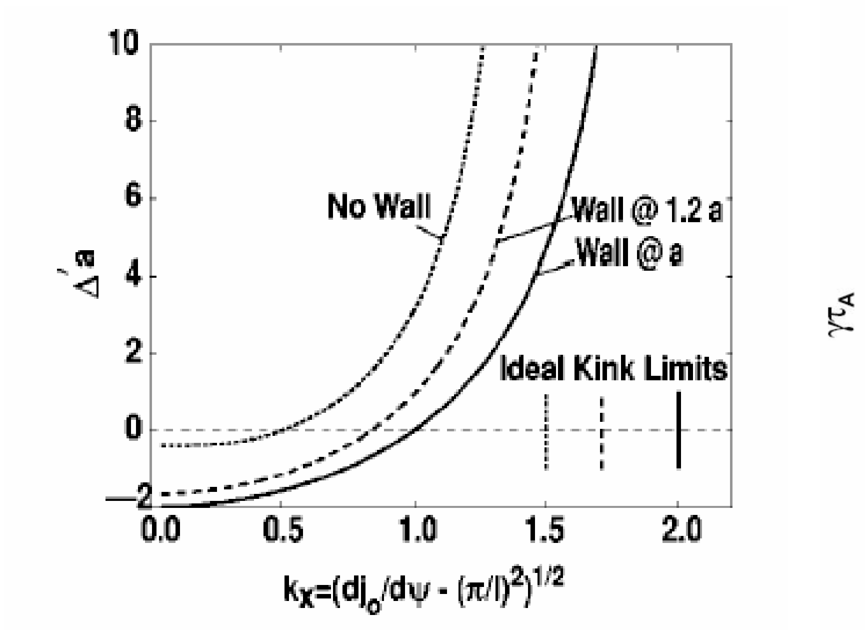
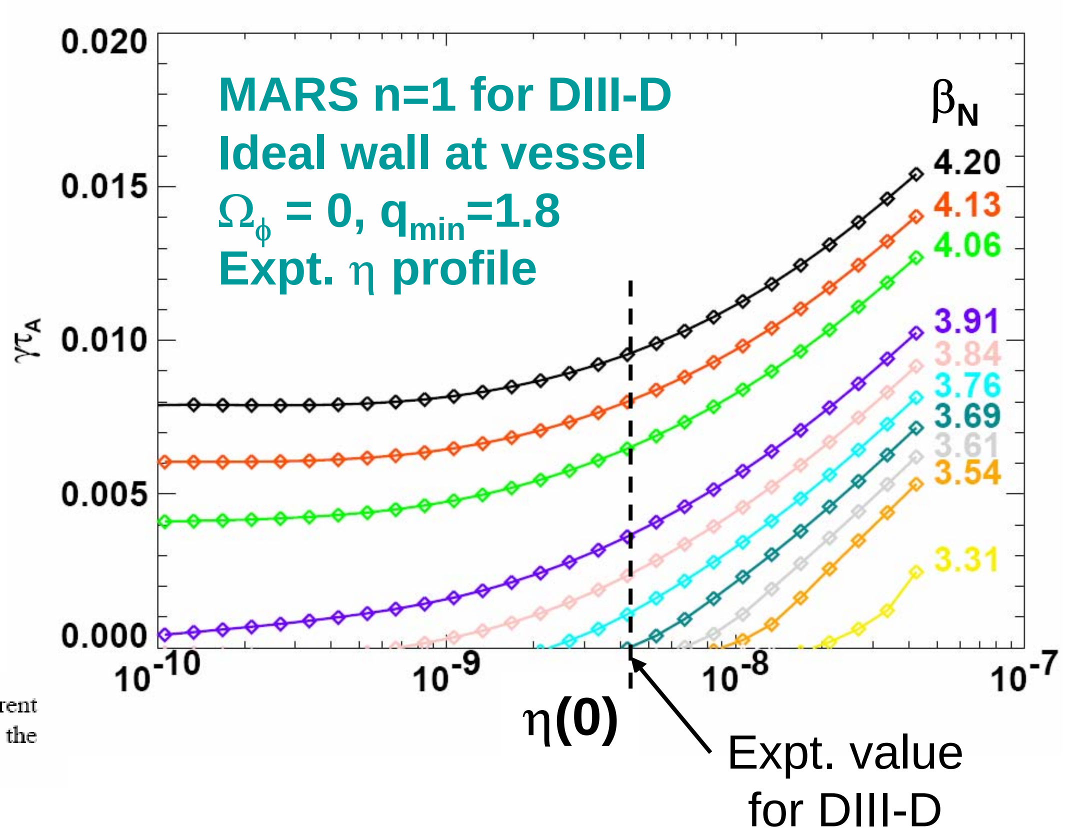


FIG. 1. The Δ' solution from a simple slab model as a function of current gradient. Varying the location of the conducting wall changes not only the ideal limit, but also the tearing stability index.

