Rotational Stabilization of the Resistive Wall Mode in DIII-D

H. Reimerdes[1]

in collaboration with

J. Bialek,[1] M.S. Chance,[2] M.S. Chu,[3] A.M. Garofalo,[1] P. Gohil,[3] G.L. Jackson,[3]
R.J. Jayakumar,[4] T.H. Jensen,[3] R.J. La Haye,[3] Y.Q. Liu,[5] J.E. Menard,[2]
G.A. Navratil,[1] M. Okabayashi,[2] J.T. Scoville,[3] E.J. Strait[3] and H. Takahashi[2]

[1]Columbia University, New York, New York, USA
[2]Princeton Plasma Physics Laboratory, Princeton, New Jersey, USA
[3]General Atomics, San Diego, California, USA
[4]Lawrence Livermore National Laboratory, Livermore, California, USA
[5]Chalmers University of Technology, Göteborg, Sweden

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Outline

- **Passive measurement** of the plasma rotation required for stability $\Omega_{\mathbf{crit}}$
  - Ω_{crit} in two scenarios (low-l_i and moderate-l_i)
  - Comparison with MARS calculations
- **Active measurement** of growth rate $\gamma_{\mathbf{RWM}}$ and mode rotation frequency $\omega_{\mathbf{RWM}}$ of the stable n=1 RWM
  - Measurement of γ_{RWM} and ω_{RWM} with **pulsed fields** in the low-l_i scenario
  - Measurement of γ_{RWM} and ω_{RWM} with **rotating fields** in the moderate-l_i scenario
  - Comparison with MARS calculations
- Summary

Plasma rotation predicted to stabilize the RWM

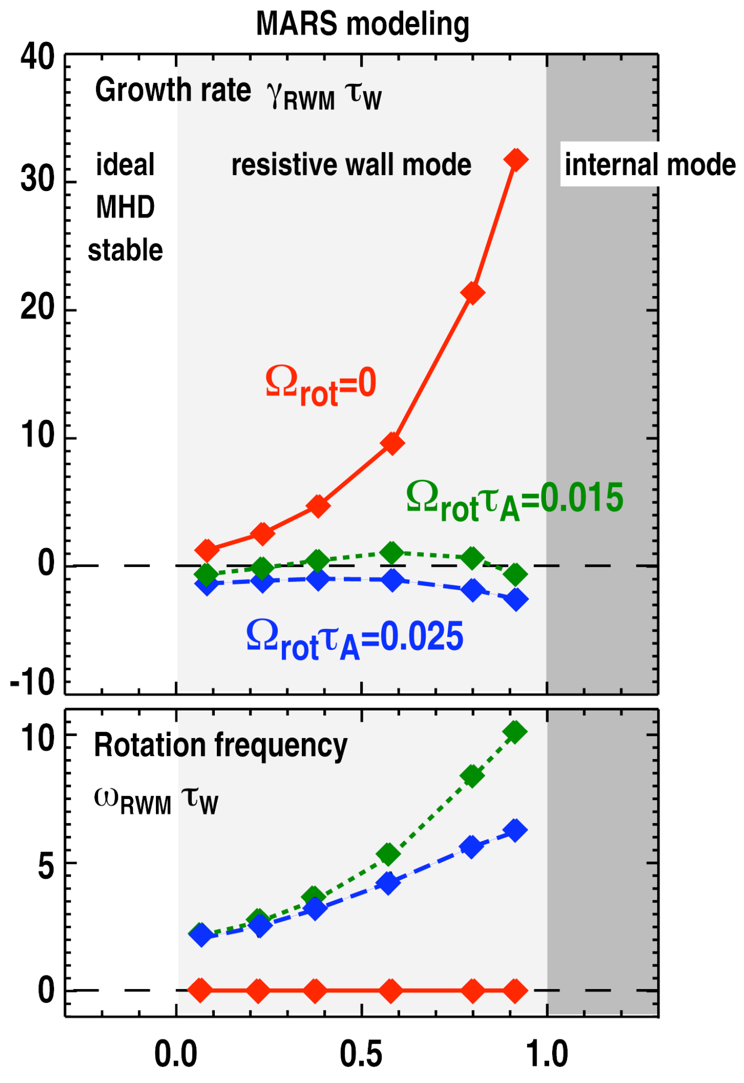
- **Resistive Wall mode (RWM):**

  Free-boundary ideal MHD kink mode in the presence of a resistive wall

  - Observed between no-wall and ideal wall ideal MHD limit
  - "Slow" RWM growth $\gamma_{RWM} \sim \tau_w^{-1}$
    → Stabilization by feedback control
  - "Slow" mode rotation $\omega_{RWM} << \Omega_{rot}$
    → Quasi-static magnetic perturbation in a fast plasma flow

- **Plasma flow** and some **dissipation** alters linear stability [Bondeson and Ward, *Phys Rev Lett* **72** (1994) 2709]

➔ Test dissipation models by comparison of predictions with experiment



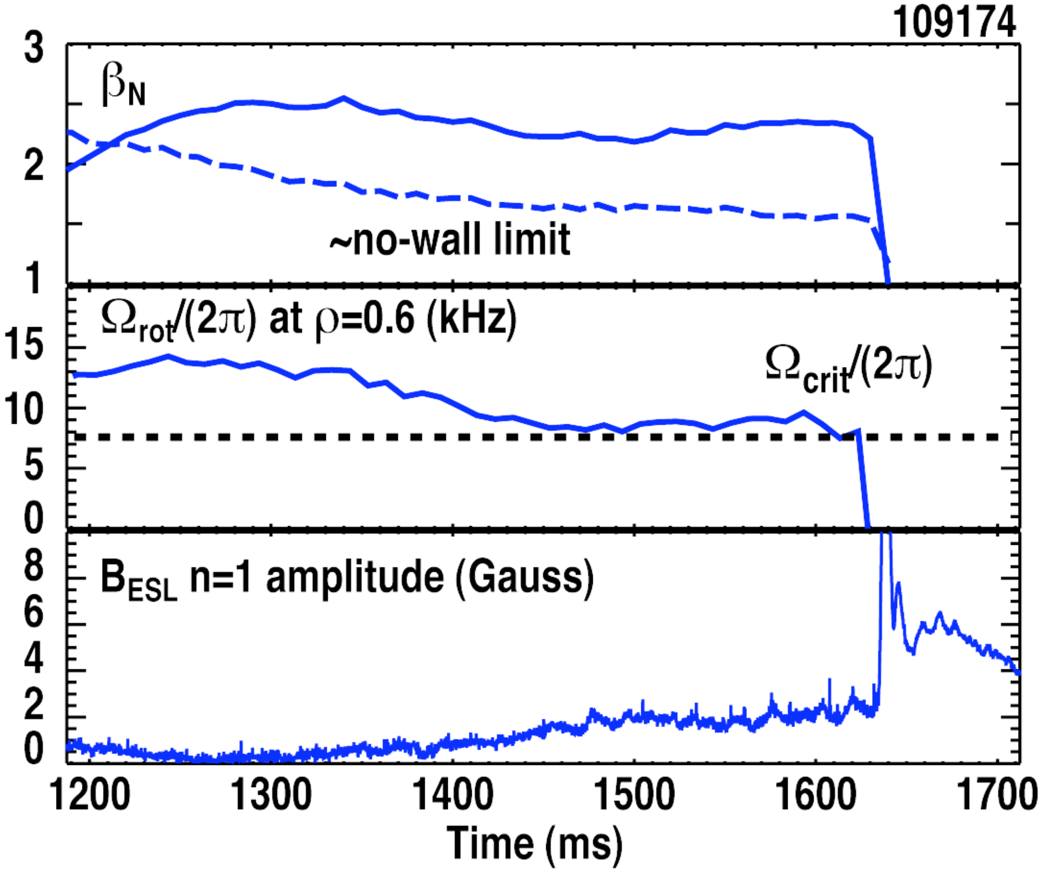
$$C_\beta = \frac{\beta - \beta_{no\text{-}wall}}{\beta_{ideal\text{-}wall} - \beta_{no\text{-}wall}}$$

Several dissipation models are proposed

- **Sound wave damping**: perturbed plasma rotation v_1 couples to sound waves, which are subject to ion Landau damping [Bondeson and Ward, *Phys Rev Lett* **72** (1994) 2709]
  - Described by a parallel viscous force: $\mathbf{F}_{visc} = -\kappa_{||} |k_{||} v_{th,i}| \rho \mathbf{v}_{1||}$
  - Cylindrical theory with a free parameter $\kappa_{||}$ to describe the effects of toroidicty and shaping
- **Kinetic damping**: electromagnetic perturbation kinetically damped through Landau damping process [Bondeson and Chu, *Phys Plasmas* **3** (1996) 3013]
  - No adjustable parameter
- Additional stabilization models
  - Resonance with precession drift frequency [Hu and Betti, *Phys Rev Lett* **93** (2004) 105002]
  - Neoclassical toroidal viscosity [Shaing, *Phys Plasmas* **10** (2003) 1443]

- Main computational tool is the **MARS-F** code [Liu et al, *Phys Plasmas* **7** (2000) 3681], which includes sound wave or kinetic damping model

