Rotational Stabilization of the Resistive Wall Mode in DIII-D

By
H. Reimerdes[1]

With
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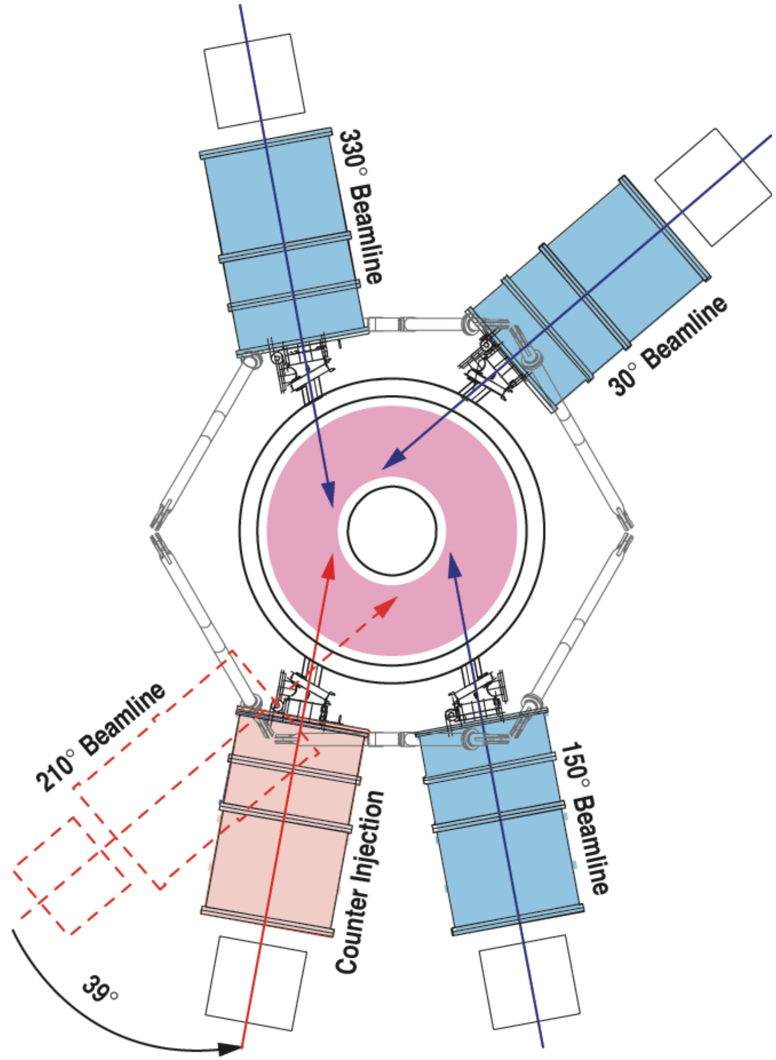
[4]Chalmers University of Technology, Göteborg, Sweden



