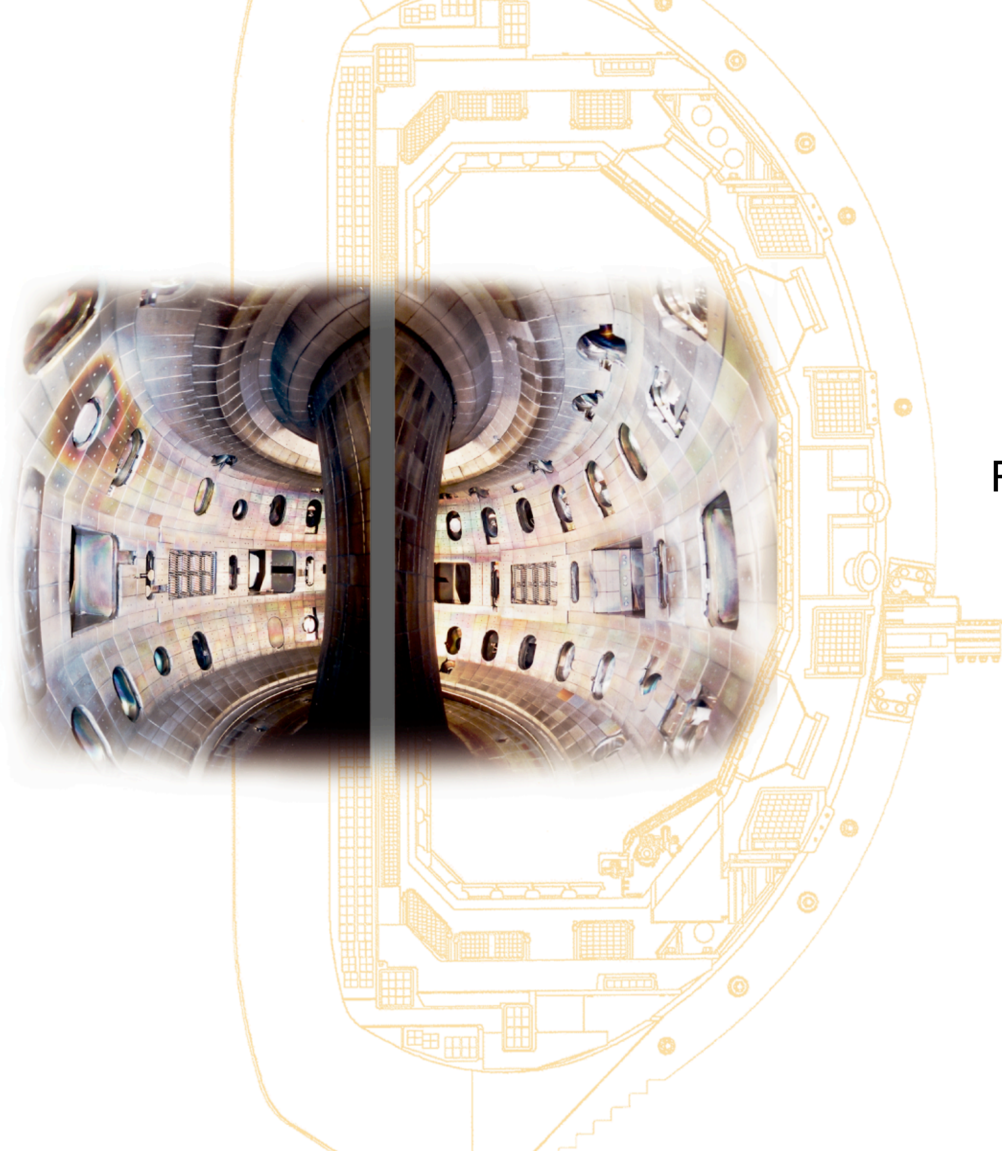
Active MHD Spectroscopy on the Resistive Wall Mode in DIII–D and JET



