Rotational Stabilization of the Resistive Wall Mode in DIII-D

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in collaboration with

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Outline

- **Passive measurement** of the plasma rotation required for stability $\mathbf{\Omega_{crit}}$
  - Ω_{crit} in two scenarios (low-l_i and moderate-l_i)
  - Comparison with MARS calculations
- **Active measurement** of growth rate $\boldsymbol{\gamma_{RWM}}$ and mode rotation frequency $\boldsymbol{\omega_{RWM}}$ 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

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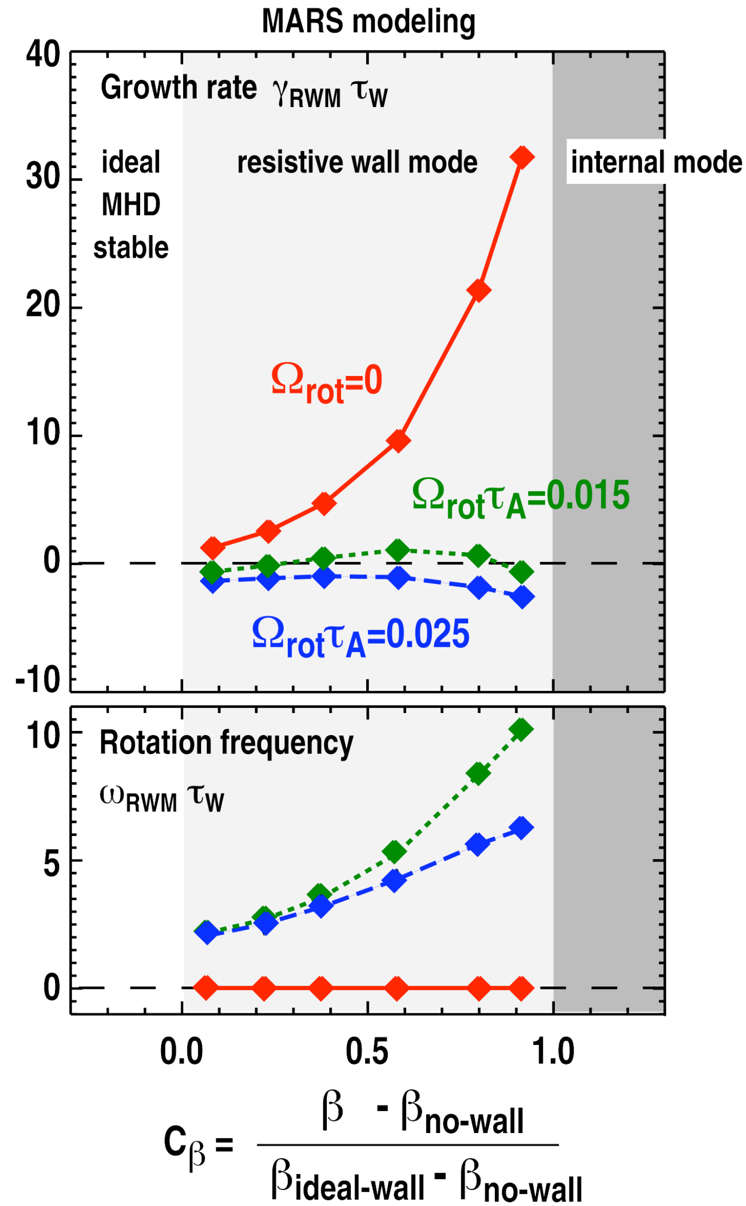
Plasma rotation predicted to stabilize the RWM

- **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 $\gamma_{RWM} \sim \tau_w^{-1}$
    $\rightarrow$ Stabilization by feedback control
  - "Slow" mode rotation $\omega_{RWM} << \Omega_{rot}$
    $\rightarrow$ 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



