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MARS analysis of rotational stabilization of the RWM in NSTX & DIII-D AT plasmas

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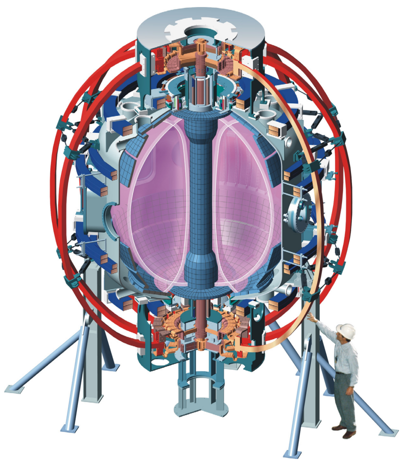
Thanks to M.S. Chu and A. Bondeson for their help

Active Control of MHD Stability: Extension to the Burning Plasma Regime



Monday, November 3, 2003
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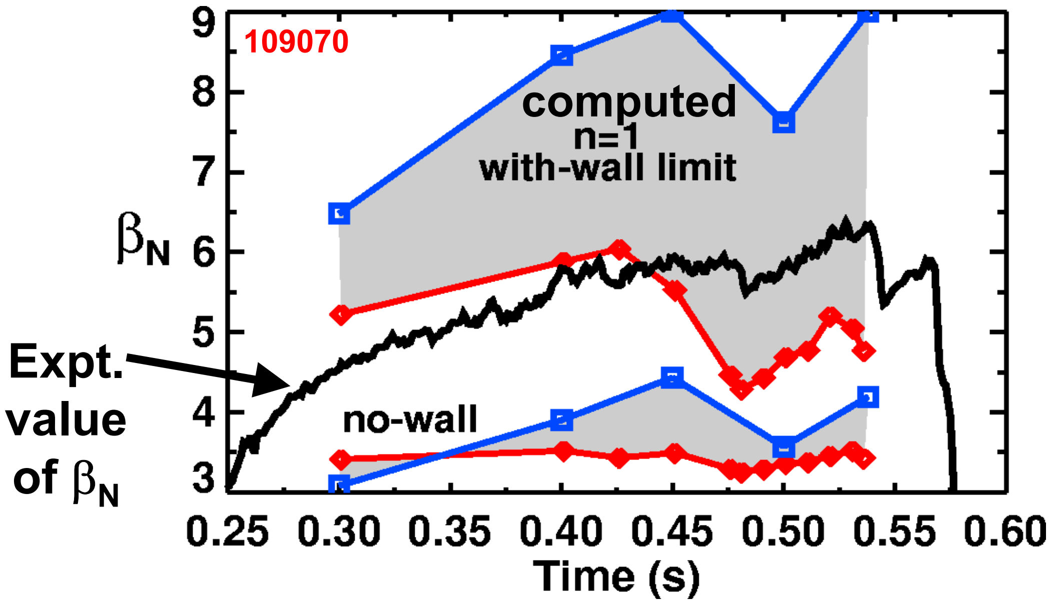
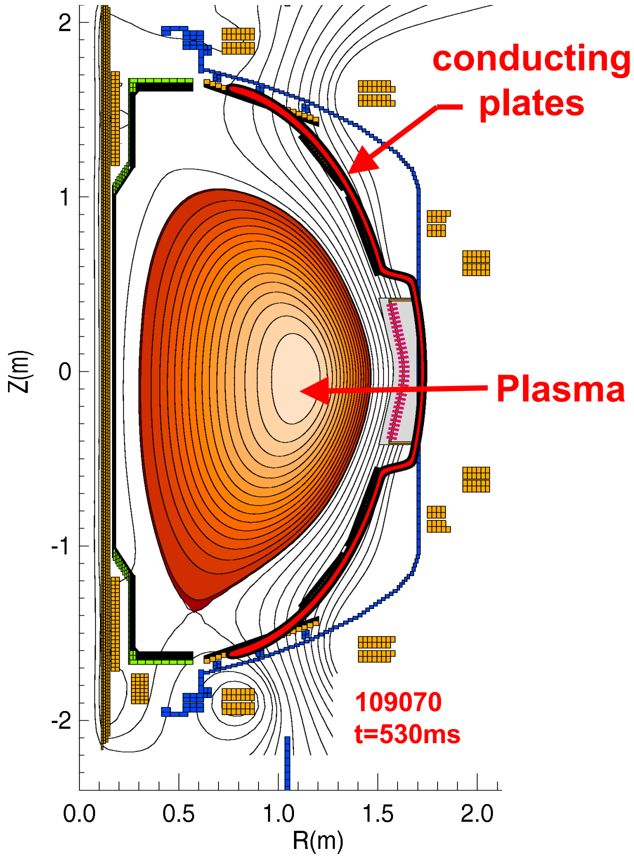
Motivation

- Learning new codes more fun than vacation
- Aid understanding of rotational stabilization of RWM in NSTX long-pulse discharges
  - Sustained operation above no-wall limit observed
  - Eventually want to model EFA for NSTX
- Assess stability in DIII-D AT plasmas
  - How do RWM and plasma mode stability change with q profile and shape? (work in progress…)

Elevated *q* sustains operation above no-wall limit

- Increase *q* the old-fashioned way:
  - Raise field from 0.3T to 0.5T + early H-mode
  - Decrease current to 0.8MA $\Rightarrow f_{BS} \rightarrow 50\%$
- Operate with $\beta_N > 5$ for $\Delta t > \tau_{CR}$=0.25s
  - **No rotation slow-down or evidence of RWM**





- Stabilization of RWM with rotation+dissipation demonstrated on DIII-D
- **Compare NSTX RWM predictions to DIII-D using MARS code**

MARS linear resistive MHD model

NSTX

See Chu, et al., PoP 1995 and Bondeson & Ward, PRL 1994

MARS solves 10 coupled differential equations for perturbed p, **b**, **v**, **j** yielding a complex eigenvalue (growth rate)

$$(\tilde{\gamma}+\underline{in\Omega_0})p_1 = -(\mathbf{v}_1\cdot\nabla)p_0 - \Gamma p_0 \nabla\cdot\mathbf{v}_1, \quad (10)$$

Pressure (p)

$$(\tilde{\gamma}+\underline{in\Omega_0})\mathbf{b}_1 = \nabla\times(\mathbf{v}_1\times\mathbf{B}_0 - \eta\mathbf{j}_1) + \underline{(\mathbf{b}_1\cdot\nabla\Omega_0)R^2\nabla\phi}, \quad (11)$$

Ohm's law (**b**)

$$\rho(\tilde{\gamma}+\underline{in\Omega_0})\mathbf{v}_1 = -\nabla p_1 + \mathbf{j}_1\times\mathbf{B}_0 + \mathbf{j}_0\times\mathbf{b}_1 - \underline{\nabla\cdot\mathbf{\Pi}_1} - \underline{\rho_0\mathbf{U}}, \quad (12)$$

