Measurement of RWM damping by plasma rotation using active MHD spectroscopy

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"Active Control of MHD Stability: Extension to the Burning Plasma Regime"
Workshop at the University of Texas-Austin Austin, Texas, USA
November 3-5, 2003

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Outline

- Understand interaction between an externally applied field and the marginally stable RWM at various frequencies.
  - Predictions of the resonant field amplification (RFA) spectrum by a single-mode model.
- Use RFA spectrum as a measurement of the RWM stability in a rotating plasma.
  - Absolute measurement of complex growth rate.
- Compare to the DC measurements.
- Test predictions of the sound wave dissipation model.

Stabilization of Resistive Wall Mode (RWM) can extend operating regime to higher pressure

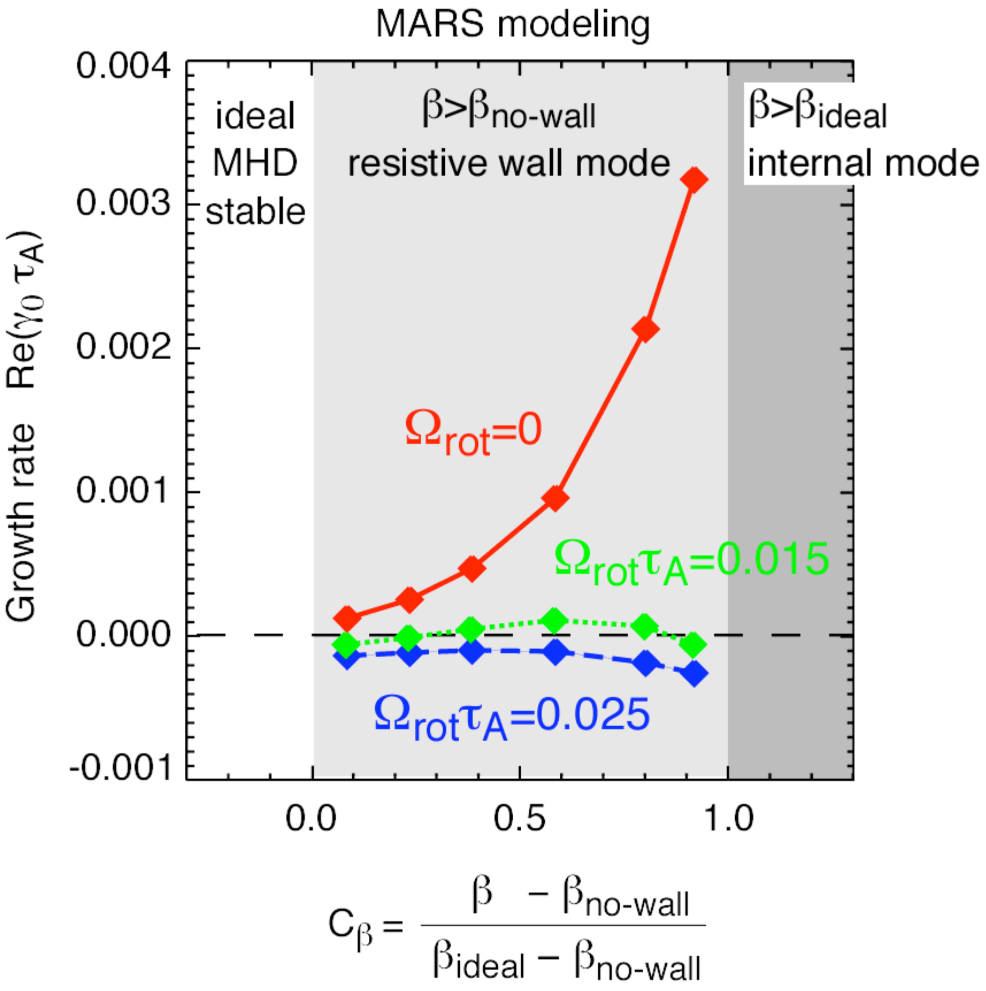
- **Resistive Wall mode (RWM):**

  The stabilization of the RWM can extend the operating regime from the ideal MHD no-wall limit to the ideal wall ideal MHD limit.

  – “Slow” RWM growth
    Stabilization by feedback control.

  – “Slow” mode rotation Quasi-static magnetic perturbation in a fast (toroidal) plasma flow.

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



Active MHD spectroscopy advances understanding of the stabilizing effect of plasma flow on the RWM

