Measurement of Resistive Wall Mode Stability in Rotating High Beta Plasmas

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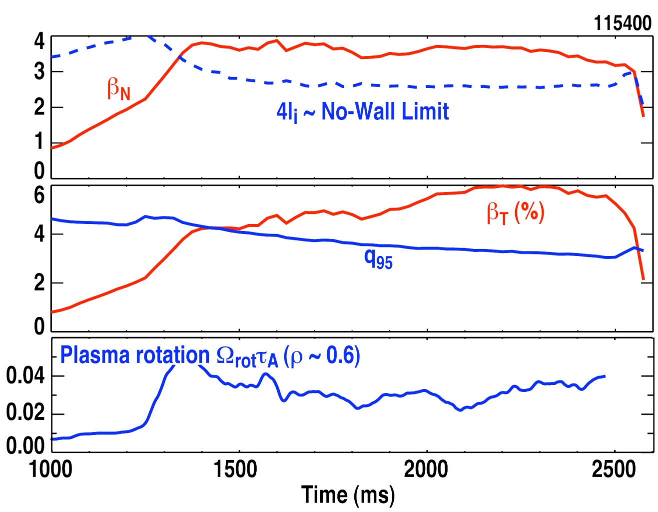
Stabilization of the Resistive Wall Mode (RWM) can extend the operating regime from the no-wall up to the ideal wall limit



- 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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Outline

- Passive measurement of the toroidal plasma rotation required for stability Ω_{crit}
  - Ω_{crit} in two scenarios (low-l_i and moderate-l_i)
  - Comparison with MARS calculations
- Active measurement of RWM growth rate γ_{RWM} and mode rotation frequency ω_{RWM}
  - Static and dynamic response to externally applied pulsed n = 1 fields yields γ_{RWM} and ω_{RWM}
  - Measurement of γ_{RWM} and ω_{RWM} with pulsed fields in the low-l_i scenario
  - Plasma response to externally applied rotating n=1 fields yields γ_{RWM} and ω_{RWM} (MHD spectroscopy)
  - Measurement of γ_{RWM} and ω_{RWM} with rotating fields in the moderate-l_i scenario
  - Comparison with MARS calculations
- Application of MHD spectroscopy as a continuous stability measurement
- MARS predictions of Ω_{crit} for DIII-D AT scenarios

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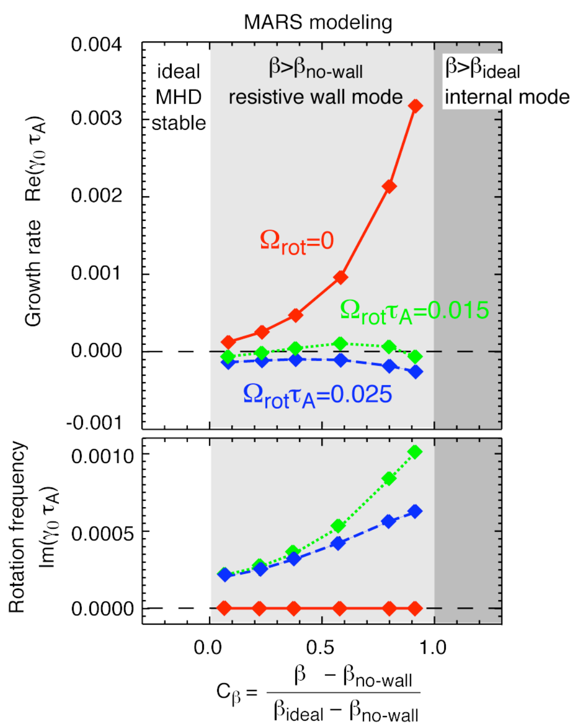
Plasma rotation predicted to stabilize the RWM

- **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 $\gamma_{RWM} \sim \tau_w^{-1}$
    → 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]
- Understanding of dissipative process essential for extrapolation to future experiments