Momentum (**v**)

$$\mathbf{j}_1 = \nabla\times\mathbf{b}_1, \quad (13)$$

Ampere's law (**j**)

where $\tilde{\gamma}=\gamma-i\omega$ is the complex growth rate. In Eq. (12),

$$\mathbf{U} = \mathbf{v}_1\times\left(\frac{\mathbf{v}_0}{R}\times\hat{R}\right) + (\mathbf{v}_1\cdot\nabla)\mathbf{v}_0 \quad (14)$$

and

$$-\nabla\cdot\mathbf{\Pi}_1 = \text{perturbed viscous force.} \quad (15)$$

Damping enters through perturbed viscous force

$$-\nabla\cdot\mathbf{\Pi} = \mathscr{F}_{S,D} \qquad \mathscr{F}_{SD} = -\kappa_\parallel\sqrt{\pi}|k_\parallel v_{\text{th }i}|\rho\mathbf{v}_1\cdot\hat{b}\hat{b},$$

Sound wave damping model

Code Execution Details (1)

- Generate CHEASE input files from GEQDSK
  - Use IDL routines to compute $I_{||} \equiv \langle J \bullet B \rangle / \langle B \bullet \nabla\phi \rangle$
    - Fixing this profile in CHEASE allows p' and β to be scaled with little change in I_P and $q(\psi) \Rightarrow \beta \propto \beta_N$
      - Fixing FF′ while scaling p' (i.e. β) leads to large variations in $q(\psi)$
  - Scale p' to span no-wall and ideal-wall limits
    - Typically use 50+ equilibria in β scan
    - Use IDL to write $I_{||}$, p', and boundary data for CHEASE input

- Run CHEASE $\rightarrow$ DCON and MARS input files
  - Use DCON to find no-wall and ideal-wall limits
  - Use knowledge of limits to aid MARS scans

Code Execution Details (2)

- After CHEASE, primary difficulty in using MARS is finding & tracking eigenvalues
  - Generally, MARS will converge rapidly given a good initial guess
  - The eigenvalue from a nearby β is often a good guess
    - This is the reason for the high-resolution β scan
    - Wall position and rotation scans can be accomplished the same way

- Different modes use different first guesses and tracking
  - Initial plasma mode γ most easily found above ideal-wall limit
    - $\gamma\tau_A$ of a few % is typical
    - Scan downward in β_N until $\gamma = 0$, after which mode not easily tracked.
  - Initial RWM γ most easily found between no-wall and ideal-wall limits
    - $\gamma\tau_W$ of a few is typical
    - Scan upward and downward in β_N toward no-wall and ideal-wall limits

Equilibrium details of NSTX & DIII-D cases studied

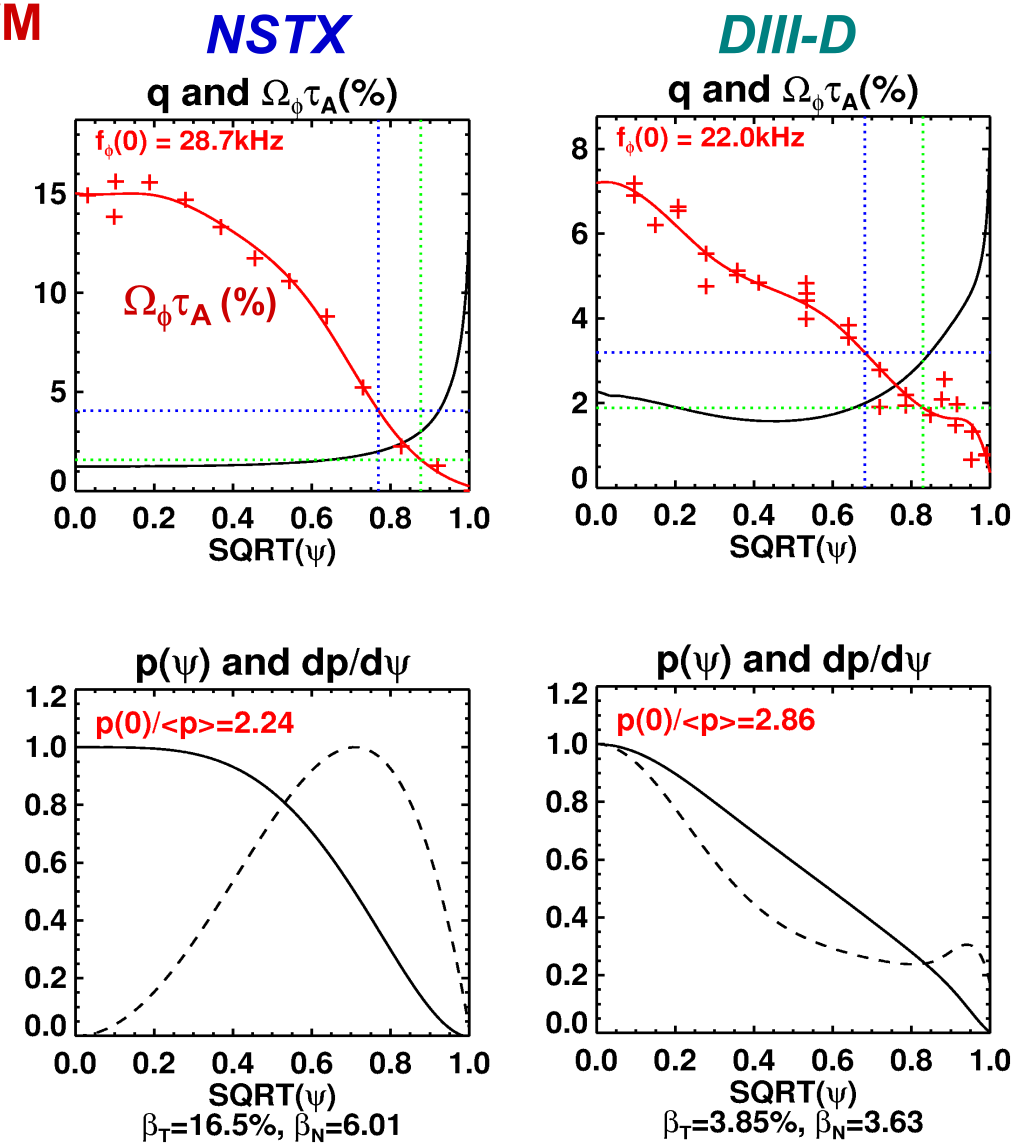
Neither discharge exhibits n=1 RWM

NSTX 109070: LSN, 0.8MA, 0.5T
n=1 internal disruptions at $\beta_N \approx 6$

DIII-D 113850: DND, 1.2MA, 1.8T
n ≤ 3 ELM-like bursts limit $\beta_N \approx 4$

	NSTX 109070, 429ms	DIII-D 113850, 2802ms
q_{95}	7	5
q_0	1.3	2.3
q_{min}	1.3	1.6
r/a(q=2)	0.77	0.68
$\Omega_\phi\tau_A$(r=0)	15%	7%
$\Omega_\phi\tau_A$(q=2)	4.1%	3.2%
l_i	0.83	0.79
$p(0)/\langle p\rangle$	2.2-2.7	2.8-2.9