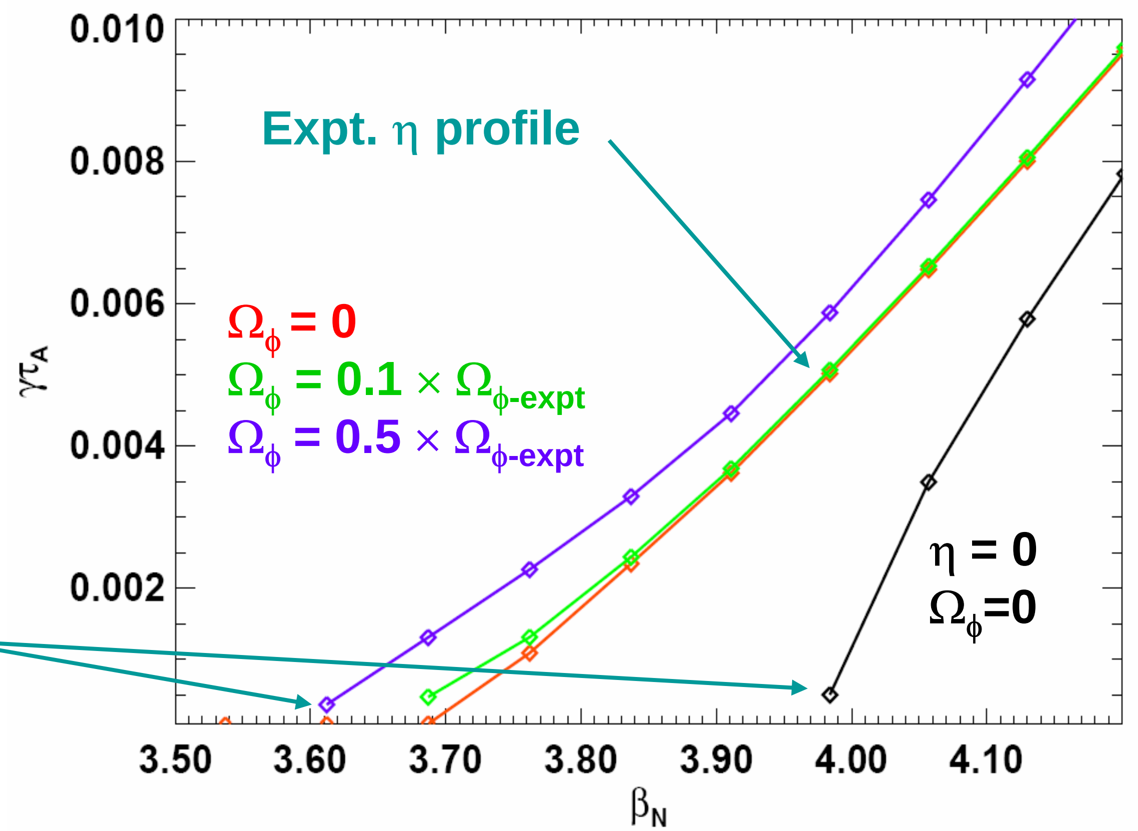
Brennan, Phys. Plasmas, Vol.10, No.5, May 2003



Rotation can enhance resistive-kink-tearing mode growth

MARS n=1 for DIII-D
Ideal wall at vessel
q_{min}=1.8

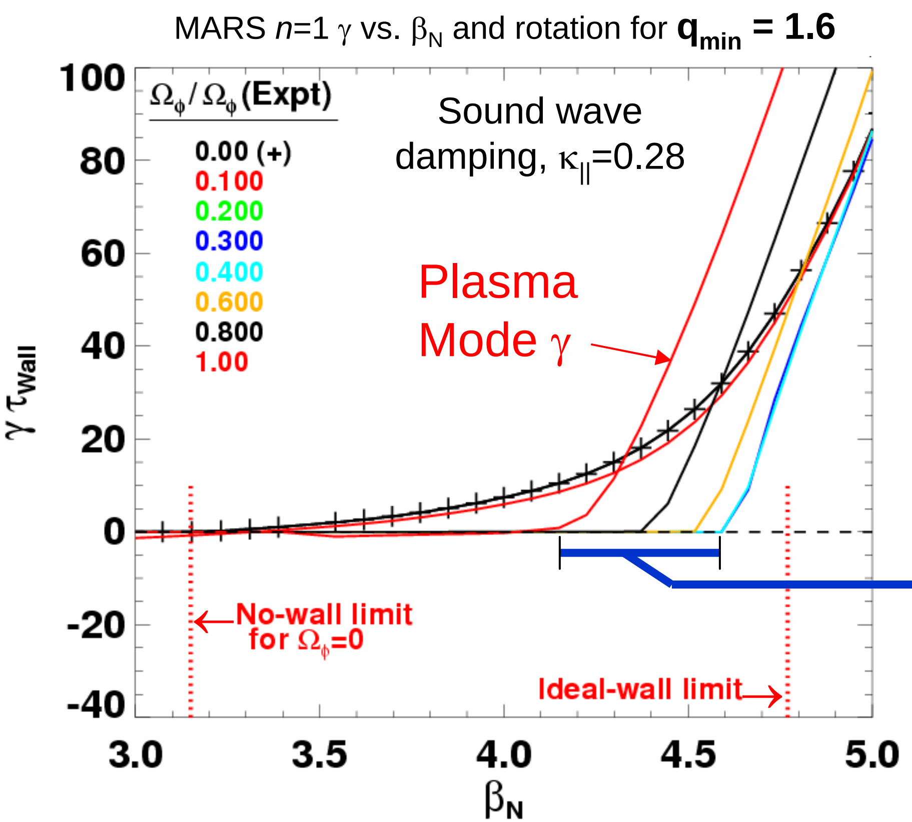
Note smaller dγ/dβ near marginality from finite η