by

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GENERAL ATOMICS

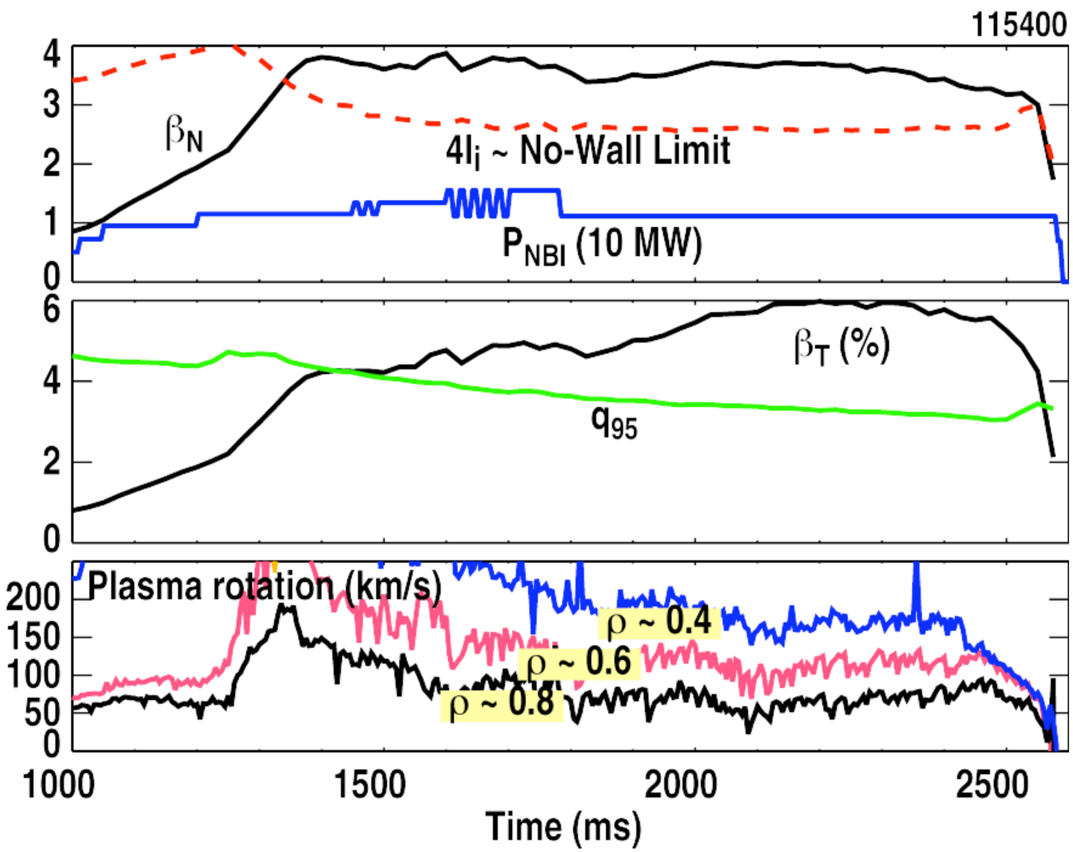
Columbia University

Outline

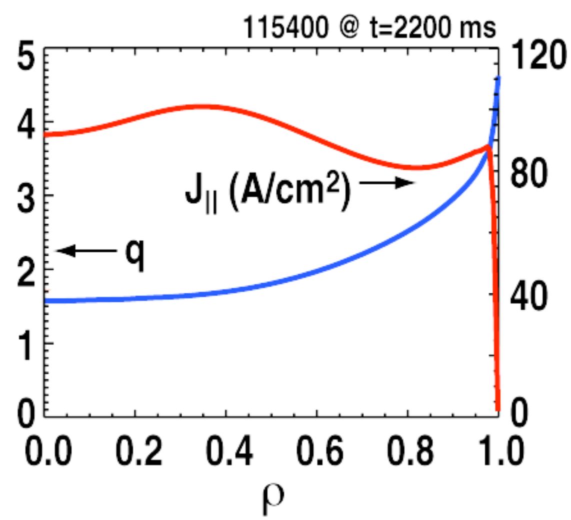
- Advanced tokamak operation with wall stabilization of the external kink mode
  - Dispersion relation of the resistive wall mode (RWM) and modifications due to plasma rotation
- Extend technique of active MHD spectroscopy to very low frequencies
  - Resonant field amplification (RFA)
- Frequency dependence of n=1 RFA in DIII-D
  - Description of RFA spectrum by a single mode approach
  - Measurement of the RWM growth rate and mode rotation frequency
- Frequency dependence of n=1 RFA in JET
- Application of active MHD spectroscopy
  - Test of sound wave dissipation model
  - Comparison of co- and counter NBI discharge
- Summary

Operation in the wall stabilized regime with β_N~6li and β_T reaching 6%

- Beta exceeds estimated no-wall limit for >1s.



- Broad current profiles can greatly benefit from wall stabilization.



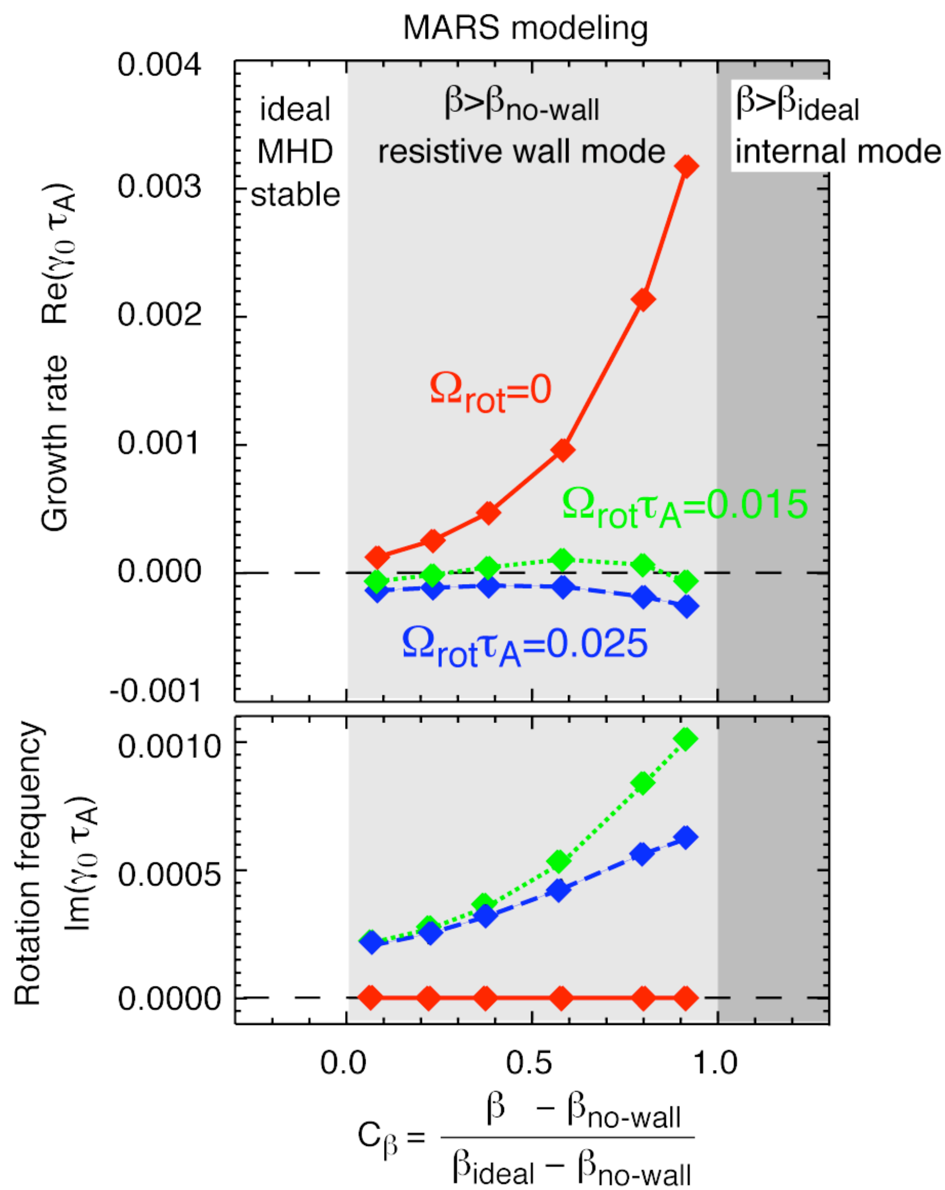
Stabilization of Resistive Wall Mode (RWM)

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

  In the presence of a resistive wall, the free-boundary ideal MHD kink mode becomes a slowly growing RWM

  - 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 (toroidal) plasma flow.