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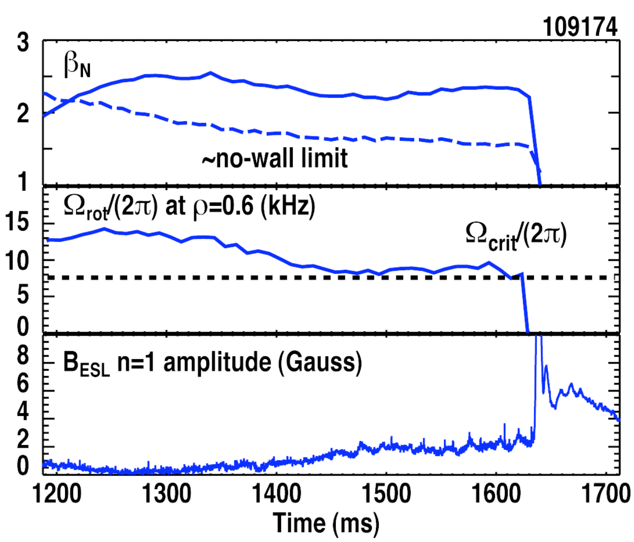
Several dissipation models are proposed

- **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 the sound wave or kinetic damping model

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

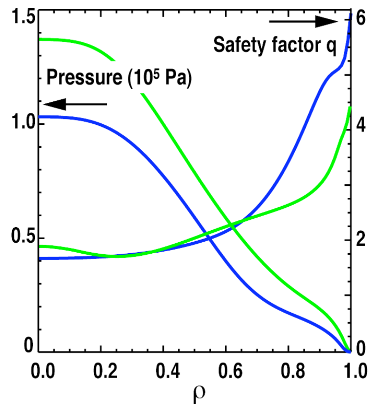


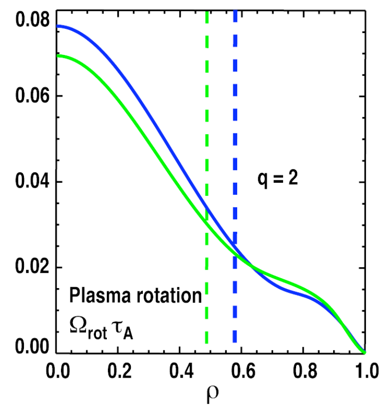
- Passive measurement of Ω_{crit}
  - Insufficient error field correction causes slow-down of toroidal rotation
  - Onset of RWM marks Ω_{crit}

- 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

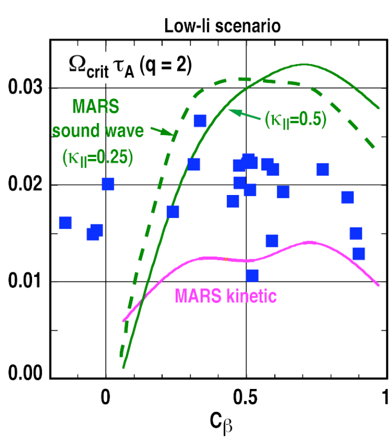
Low-li scenario / Moderate-li scenario

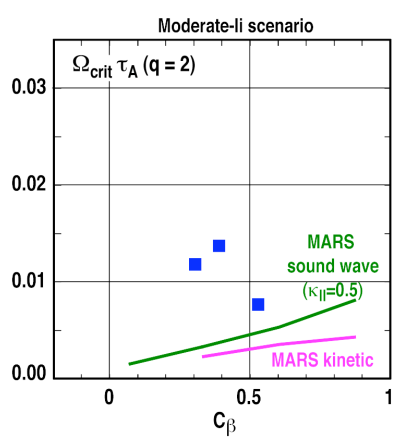




- Low-l_i scenario greatly benefits from wall stabilization
  - $\beta_{N,no-wall}$ ~1.6 ~2.4 l_i
  - $\beta_{N,ideal-wall}$ ~3.2 (~4.8 l_i)
- Moderate-l_i scenario has a higher no-wall limit
  - $\beta_{N,no-wall}$ ~2.0 ~2.4 l_i
  - $\beta_{N,ideal-wall}$ ~3.2 (~3.8 l_i)
- Moderate-li scenario has a higher safety factor q95 (includes q=5 and 6 surfaces)

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





- Low-l_i scenario yields $\Omega_{crit}\,\tau_A \sim 0.02$ with weak β dependence
- Moderate-l_i scenario yields significantly lower Ω_{crit}
- Both damping models predict Ω_{crit} within a factor of 2
  - **Kinetic damping** generally underestimates Ω_{crit}
- 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

- **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* **75** (1995) 645]