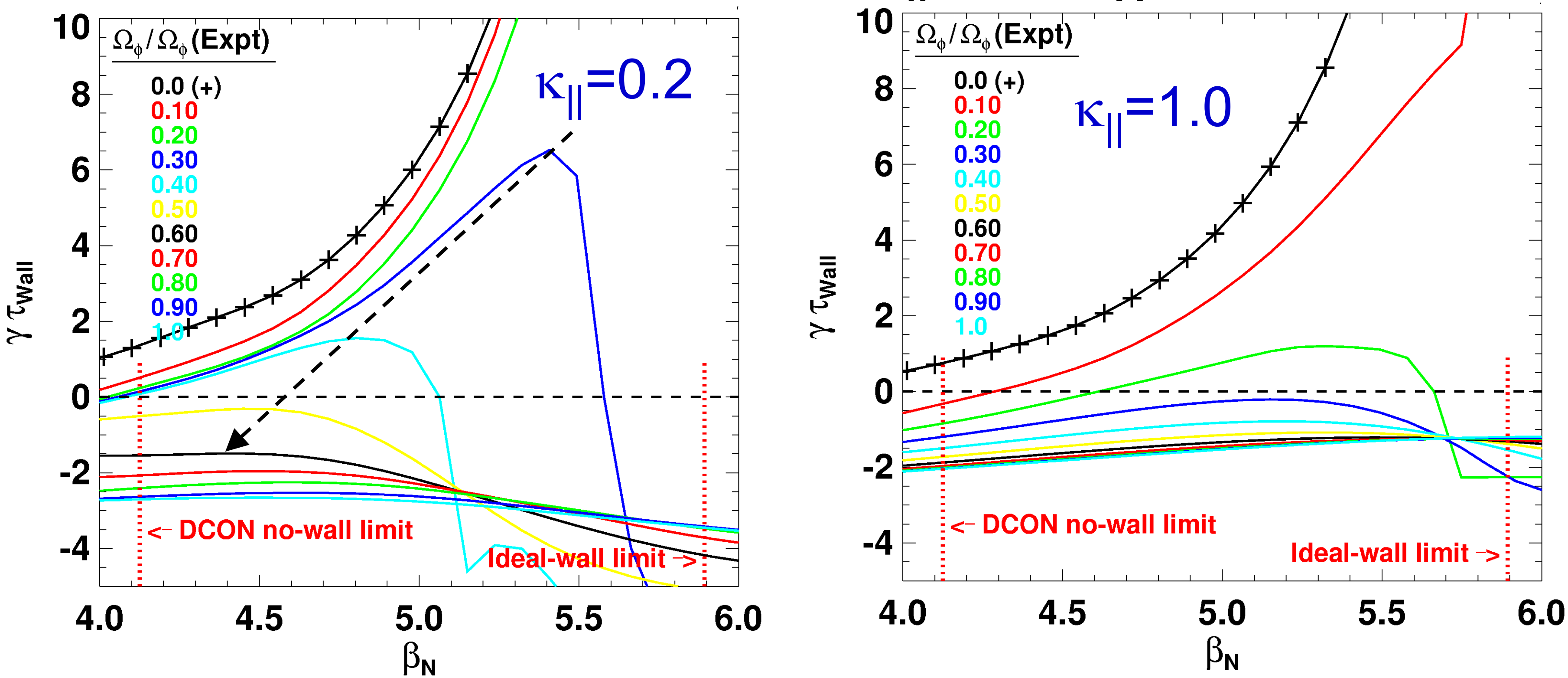
NOTE: NSTX w/o MSE



NSTX RWM growth rate vs. β_N, Ω_ϕ, $\kappa_{||}$

- RWM critical $\Omega_\phi \tau_A$ (q=2) = 2.1% for $\kappa_{||}$ = 0.2, 1.3% for $\kappa_{||}$=1
  - β_N at critical $\Omega_\phi \tau_A$ decreases with weaker dissipation
  - Damping rate of stable RWM higher with weaker dissipation

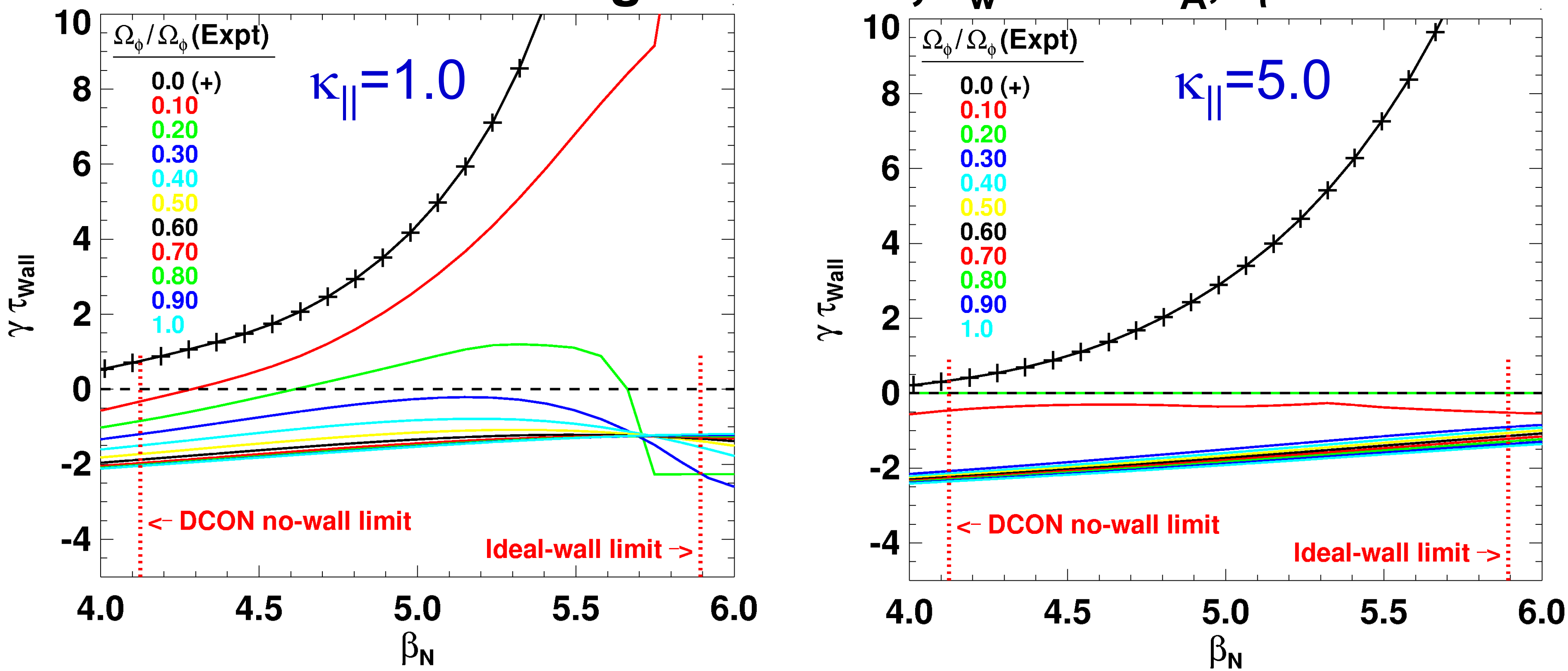
MARS n=1 growth rate, $\tau_w = 10^4 \tau_A$, η=0