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



Direct measurement of the RWM dispersion relation through active MHD spectroscopy

- **Active MHD spectroscopy**

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

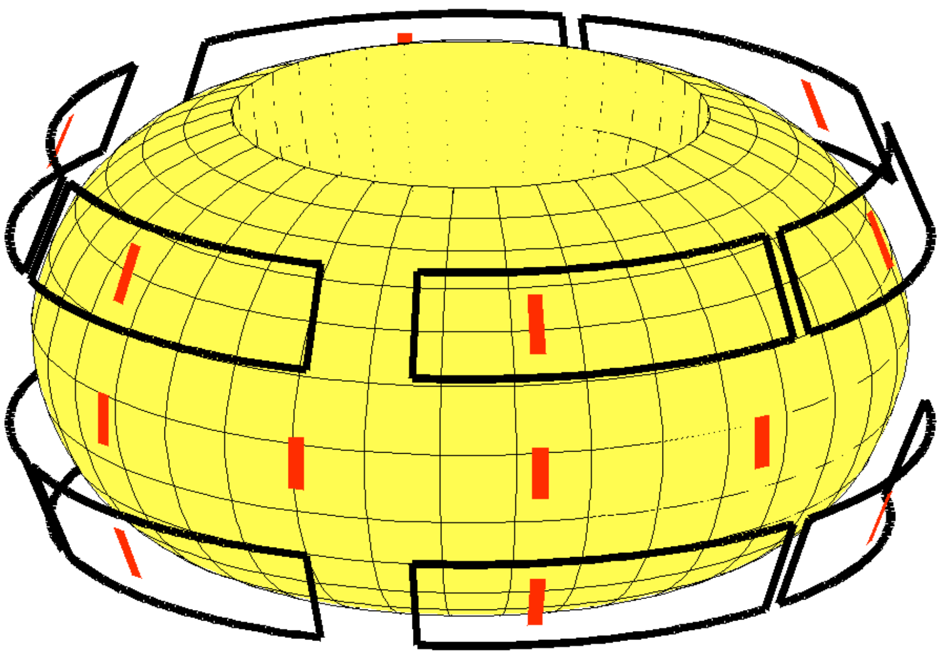
  Example: Analysis of Alfvén eigenmodes in JET [Fasoli et al, *Phys Rev Lett* **74** (1995) 645]
  - $\omega_{ext}/2\pi > 10^4$ Hz

- **Apply on Resistive Wall Mode** (where $\omega_{RWM} \sim 0$)

  Understand interaction between external field and RWM (also important for feedback control), now for
  - $\omega_{ext}/2\pi < 100$ Hz, i.e. $\omega_{ext} \sim \tau_w^{-1}$, where τ_w is the characteristic decay time of wall eddy currents.

- **Resonant field amplification** (RFA):
  External fields excite a marginally stable mode [Boozer, *Phys Rev Lett* **86** (2001) 1176].
- Dynamic response to externally applied resonant field pulses has been used to measure the RWM stability [Garofalo et al, *Phys Plasmas* **10** (2003) 4776].

DIII-D has versatile sets of antennas and detectors



Antenna:

- 12 internal saddle coils (I-coils).

- Phase coil currents to generate a **rotating magnetic field** with a large overlap with the **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.

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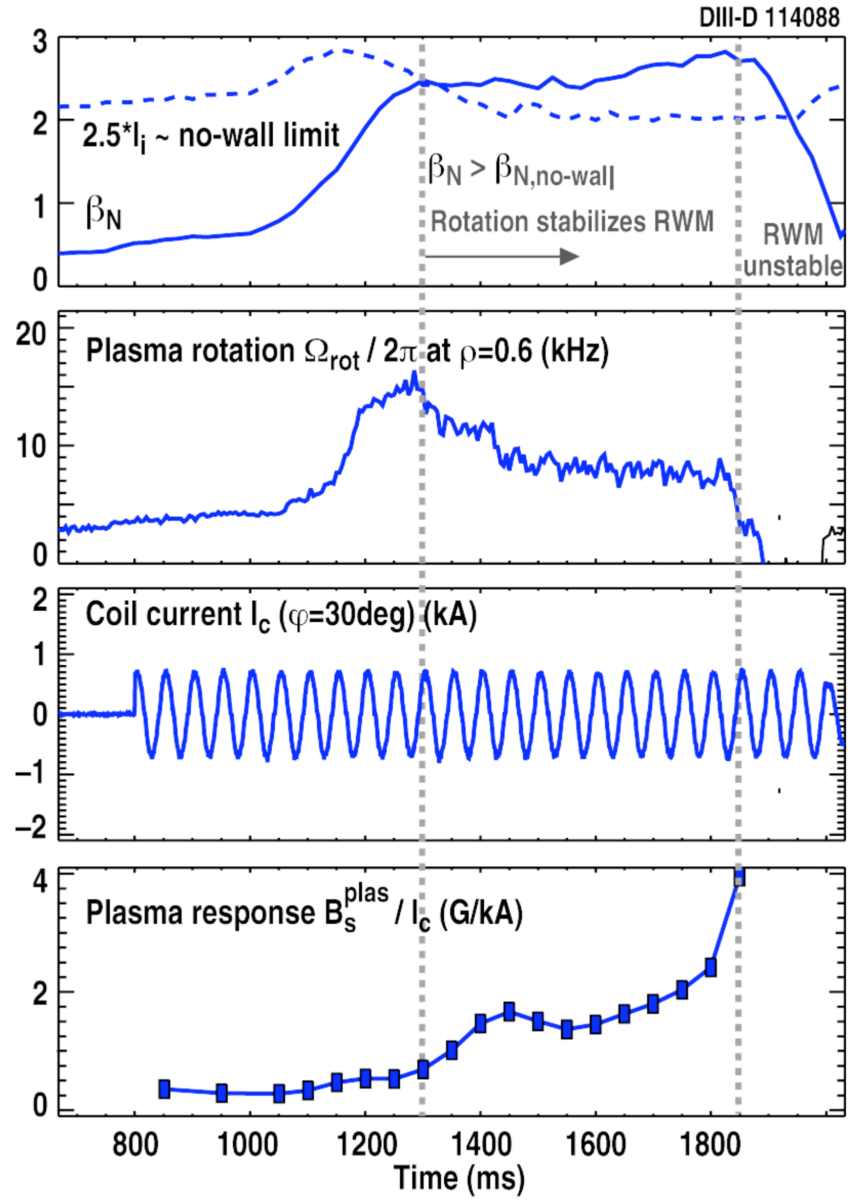
Rotating magnetic field applied to probe wall-stabilized DIII-D plasmas

- Apply a rotating low amplitude n=1 field:

$$I_c(t) = I_c \; e^{i\omega_{ext}t}$$

⇒ Plasma response increases significantly when beta exceeds the no-wall limit.