- **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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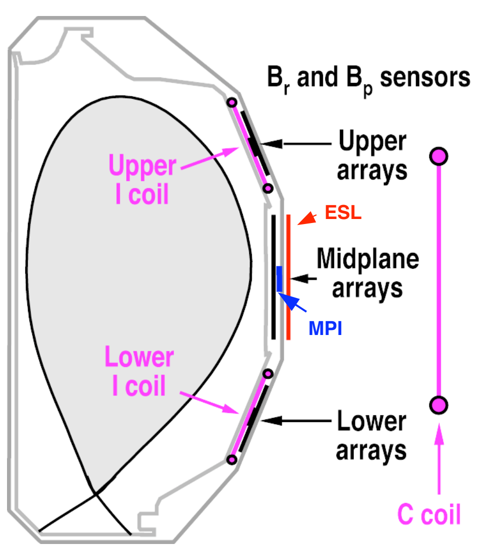
DIII-D has versatile sets of antennas and detectors



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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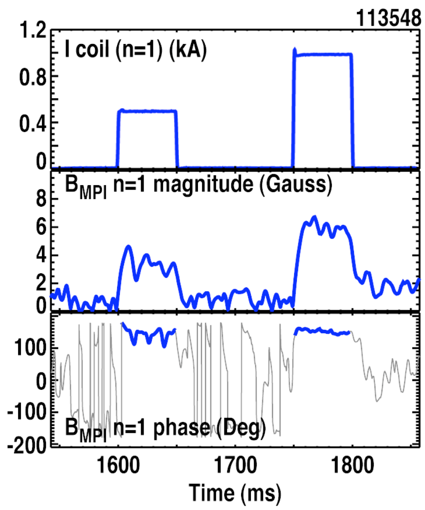
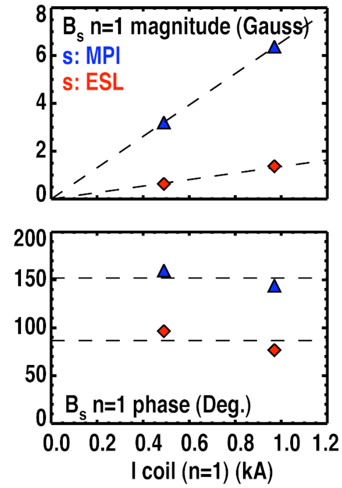
Plasma response is in the linear regime





- Applied I-coil field ~10 Gauss/kA
- Linear response
  - Amplitude depends on sensor:
    "**MPI**": midplane poloidal field probes
    "**ESL**": midplane saddle loops

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 $\Lambda = -(\phi'/\phi)\big|_w$
  - **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

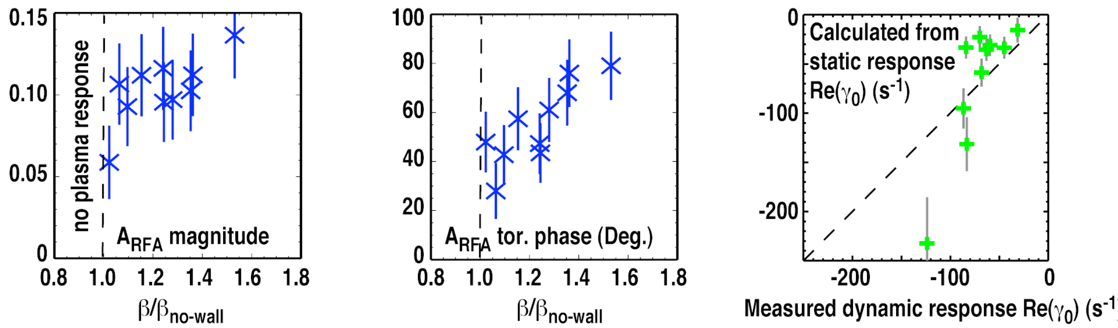
Dynamic response to resonant field pulses consistent with single-mode model

- 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



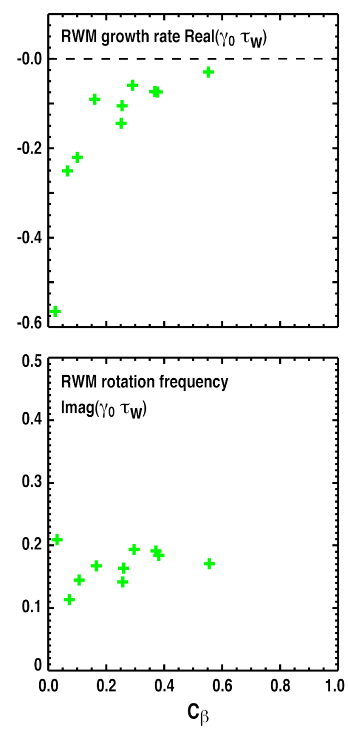
[Garofalo et al, *Phys. Plasmas* **10** (2003) 4776]