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Columbia University

Outline

- **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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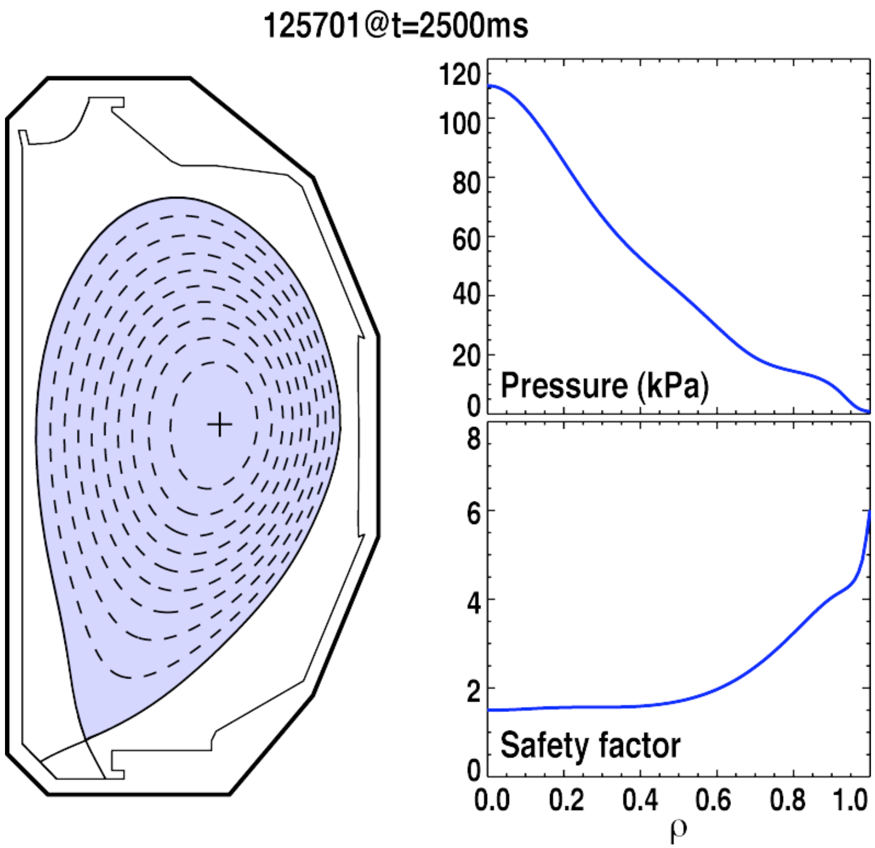
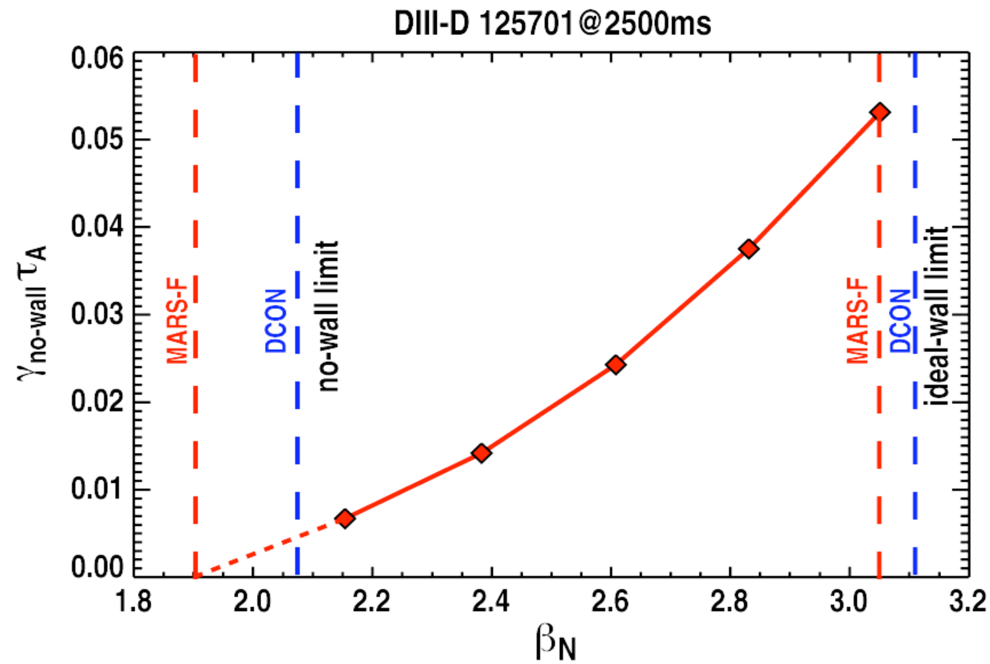
Discharges are designed to have a low ideal MHD no-wall stability limit