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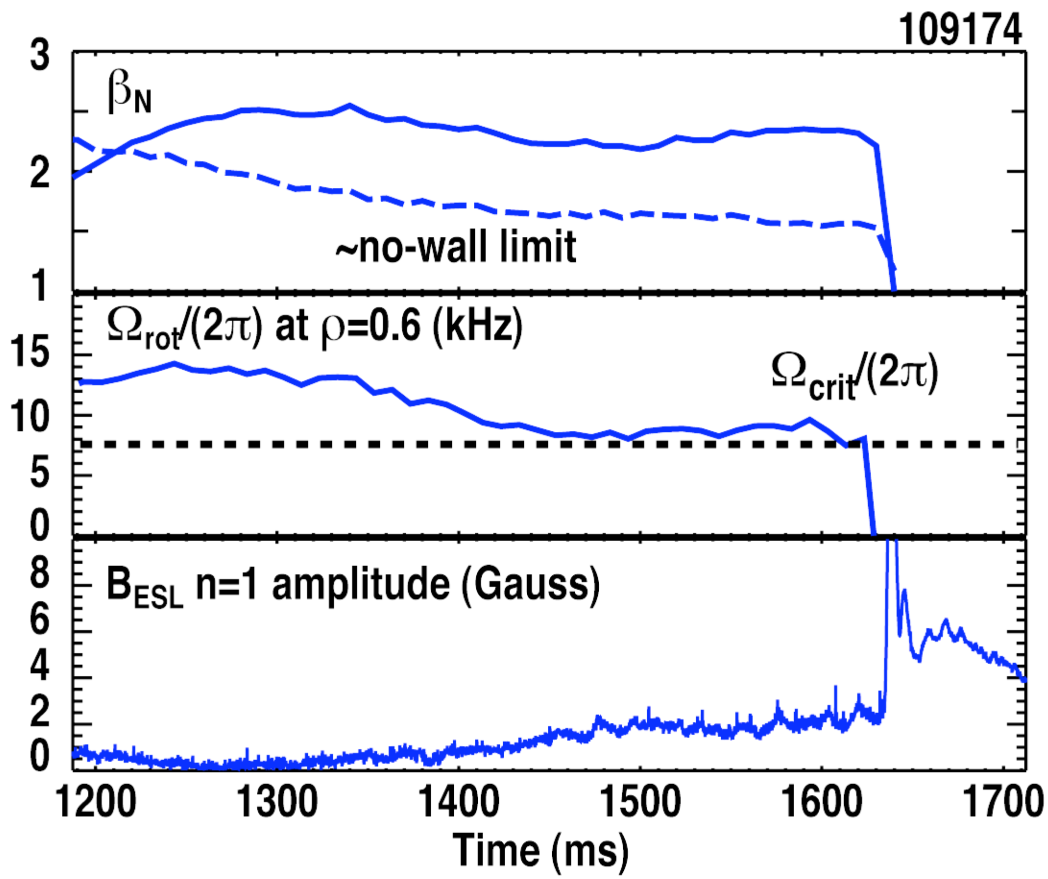
Several dissipation models are proposed

- **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

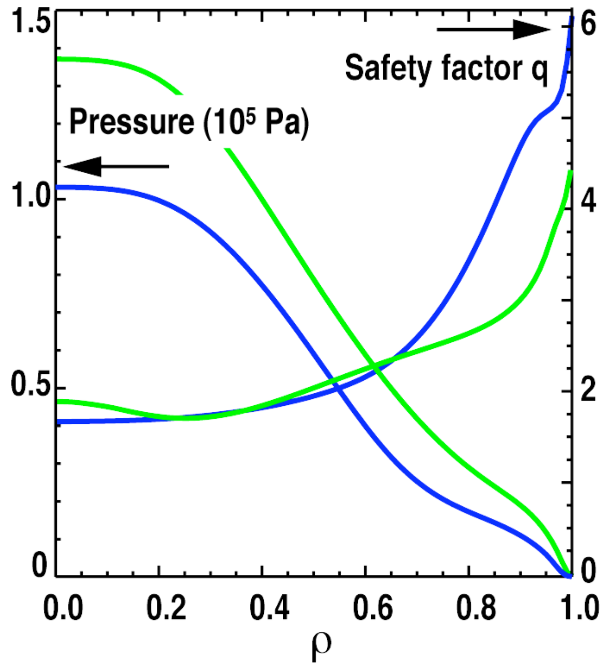
How much plasma rotation is required to stabilize the n=1 RWM?

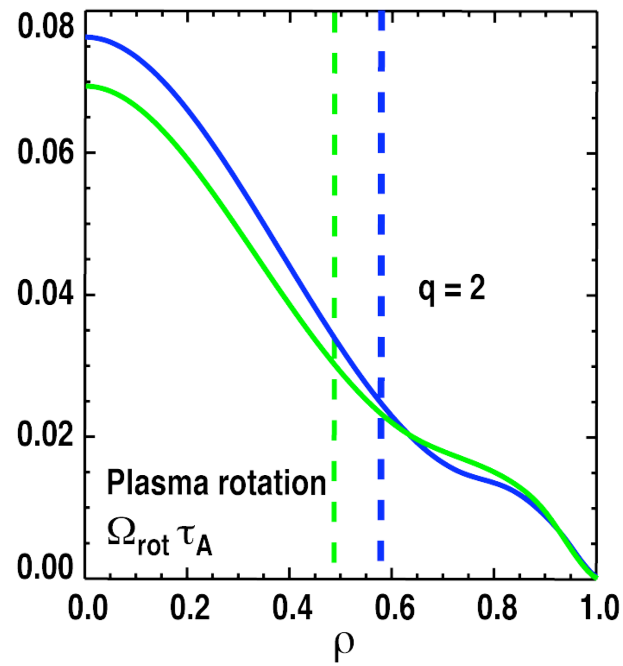


- Passive measurement of Ω_{crit}
  - Insufficient error field correction causes slow-down of toroidal rotation
  - Onset of RWM marks Ω_{crit}
- Systematic scan of β in a **low-l_i plasma** [R.J. La Haye et al, accepted for publication in *Nucl. Fusion*]
  - Ω_{crit} scales with τ_A^{-1}
- Additional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