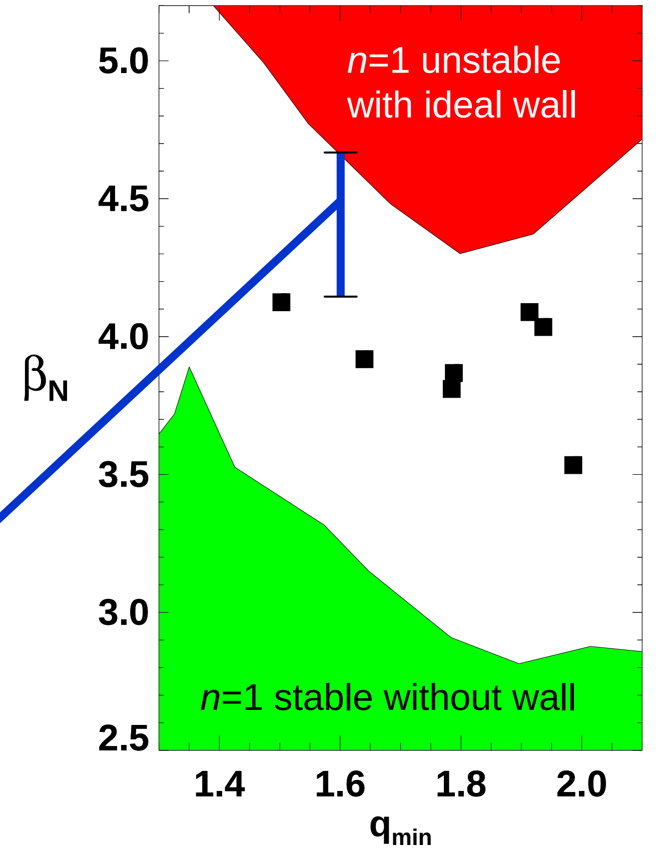


- Need to test role of rotational-shear on stability
  - Flat Ω_ϕ profile not destabilizing to plasma mode in similar RWM studies with stronger dissipation.

SHEARED ROTATION PREDICTED TO REDUCE *n*=1 IDEAL-WALL LIMIT

- 10% reduction in *n*=1 ideal-wall limit near q_{min}=1.6 typical



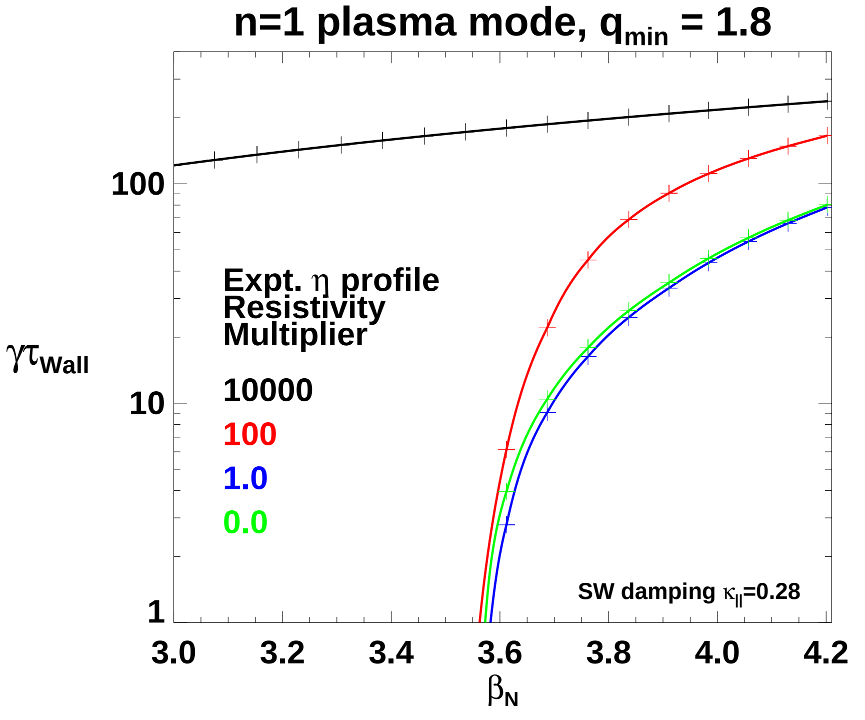


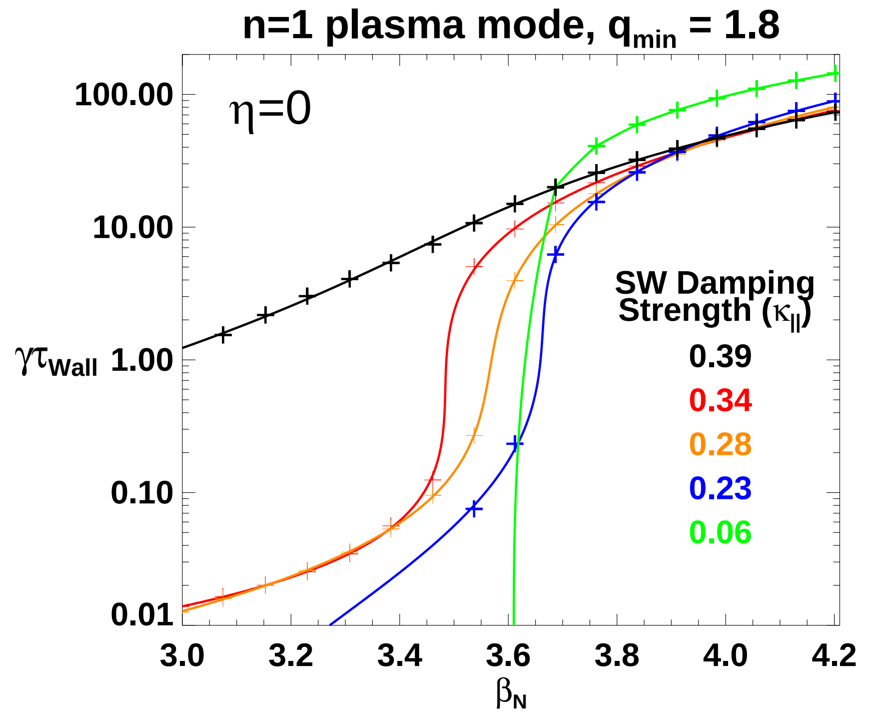
- Possible explanation for observed offset in limits?
  - Strong dissipation enhances destabilization effect
- Experimental uncertainty in β and β-limit also ≈ 5–10%

Dissipation predicted to dominate η in high-Ω_ϕ conditions

- Plasma-mode γ insensitive to η for sound wave damping & Ω_ϕ required to stabilize RWM