- Measure plasma response at different frequencies in multiple identical discharges.



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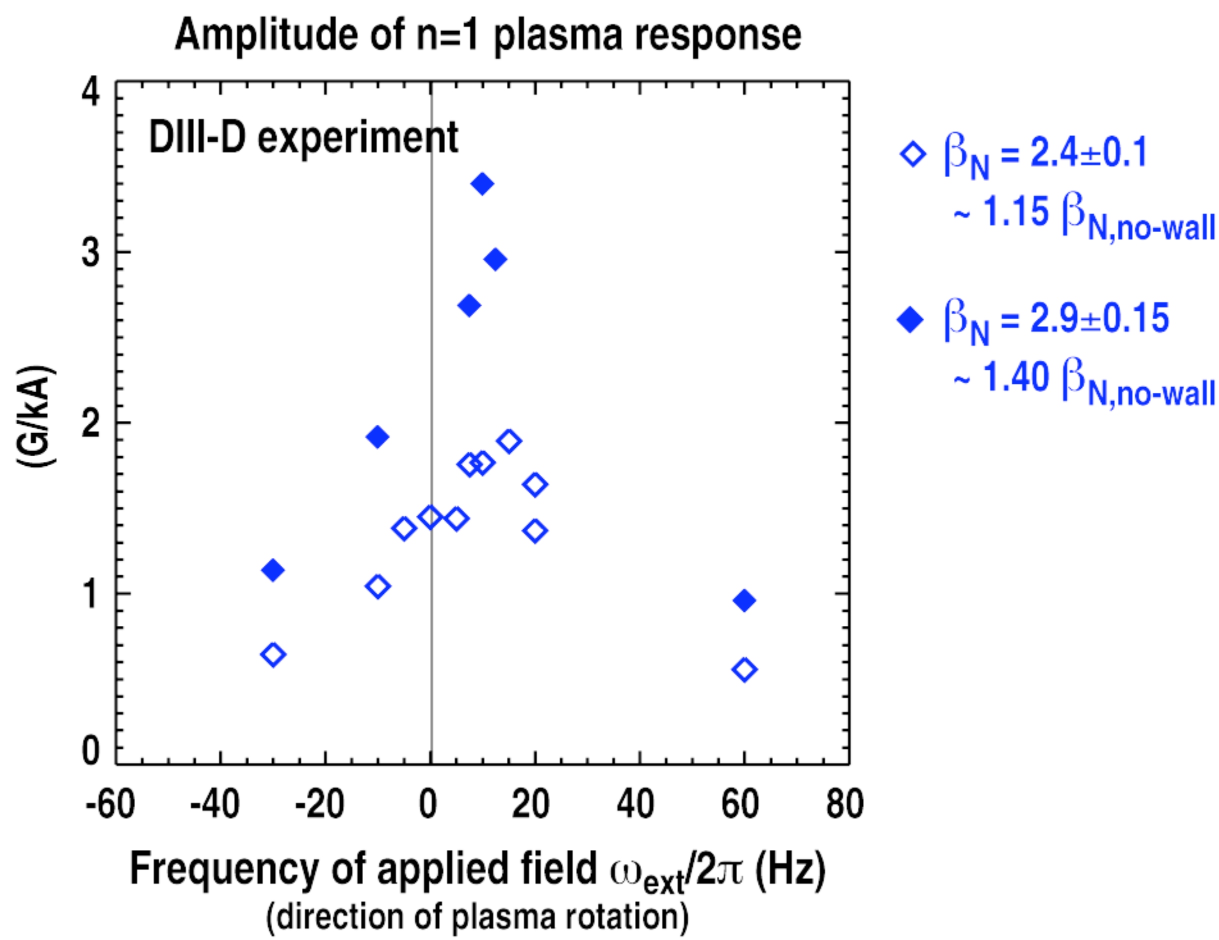
Plasma response peaks for an externally applied field rotating in the direction of the plasma rotation

- Largest plasma response for $\omega_{ext}/ 2\pi \sim 10$ to 15 Hz, corresponding to $\omega_{ext} \sim 15$ to 25% of inverse wall time).
- Amplitude of plasma response increases with β.



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Single mode model describes the interaction between the RWM and an externally applied field

- Single mode RWM model in slab geometry [Garofalo, Jensen, Strait, *Phys Plasmas* **9** (2002) 4573] yields relation between the perturbed radial field at the wall, B_s, and currents in the control coils, I_{ext},

$$\tau_w \frac{dB_s}{dt} - \gamma_0 \tau_w B_s = M_{sc}^* \ I_{ext}$$

- This expression holds for **general toroidal geometry** [Chu et al, *Nucl Fusion* **43** (2003) 196] and is **independent** of the details of the dispersion relation.

- Dispersion relations predict (complex) RWM growth rate, $\gamma_0 = \gamma_{RWM} + i\ \omega_{RWM}$, in the absence of external currents, e.g.:
  - **Ideal MHD with rotation and dissipation:** $\gamma_0\tau_w$ from MARS calculations with various dissipation models [Liu, et al, *Phys. Plasmas* **7** (2000) 3681].

Single mode model predicts frequency dependence of the plasma response

- Distinguish between externally applied field and plasma response,

$$B_s = B_s^{plas} + B_s^{ext}$$

- Predicted plasma response to an externally applied field **rotating** with ω_{ext}:

$$B_s^{plas}(t) = \frac{\gamma_0 \tau_w + 1}{(i\omega_{ext}\tau_w - \gamma_0 \tau_w)(i\omega_{ext}\tau_w + 1)} M_{sc}^* I_c e^{i\omega_{ext} t}$$

- Here, M_{sc}^* is the **effective** mutual inductance describing the **resonant** component of the perturbed field at the wall due to coil currents I_c.