Equilibrium profiles of low-l_i and moderate-l_i scenarios

Low-li scenario / 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)
- Moderate-li scenario has a higher safety factor q_{95} (includes q=5 and 6 surfaces)

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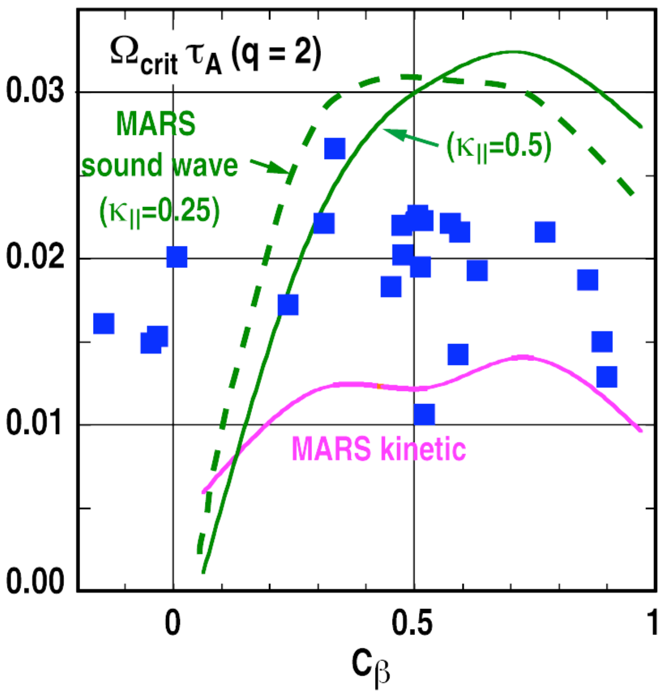
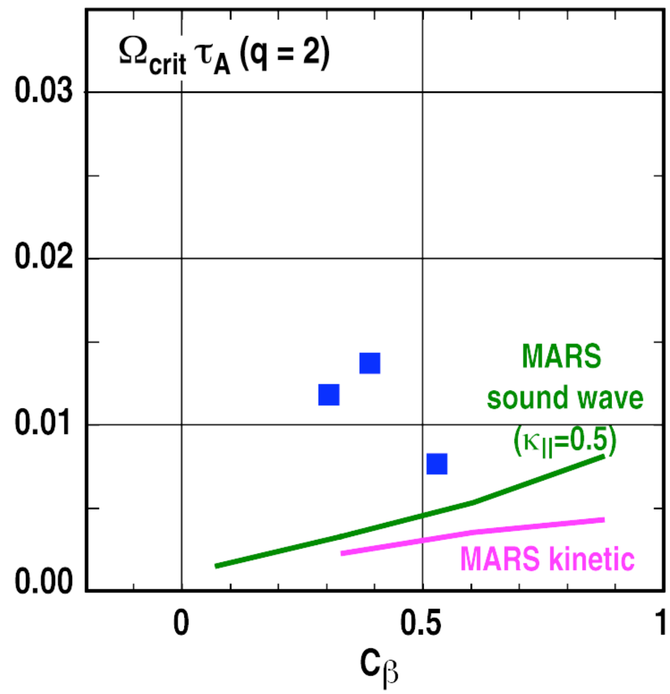
MARS predictions of Ω_{crit} in qualitative agreement with measurements

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

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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