NSTX RWM growth rate vs. β_N, Ω_ϕ, $\kappa_{||}$

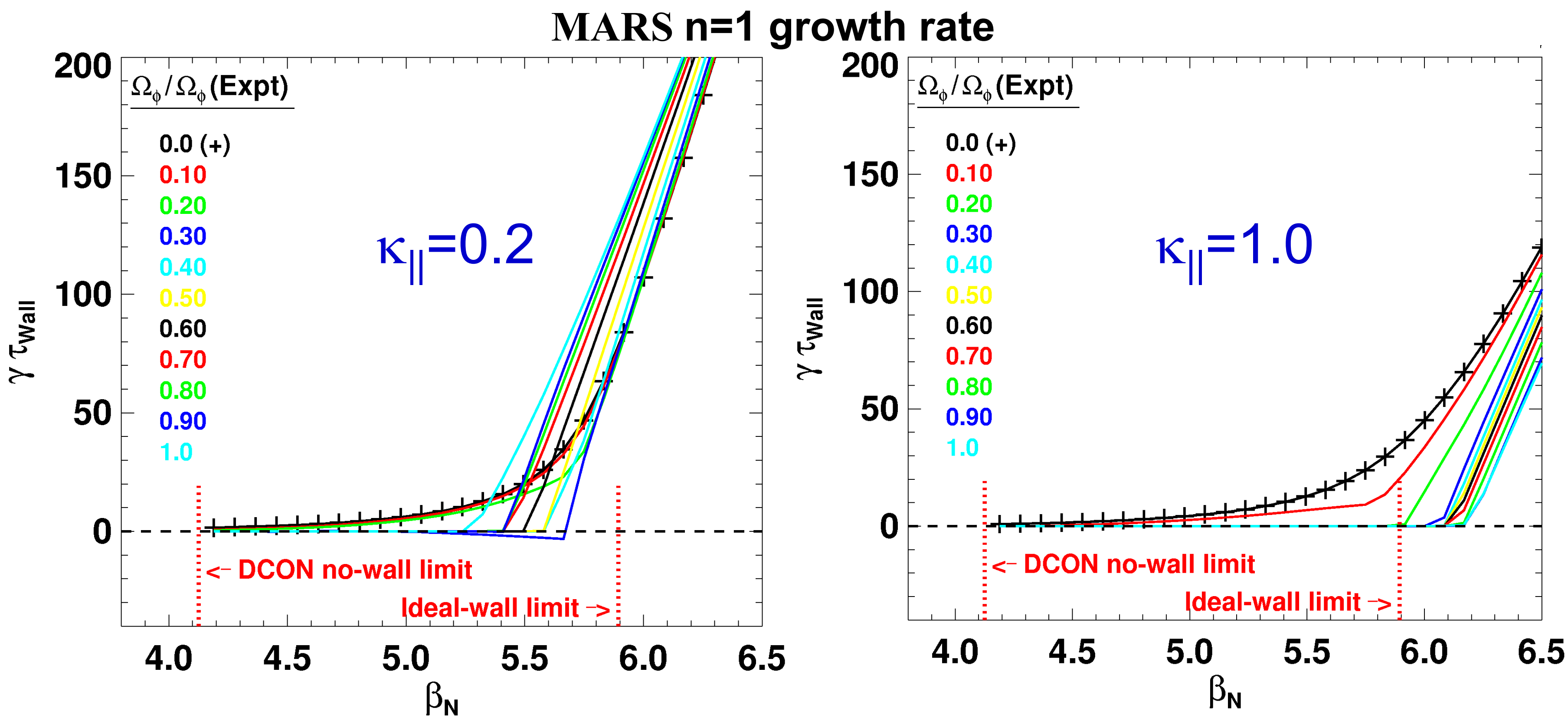
- In high dissipation limit at high rotation, stable RWM damping rate becomes nearly independent of rotation and β_N
  - $\gamma\tau_{Wall} \rightarrow$ approximately -2 (no-wall) to –1 (ideal-wall)

MARS n=1 growth rate, $\tau_w = 10^4\ \tau_A$, η=0



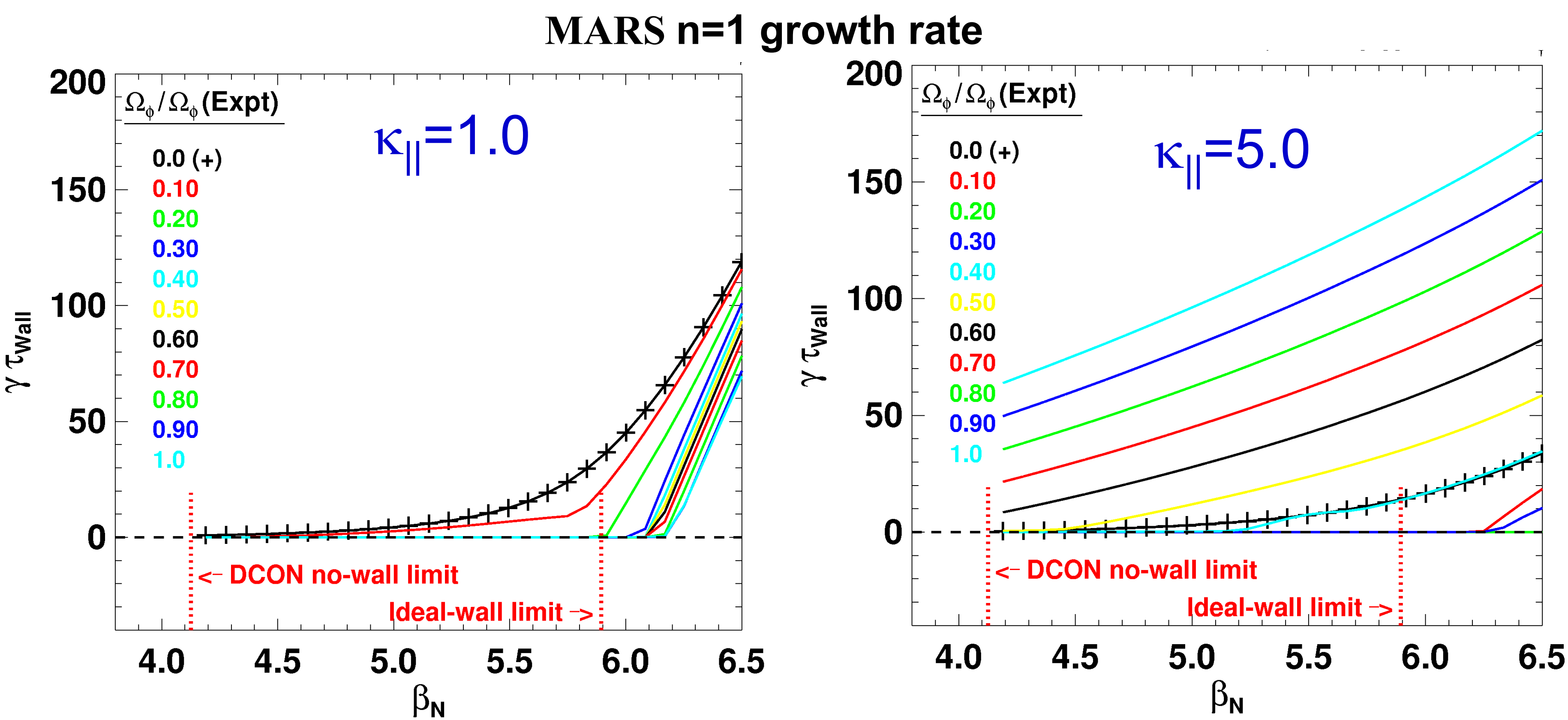
Dissipation can modify plasma mode stability