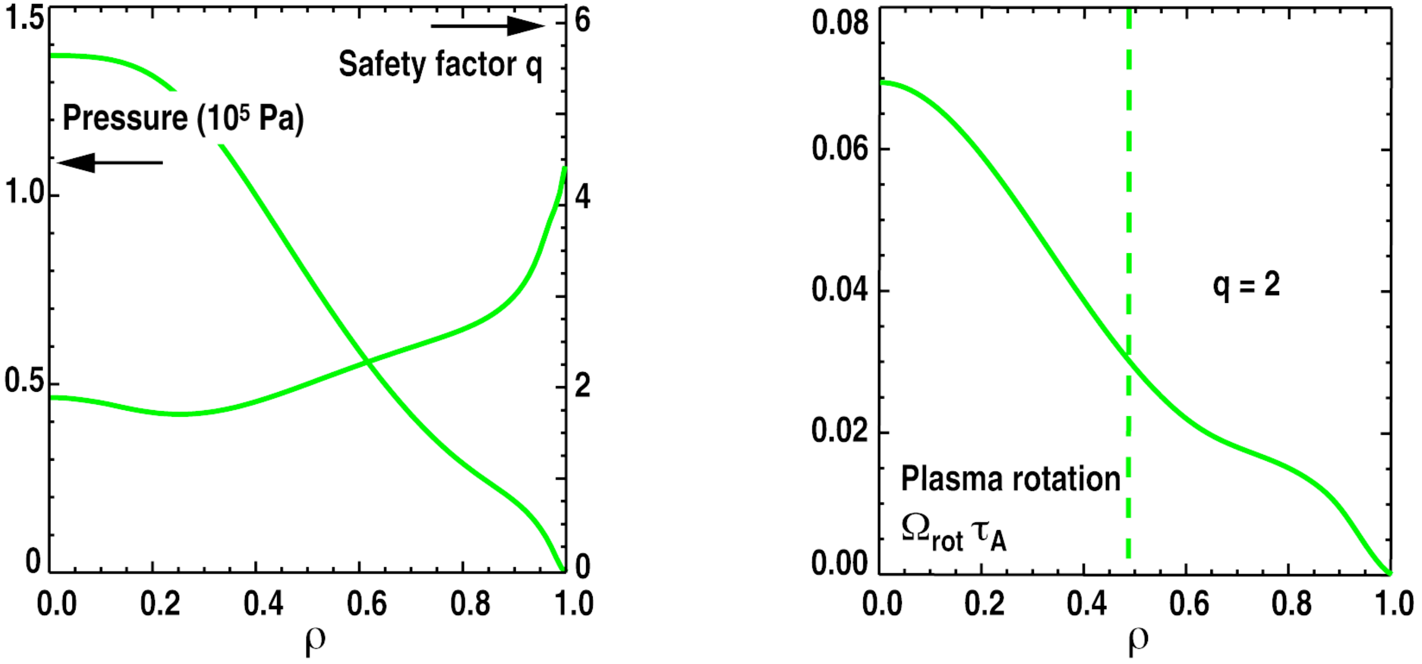
How much plasma rotation is required to stabilize the n=1 RWM?



- Passive measurement of Ω_{crit}
  - Insufficient error field correction causes slow-down of toroidal rotation
  - Onset of RWM marks Ω_{crit}
- Systematic scan of β in a **low-l_i plasma** [R.J. La Haye et al, accepted for publication in *Nucl. Fusion*]
  - Ω_{crit} scales with τ_A^{-1}
- Additional data in a **moderate-l_i plasma**

Equilibrium profiles of low-l_i and moderate-l_i scenarios

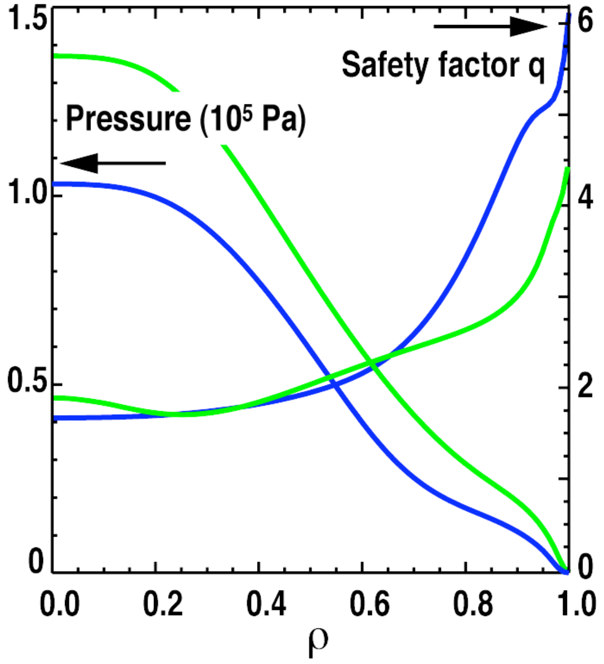
Low-li scenario

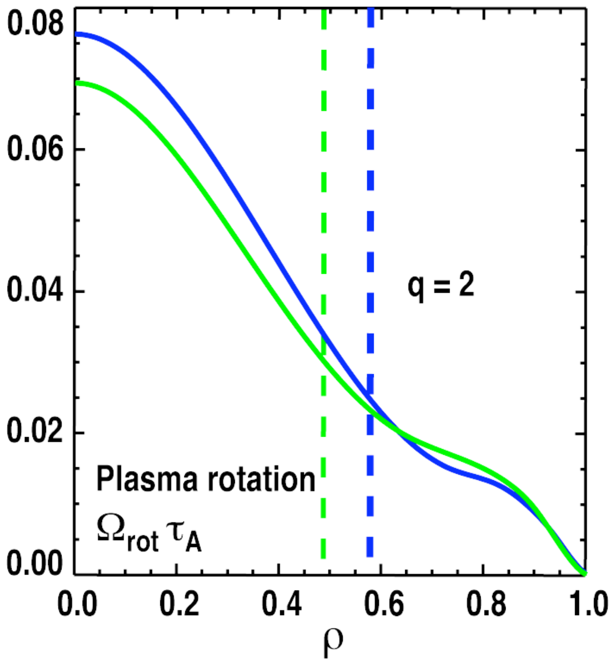


- Low-l_i scenario greatly benefits from wall stabilization
  - $\beta_{N,\text{no-wall}} \sim 1.6 \sim 2.4\, l_i$
  - $\beta_{N,\text{ideal-wall}} \sim 3.2\ (\sim 4.8\, l_i)$

Equilibrium profiles of low-l_i and moderate-l_i scenarios

Low-li scenario / Moderate-li scenario





- Low-l_i scenario greatly benefits from wall stabilization
  - $\beta_{N,\text{no-wall}}$ ~1.6 ~2.4 l_i
  - $\beta_{N,\text{ideal-wall}}$ ~3.2 (~4.8 l_i)

- Moderate-l_i scenario has a higher no-wall limit
  - $\beta_{N,\text{no-wall}}$ ~2.0 ~2.4 l_i
  - $\beta_{N,\text{ideal-wall}}$ ~3.2 (~3.8 l_i)

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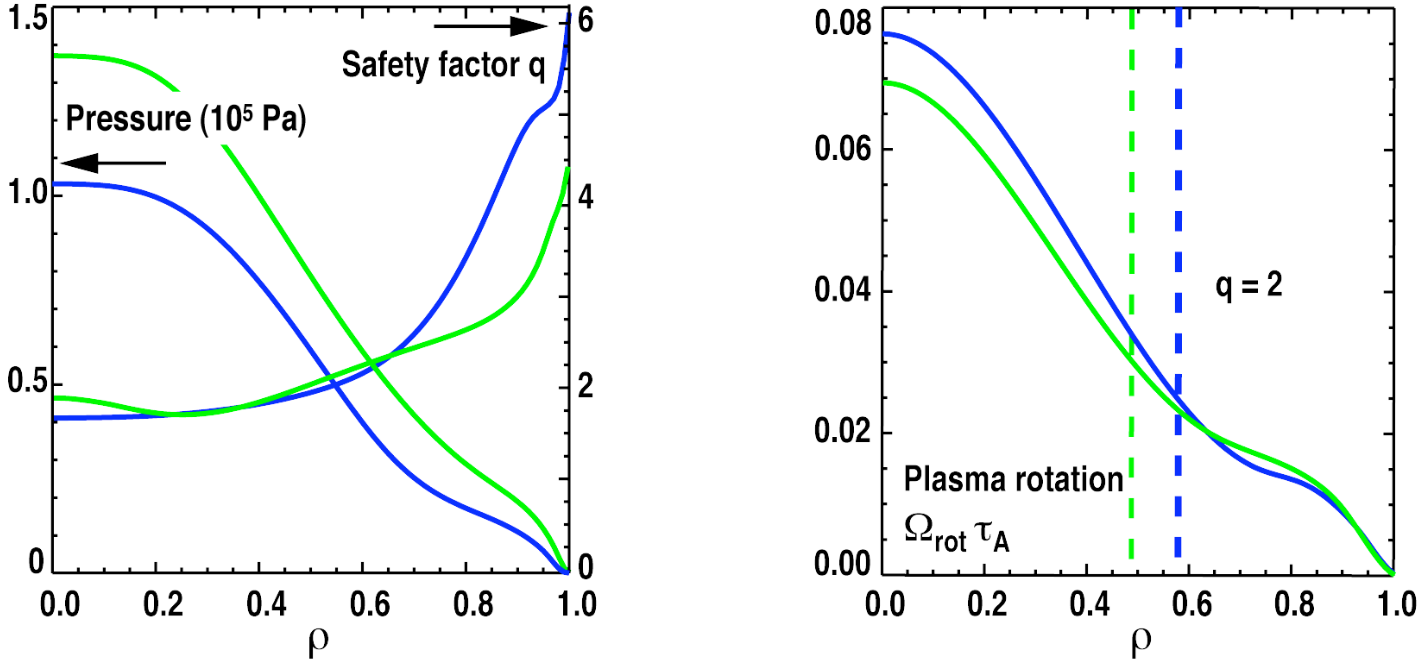
Equilibrium profiles of low-l_i and moderate-l_i scenarios