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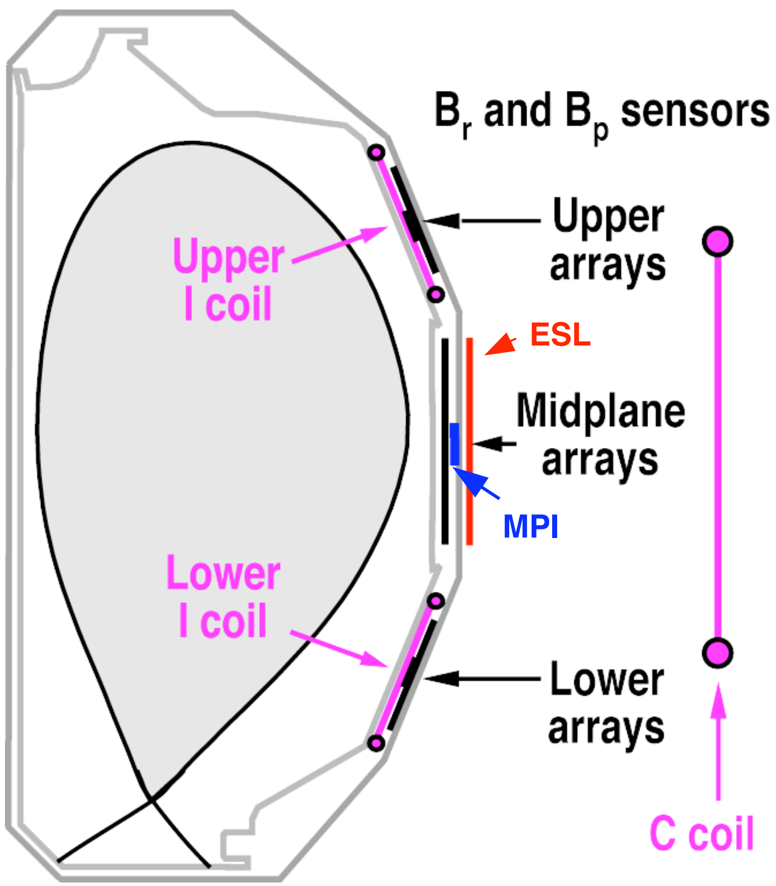
DIII-D has versatile sets of antennas and detectors



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

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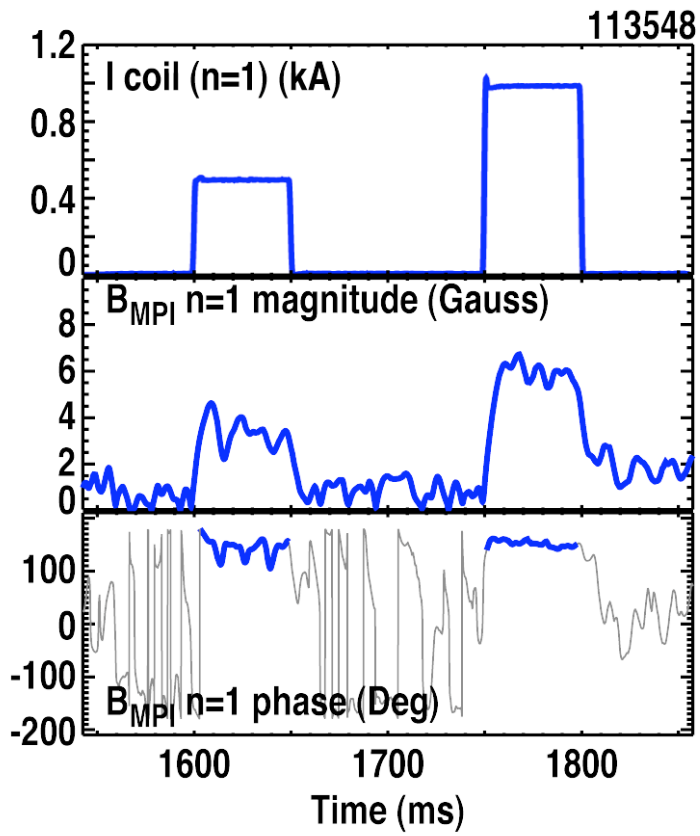
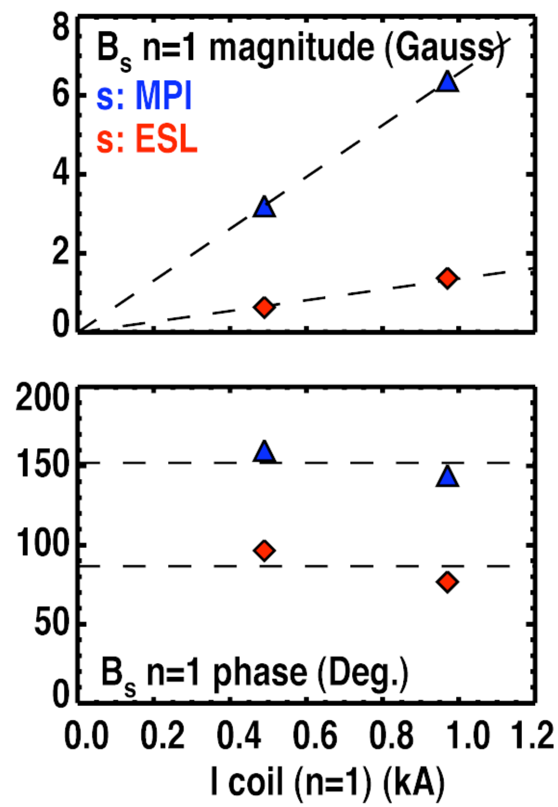
Plasma response is in the linear regime