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

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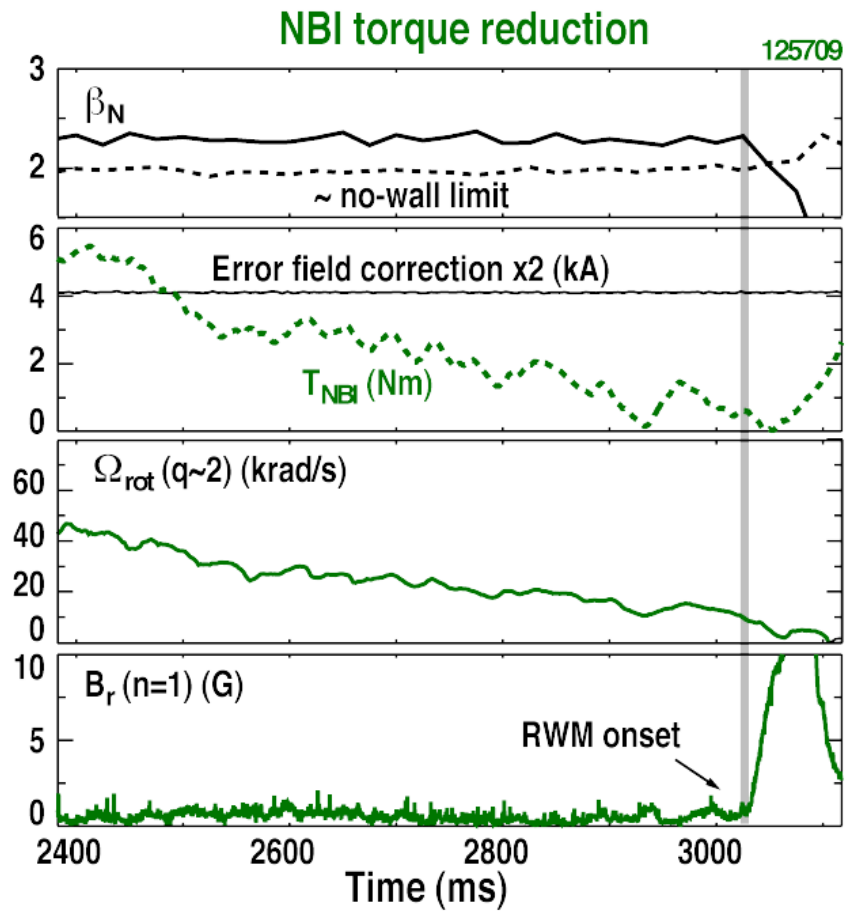
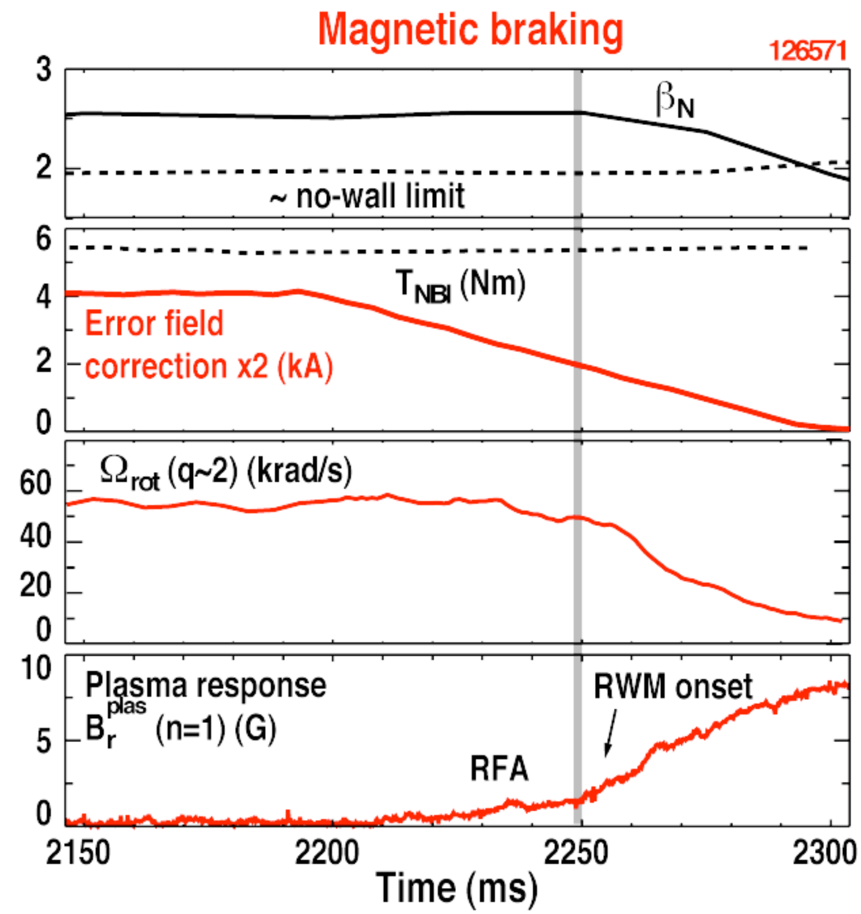
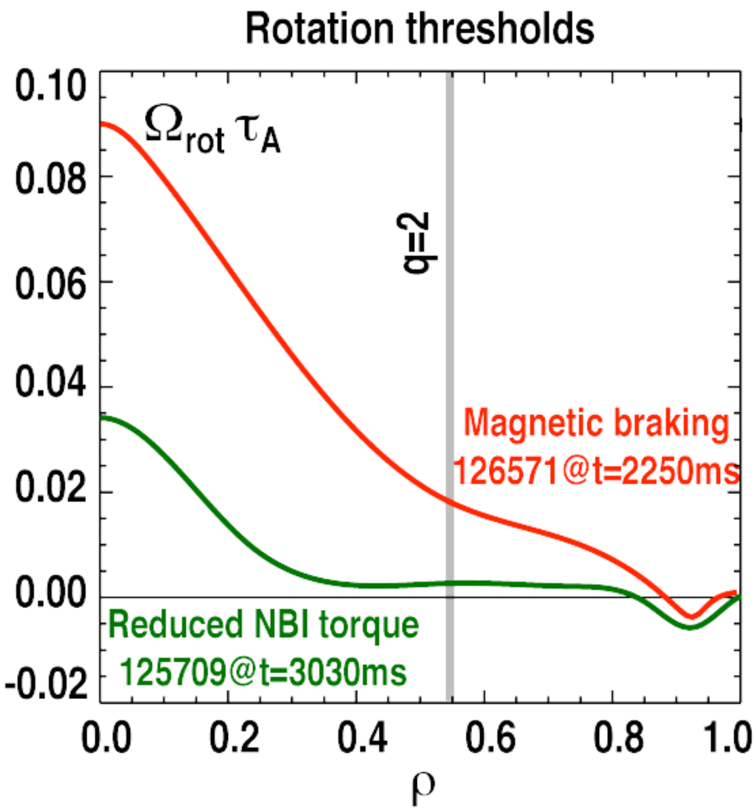
Reducing NBI torque and *n*=1 magnetic braking yield very different rotation thresholds