- **Active MHD spectroscopy**

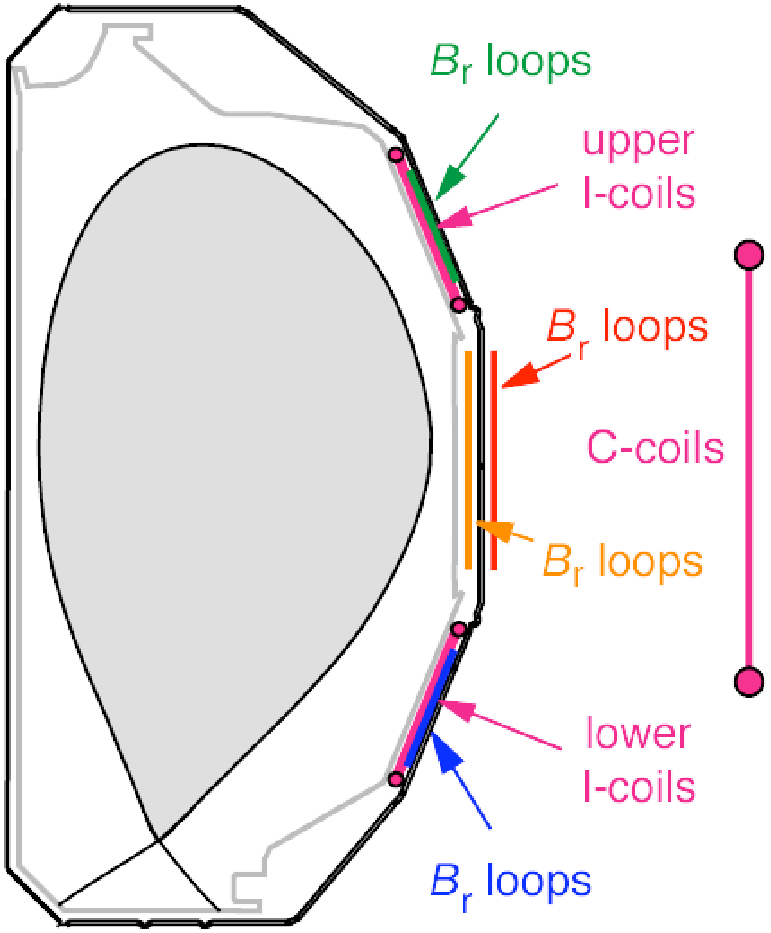
  Drive a low amplitude perturbation at various frequencies using external antennas and extract the plasma response with synchronous detection.

  Example: Analysis of Alfvén eigenmodes in JET [Fasoli et al, *PRL* **72** (1995) 645]
  - $f > 10^4$ Hz
  - l□/□l << 1 (weak damping)

- First step: Understand interaction between external field and RWM (also important for feedback control), now for
  - $f < 100$ Hz
  - l□l ~ □ (strong damping)

- Second step: Use plasma response to measure RWM stability.

DIII-D has versatile sets of antennas and detectors



Experimental setup:

Antenna: 12 internal saddle coils (I-coils), controlled by fast switching power supplies.

↓

Rotating magnetic field with large overlap with **RWM structure** at the wall.

Detector: Toroidal arrays of saddle loops (and poloidal field probes) above, on and below the midplane.

Frequency dependent vacuum coupling to I-coil is measured.

Probe plasma stability with a rotating magnetic field

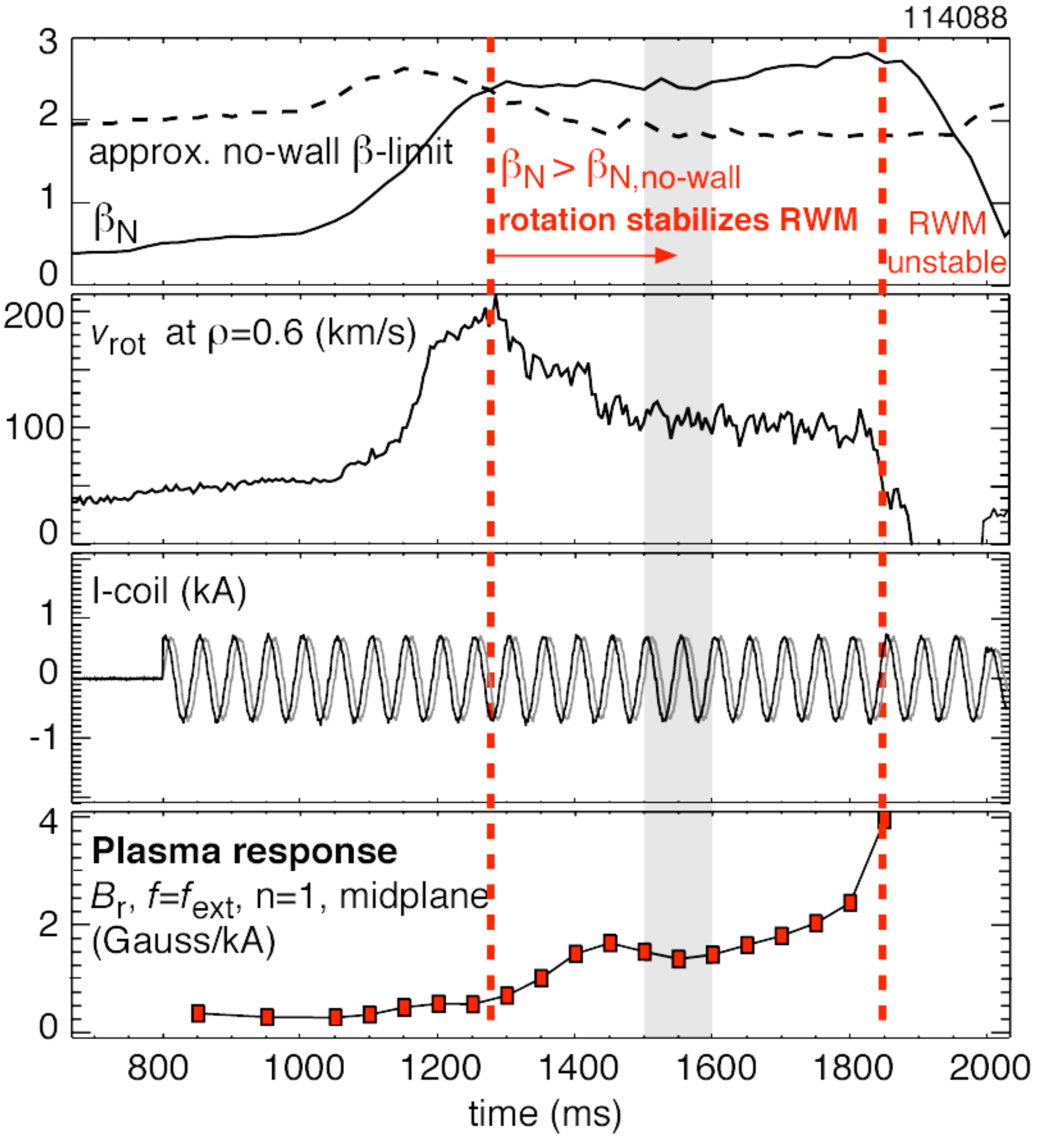
Experiment:

- Apply a rotating low amplitude m~3, n=1 field:

$$B_{w,\mathrm{ext}} = M_{wc} \cdot I_C \; e^{i\omega_{\mathrm{ext}} t}$$

⇒ Significant increase of the plasma response above the estimated no-wall limit.

- Measure plasma response while main stability parameters (β_N , l_i, v_{rot}) are kept constant.



Simple single mode models describe interaction between externally applied fields and the RWM

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

$$\left(\gamma\tau_w - \gamma_0\tau_w\right)B_w = M_{wc}I_C$$

for the RWM amplitude B_w and currents in the control coils I_C.

- The RWM growth rate for in the absence of external currents γ_0 is given by the dispersion relation:
  - **‘Simple’ RWM model:** $$\gamma_0\tau_w = \frac{1}{2}\left[\frac{\alpha}{k} - 1\right]$$

    with $\alpha = -\left(r\psi'/\psi\right)\big|_w$.

  - **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.

Simple single mode models predict response to an externally applied resonant field

- **Resonant field amplification** (RFA):
  External fields excite a marginally stable mode [Boozer, *Phys. Rev. Lett.* **86** (2001) 1176.]

$$A_{RFA} = \frac{B_w - B_{w,vac}}{B_{w,vac}}$$

- Predicted response to an externally applied frequency ω_{ext}:

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

- Analysis of DC RFA-experiments* with the Garofalo-Jensen-Strait model yielded values for γ_0 ,predicting a resonance at 10Hz in the direction of the plasma rotation.

*[Garofalo and Jensen, accepted for publication in *Phys. Plasmas*]

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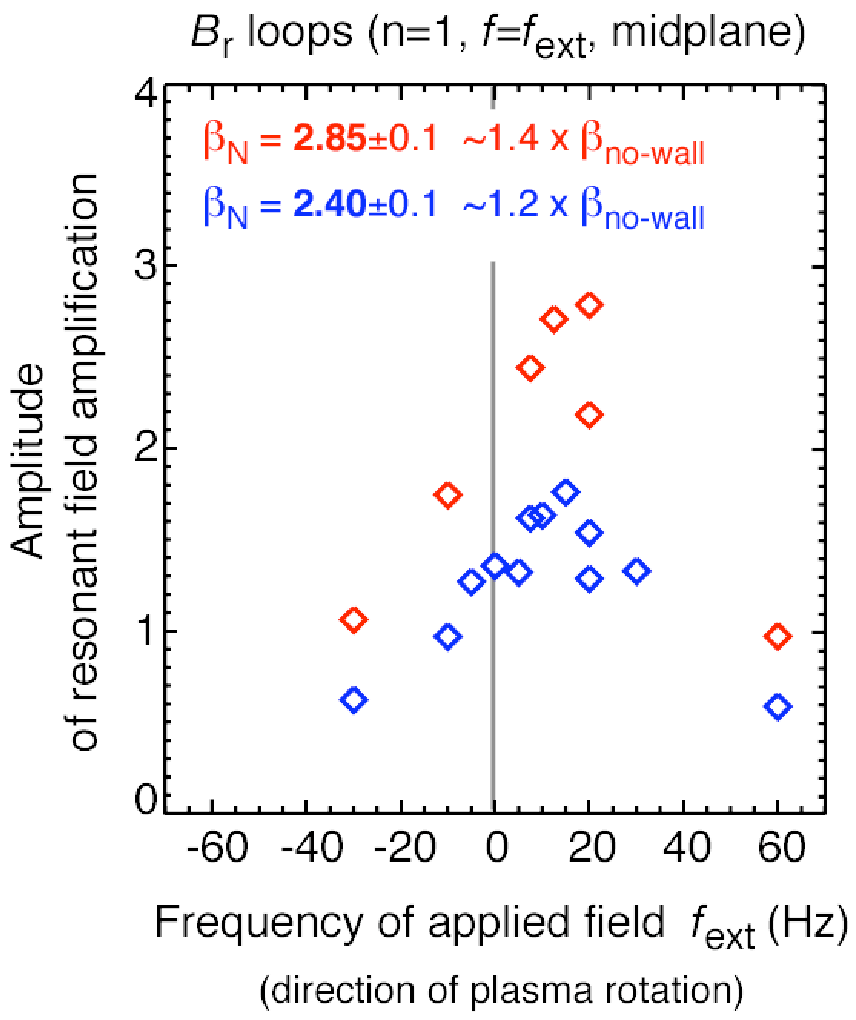
Plasma response peaks for an externally applied field rotating in the direction of the plasma rotation