However, dissipation may be destabilizing below ideal-wall limit



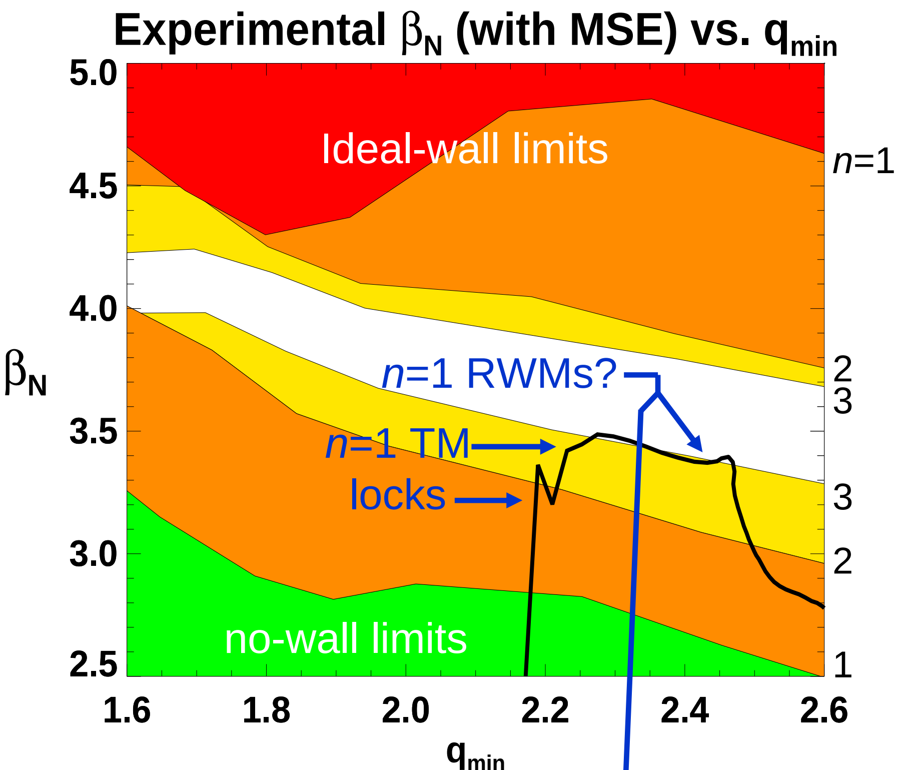


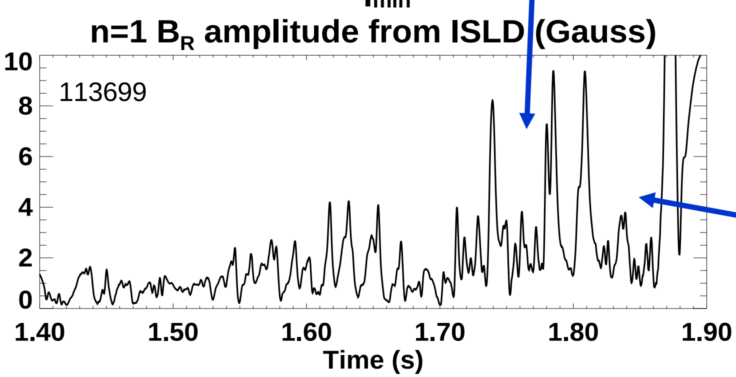
➔ Ideal plasma treatment of plasma-mode stabilization valid for DIII-D $S=\tau_R/\tau_A$ values?

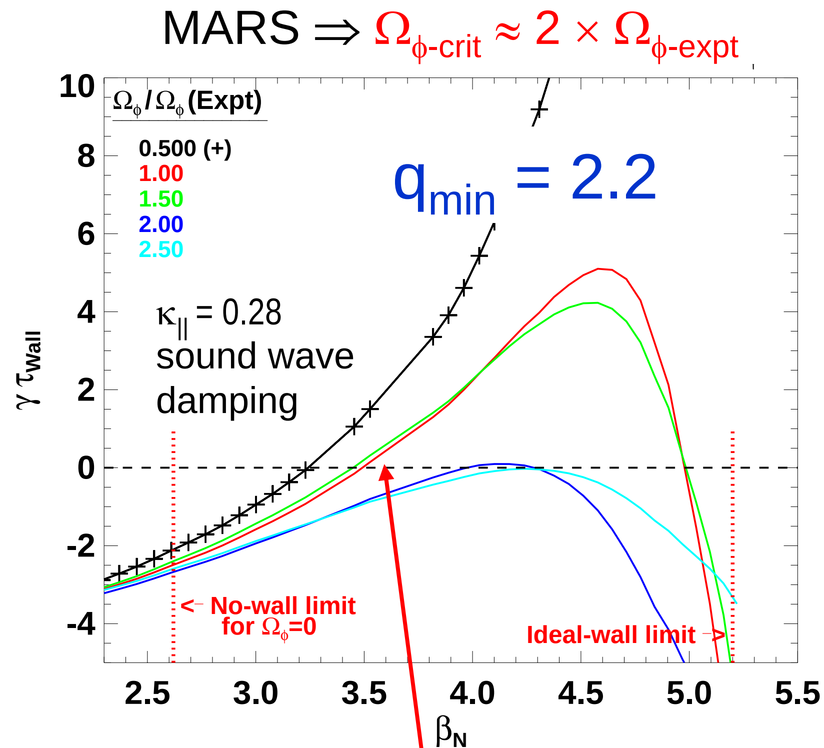
Do these results change if the (perpendicular) kinetic damping model is used?