- Lowest $\kappa_{||}$ destabilizing as $\Omega_\phi \rightarrow \Omega_\phi$(expt)
- Higher $\kappa_{||}$ stabilizing as $\Omega_\phi \rightarrow \Omega_\phi$(expt)
- Not obvious what controls this dependence…



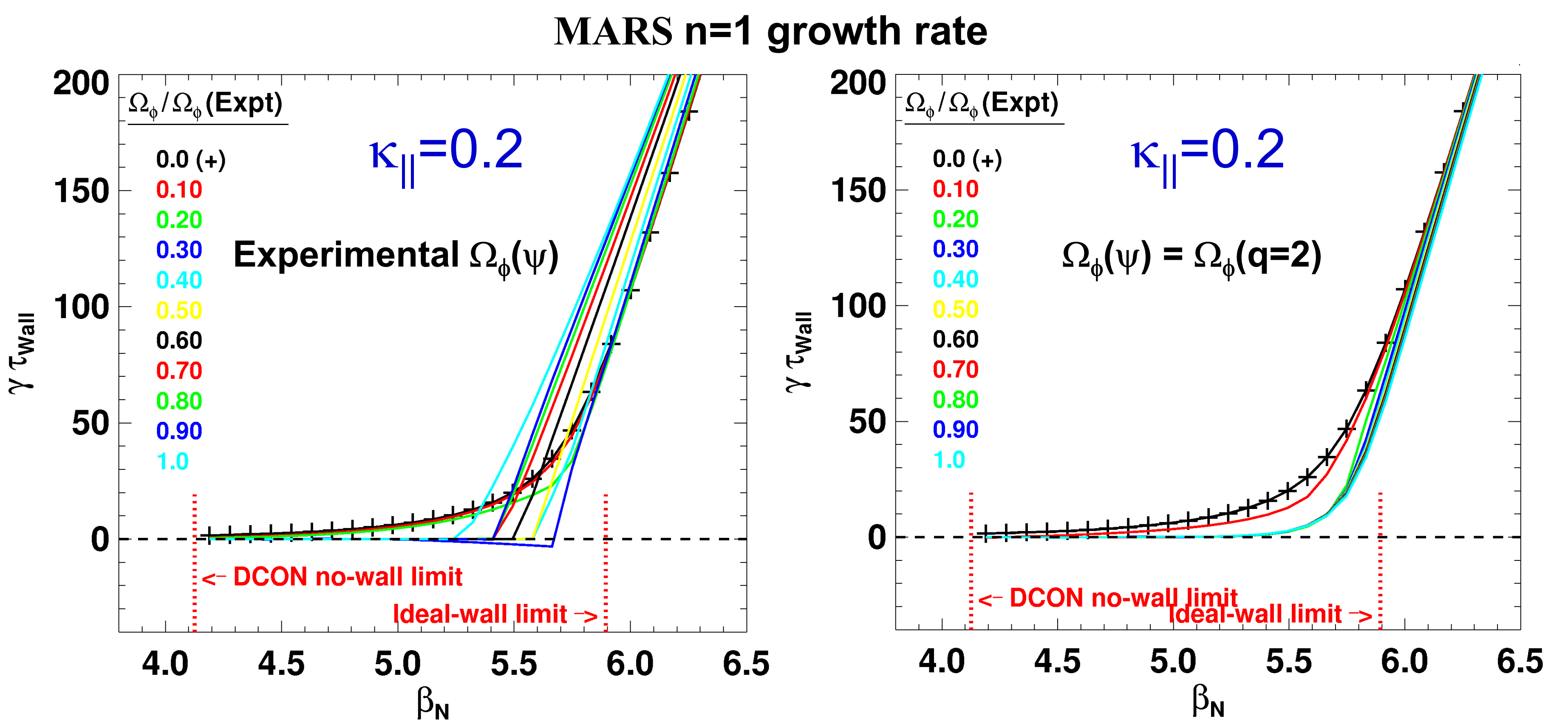
Very high dissipation unphysically destabilizing

- $\kappa_{||}$=5.0 destabilizes plasma mode below no-wall limit
  - This trend implies the sound wave damping coefficient cannot be much larger than 1 – same trend found for DIII-D AT modeling
  - Plasma mode still satisfies $\omega\tau_W$ >> 1 (not shown)….



Ω_ϕ' controls $\gamma(\Omega_\phi, \beta_N)$ dependence

- Flat Ω_ϕ profile with $\Omega_\phi(\psi) = \Omega_\phi(q=2)$ makes growth rate independent of rotation at high rotation values
  - Consistent with previous analytic treatments which assume flat rotation