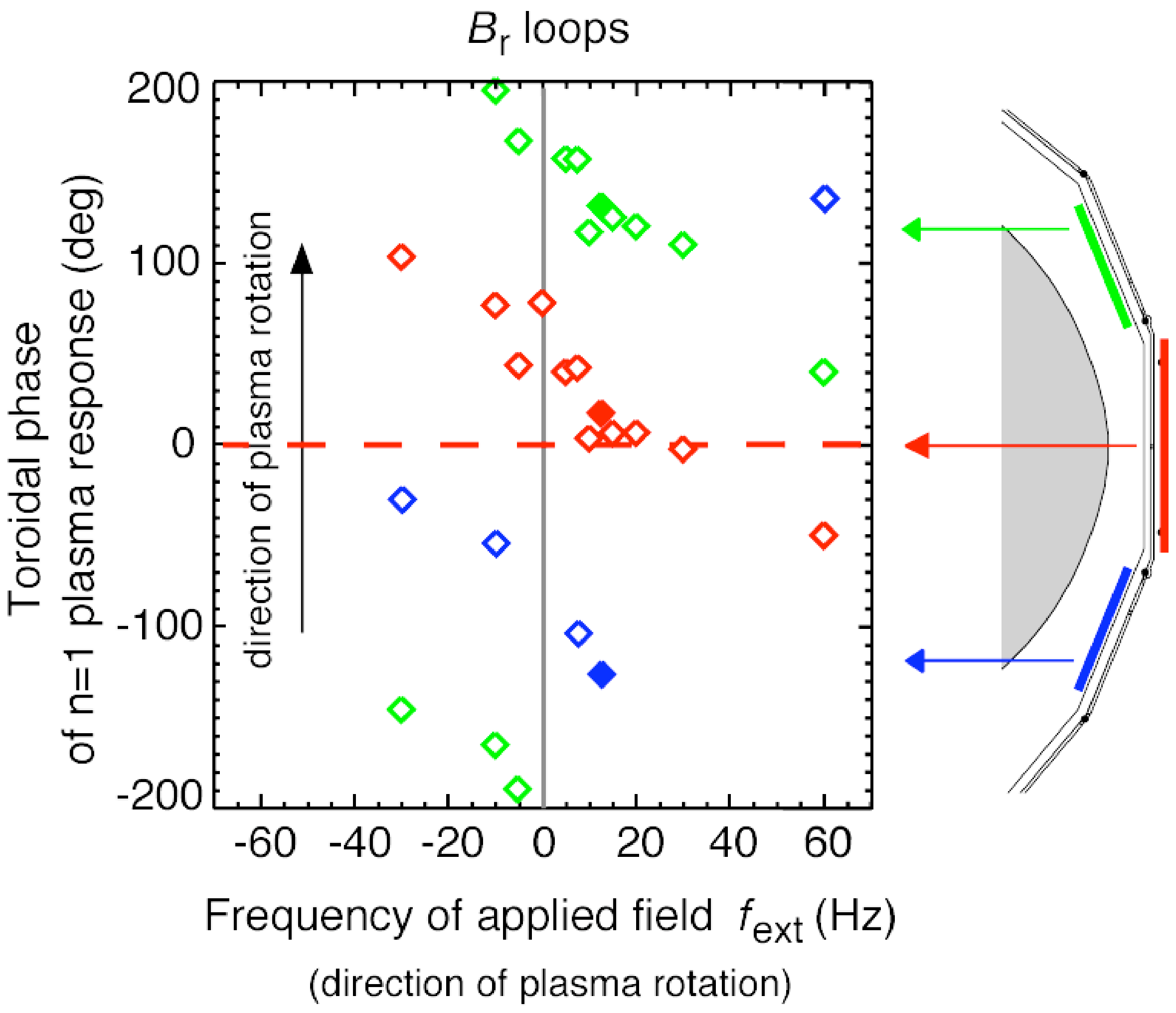
- Largest response for f_{ext} between 10 and 20Hz (fraction of the **inverse wall time** in the direction of the **plasma rotation**).
- Plasma response increases with β.



Plasma response is consistent with single-mode RWM model

- Phase difference among B_r-arrays consistent with **RWM structure**.
- Phase of plasma response changes from leading to trailing the external field as its frequency increases.
- Phase difference among arrays independent of f_{ext} .