- **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**

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



- **With reduced NBI torque the RWM rotation threshold (for ρ<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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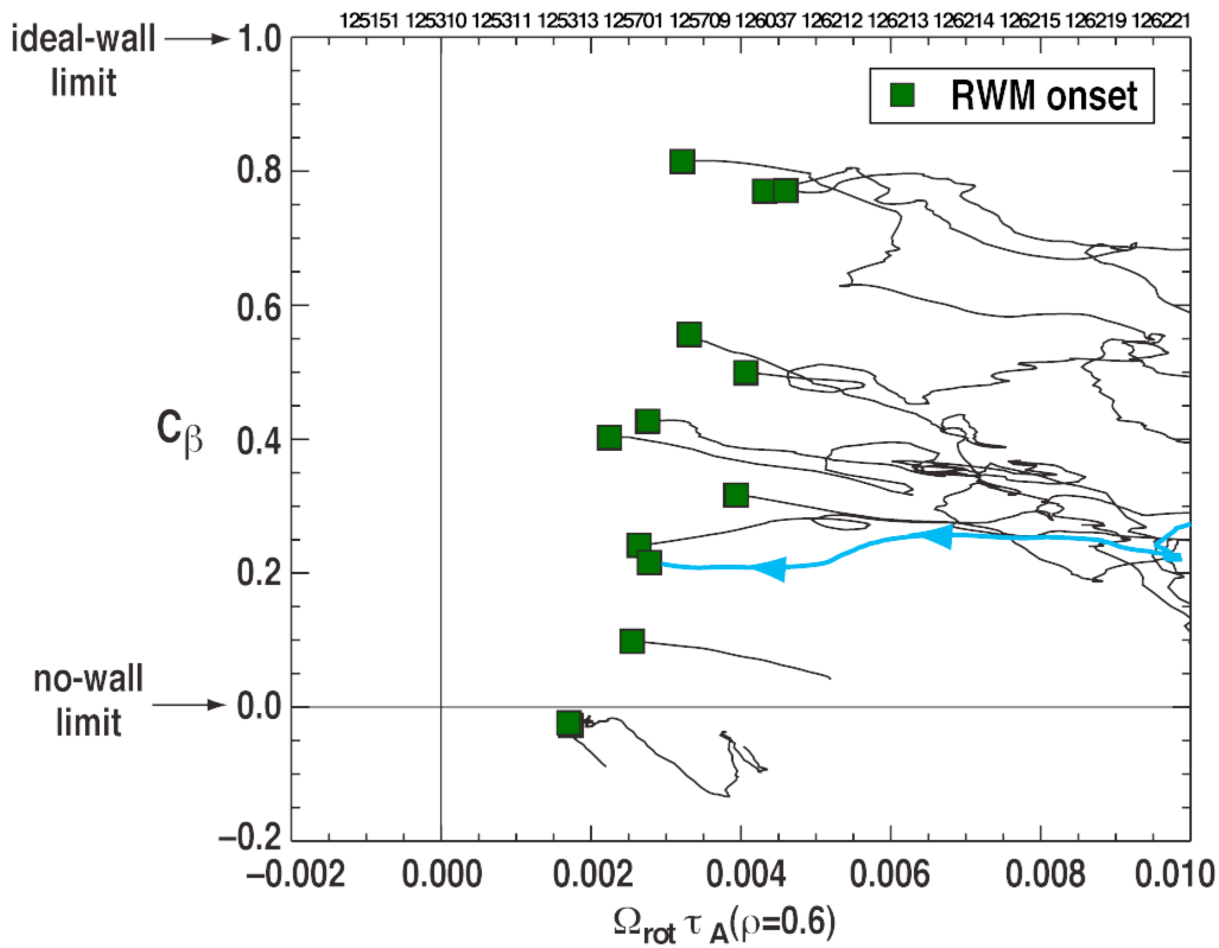
Rotation threshold with reduced NBI torque and corrected error field has only a weak β-dependence



- **RWM onset occurs when rotation at ρ=0.6 (*q*~2) reduced to $\Omega_{rot}\tau_A$=0.2-0.3%**