- 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:** $$\gamma_0 \tau_w = \tfrac{1}{2}\left(\frac{\Lambda}{k} - 1\right)$$

  with $\Lambda = -\left(\phi' / \phi\right)\big|_w$

  – **Extended lumped parameter model:** $$\gamma_0 \tau_w = -\frac{\delta W_{no-wall} + i\Omega_{rot} D}{\delta W_{ideal-wall} + i\Omega_{rot} D}$$

  with D describing the dissipation

  – **Ideal MHD with rotation and dissipation:** $\gamma_0 \tau_w$ from MARS

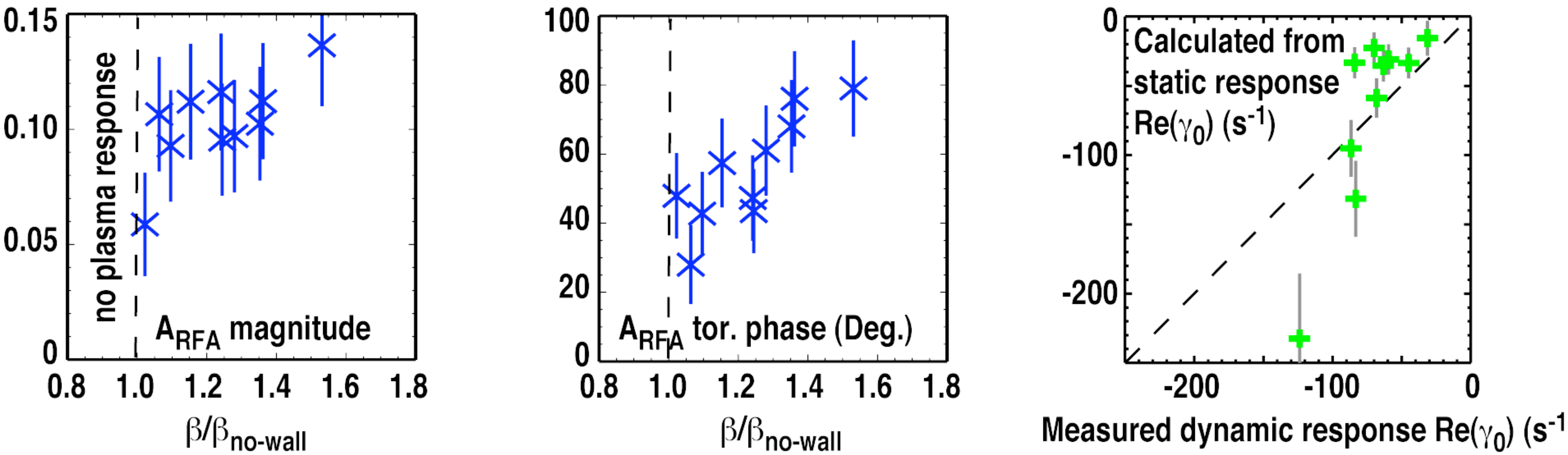
Dynamic response to resonant field pulses consistent with single-mode model

- 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]

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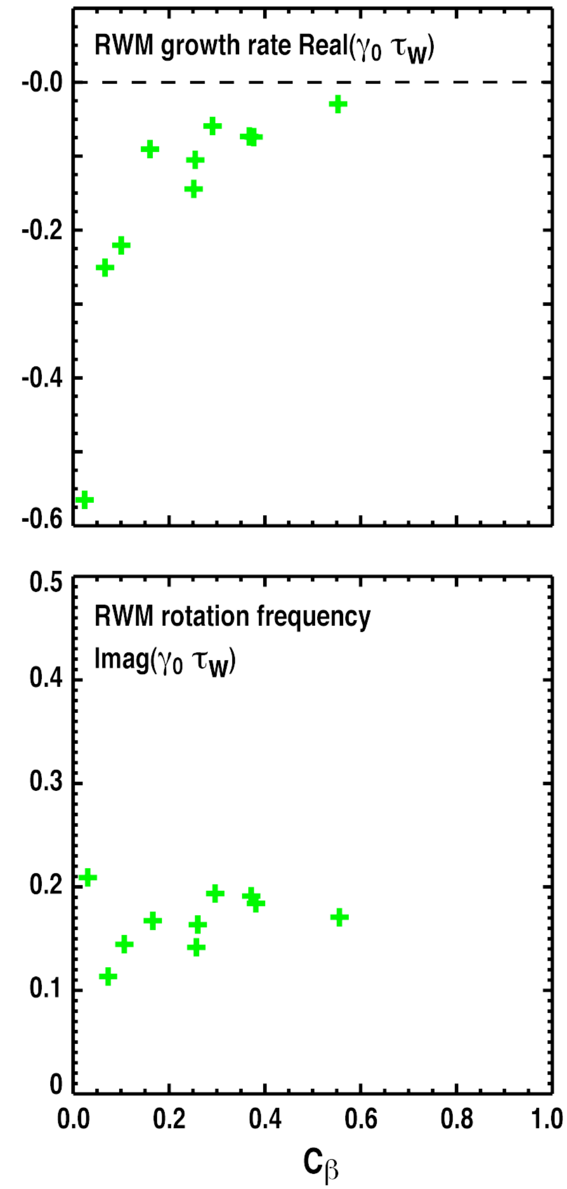
Dynamic response to C-coil pulses yields a measurement of the RWM damping rate and mode rotation frequency