Need to understand interplay between dissipation and η at mode-rational surfaces…

q_{min} >2 MAY BE MORE UNSTABLE TO n=1 RESISTIVE WALL MODES







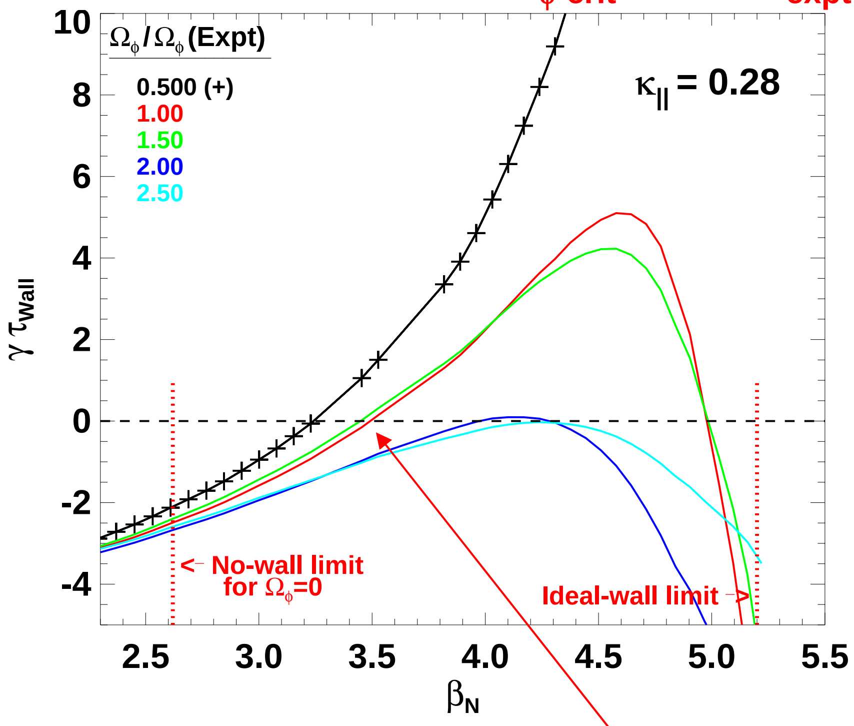
- Predict n=1 RWM unstable near β_N = 3.5 for $\Omega_\phi \approx \Omega_{\phi\text{-expt}}$ for q_{min} > 2
- Observe increased RWM/EF feedback activity at high β_N (using C-coil feedback)

n=1 RWM stability depends strongly on damping model

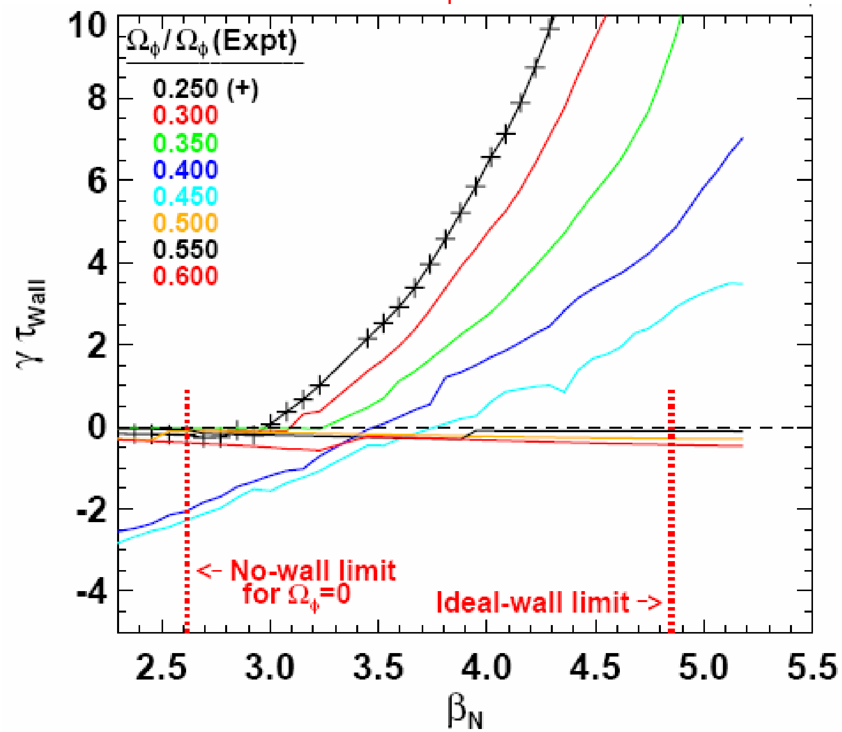
- Critical rotation frequency differs by factor of 4 for q_{min} = 2.2
- Kinetic damping model → RWM most unstable near ideal-wall limit

q_{min} = 2.2

MARS SW damping ⇒ $\Omega_{\phi\text{-crit}} \approx 2 \times \Omega_{expt}$



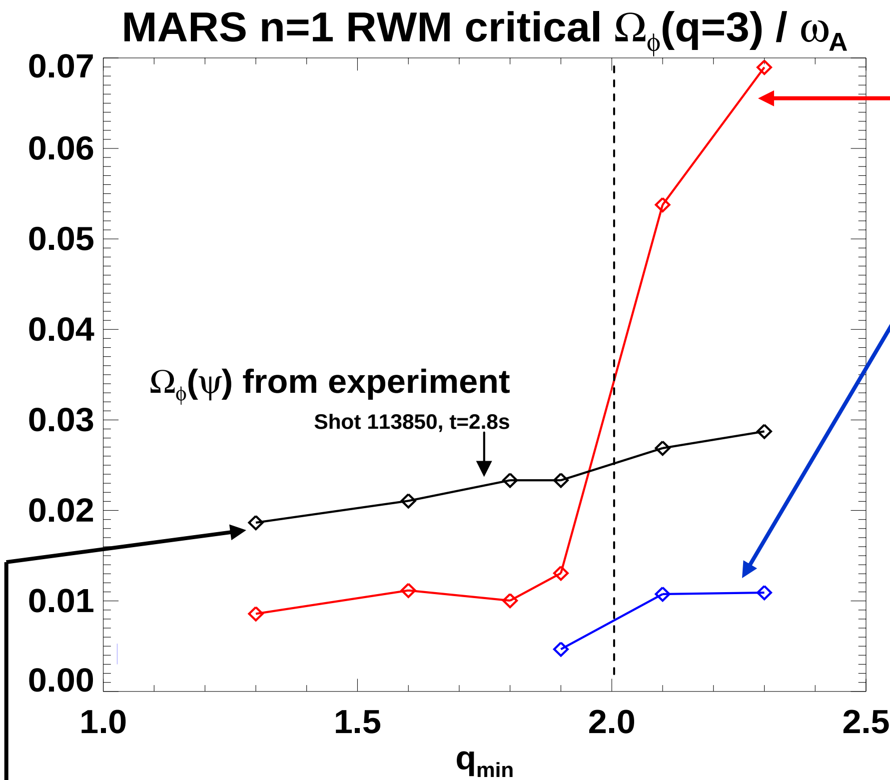
Kinetic damping ⇒ $\Omega_{\phi\text{-crit}} \approx 0.5\text{-}0.6 \times \Omega_{expt}$