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

- Predicted frequency dependence of the plasma response,

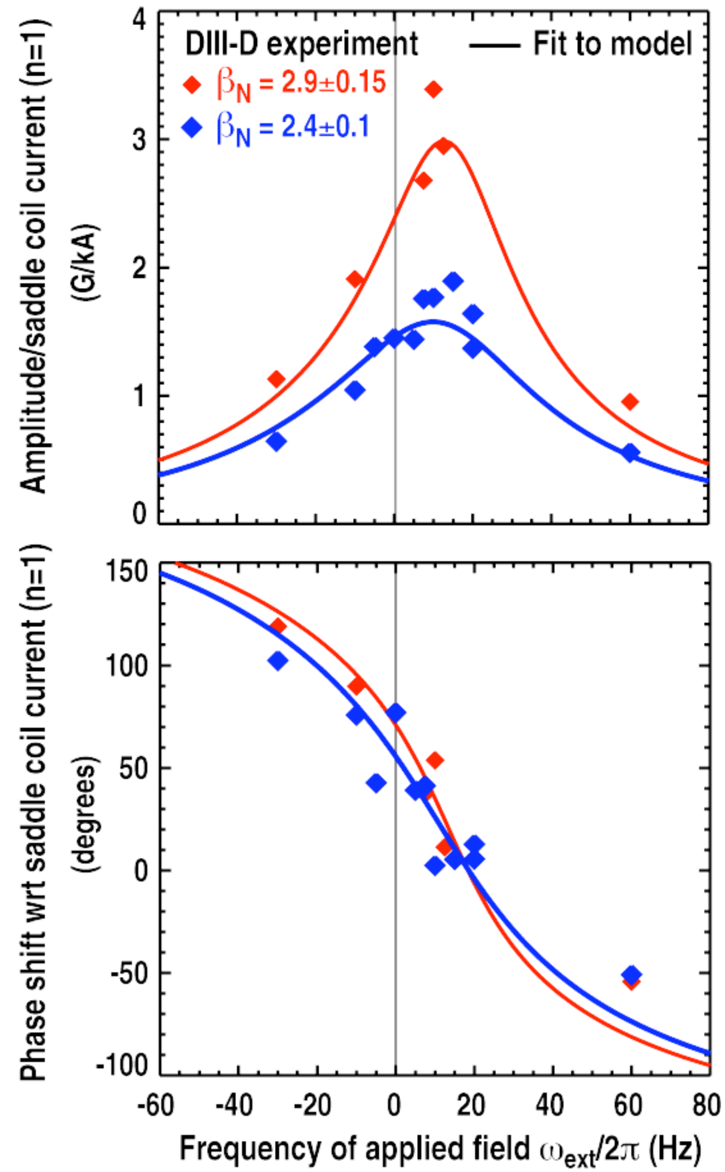
$$B_s^{plas}(t) = \frac{\gamma_0\tau_w + 1}{(i\omega_{ext}\tau_w - \gamma_0\tau_w)(i\omega_{ext}\tau_w + 1)} M_{sc}^* I_c e^{i\omega_{ext}t}.$$

- Fit γ_0 and M_{sc}^* to match measurements.

- Good agreement:
  - Indicates that a single-mode approach is applicable.
  - Yields measurement of the damping rate and mode rotation frequency:

    $\gamma_0 = (-157 + i80)s^{-1}$ for $\beta_N = 2.4$

    $\gamma_0 = (-111 + i73)s^{-1}$ for $\beta_N = 2.9$



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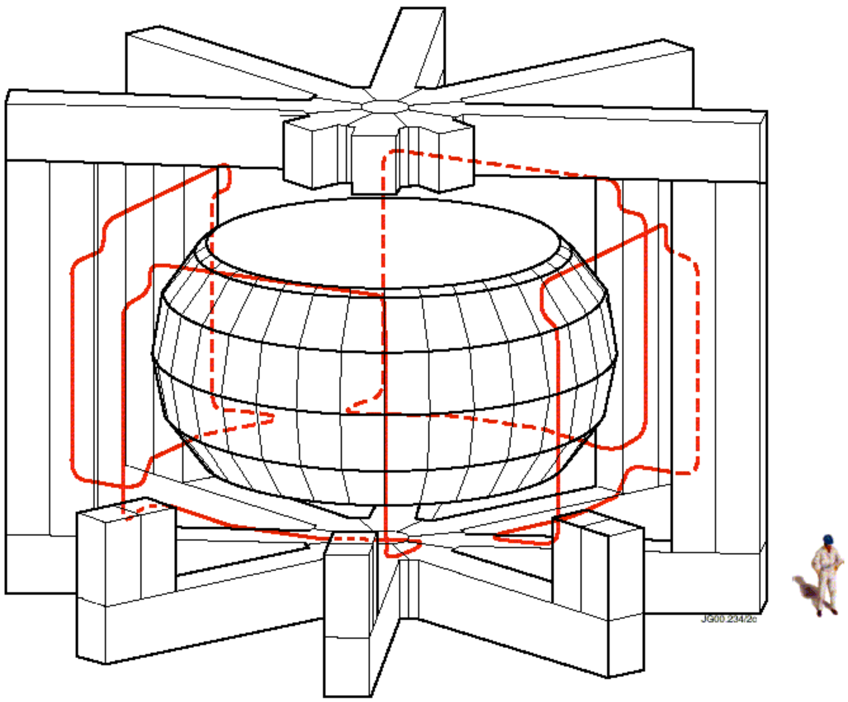
Measurement of the RFA spectrum on JET using the error field correction coils