□ Interaction between external fields and plasma consistent with single-mode RWM model.



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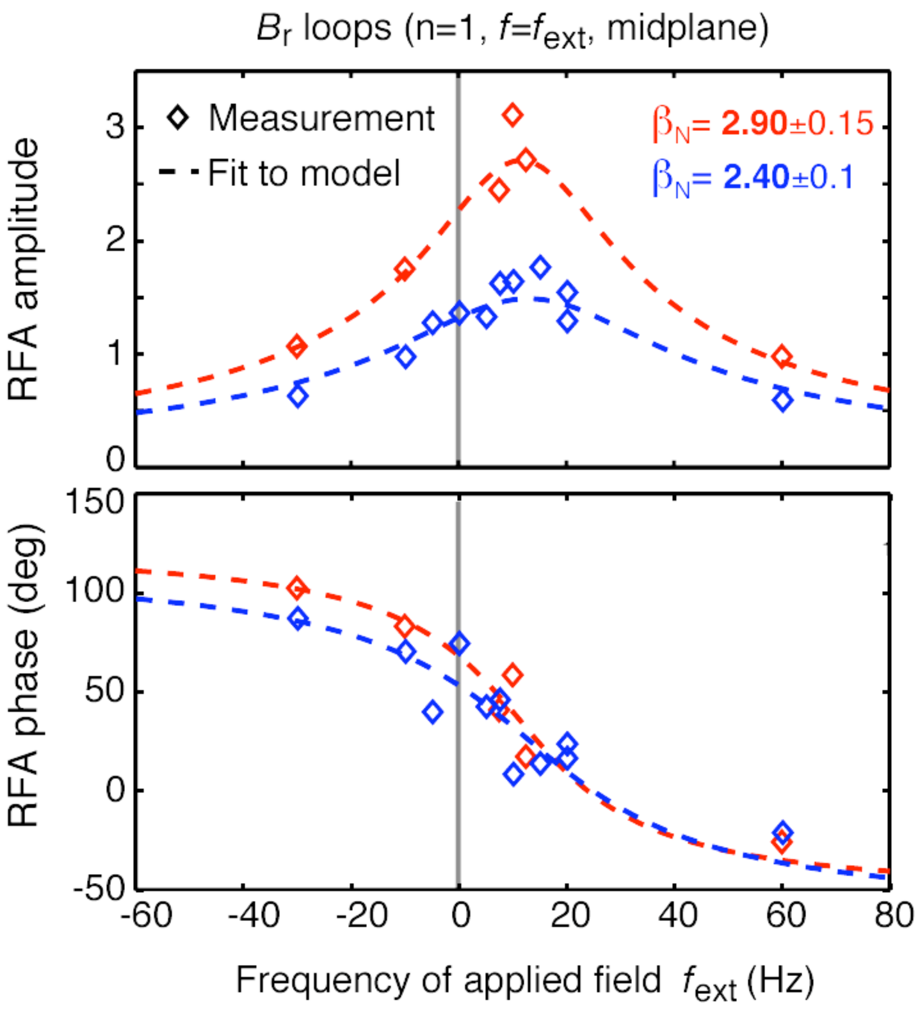
Measured spectrum consistent with predictions of a marginally stable RWM in a rotating plasma

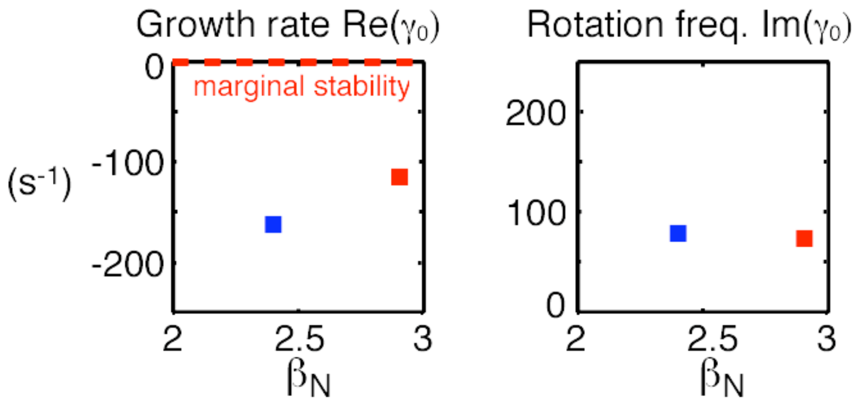


Fitted γ_0: **$(-157 + i\,80)\ s^{-1}$** **$(-111 + i\,73)\ s^{-1}$**

- Fit measured $A_{RFA}(\square_{ext})$ to predictions.