- Predict n=1 RWM instability near β_N = 3.5 for expt. rotation for q_{min} > 2 ***only for the sound-wave damping model***.

BOTH MARS DAMPING MODELS PREDICT INCREASED $\Omega_{\phi\text{-CRIT}}$ WHEN q_{min} >2

- Resonances at q=2 surface dominate collisionless damping when $q_{min} < 2$



Sound wave (SW) damping model predicts much larger $\Omega_{\phi\text{-crit}}$ than kinetic damping model for $q_{min} > 2$

- DIII–D n=1 RWM critical-Ω_ϕ studies:
  - Usually, q_{min} = 1.5 – 1.8
  - $\Omega_{\phi\text{-crit}}(q=3)/\omega_A \approx 1\%$ in experiment
  - SW damping over-predicts $\Omega_{\phi\text{-crit}}$
  - Kinetic damping under-predicts

  (La Haye, to be published in NF)

- Actual $\Omega_{\phi\text{-crit}}$ bounded by these?

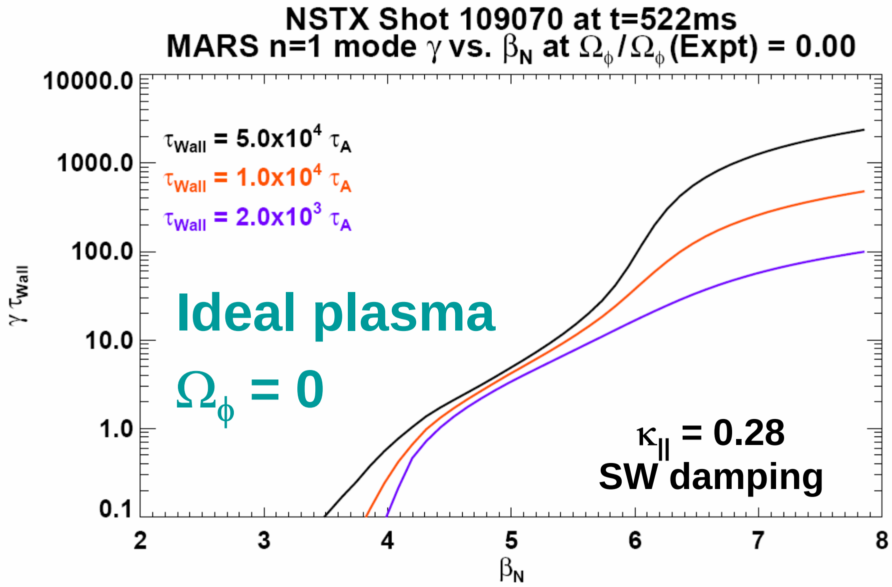
- AT shape experiment used $q_{min} < 2$
  - Experiment approached ideal-wall limits using C-coil EF correction only
  - $\Omega_{\phi\text{-expt}} > \Omega_{\phi\text{-crit}}$ from both damping models - consistent with experiment

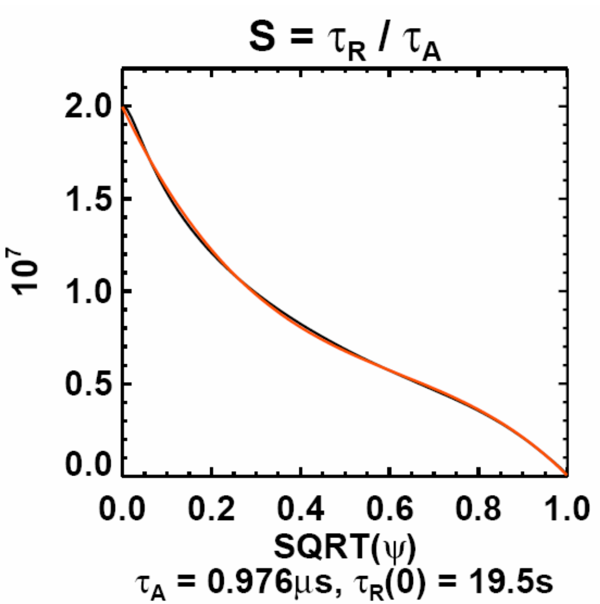
Plasma η can enhance instability of Ω_ϕ=0 RWM