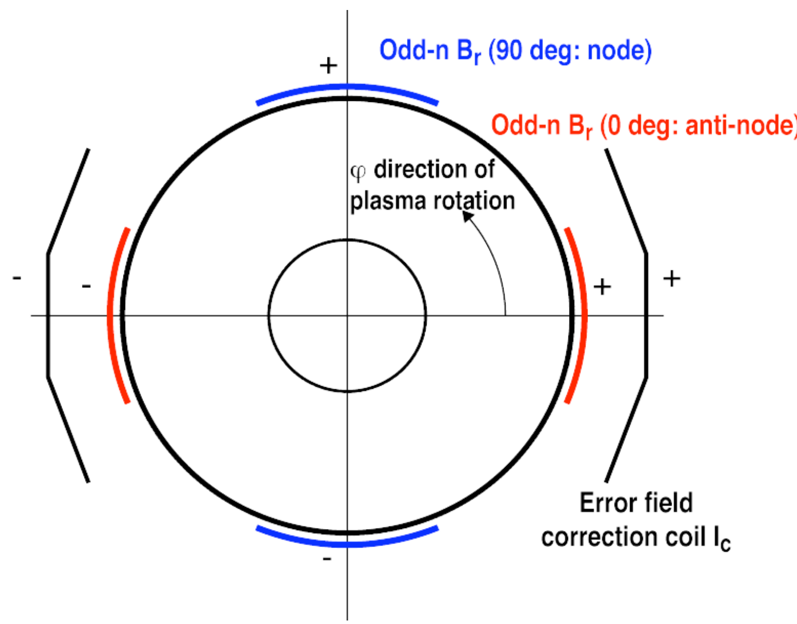
Antenna:

- One pair of the error field correction coils located in the midplane ⇒ apply n=1 **pulses** or **standing waves**.

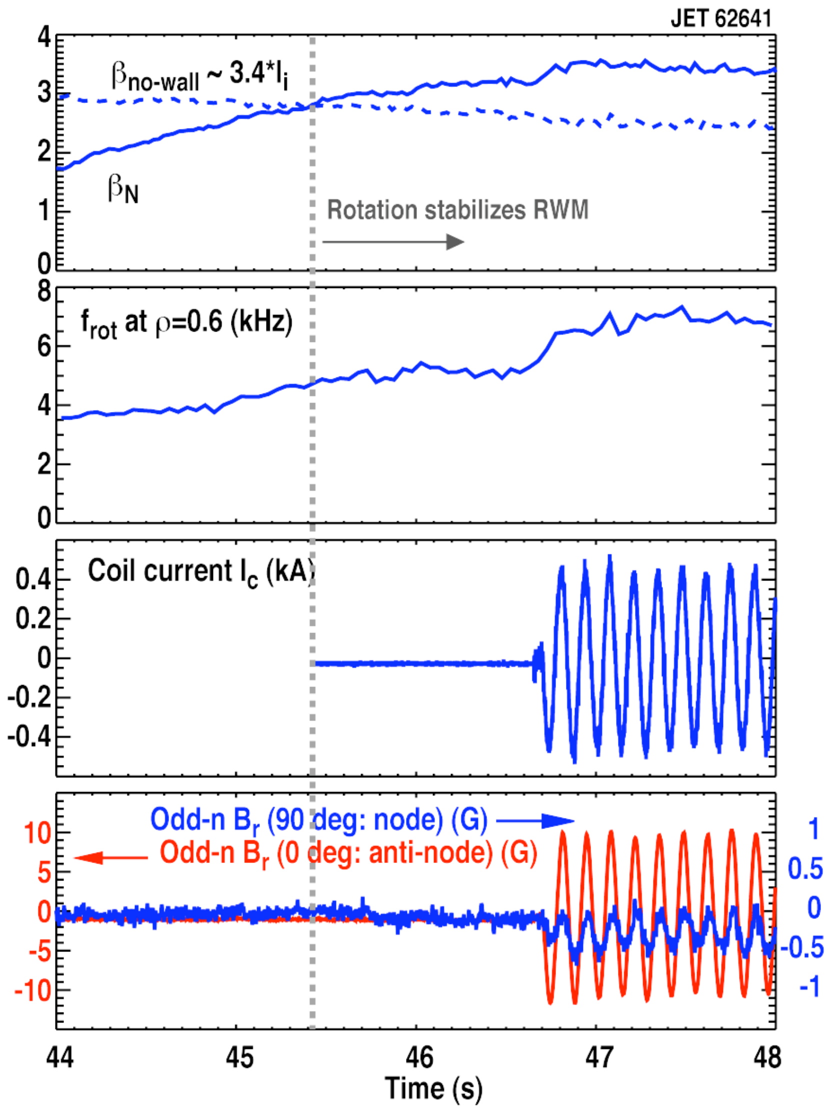
Detectors:

- Two pairs of external odd-n B_r loops located at the **anti-node** and **node** of standing wave.





Standing wave applied to probe wall-stabilized JET plasmas



- Exceed the no-wall beta limit
  - $B_T = 1.4T$
  - $I_P = 1MA$
  - $P_{NBI} \leq 20MW$
  - $P_{ICRH} \leq 5MW$
- Apply an n=1 standing wave

$$I_c(t) = \tfrac{1}{2} I_c \, e^{i\omega_{ext}t} + \tfrac{1}{2} I_c \, e^{-i\omega_{ext}t}$$

- Odd-n B_r at the node shows a plasma response.

Frequency dependence of plasma response in JET consistent with the single mode prediction