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

- **Low-l_i target** (l_i ~0.67)
- Optimum error field correction sustains plasma rotation at $\Omega_{rot}\tau_W$~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

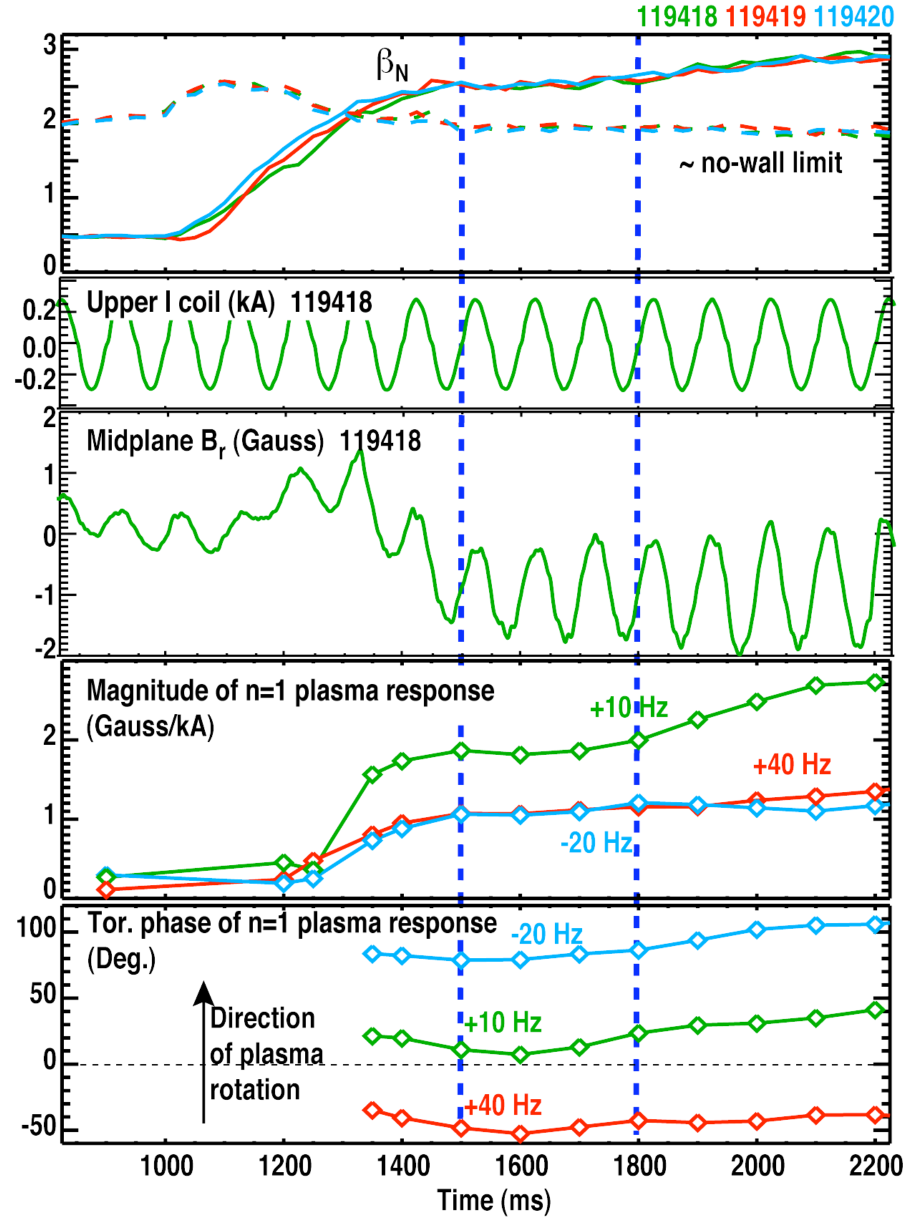
- Plasma approaches marginal stability at C_β~0.6
  - consistent with measured $\Omega_{crit}\tau_W$ ~0.02
- Mode rotation frequency is low (fraction of τ_W^{-1}) and has a weak β dependence