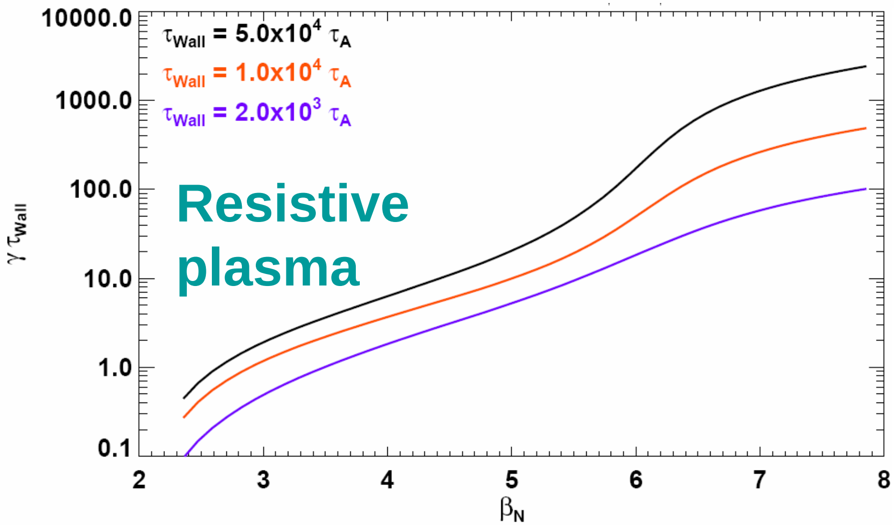
Compute γ with varied τ_{WALL}

NSTX

- Ideal plasma
  - $\gamma\tau_{WALL} \approx$ constant
  - $\gamma \approx \gamma_{Alfven}$ above ideal-wall limit
- Resistive plasma:
  - η increases $\gamma\tau_{WALL}$ for large τ_{WALL}
    - Factor of 2 in γ near C_β = 0.5
  - Apparent lowering of no-wall limit