Low-li scenario / **Moderate-li scenario**



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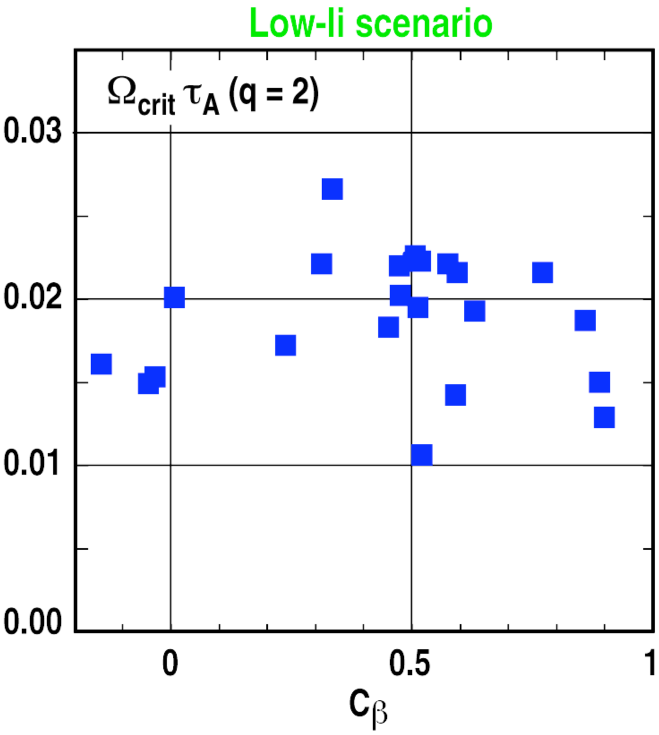
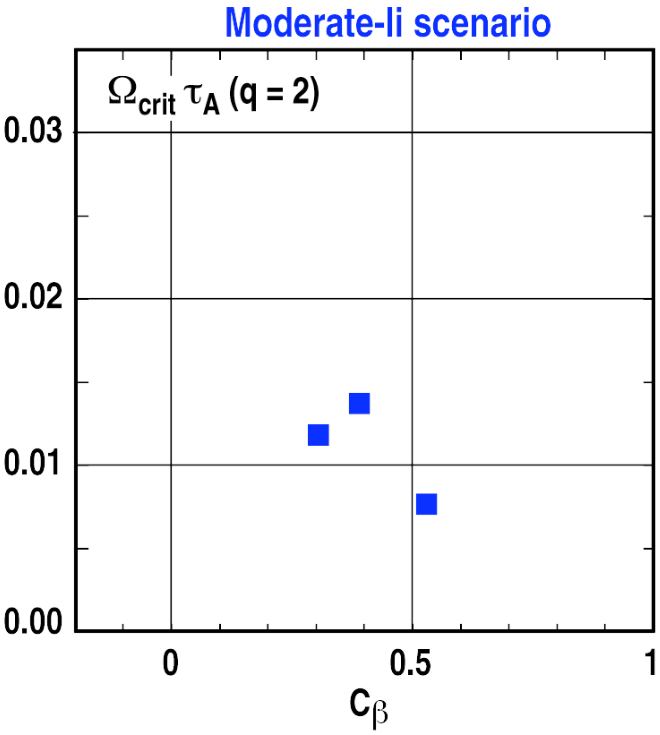
  - $\beta_{N,ideal\text{-}wall}$ ~3.2 (~3.8 l_i)
- Moderate-li scenario has a higher safety factor q_{95} (includes q=5 and 6 surfaces)

Ω_{crit} measurements in the low-l_i and moderate-l_i scenario

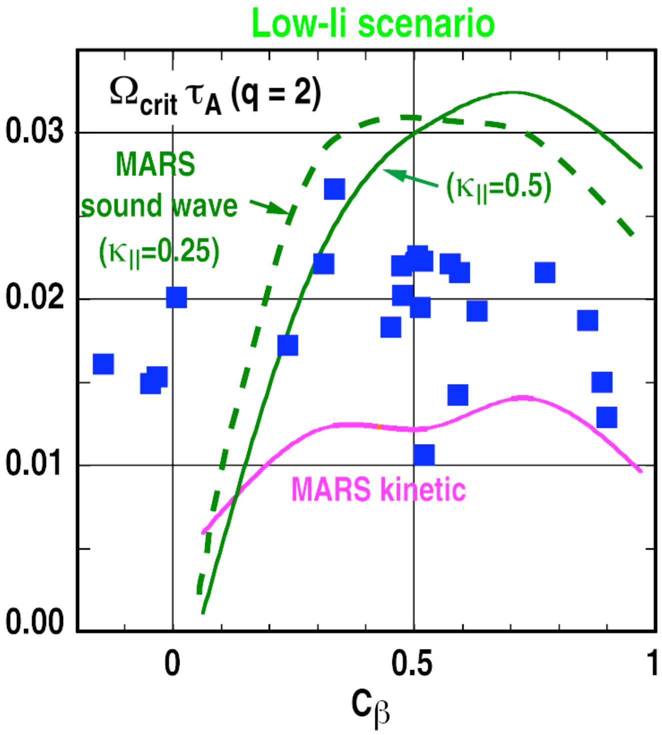




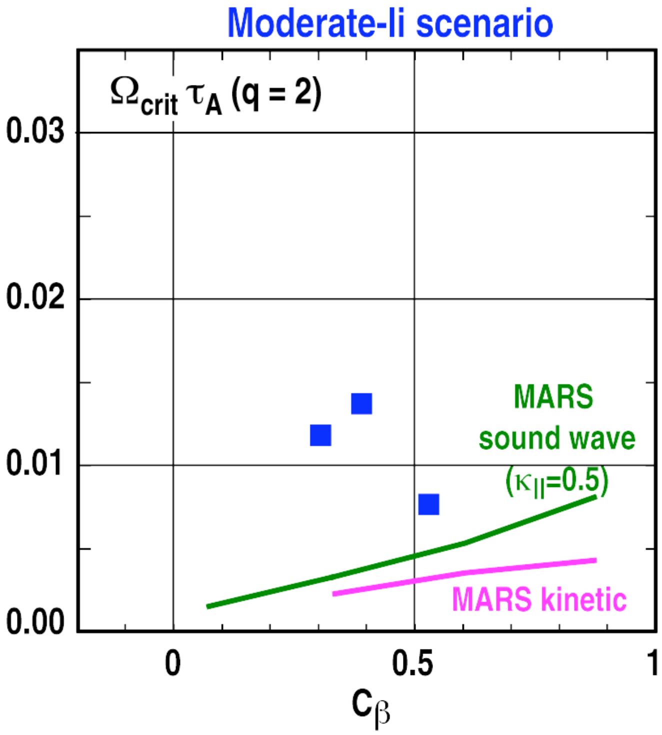
- Low-l_i scenario yields $\Omega_{crit}\,\tau_A \sim 0.02$ with weak β dependence [R.J. La Haye et al, accepted for publication in *Nucl. Fusion*]

- Moderate-l_i scenario yields significantly lower Ω_{crit} [G.L. Jackson et al, APS 2004]

MARS predictions of Ω_{crit} in qualitative agreement with measurements



Low-li scenario



Moderate-li scenario

- Low-*l*$_i$ scenario yields $\Omega_{crit}\,\tau_A \sim 0.02$ with weak β dependence [R.J. La Haye et al, accepted for publication in *Nucl. Fusion*]
- Moderate-*l*$_i$ scenario yields significantly lower Ω_{crit} [G.L. Jackson et al, APS 2004]

- Both damping models predict Ω_{crit} within a factor of 2
- Both models predict the trend of a lower Ω_{cri} in the moderate-*l*$_i$ scenario

Probe RWM stability by applying an external resonant magnetic field while the plasma remains stable

- **Resonant field amplification** (RFA):

  Resonant external magnetic fields excite a marginally stable mode

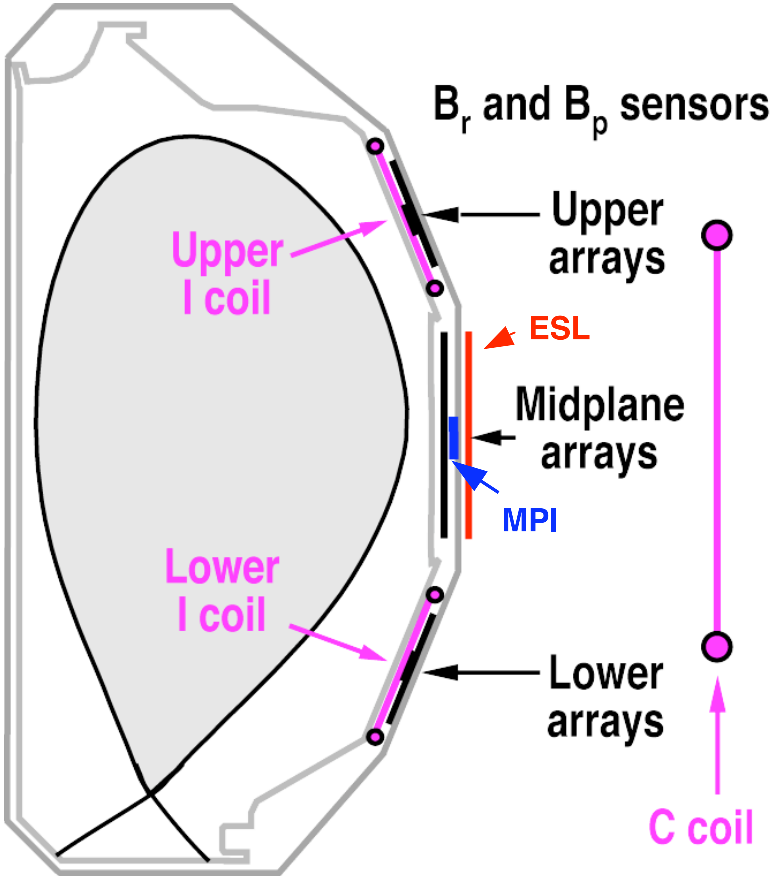
  [Boozer, *Phys Rev Lett* **86** (2001) 1176]

  - Source of external field can be currents in control coils or intrinsic error field
  - RFA amplitude defined as ratio of plasma response and applied field

$$A_{RFA,s} = \frac{B_s - B_s^{ext}}{B_s^{ext}}$$

Complex notation: $f(t,\varphi) = \Re\left(F(t) \cdot e^{-in\varphi}\right)$ where φ is the toroidal angle

DIII-D has versatile sets of antennas and detectors



Experimental setup:

