Rotational Stabilization of the Resistive Wall Mode in DIII-D

By
H. Reimerdes

With
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Princeton Plasma Physics Laboratory
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• Measurement of rotation threshold for RWM stabilization with low NBI torque and good n=1 error field correction rotation
  – Rotation threshold significantly lower than thresholds obtained with n=1 magnetic braking

• Active MHD spectroscopy in low rotation plasmas
  – Evidence of weakly damped RWM with zero mode rotation frequency

• Comparison of low rotation threshold with theory
  – (Surprisingly) good agreement between kinetic damping model (in MARS-F) and measurements

• Revisiting previous predictions of kinetic damping model
  – Weighted sum of the rotation at all resonant surfaces yields a better stability criterion
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Discharges are designed to have a low ideal MHD no-wall stability limit.

- Ideal MHD stability limits for DCON and MARS-F agree within 10%
  - $\beta_{N,\text{no-wall}} (n=1) \sim 2.0 \sim 2.5 \ell_i$
  - Supported by magnetic braking experiments
  - $\beta_{N,\text{ideal-wall}} (n=1) \sim 3.1$

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Reducing NBI torque and $n=1$ magnetic braking yield very different rotation thresholds

- **NBI torque reduction and correction of $n=1$ error field** yield RWM onset at low rotation

- **Magnetic braking by removing correction of $n=1$ error field** yields RWM onset at high rotation

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Reducing NBI torque and n=1 magnetic braking yield very different rotation thresholds

- With reduced NBI torque the RWM rotation threshold (for $\rho < 0.85$) is significantly lower than with magnetic braking
  - Resonant braking can lead to overestimation of linear RWM threshold

→ A.M. Garofalo, Tuesday 11:45AM

- Charge exchange recombination (CER) diagnostic measures carbon impurity rotation
  - Correction for deuterium expected to be important

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Rotation threshold with reduced NBI torque and corrected error field has only a weak $\beta$-dependence

- **RWM onset occurs when rotation at $\rho=0.6$ ($q \sim 2$) reduced to $\Omega_{\text{rot}} \tau_A(\rho=0.6)=0.2-0.3\%$**
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Measure frequency response to externally applied $n=1$ magnetic fields

- **Identical discharges**
  - $\beta_N = 2.3 \sim 2.9 \zeta_i$
  - moderate rotation

- **Apply rotating**
  - $(3/1)$ magnetic field with I-coil
  - $I_{\text{I-coil}} = 100 - 180A$
  - $f_{\text{I-coil}} = -20 - +50Hz$

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Measure frequency response to externally applied $n=1$ magnetic fields

- **Frequency response described by single mode:**
  \[ \tau_W \frac{dB_s}{dt} - \gamma_0 \tau_W B_s = M_{sc}^* \cdot I_c \]

- **Frequency response fit yields:**
  - $M_{sc} = (2.73 + i0.15) \text{ G/kA (coupling coeff.)}$
  - $\gamma_0 = (-141 + i108) \text{ s}^{-1}$ (growth rate)

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Active RWM spectroscopy measures evolution of RWM stability

Active MHD spectroscopy: \( f(\text{coil})=25 \text{Hz}, \; I(\text{coil})=180 \text{A} \)

- \( \beta_N \)
- \( \Omega_{\text{rot}} (q-2) \) (krad/s)
- RWM growth rate (s^{-1})
- RWM rotation frequency (Hz)

Time (ms):

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1. Beta exceeds $\beta_{\text{no-wall}}$
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   - RWM stable with near zero mode frequency

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2. **Rotation increases**
   - Mode rotation increases, too

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RWM stabilized despite near zero mode frequency

- Measured growth (damping) rate and mode rotation frequency:

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Can theory explain the new low RWM stabilization rotation threshold?

- “Low li” plasmas ($\ell_i \sim 0.67$) [La Haye et al, Nucl. Fusion 2004]
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Kinetic damping model consistent with low rotation threshold

- **Marginal stability predicted with ~65% of the experimental rotation**
  - Corresponds to $\Omega_{\text{crit}}\tau_A = 0.2\%$ - similar to experimental results

- **Negative mode rotation**
  - Suggests strong interaction near plasma edge (e.g. $q=4$)

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Kinetic damping model in surprisingly good agreement with observed $\beta$-dependence of RWM rotation threshold

- Kinetic damping predictions forms lower bound of observed rotation threshold

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• Multiple reasons why experiment and theory should not agree
  – Difference between measured carbon impurity and deuterium main ion rotation can be significant
  – Model does not include poloidal rotation
  – NBI torque reduction is not described by simple scaling of rotation profile

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Weighted sum over rotation at all resonant surfaces may yield a better criterion for marginal stability

| $\Omega_{\text{crit}} \tau_A$ | $q=2$   | $q=3$   | $q=4$   | $q=5$   | $\sum (|\Omega_{\text{crit}} \tau_A|)_k$ | $\sum (|\Omega_{\text{crit}} \tau_A|)_k q_k$ | $\sum (|\Omega_{\text{crit}} \tau_A|)_k q_k^2$ |
|-----------------------------|---------|---------|---------|---------|-----------------------------------------|-----------------------------------------|-----------------------------------------|
| **Fast $I_p$ ramp**          | 0.0120  | 0.0035  | 0.0004  | -       | 0.0159                                  | 0.0361                                  | 0.0859                                  |
| **Slow $I_p$ ramp**          | 0.0030  | 0.0018  | 0.0015  | 0.0002  | 0.0065                                  | 0.0184                                  | 0.0572                                  |
| **JETshape**                 | 0.0060  | 0.0007  | 0.0007  | 0.0001  | 0.0075                                  | 0.0174                                  | 0.0440                                  |
| **Reduced $T_{\text{NBI}}$** | 0.0020  | 0.0010  | 0.0031  | 0.0011  | 0.0072                                  | 0.0249                                  | 0.0941                                  |
| **Mean**                     | 0.0058  | 0.0018  | 0.0014  | 0.0005  | 0.0093                                  | 0.0242                                  | 0.0703                                  |
| **$\sigma$/mean**           | 78%     | 72%     | 86%     | 120%    | 47%                                     | 36%                                     | 32%                                     |

- **Kinetic damping predictions of $\Omega_{\text{crit}} \tau_A$** at $q=2$ varies by a factor of 6
- **Weighted sums over all rational surfaces reduce the deviations in the criterion for marginal stability**
  - Kinetic damping [Bondeson and Chu, PHP 1996] suggests $\Omega_{\text{crit}} \tau_A \propto q^{-2}$
  - Displacement profile expected to play a significant role, too

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Low rotation threshold for RWM stabilization obtained with low NBI torque and good n=1 error field correction

- Critical rotation at the $q=2$ surface found as low as $\Omega_{crit} = 0.2-0.3\%$
  - Rotation threshold evaluated at $q=2$ is 2 to 10 times lower than suggested by previous experiments using $n=1$ “magnetic braking”
- Active MHD spectroscopy yields damped RWM with zero mode rotation frequency in plasmas with low NBI torque
  - Strong interaction with rotation near plasma edge, i.e. at $q>2$
- “Kinetic damping” model (calculated with MARS-F code) found consistent with the observed low rotation threshold
  - Rotation at higher $q$-surfaces ($q>2$) predicted to be important
  - Previous kinetic damping predictions of higher critical values at $q=2$ caused by different rotation profile shapes
  - Weighted sum of rotation at resonant surfaces (or volume integral) may lead to a better criterion for marginal stability
- Overestimation of rotation threshold with resonant magnetic braking and different rotation profile shapes with balanced beams, both, may reconcile new results with previous magnetic braking experiments