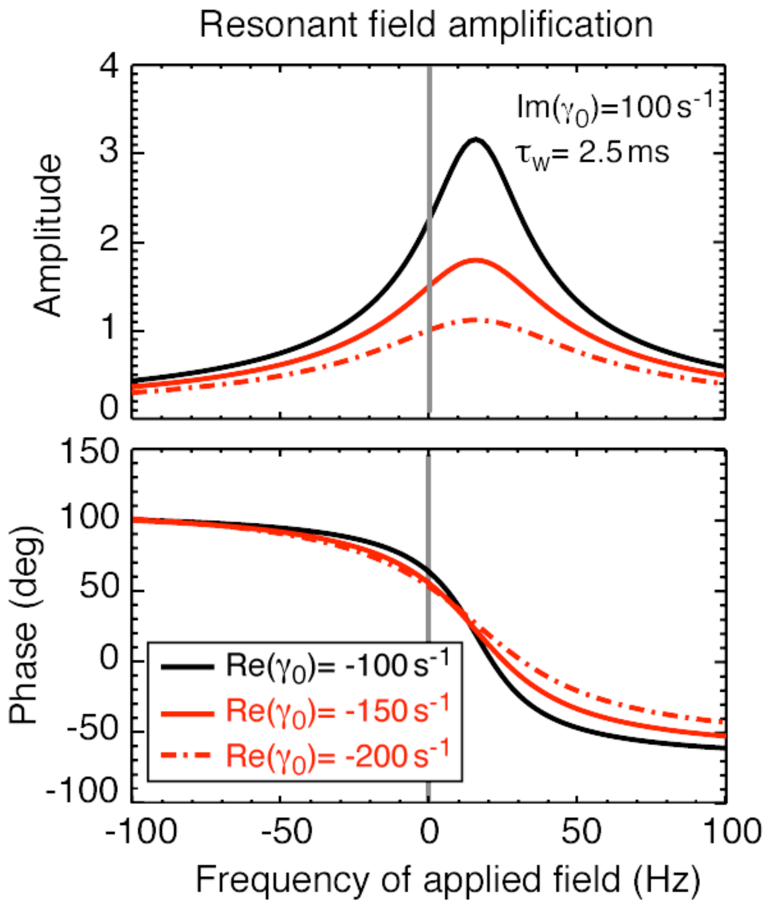
$$A^{s}_{RFA} = \frac{c_s \cdot \left(1/\square_w + \square_0\right)}{i\square_{ext} \,\square\, \square_0}$$

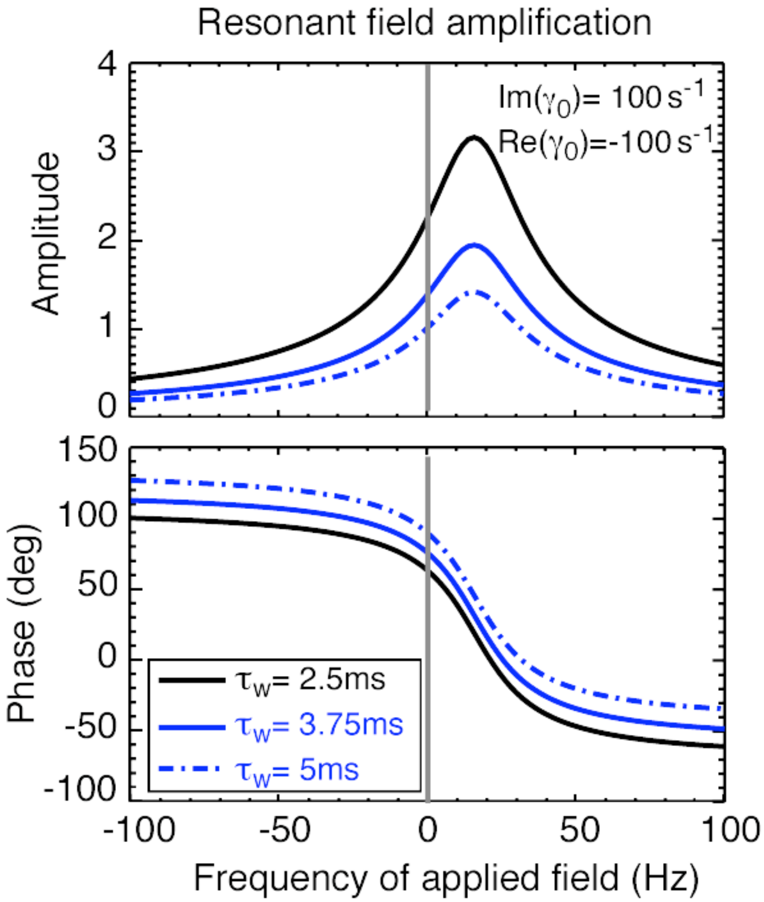
- Good agreement:
  - Indicates that a single-mode model is applicable.
  - Yields measurement of the damping caused by plasma flow.



Curve fit separates γ_0 and geometrical factor

- Re(γ_0) determined by resonance width.
- τ_w determined by (complex) multiplier (like c_s).