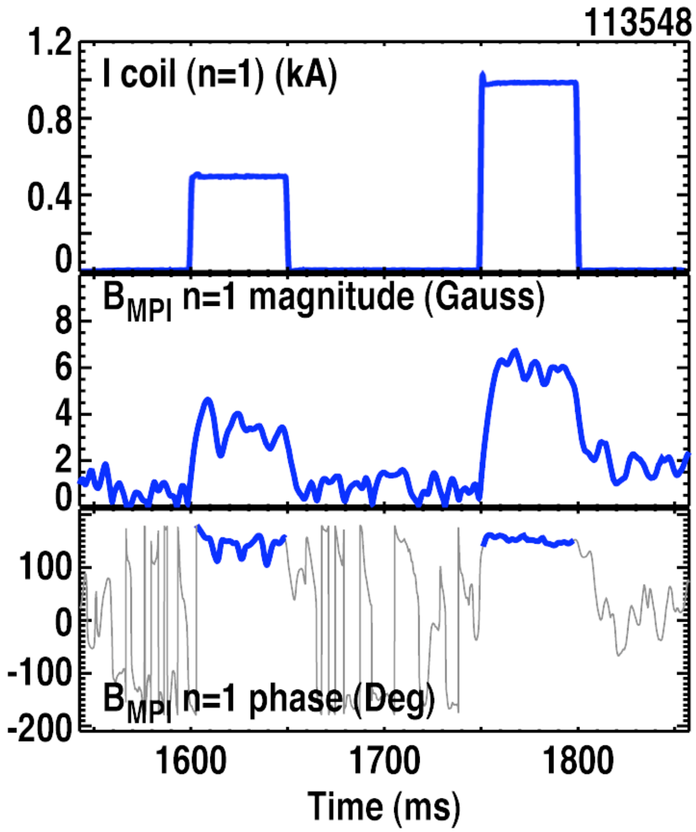
Antennas: 6 external (C-coil) and 12 internal (I-coil) saddle coils

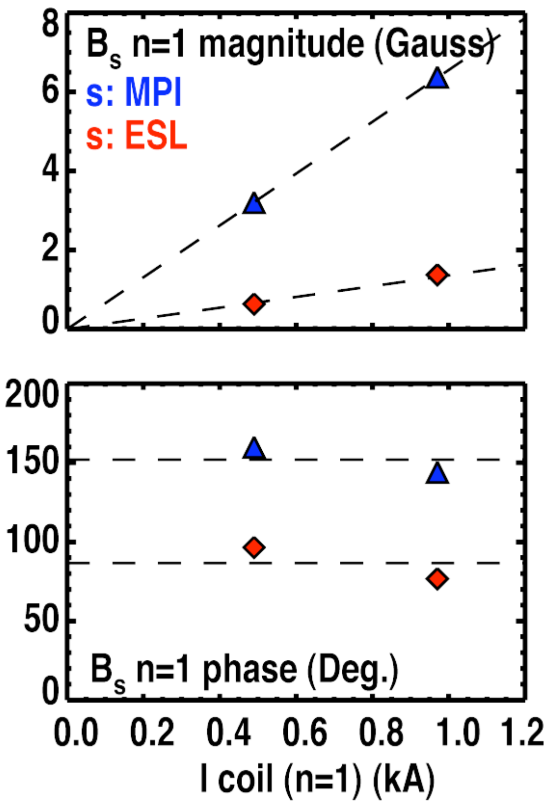
↓

Static or **rotating magnetic field** with large overlap with **RWM structure** at the wall.

Detectors: Toroidal arrays of saddle loops and poloidal field probes

Plasma response is in the linear regime





- Applied I-coil field ~10 Gauss/kA

- Linear response
  - Amplitude depends on sensor:
    "**MPI**": midplane poloidal field probes
    "**ESL**": midplane saddle loops

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Single-mode models describe interaction between externally applied fields and the RWM

- The "Simple" RWM model [Garofalo, et al, *Phys Plasmas* **9** (2002) 4573] and the extended lumped parameter model [Chu et al, *Nucl Fusion* **43** (2003) 196], both, yield

$$\tau_w \frac{dB_s}{dt} - \tau_w \gamma_0 B_s = M^*_{sc}\; I_c$$

  for the perturbed field B_s and currents in the control coils I_c

- The RWM growth rate for in the absence of external currents $\gamma_0 = \gamma_{RWM} + i\,\omega_{RWM}$ is given by the dispersion relation:
  - **'Simple' RWM model:** $\gamma_0 \tau_w = \frac{1}{2}\left(\frac{\Lambda}{k} - 1\right)$

    with $\Lambda = -\left(\phi' / \phi\right)\Big|_w$
  - **Extended lumped parameter model:** $\gamma_0 \tau_w = -\dfrac{\delta W_{no-wall} + i\Omega_{rot} D}{\delta W_{ideal-wall} + i\Omega_{rot} D}$

    with D describing the dissipation
  - **Ideal MHD with rotation and dissipation:** $\gamma_0 \tau_w$ from MARS

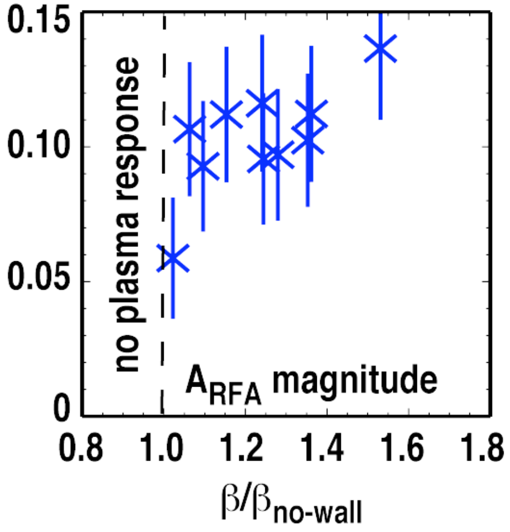
Dynamic response to resonant field pulses consistent with single-mode model

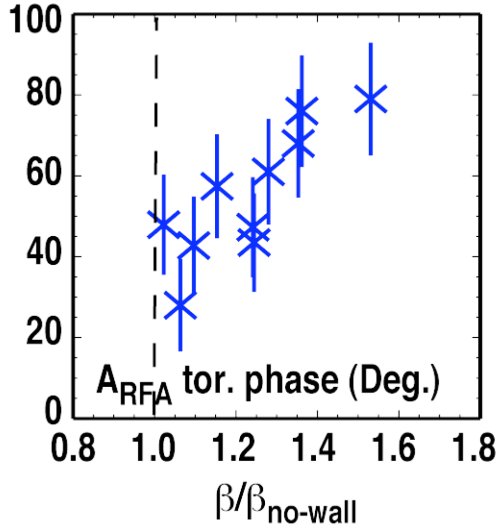
- Response to static pulse

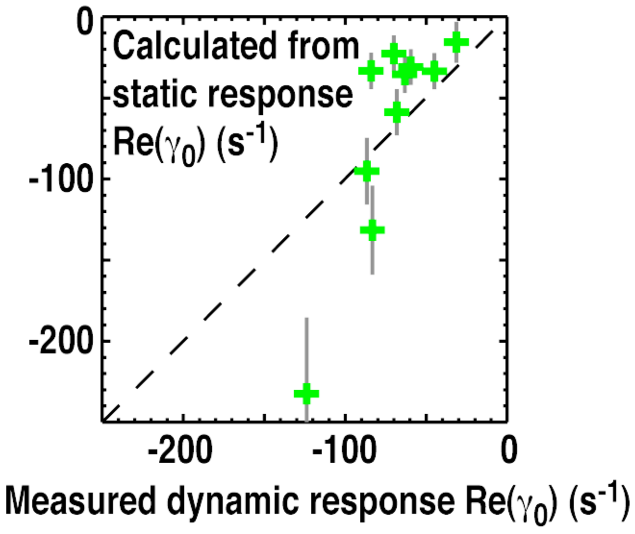
$$A_{RFA,s} = c_s \frac{1+\gamma_0 \tau_W}{-\gamma_0 \tau_W}$$

with $c_s = M^*_{sc} / M_{sc}$ being the ratio of the resonant component and the total externally applied field yields γ_0

- Decay of perturbation after pulse $B_s(t) = B_s(t_0)\ e^{\gamma_0 t}$ yields independent measurement of γ_0







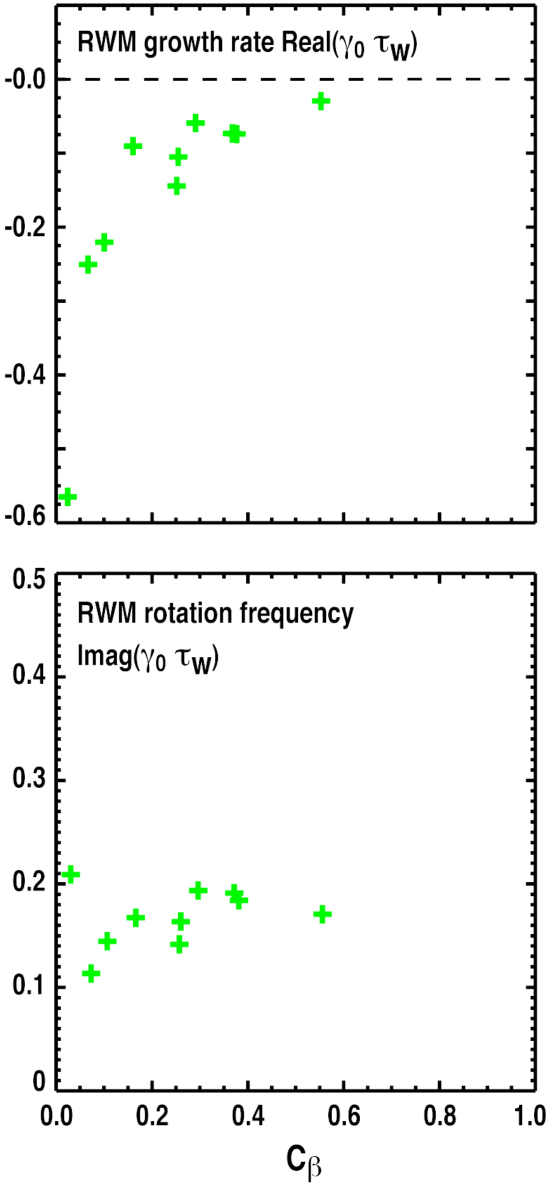
[Garofalo et al, *Phys. Plasmas* **10** (2003) 4776]

Dynamic response to C-coil pulses yields a measurement of the RWM damping rate and mode rotation frequency