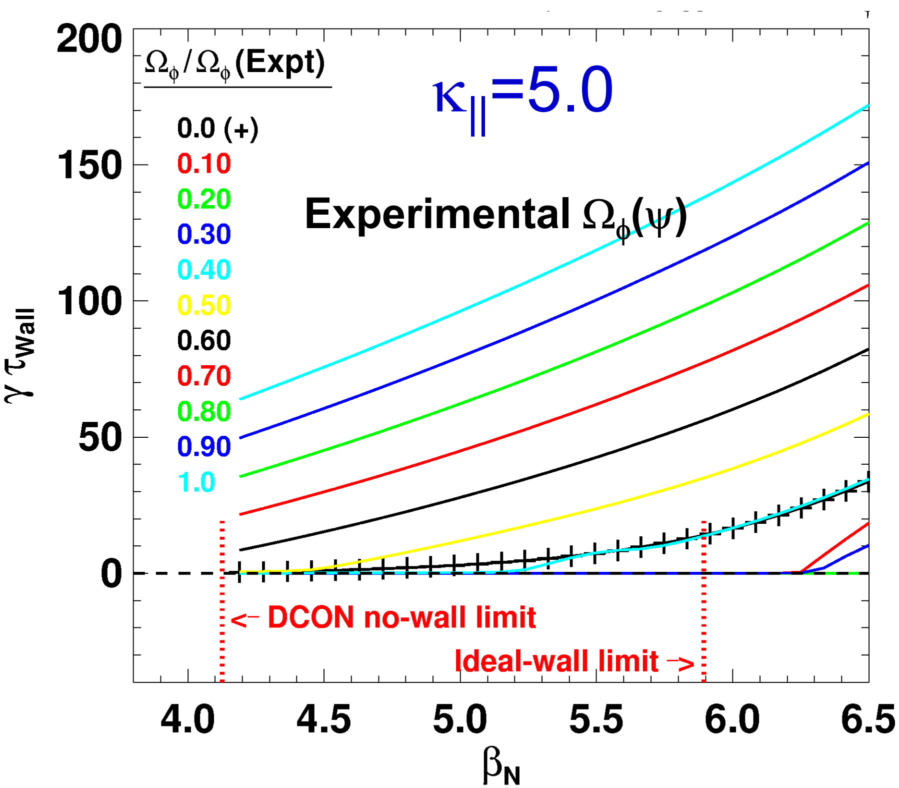


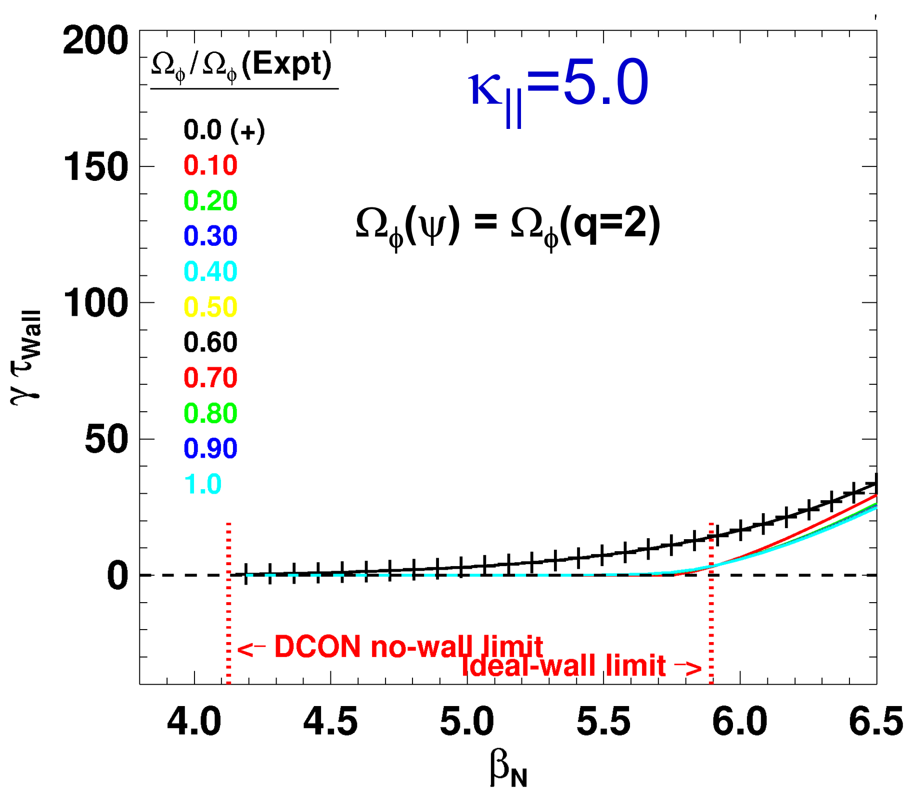
$\Omega_\phi{}'$ effect on $\gamma(\Omega_\phi, \beta_N)$ independent of $\kappa_{||}$

NSTX

- $d\Omega_\phi / d\psi$ effect dramatic with very high dissipation
- Local (resonant) or global effect? (I need to look at the eigenfunctions…)
- Flow-shear changes mode $\delta\mathbf{B}$ polarization - impacts wall stabilization?
  - Possible contributing factor: **$\delta\mathbf{B}_r$ coupled to $\delta\mathbf{B}_\phi$ through $\nabla\Omega_\phi$**

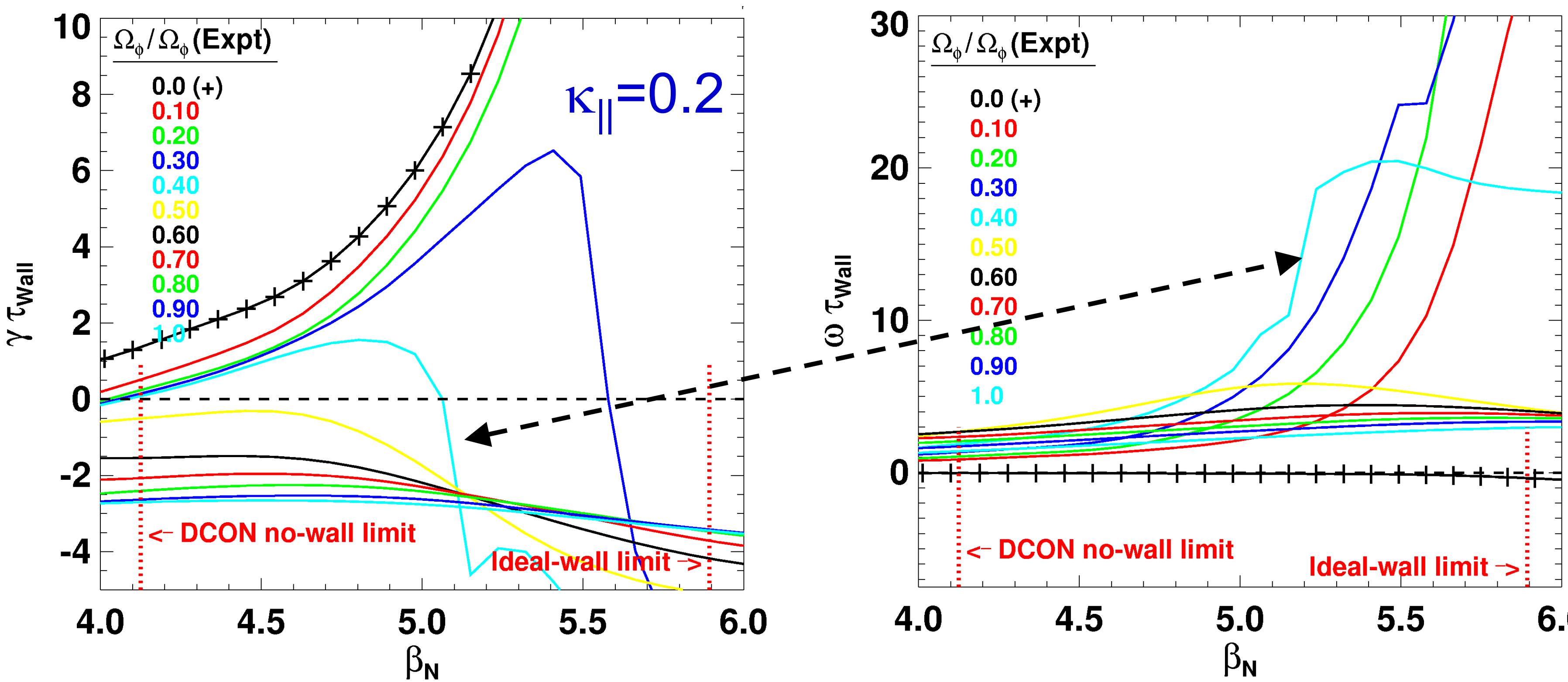
$$(\tilde{\gamma}+in\Omega_0)\mathbf{b}_1=\nabla\times(\mathbf{v}_1\times\mathbf{B}_0-\eta\mathbf{j}_1)+(\mathbf{b}_1\cdot\nabla\Omega_0)R^2\nabla\phi$$