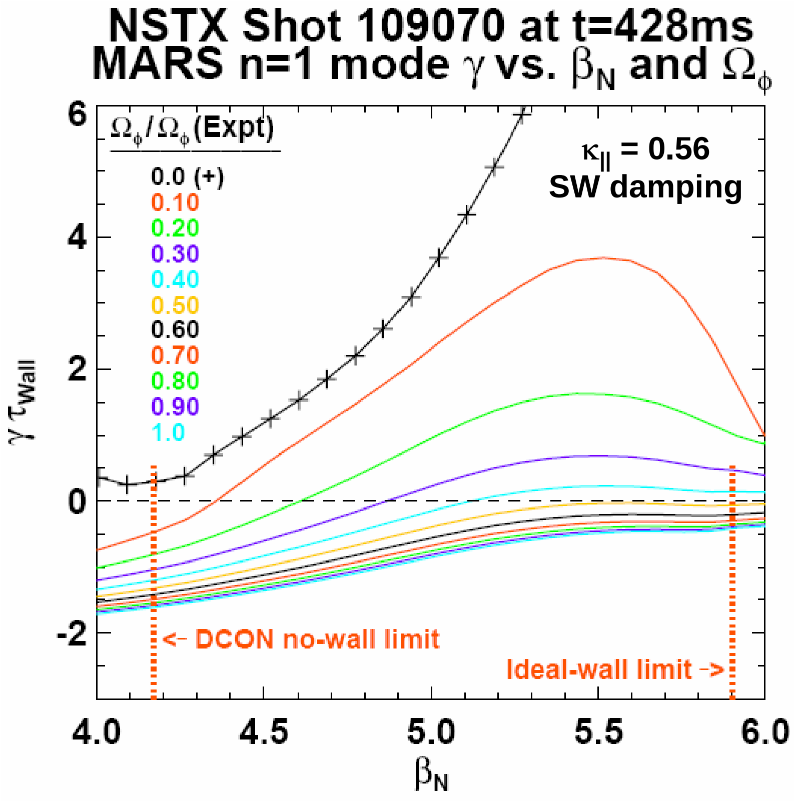


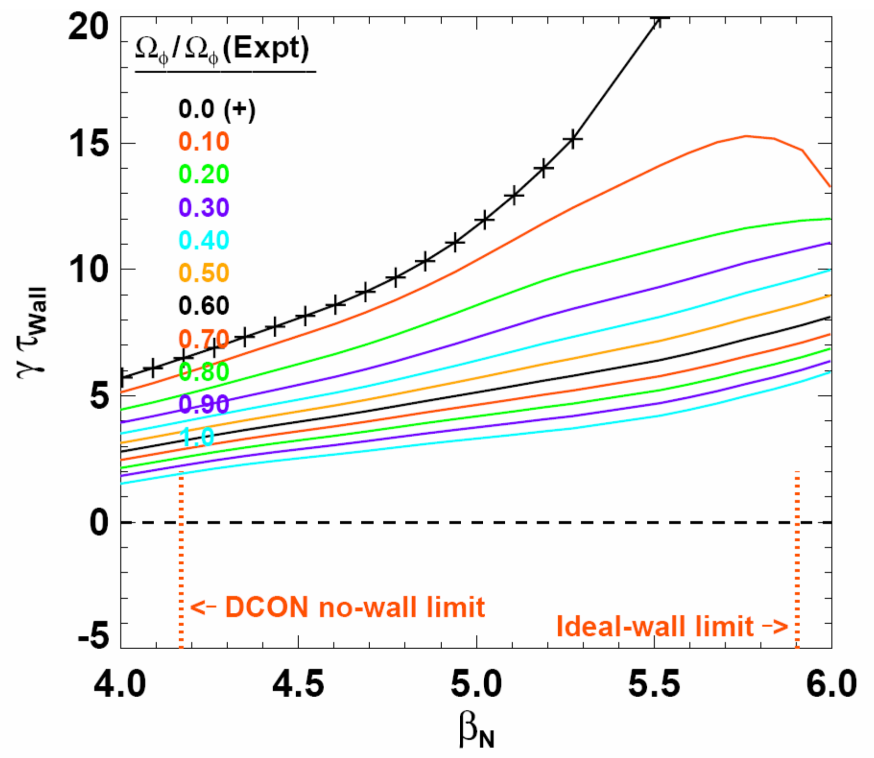




Plasma η can affect rotational stabilization of RWM

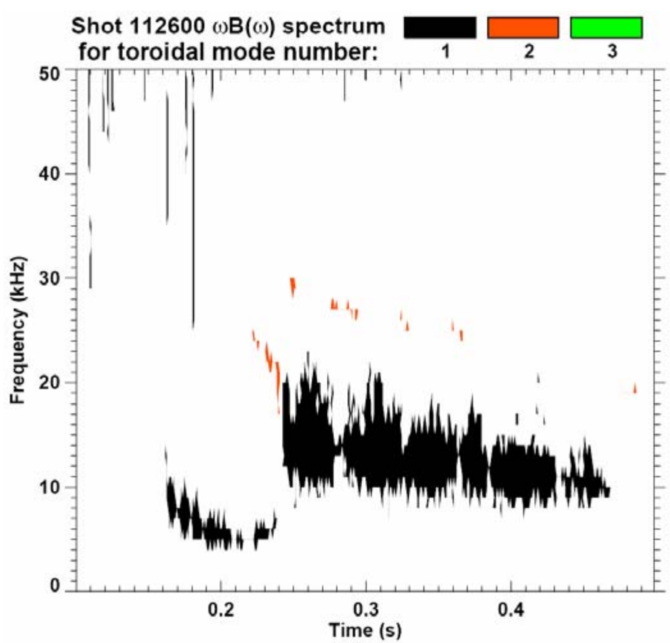
- Usual RWM stabilization via rotation observed for $\eta = 0$ with strong dissipation
- For this case, the RWM is not stabilized when $\eta = \eta_{EXPT}$
- Saturated RWM, TM, or η-kink?
  - Mode has $\omega\tau_{WALL} \approx 40$ (f = few kHz)

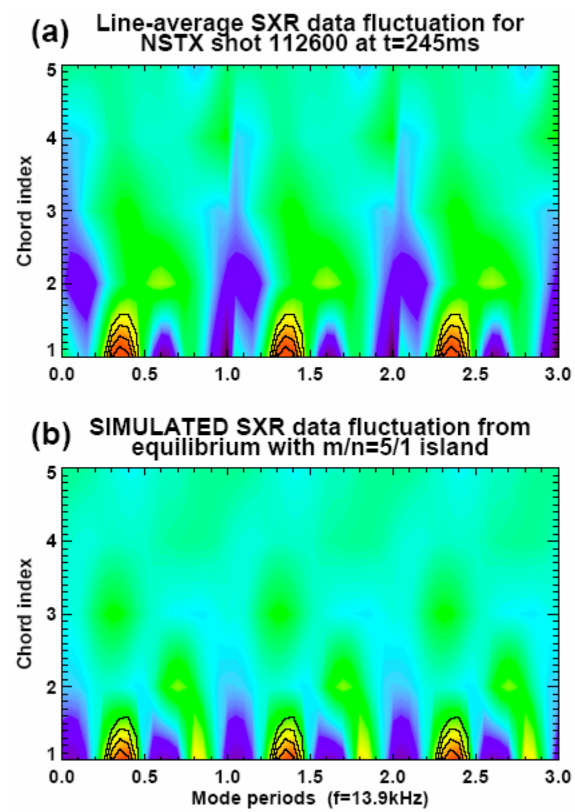


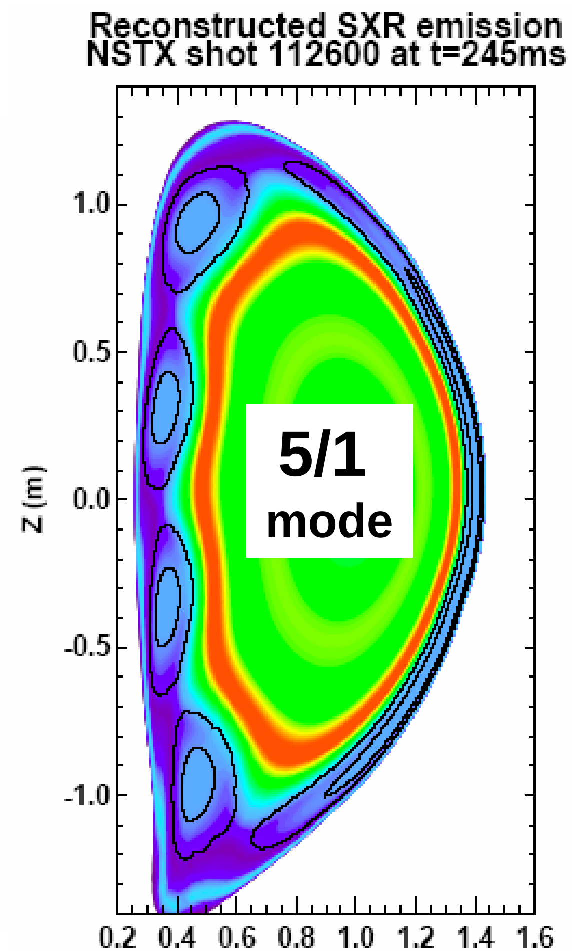


Some evidence for saturated modes on NSTX

- Broad J profile (early H-mode) excites long-lived n=1 mode
  - SXR consistent with m=5 edge island
    - Mirnovs show m ≥ 4 on similar shots
- Is this tearing of the plasma mode above the no-wall limit?
  - Result of low edge η in NSTX?







Summary

- Systematic stability studies find sustained AT operation with $\beta_N > 4$ difficult for typical profiles
  - Proximity to ideal-wall limit can excite n=1-3 TMs
    - **This effect can be modeled in MARS by including resistivity**
    - **Sheared rotation also destabilizing near ideal-wall limit**
- Collisionless/resonant dissipation models for RWM sensitive to presence of q=2 surface in plasma
  - MARS predicts n=1 RWM more unstable when $q_{min} > 2$
- Initial calculations for NSTX find plasma η can destabilize the RWM even with dissipation and Ω_ϕ
  - Dependence on S, profiles, etc. not yet clear
  - May result in weakly unstable modes that tear and saturate