[Garofalo et al, *Phys Plasmas* **10** (2003) 4776]

- **Low-l_i target** ($l_i \sim 0.67$)
- Optimum error field correction sustains plasma rotation at $\Omega_{rot}\tau_W \sim 0.02$ at $q=2$
- Apply $n=1$ field pulses with C-coil
- Best fit of RFA amplitude, phase and exponential decay to single-mode model yields γ_0

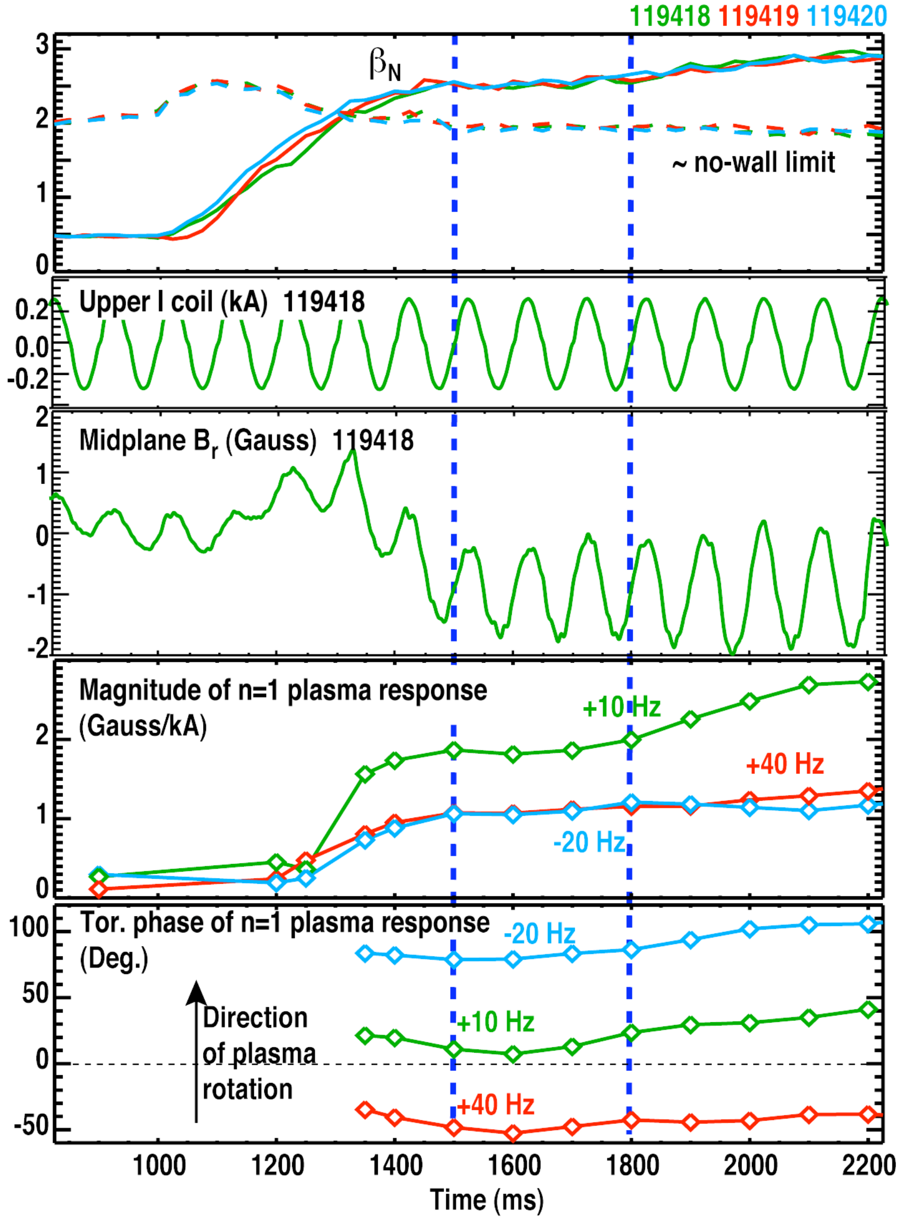
- Plasma approaches marginal stability at $C_\beta \sim 0.6$
  - consistent with measured $\Omega_{crit}\tau_W \sim 0.02$
- Mode rotation frequency is low (fraction of τ_W^{-1}) and has a weak β dependence



MHD spectroscopy probes the RWM stability while the plasma remains stable

- **Moderate-l_i target** ($l_i \sim 0.85$)
- Apply rotating n = 1 field with I-coil
- Coherent detection

- Largest plasma response for slowly co-rotating field
- Plasma response leads external field if rotation slower and trails if rotation faster than rotation of larges response



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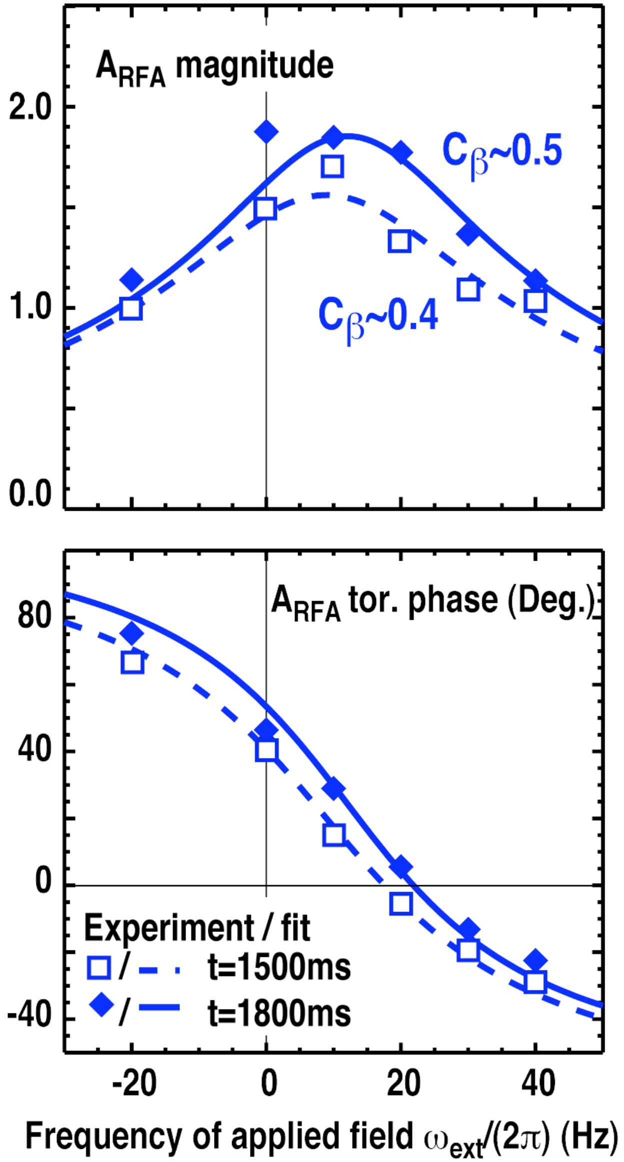
RFA peaks when the externally applied field rotates with the mode rotation frequency

[Reimerdes et al, *Phys Rev Lett* **93** (2004) 135002]

- Single-mode model predicts RFA spectrum

$$A_{RFA,s} = c_s \cdot \frac{1+\gamma_0\tau_w}{i\omega_{ext}\tau_w - \gamma_0\tau_w}$$



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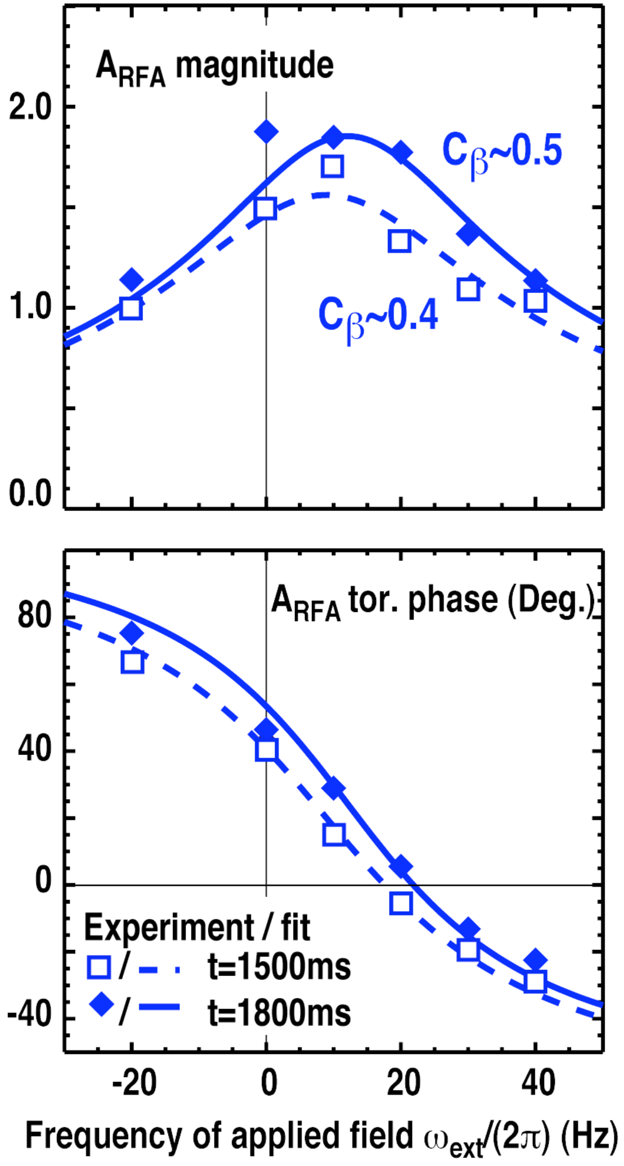
- Single-mode model predicts RFA spectrum

$$A_{RFA,s} = c_s \cdot \frac{1+\gamma_0\tau_w}{i\omega_{ext}\tau_w - \gamma_0\tau_w}$$

- Fit of γ_0 and c_s results in good agreement
  - Single-mode model applicable
  - RFA spectrum yields a measurement of γ_0 (**MHD spectroscopy**)