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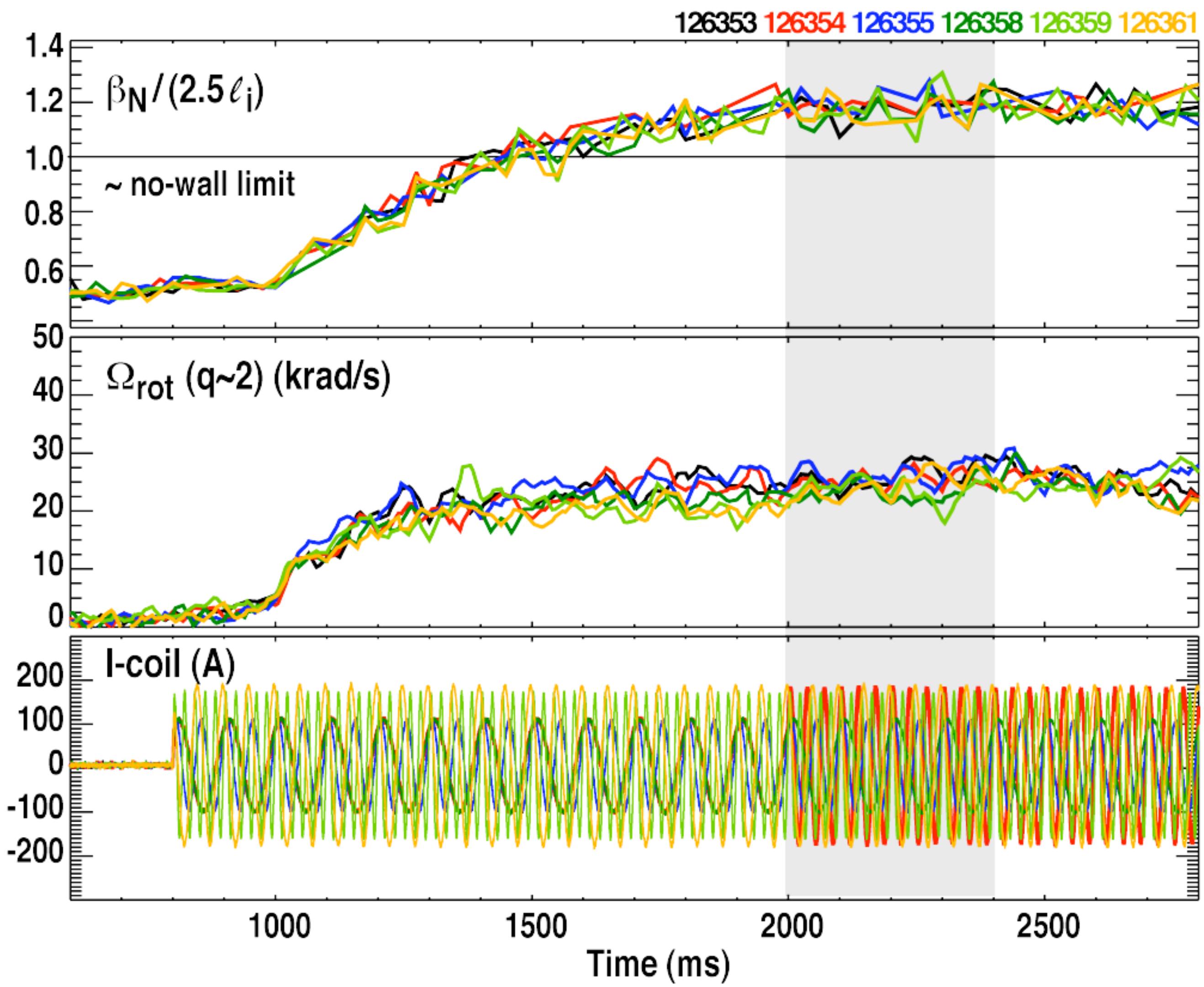
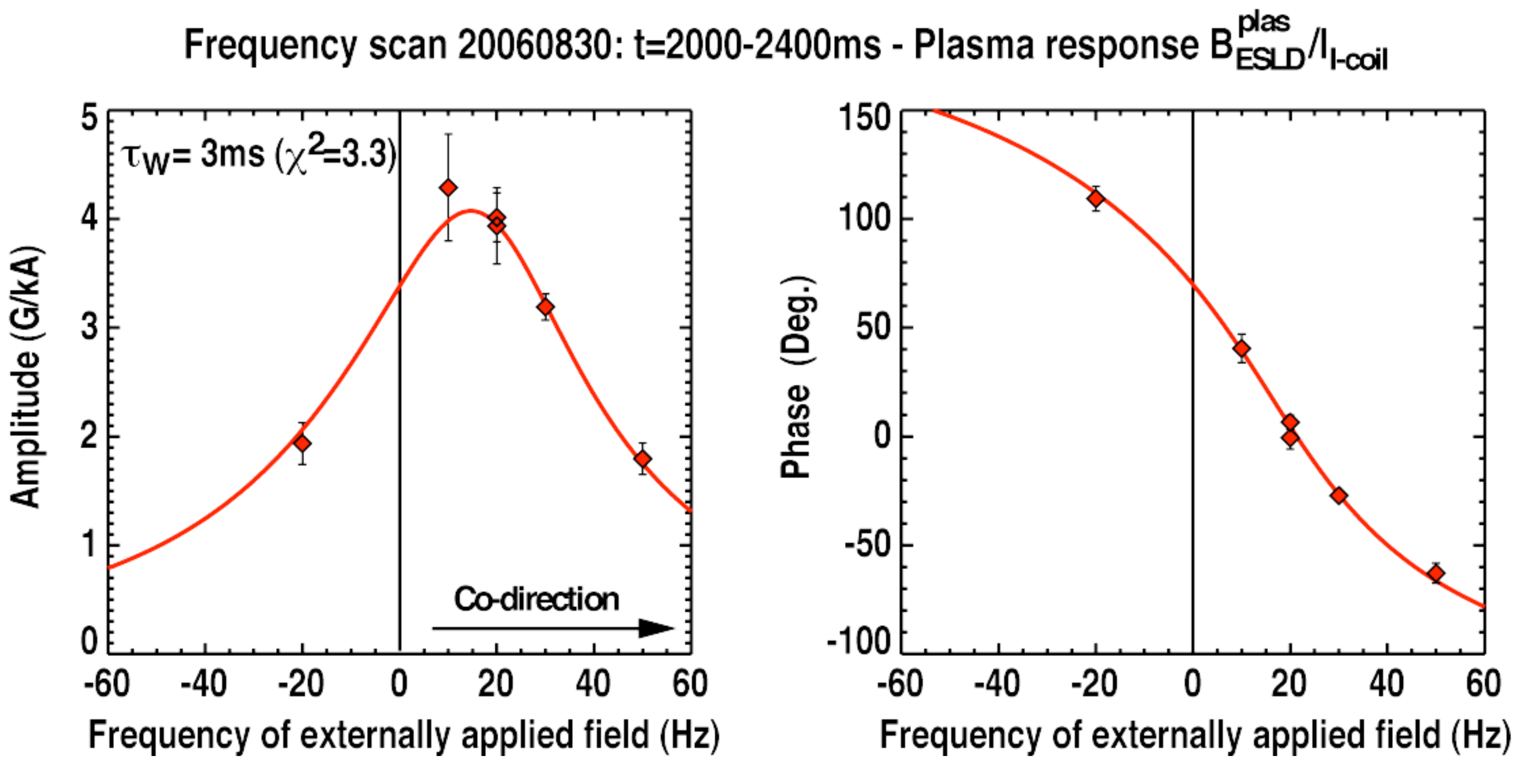
Measure frequency response to externally applied *n*=1 magnetic fields