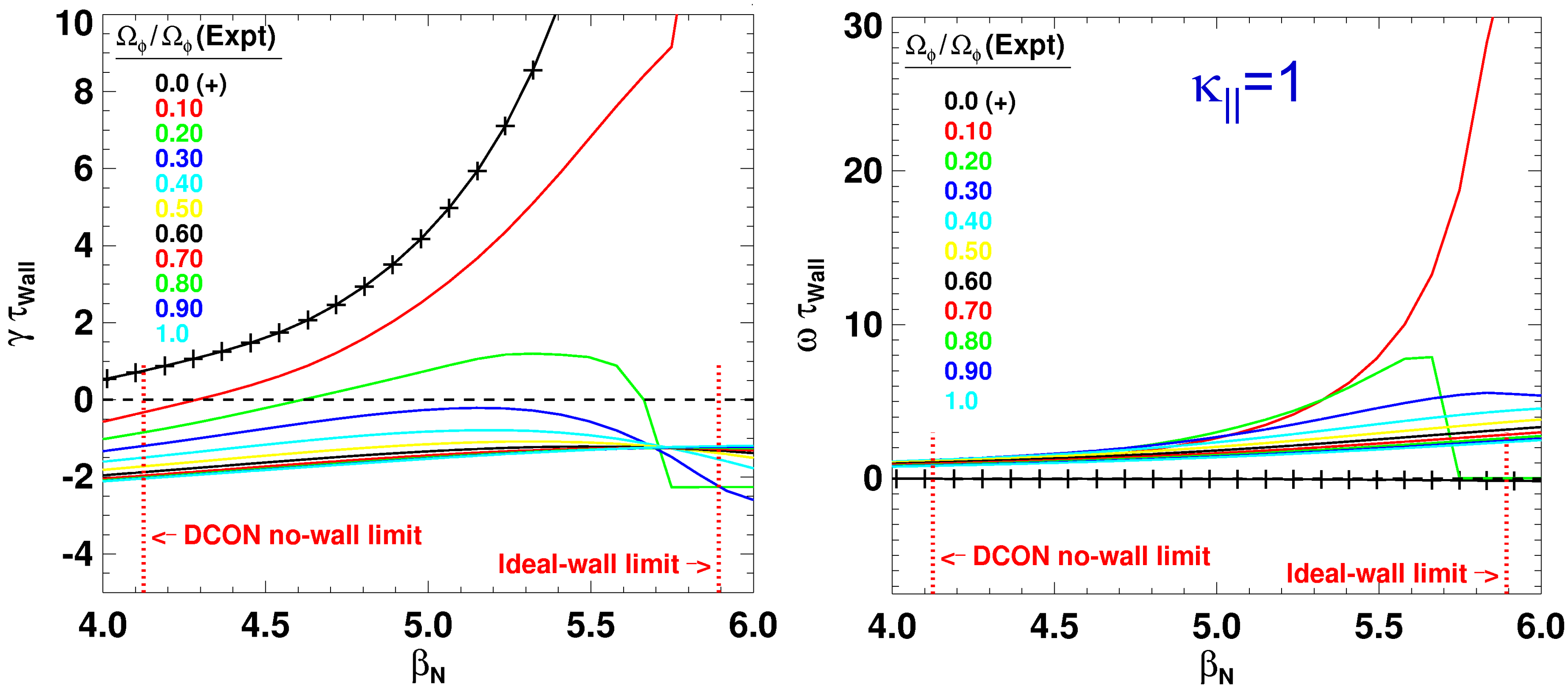
RWM ω sensitive to Ω_ϕ at low $\kappa_{||}$

- RWM $\omega\tau_W$ >> 1 in stable gap near ideal-wall limit when rotation is below critical rotation frequency
- Would MHD spectroscopy show higher resonant frequency?
  – Note ω is roughly constant well above critical Ω_ϕ



RWM $\omega \rightarrow$ weakly dependent on Ω_ϕ at higher $\kappa_{||}$

- RWM $\omega\tau_W$ >> 1 only for unstable RWM
- Note ω is again roughly constant well above critical Ω_ϕ