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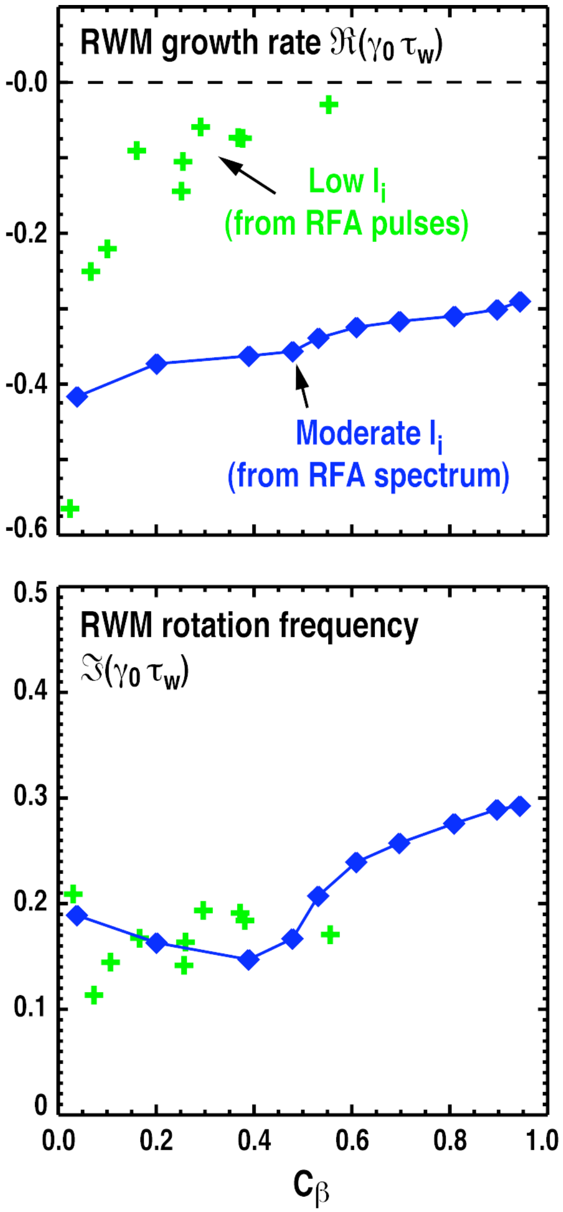
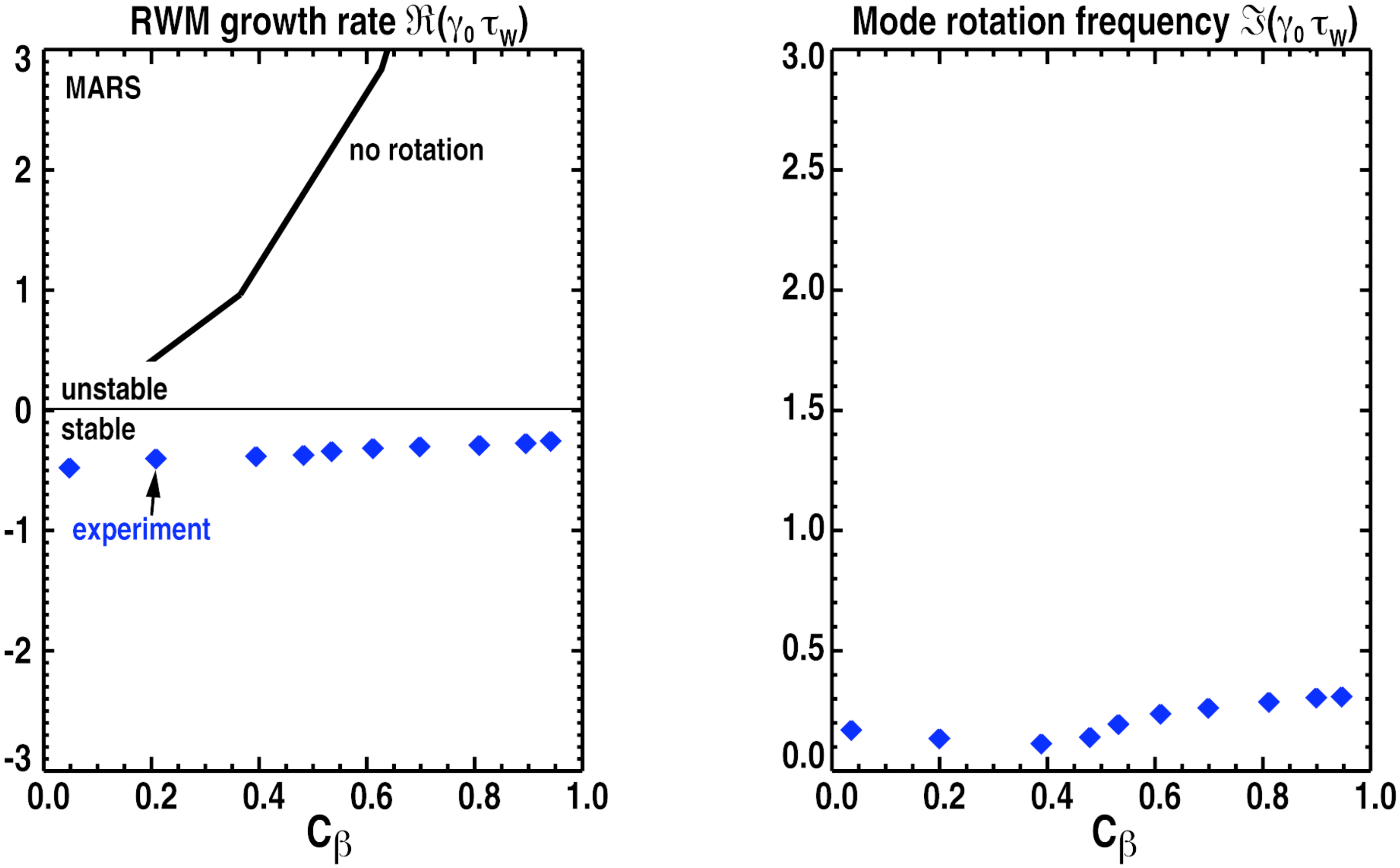
MHD spectroscopy yields a measurement of the RWM damping rate and mode rotation frequency

- MHD spectroscopy in moderate-l_i target yields β dependence of γ_0
- Optimum error field correction sustains plasma rotation at $\Omega_{rot}\tau_W \sim 0.02$ at q=2
- Growth rate is lower than in low-l_i scenario and remains below marginal stability up to $C_\beta \sim 1$
  - consistent with measured $\Omega_{crit} \sim 0.01\,\tau_W^{-1} << \Omega_{rot}$
- Mode rotation frequency is low (fraction of τ_W^{-1}) and has a weak β dependence, similar to low-l_i scenario



Comparison with MARS



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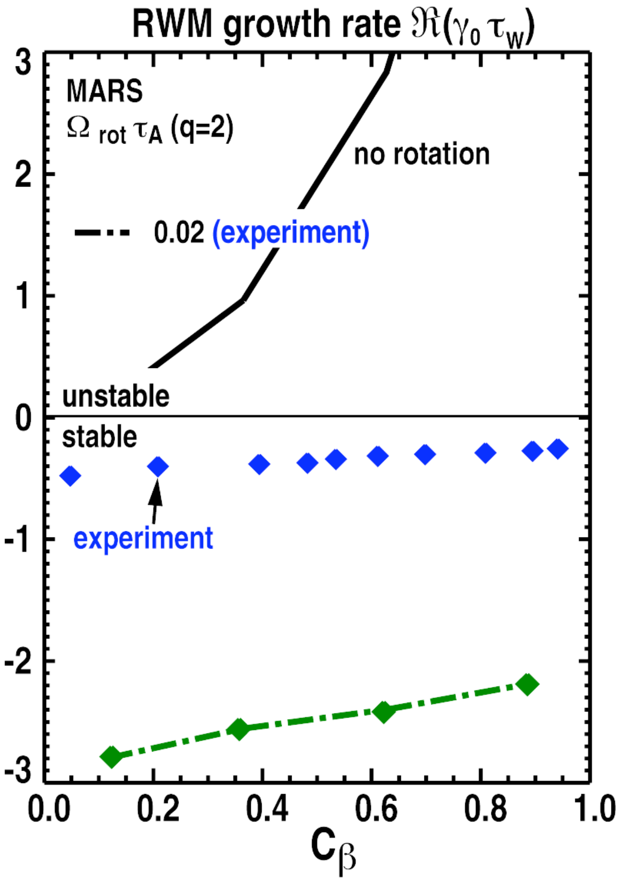