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]

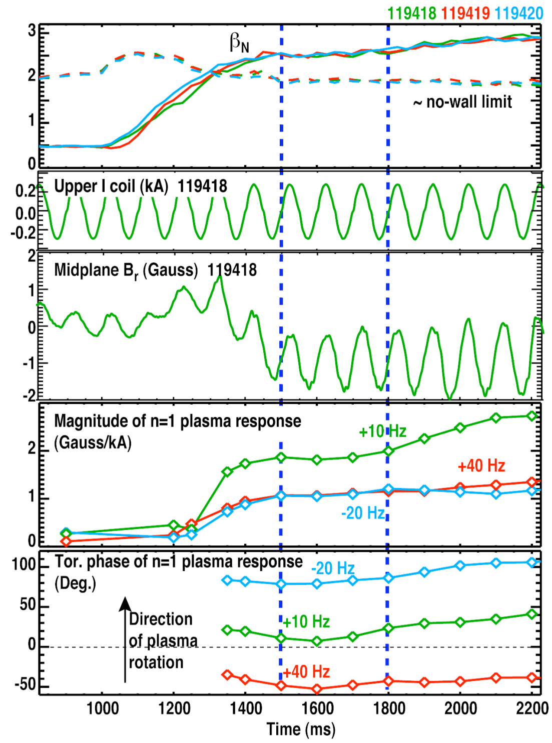
- **Low-l_i target** ($l_i \sim 0.67$)
- Optimum error field correction sustains plasma rotation at $\Omega_{rot}\tau_W \sim 0.02$ at q=2
- Apply n=1 field pulses with C-coil
- Best fit of RFA amplitude, phase and exponential decay to single-mode model yields γ_0

- 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



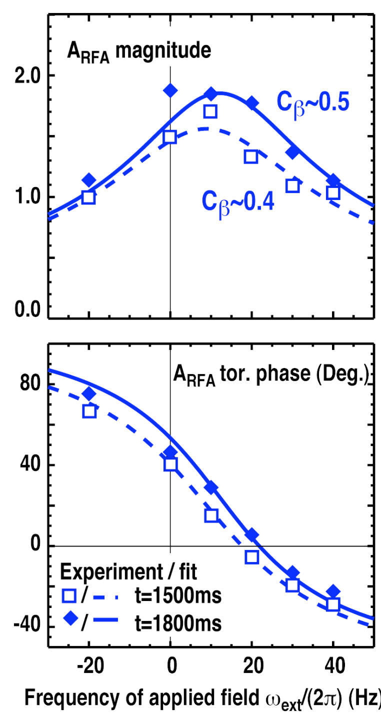
- Largest plasma response for slowly co-rotating field
- Plasma response leads external field if rotation slower and trails if rotation faster than rotation of larges response

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

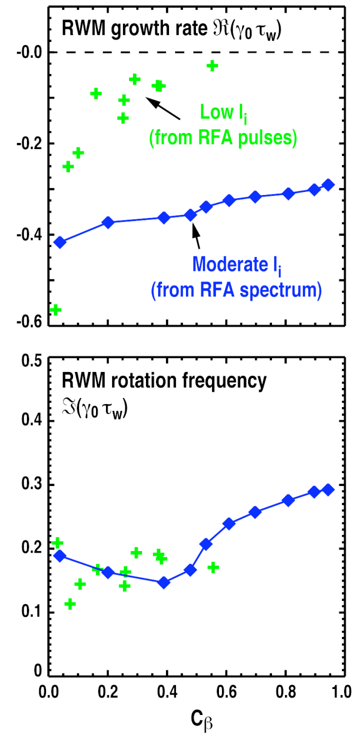
$$A_{RFA,s} = c_s \cdot \frac{1+\gamma_0\tau_w}{i\omega_{ext}\tau_w - \gamma_0\tau_w}$$



- 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**)