- **Identical discharges**
  - β_N=2.3 ~ 2.9 ℓ_i
  - moderate rotation
- **Apply rotating m~3/n=1 magnetic field with I-coil**
  - $I_{\text{I-coil}}$ = 100 -180A
  - $f_{\text{I-coil}}$ = -20 - +50Hz



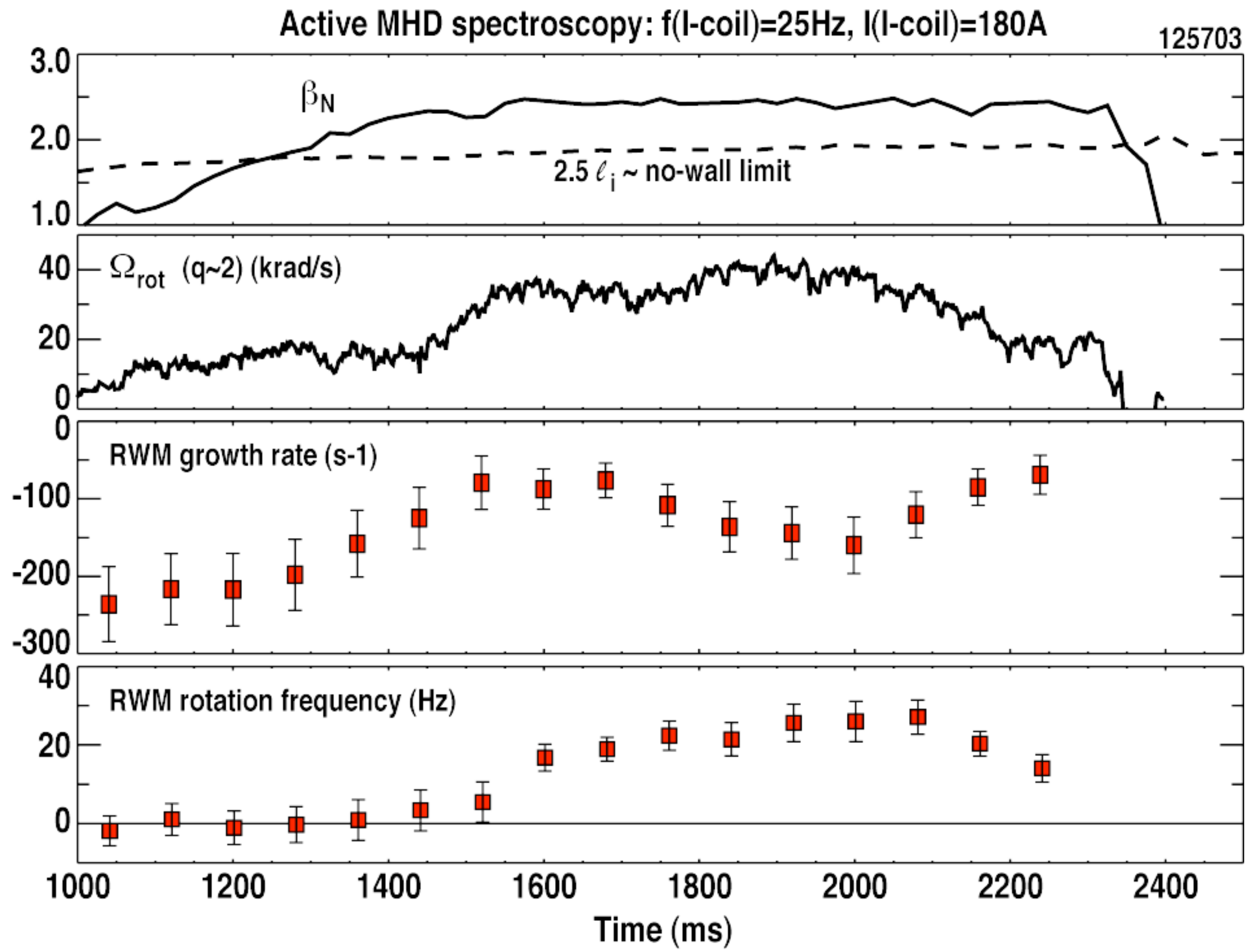
Measure frequency response to externally applied *n*=1 magnetic fields