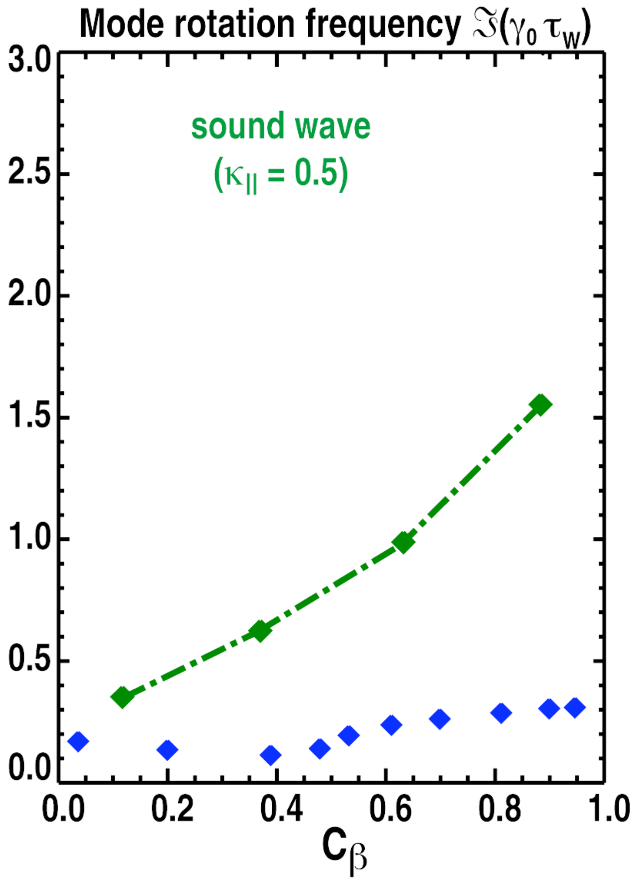

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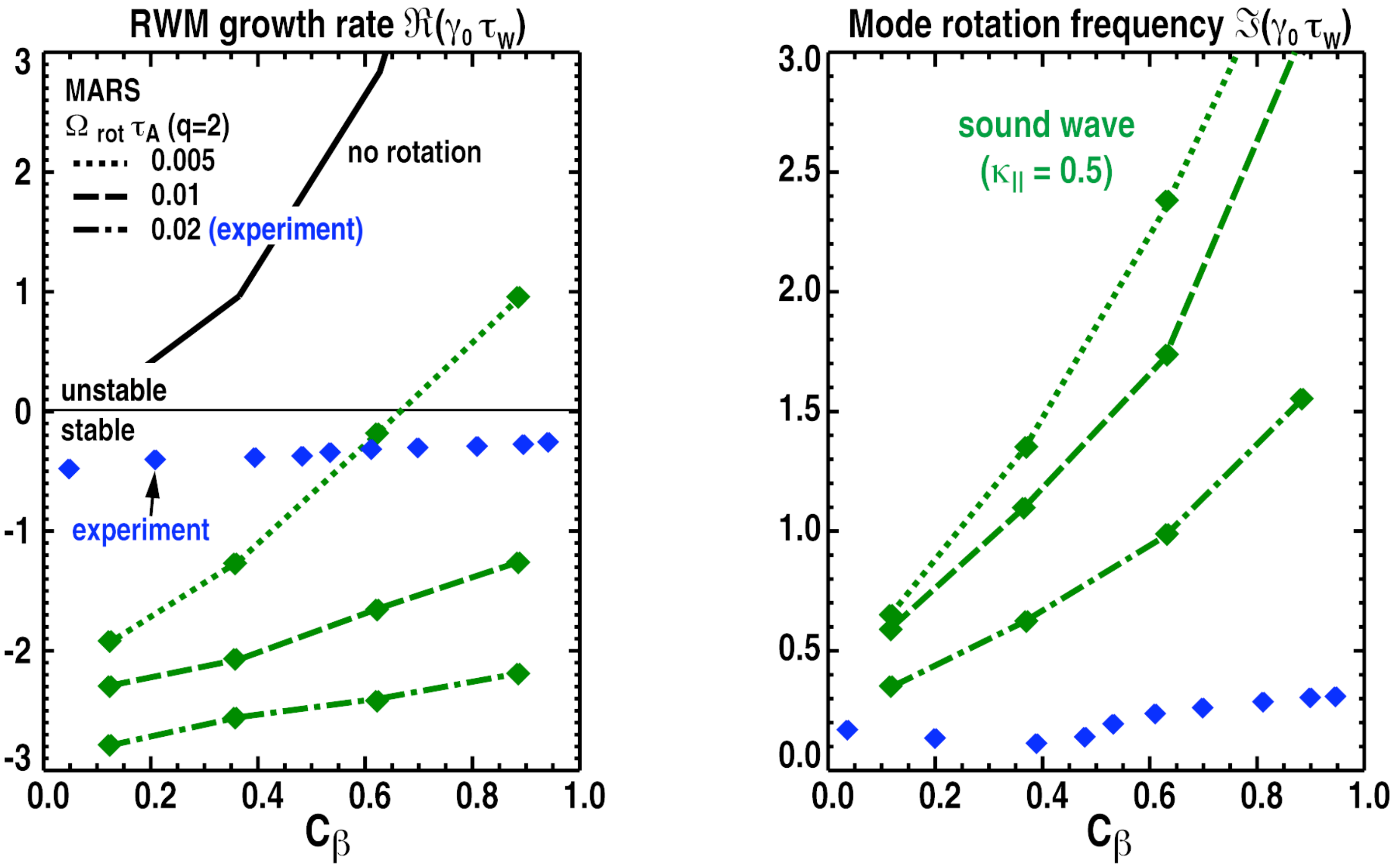

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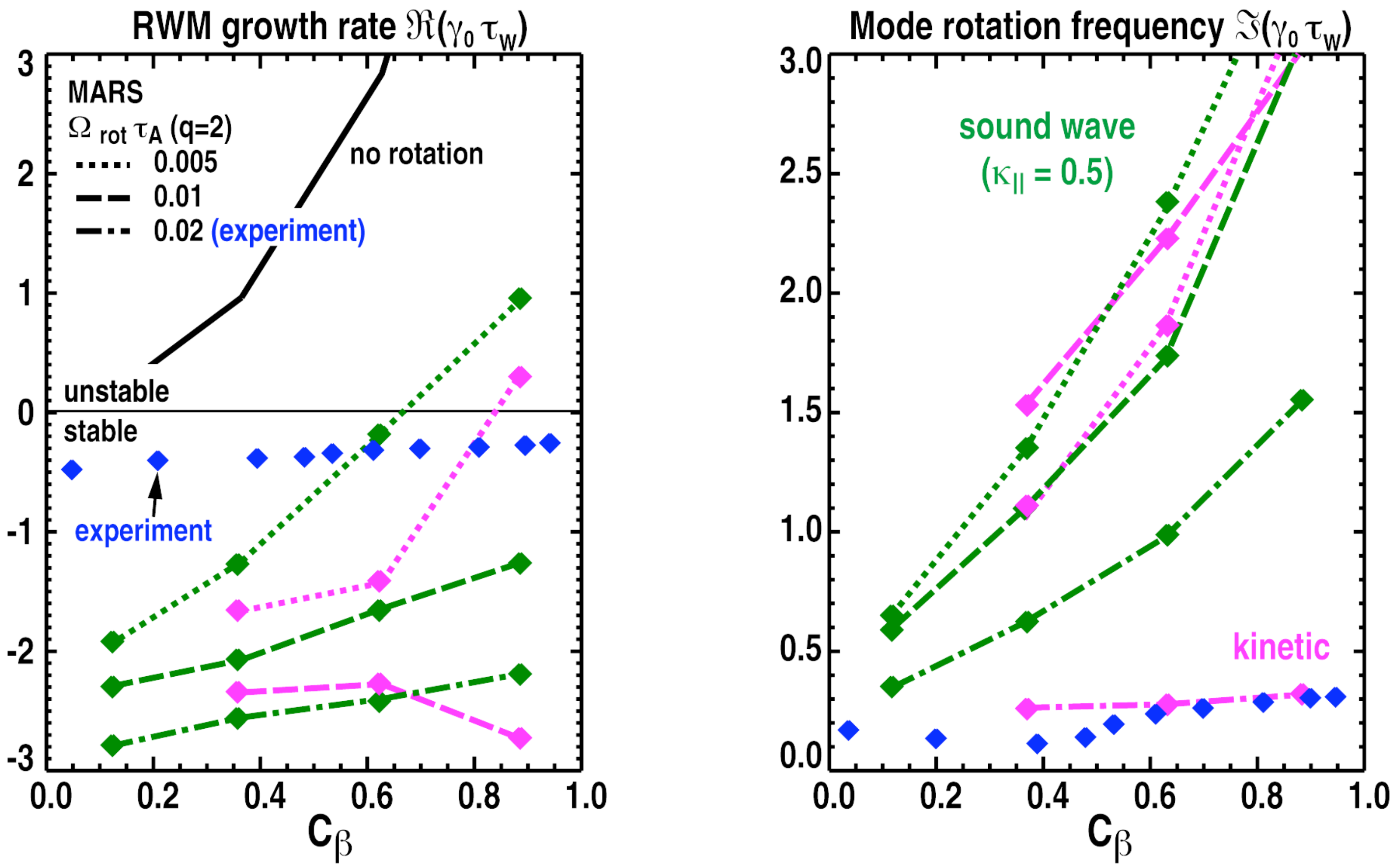

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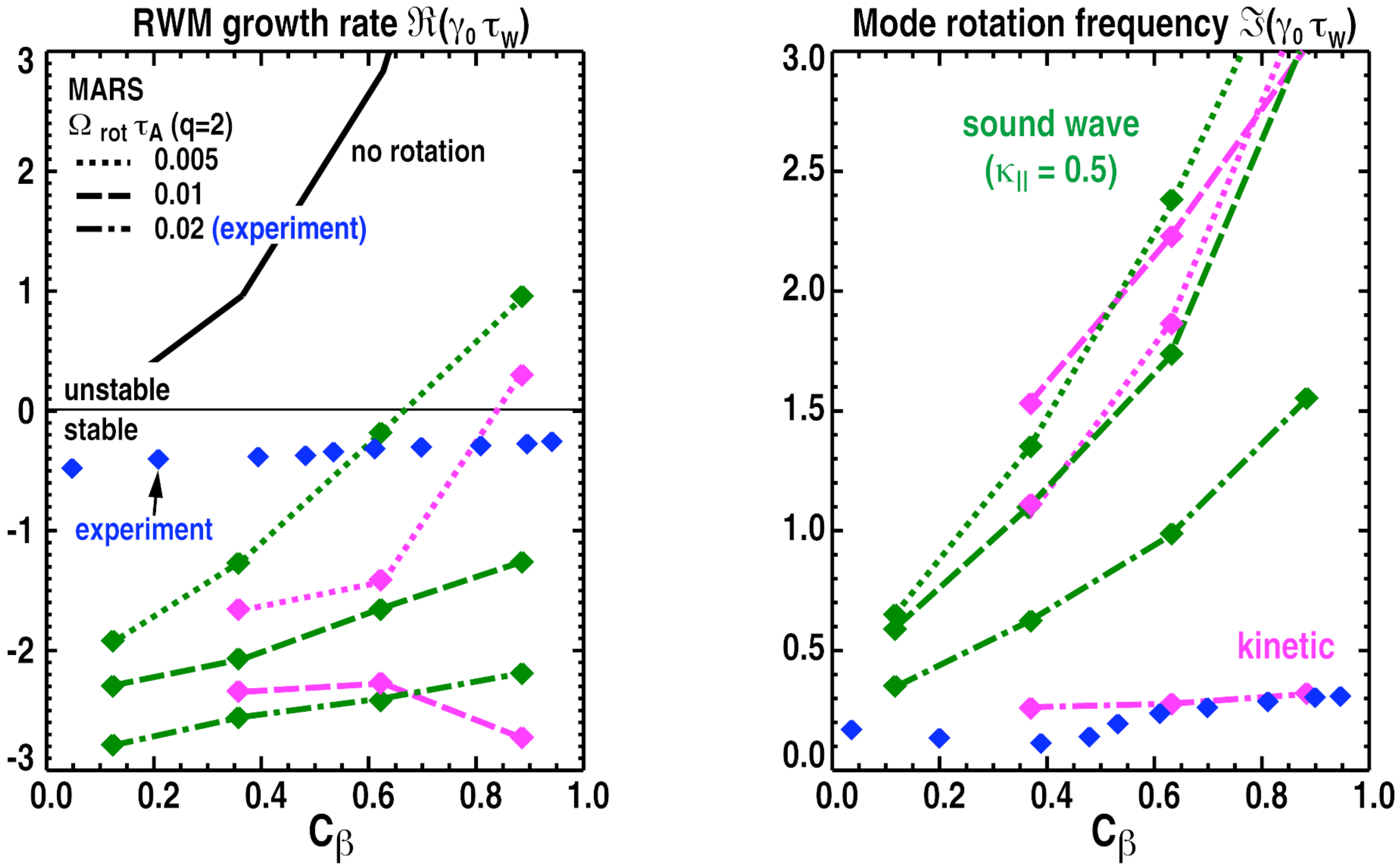