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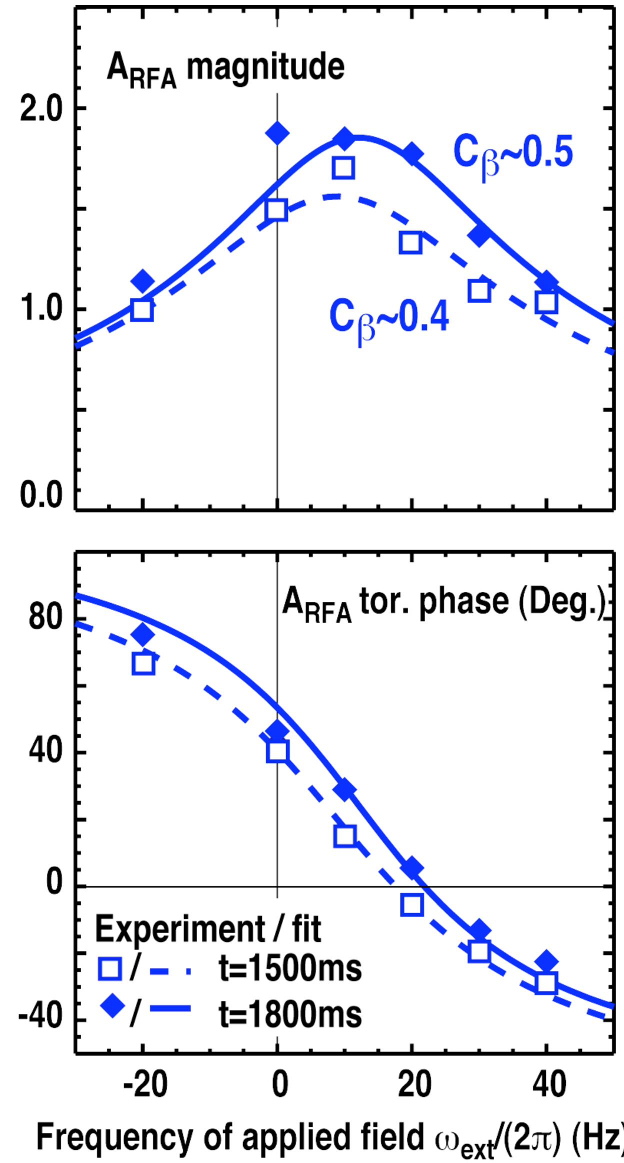
RFA peaks when the externally applied field rotates with the mode rotation frequency

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

- Single-mode model predicts RFA spectrum

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

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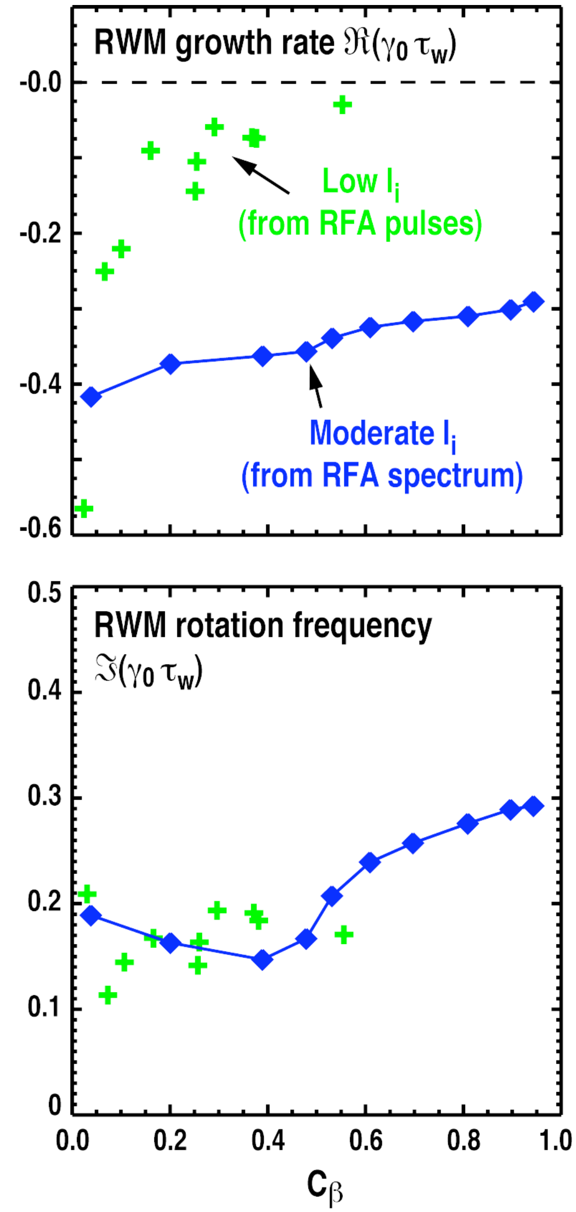
MHD spectroscopy yields a measurement of the RWM damping rate and mode rotation frequency