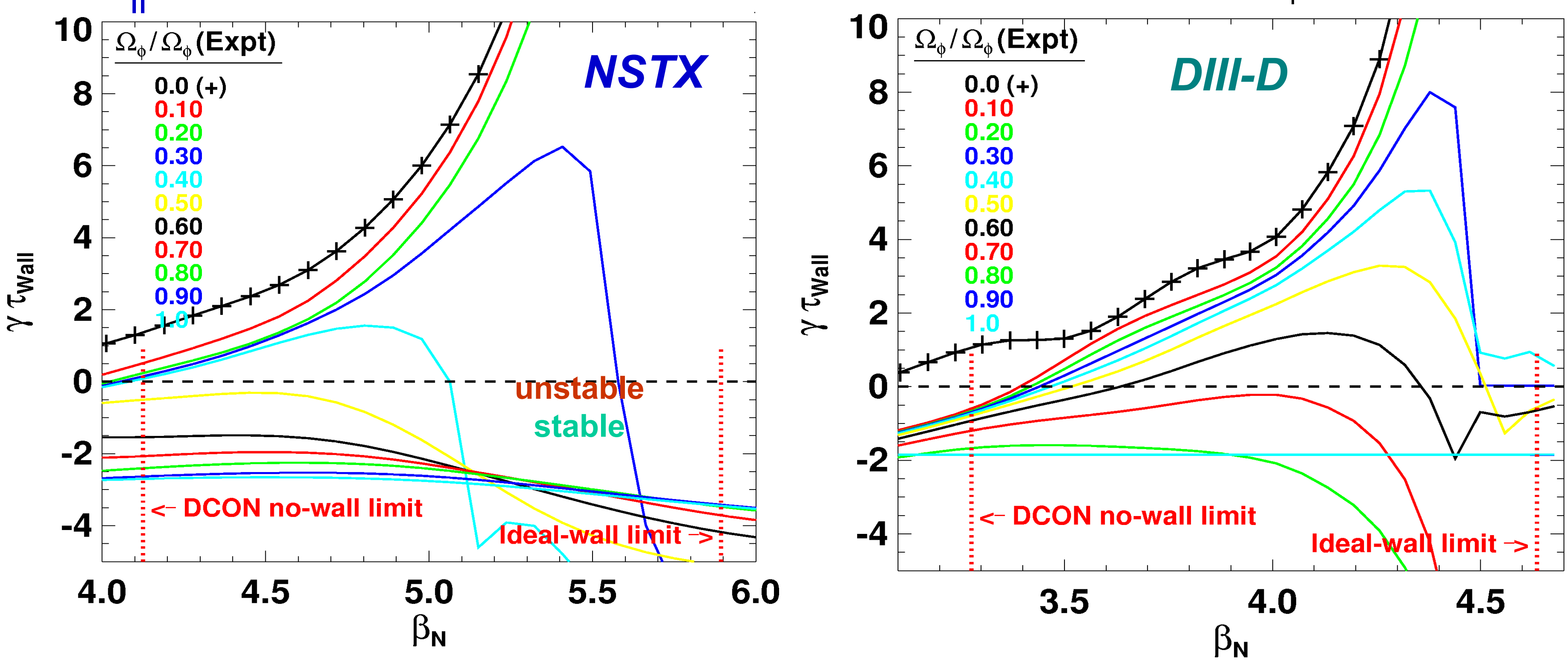


Stability comparison between NSTX and DIII-D

- **RWM computed *stable* at experimental rotation value for both**
  - RWM critical $\Omega_\phi \tau_A$ (q=2) = 2.1% for $\kappa_{||}$ = 0.2
  - $\Omega_\phi \tau_A$ (q=2) = 1.3% for $\kappa_{||}$=1

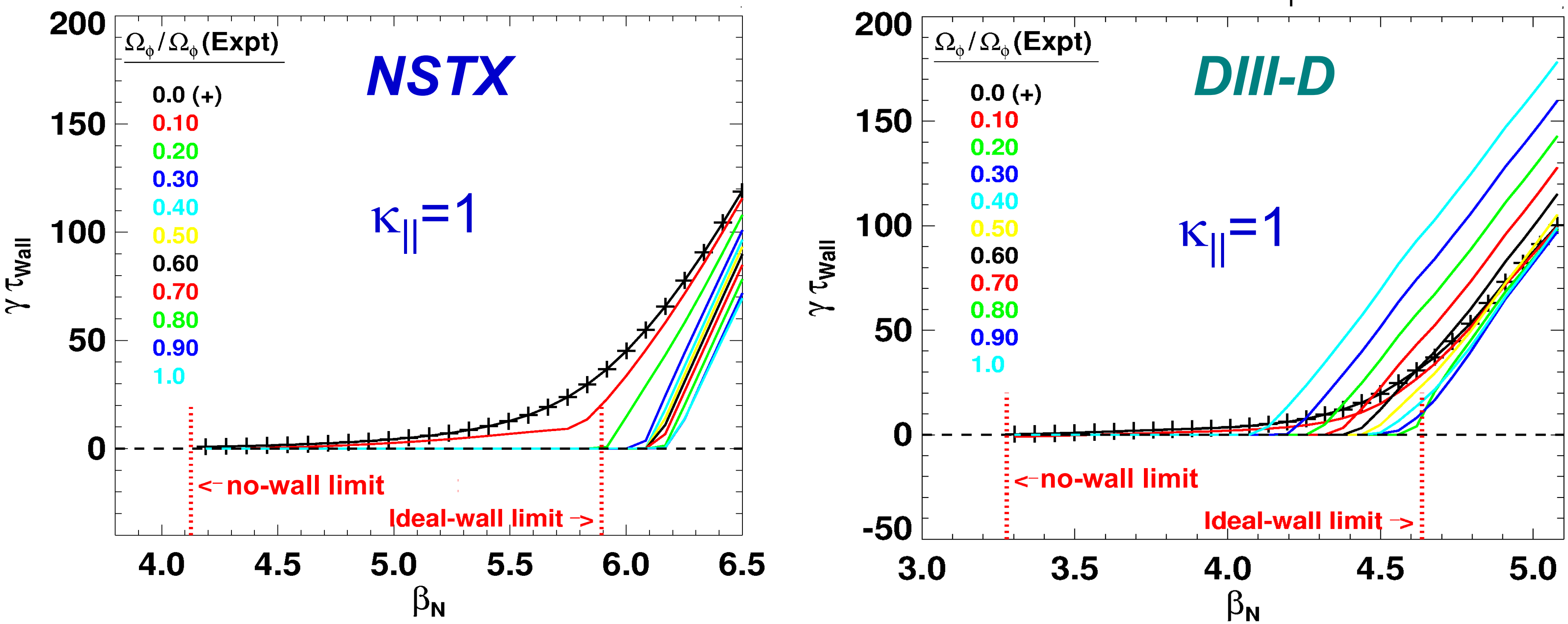
MARS n=1 growth rate vs. β_N and Ω_ϕ

$\kappa_{||}$=0.2 $\kappa_{||}$=0.2



Plasma mode stabilized at 20-30% of experimental Ω_ϕ

MARS n=1 growth rate vs. β_N and Ω_ϕ



- **As $\Omega_\phi \rightarrow \Omega_\phi$(expt), marginal stability can vary with Ω_ϕ, $\kappa_{||}$**
  - Example: $\kappa_{||}$**=0.2** and Ω_ϕ=Ω_ϕ**(expt)** $\Rightarrow$ **NSTX β_N limit = 6.1$\rightarrow$ 5.3, DIII-D 4.1 $\rightarrow$ 4.3**
    - *Inconsistent with NSTX reaching β_N = 6*
- **Need to consider both RWM and plasma mode in ST & AT optimization**

Summary and future plans

- NSTX high-*q* discharges operate above no-wall limit
  - MARS predicts rotational stabilization of n=1 RWM in NSTX
    - **Predictions quantitatively similar to high-β_N DIII-D AT**
  - Plasma mode stability sensitive to Ω_ϕ' and $\kappa_{||}$ at high Ω_ϕ
    - Plasma mode stability $\Rightarrow$ very high dissipation unphysical using SW damping model

- Future
  - Begin using MARS-F
    - Compare sound-wave damping model to "kinetic damping" model
      - Kinetic damping model:
        - » A. Bondeson and M. Chu, Phys. Plasmas, Vol. 3, No. 8, (1996) 3013
        - » Drift-kinetic treatment of MHD (includes trapped particles, no ω_{*i})
        - » good agreement w/ JET data
    - Assess how rotational stabilization depends on q profile and shape
    - Apply MARS-F to EFA problem for NSTX