- Both models predict γ_{RWM} too low
- Kinetic damping predicts experimental ω_{RWM} while the sound wave damping prediction is too high

Summary

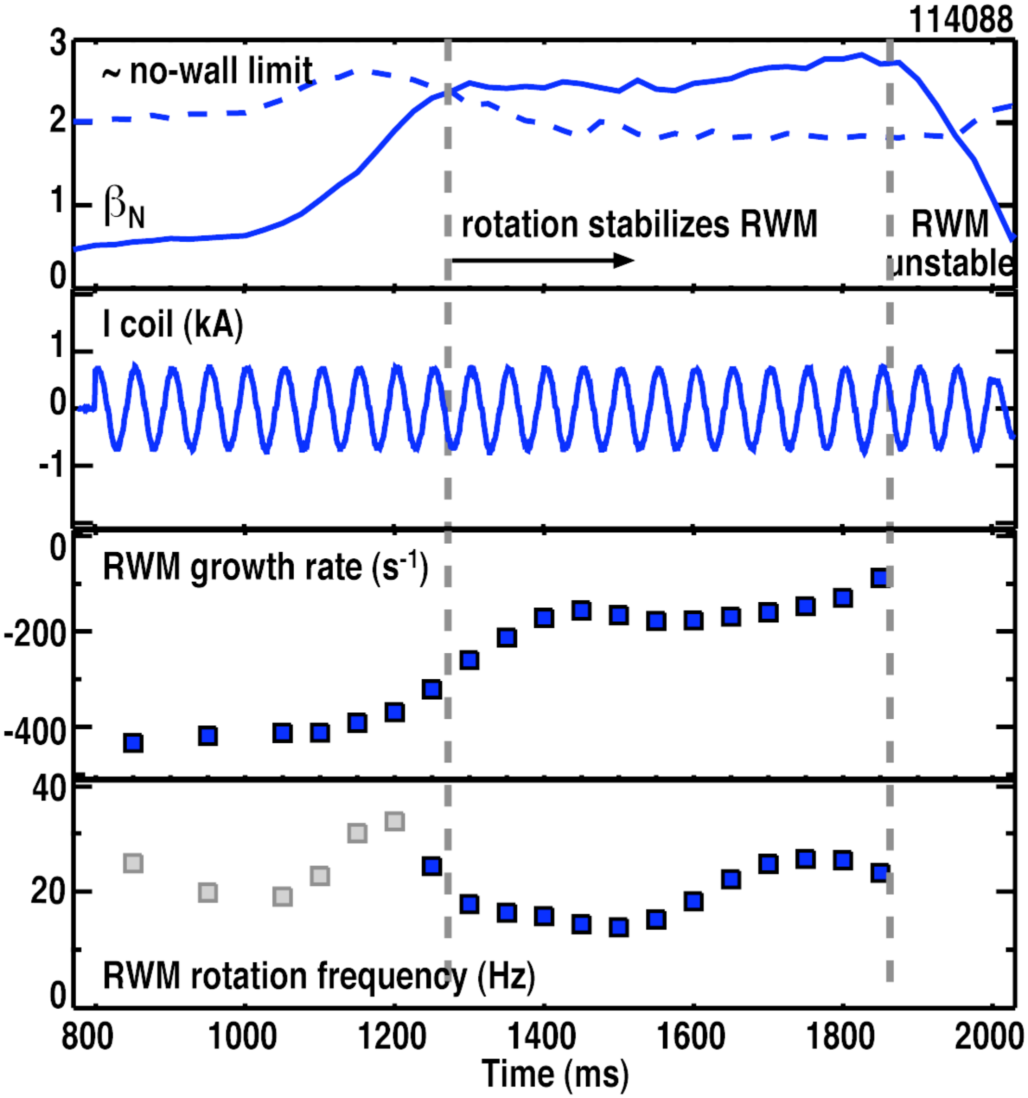
- Interaction between an externally applied magnetic field and a high-β plasma at various frequencies is well described by a single mode approach
  - Validation of the single mode approach (basis of RWM feedback models)
  - Absolute measurement of RWM damping rate γ_{RWM} and mode rotation frequency ω_{RWM}
- Passive measurement of the critical plasma rotation Ω_{crit}, and active measurement of γ_{RWM} and ω_{RWM} carried out in two scenarios (low-l_i and moderate-l_i)
  - Low-l_i scenario requires more rotation for stability ➔ importance of rational surfaces at plasma edge for damping process
- Comparison of RWM stability measurements with sound wave damping and kinetic damping implemented in the MARS code
  - Both damping models reproduce the weaker damping in the low-l_i scenario and predict Ω_{crit} within factor of 2
  - Both damping models overestimate $|\gamma_{RWM}|$ or $|\omega_{RWM}|$ or both
- Progress towards a quantitative test of our understanding of rotational stabilization requires further development of experiment and theory

Active RWM spectroscopy yields a continuous "non-perturbative" measurement of the stability

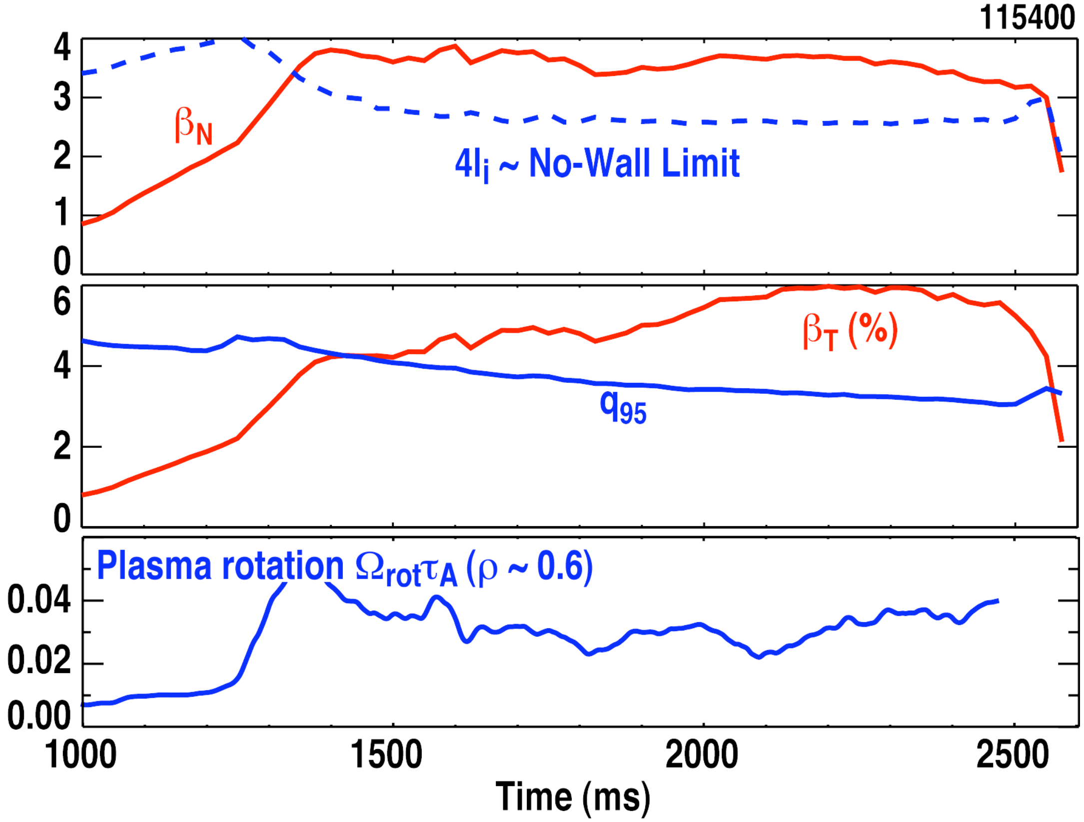
- With c_s known, $A_{RFA,s}$ becomes a continuous measurement of γ_0,

$$\gamma_0 = \frac{i\omega_{ext} A_{RFA,s}/c_s - 1/\tau_w}{A_{RFA,s}/c_s + 1}$$

- Potential for real-time indication of the approach to the stability limit



Stabilization of the Resistive Wall Mode (RWM) can extend the operating regime from the no-wall up to the ideal wall limit



- Operation above the no-wall limit particularly important for advanced tokamak (AT) scenarios
  - ATs rely on a large fraction of bootstrap current
  - Broad current profiles greatly benefit from wall stabilization

- Operation in the wall stabilized regime with $\beta_N \sim 6\, l_i$ and β_T reaching 6%

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