- 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



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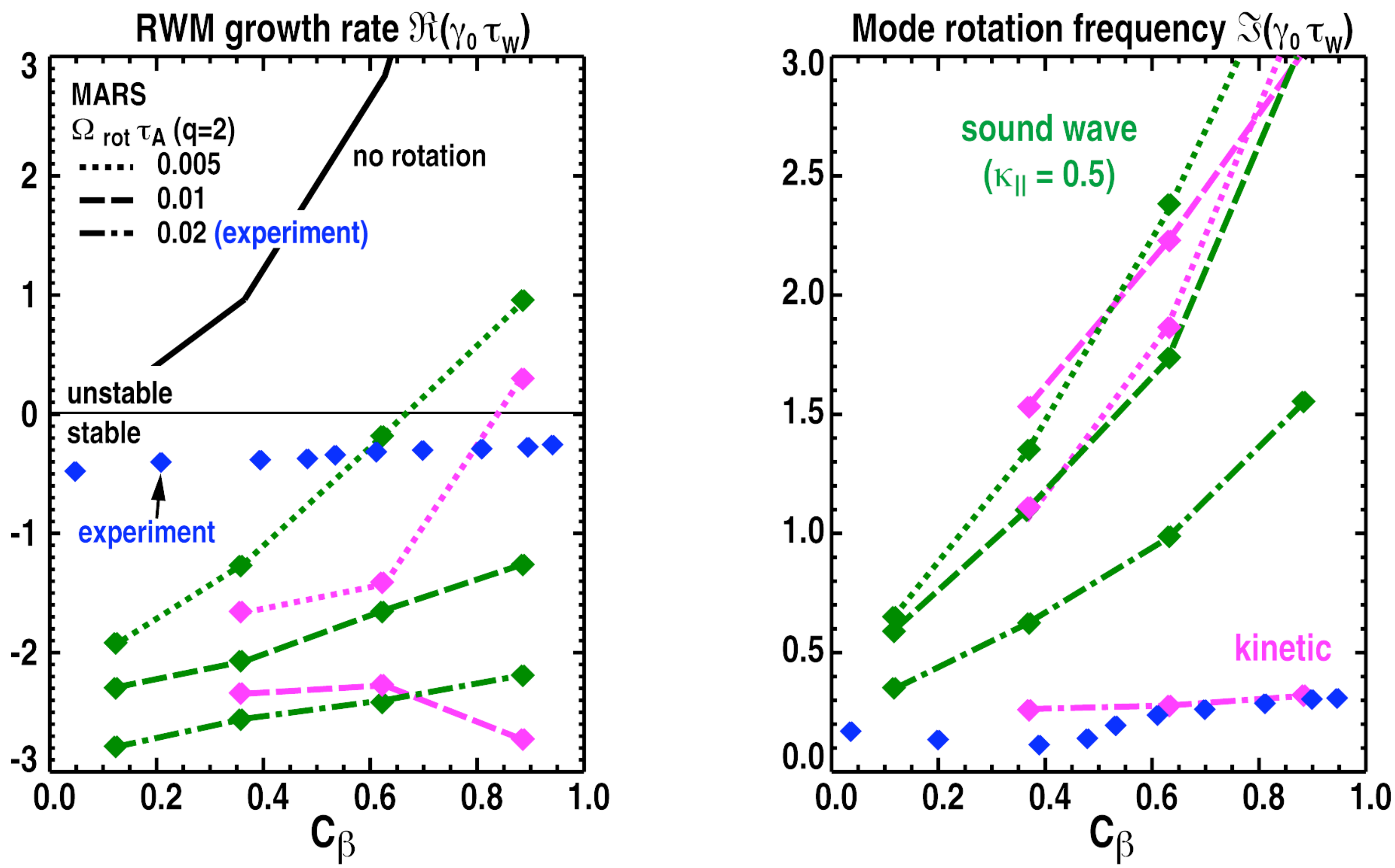
Comparison with MARS



- 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