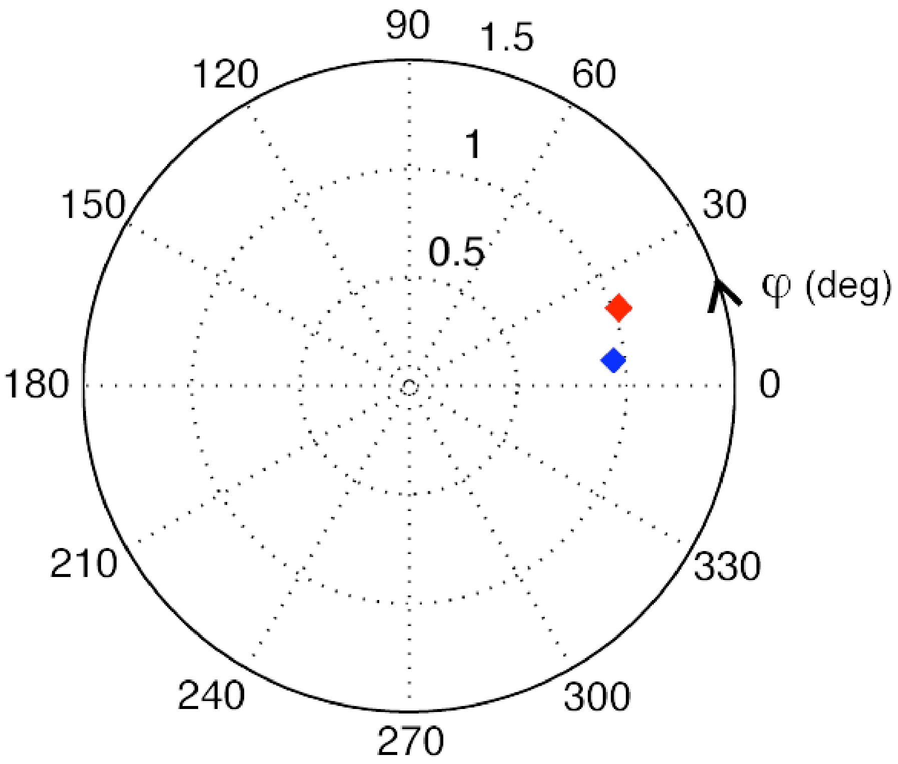




Geometrical coupling factor remains constant

$$C_s = \frac{\text{Resonant component of applied field at sensor s.}}{\text{Vacuum measurement of applied field at sensor s.}}$$

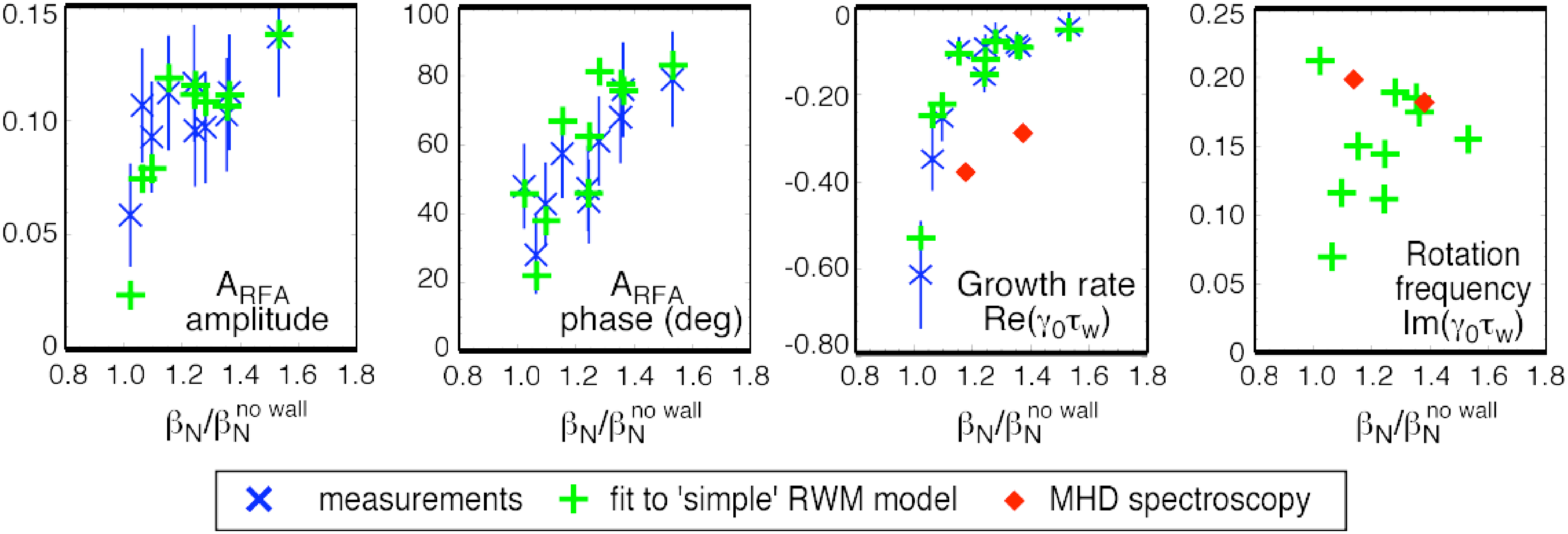
- The coupling factor is determined from the fit by assuming τ_w= 2.5ms (dominant *m*= 3 mode structure).
- The fits for both values of beta result in a similar coupling factor - consistency with single-mode model.
- The coupling factor has an amplitude of ~1 (coincidence).
- The coupling factor has a phase shift of ~10-20 degrees - up-down asymmetry.