- **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) G/kA (coupling coeff.)
  - γ_0 = (-141+ i108) s^{-1} (growth rate)

Active RWM spectroscopy measures evolution of RWM stability



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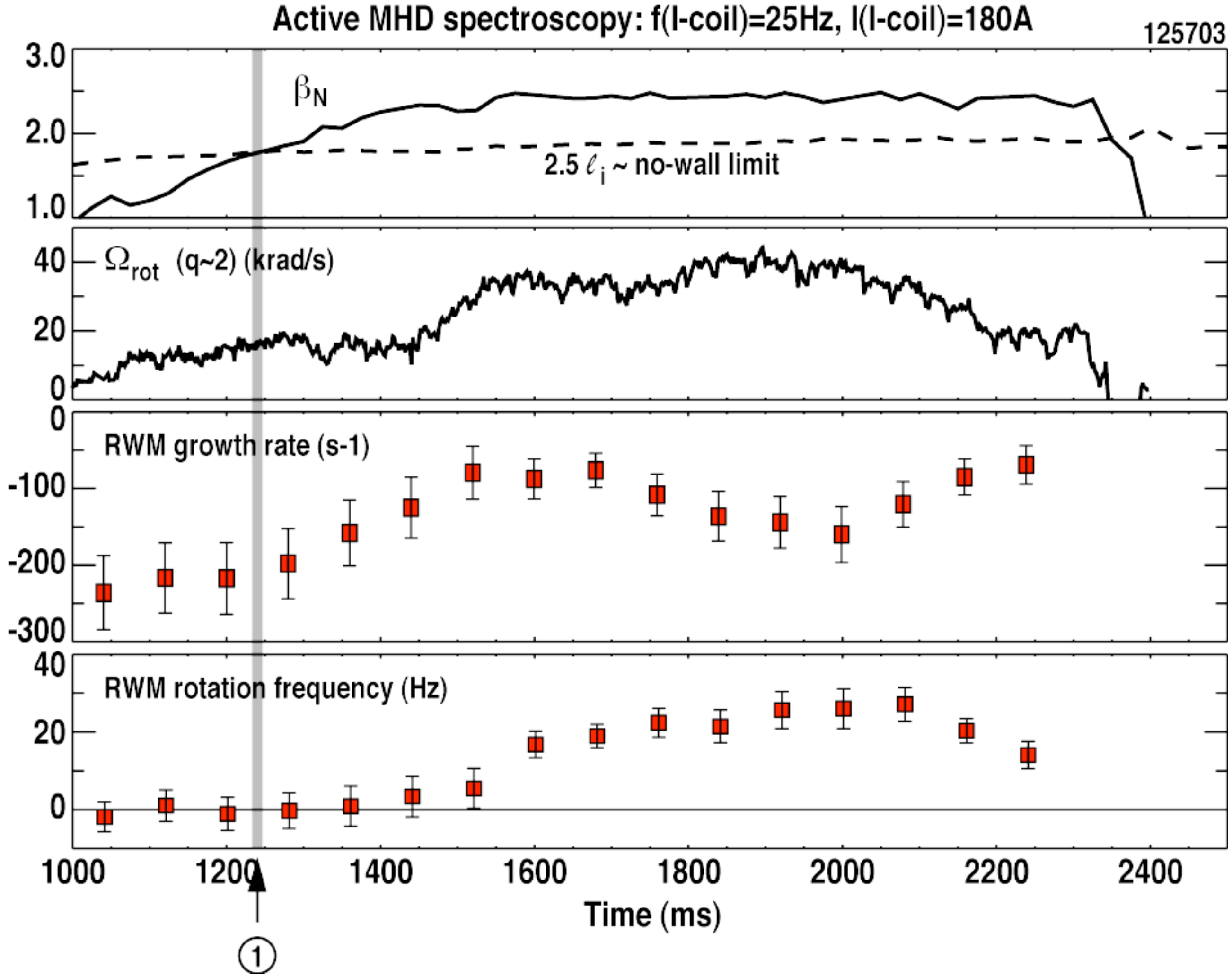
Active RWM spectroscopy measures evolution of RWM stability