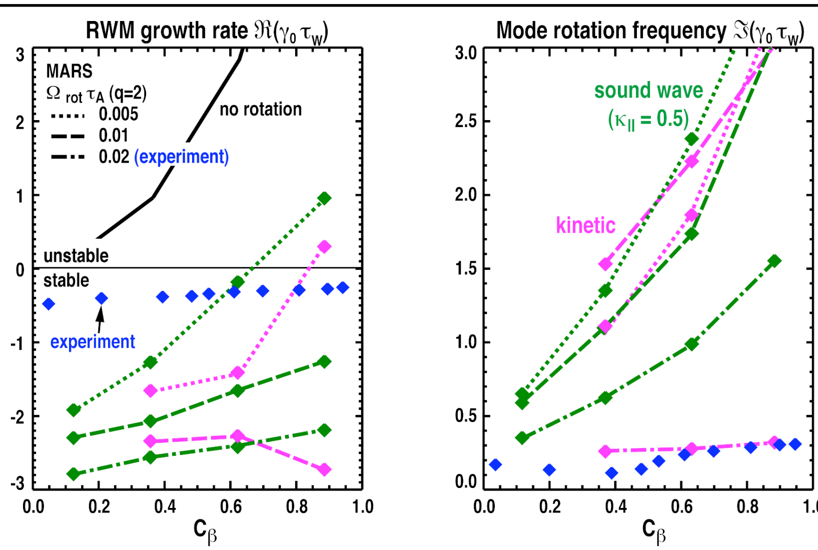
MHD spectroscopy yields a measurement of the RWM damping rate and mode rotation frequency

- 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



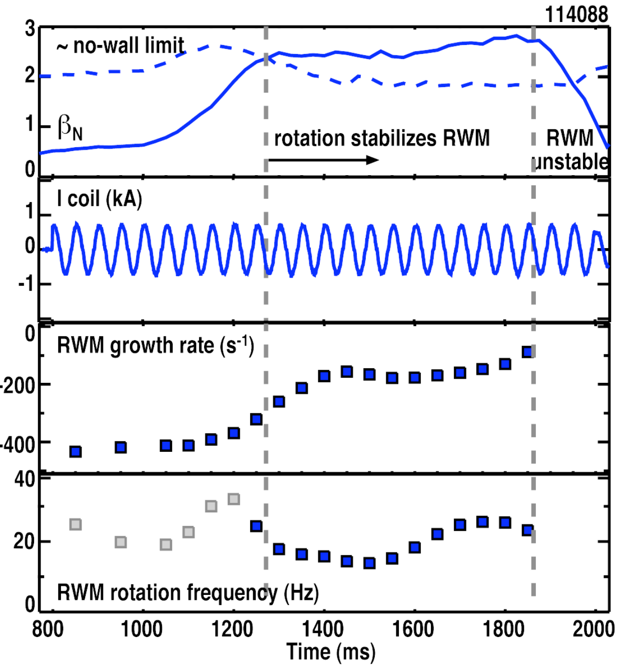
- Both models predict γ_{RWM} too low
- Kinetic damping predicts experimental ω_{RWM} while the sound wave damping prediction is too high

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



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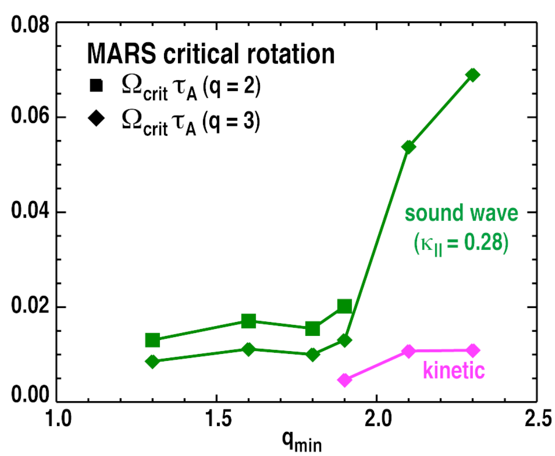
MARS predicts significant contribution of the q=2 surface towards rotational stabilization

- Set of DIII-D advanced tokamak equilibria with various q_{min} and q_a=7.2
- Calculate Ω_{crit} for stability up to ideal wall limit
- Sound wave damping predicts a weak increase of Ω_{crit} for q_{min}>3/2 and a strong increase of Ω_{crit} for q_{min}>2
- Kinetic damping predicts a significant increase of Ω_{crit} for q_{min}>2



➔ DIII-D AT scenarios could require direct RWM feedback control

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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