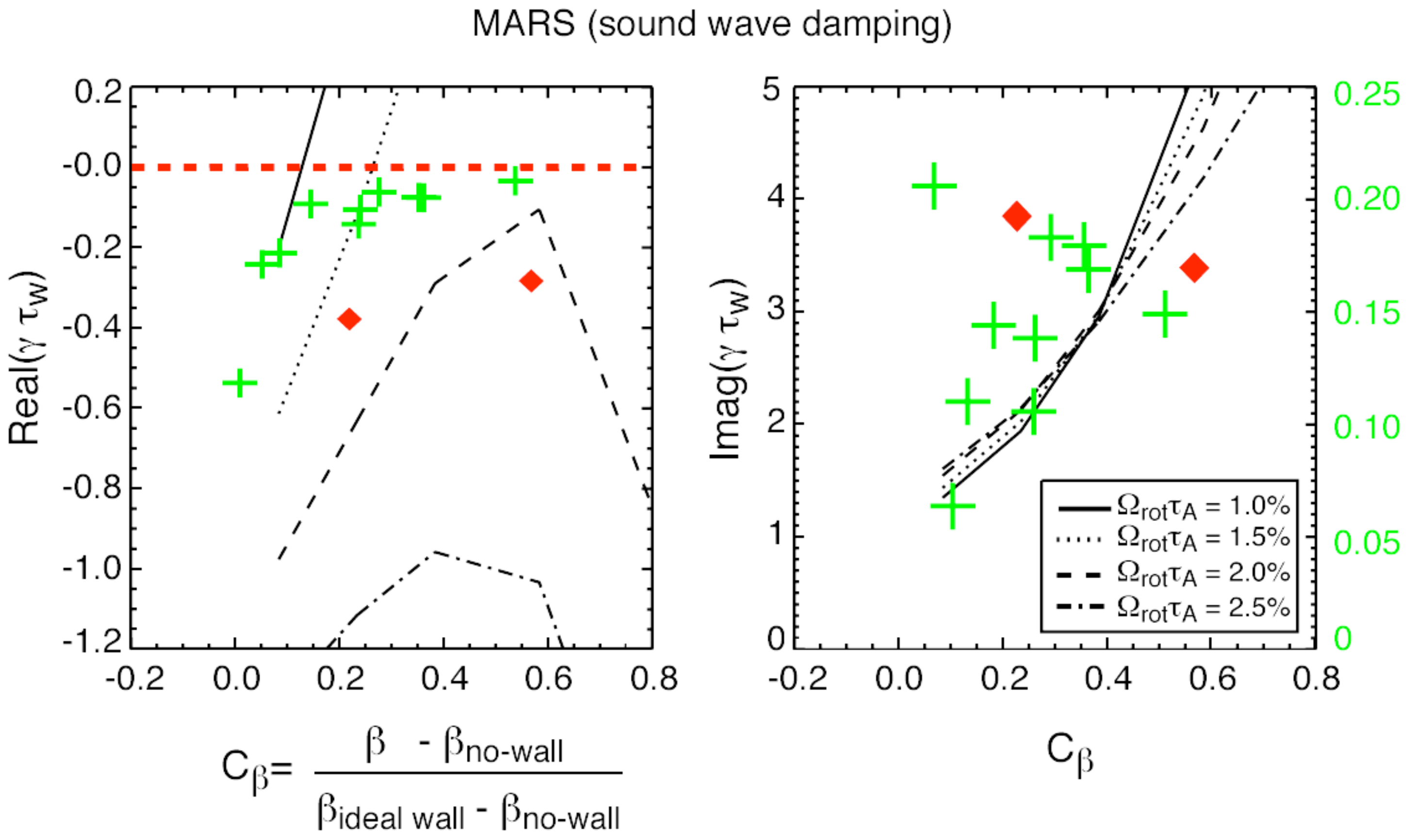
Coupling factor c_{ESLD}

Compare with DC pulse experiments

- MHD spectroscopy experiments: $\beta_{N,\text{no-wall}} \approx 2.1$, $\beta_{N,\text{ideal wall}} \approx 3.5$.
- Measurements of the **RWM damping rate** and **rotation frequency** by the DC pulse experiments [Garofalo and Jensen, to be published in *Phys. Plasmas*] and by MHD spectroscopy agree within a factor of 2!



Absolute measurement of RWM damping by plasma rotation quantitatively tests dissipation models (MARS)



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

- Use MARS as a tool to test various dissipation models:
  - Generic equilibrium + DIII-D vessel + flat rotation profile + sound wave damping model.

- Predicted rotation frequency is an order of magnitude too large.

Summary: Active MHD spectroscopic measurement of the stabilizing effect of plasma flow on the RWM

- Rotating externally applied magnetic fields cause a plasma response, which:
  - increases with beta once beta exceeds the no-wall stability limit.
  - peaks for a field rotating with a fraction (25-30%) of the inverse wall time in the direction of the plasma rotation.
- The plasma response is identified as an RWM, which is stabilized by plasma flow.

- The frequency dependence, in particular the rigid response, is in good agreement with single mode models.
- Confirms our understanding of the interaction between externally applied fields and the RWM.
- Yields an absolute measurement of the damping of the RWM by plasma flow.
- The measurement of the damping can now be used to quantitatively test dissipation models.