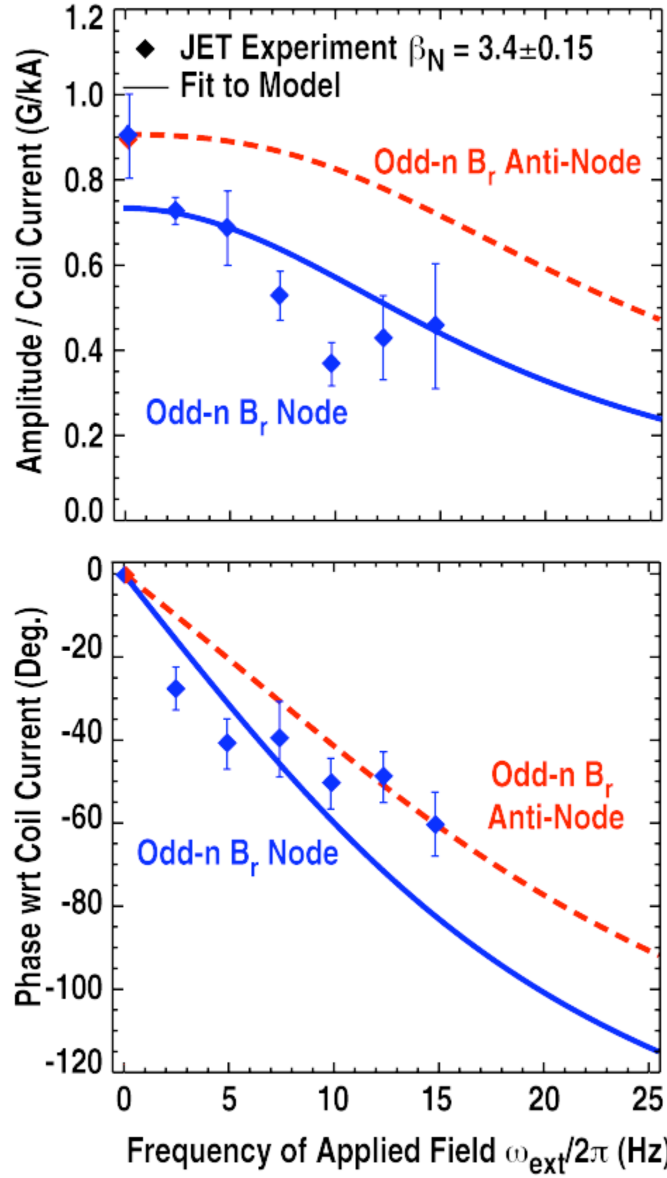
- Large direct coupling to the anti-node sensor (30 times larger than B_s^{plas}) leads to a significant uncertainty of this measurement ⇒ use only data for 0 Hz.

- Measurements are consistent with the single mode approach:
  – Fit yields the damping rate and mode rotation frequency:

    $\gamma_0 = (-100+i35)s^{-1}$ **for** $\beta_N = 3.4$

- The values for $\gamma_0\tau_w$ (with τ_w ~2.5 ms in DIII-D versus τ_w ~ 5 ms in JET) in both experiments are of similar magnitude,

  $$\gamma_0\tau_w \sim -0.4 + i\ 0.2\ .$$



MHD spectroscopy yields a continuous - potentially real-time - measurement of global n=1 stability

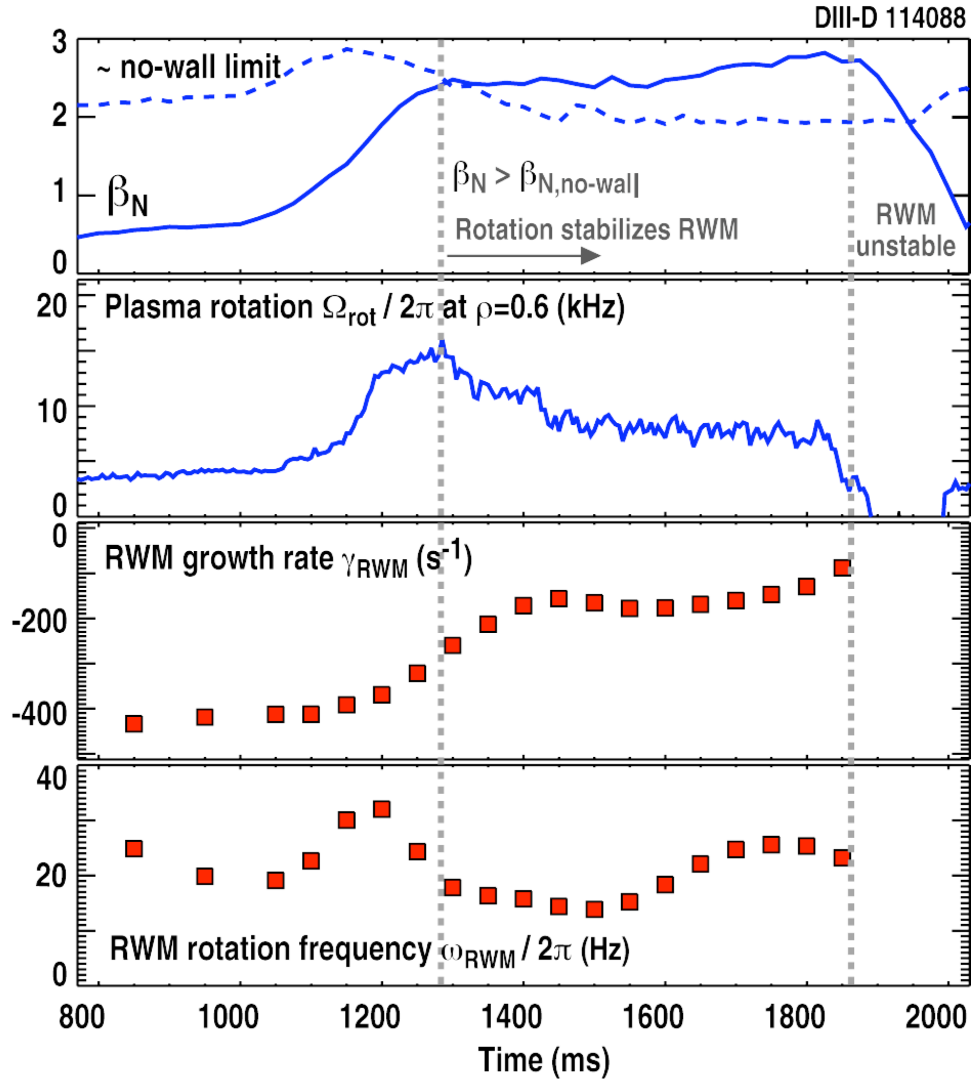
- With M_{sc}^{*} known from the fit of the entire spectrum the measurement of B_s^{plas} at a single frequency yields

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

with $A_{RFA,s} = B_s^{plas} / B_s^{ext}$

and $c_s = M_{sc}^{*} / M_{sc}$

- Apply a low amplitude perturbation (300-700 A corresponding to 3-7 G at the antenna).



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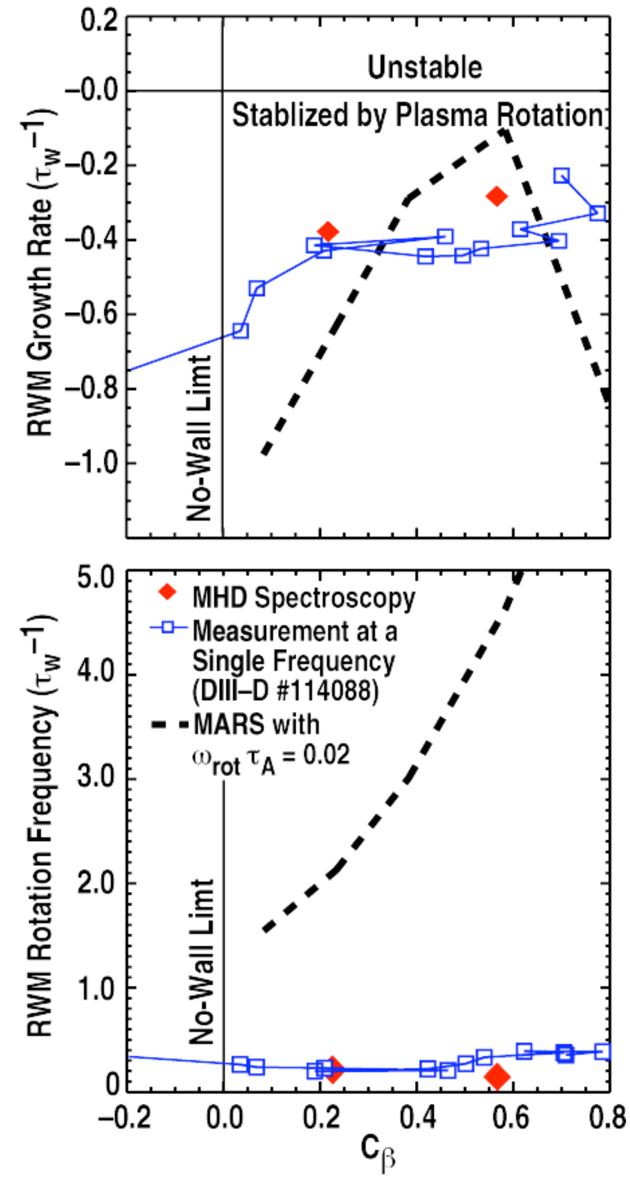
Measurement of RWM stability quantitatively tests dissipation models (MARS)

- First comparison with MARS code
  [Liu, et al, *Phys Plasmas* **7** (2000) 3681].
  - Generic equilibrium + DIII-D vessel + flat rotation profile + sound wave damping model.
- Observed damping rate is in good agreement with predictions
- Observed mode rotation frequency is an order of magnitude lower than predictions.

⇒Further theoretical and experimental work is needed.



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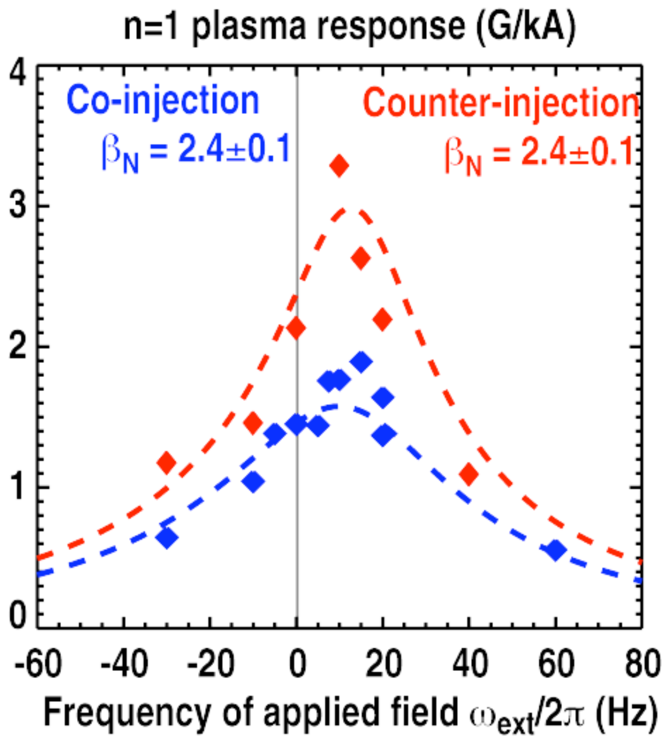
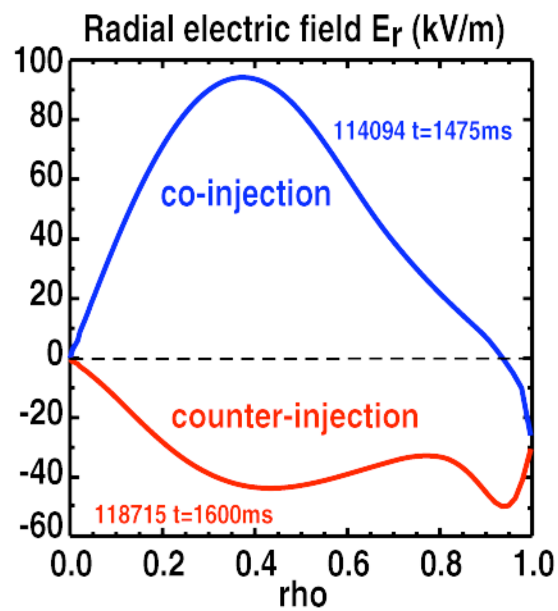
MHD spectroscopy allows investigation of models for RWM stabilization

Preliminary result

- Smaller plasma response indicates stronger damping with co-injection.



- Radial electric field varies.



Test predictions of dissipation mechanisms

- Soundwave damping [Bondeson and Ward]
- Kinetic damping [Bondeson and Chu]
- Neoclassical toroidal ripple viscosity [Shaing]
- Resonance with trapped particle precession [Hu and Betti]

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Summary

- Interaction between externally applied resonant magnetic fields and the RWM in DIII-D and JET well described by a single marginally stable mode.
- RFA spectrum yields measurement of the RWM damping rate and mode rotation frequency.
  - Extension of “Active MHD Spectroscopy” to very low frequencies.
  - Rotating fields can provides a continuous, potentially real-time, measurement of RWM stability.
- Stability measurement allows for direct comparison with models of RWM stabilization by plasma rotation.
  - Comparison with soundwave-damping model shows qualitative agreement for damping rate, but observed mode rotation frequency is an order of magnitude lower than predictions
  - Different damping observed in co- and counter NBI discharges allowing test of predictions of stabilization models.

  $\Rightarrow$ Further theoretical and experimental work is needed.