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



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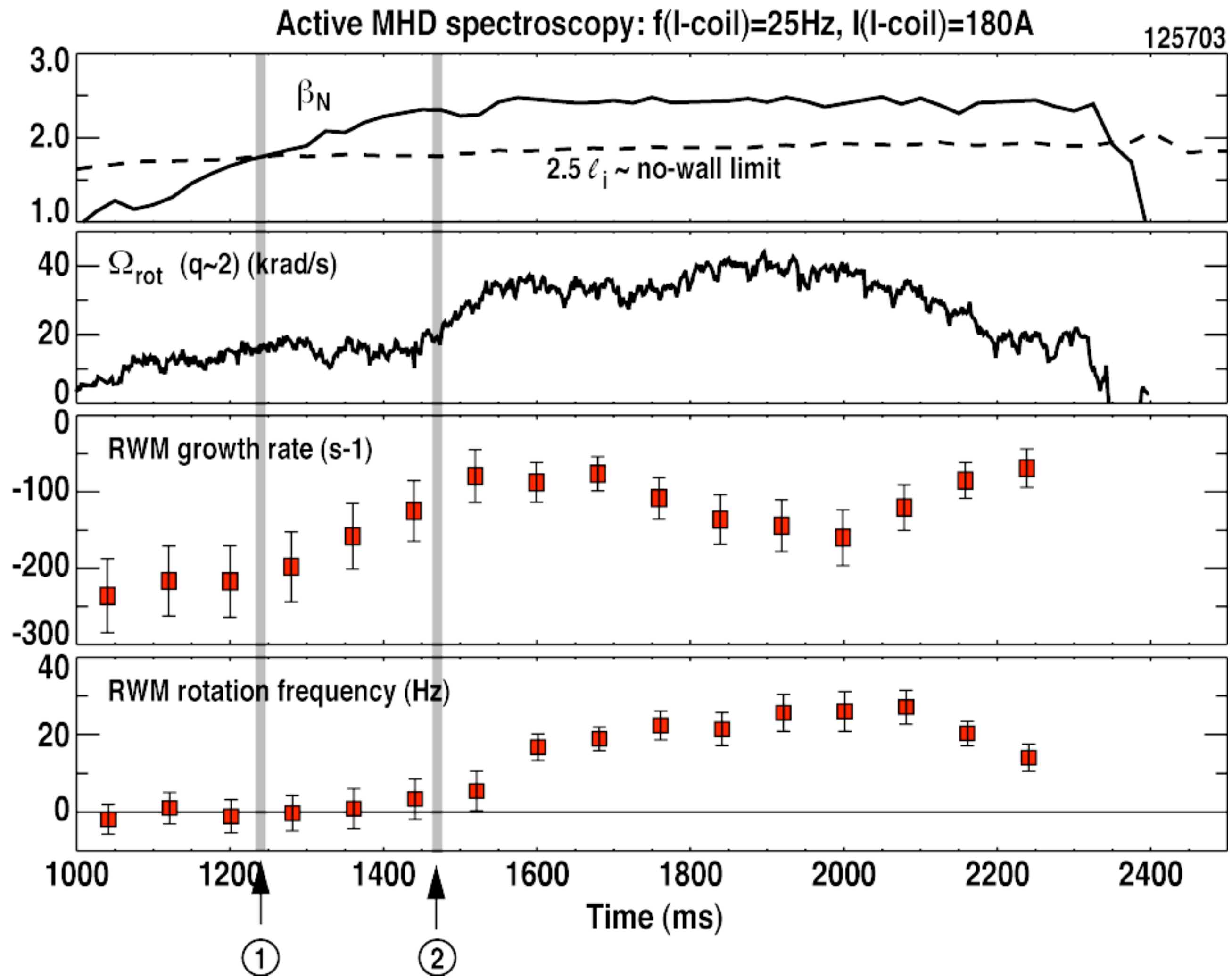
2. Rotation increases
- Mode rotation increases, too



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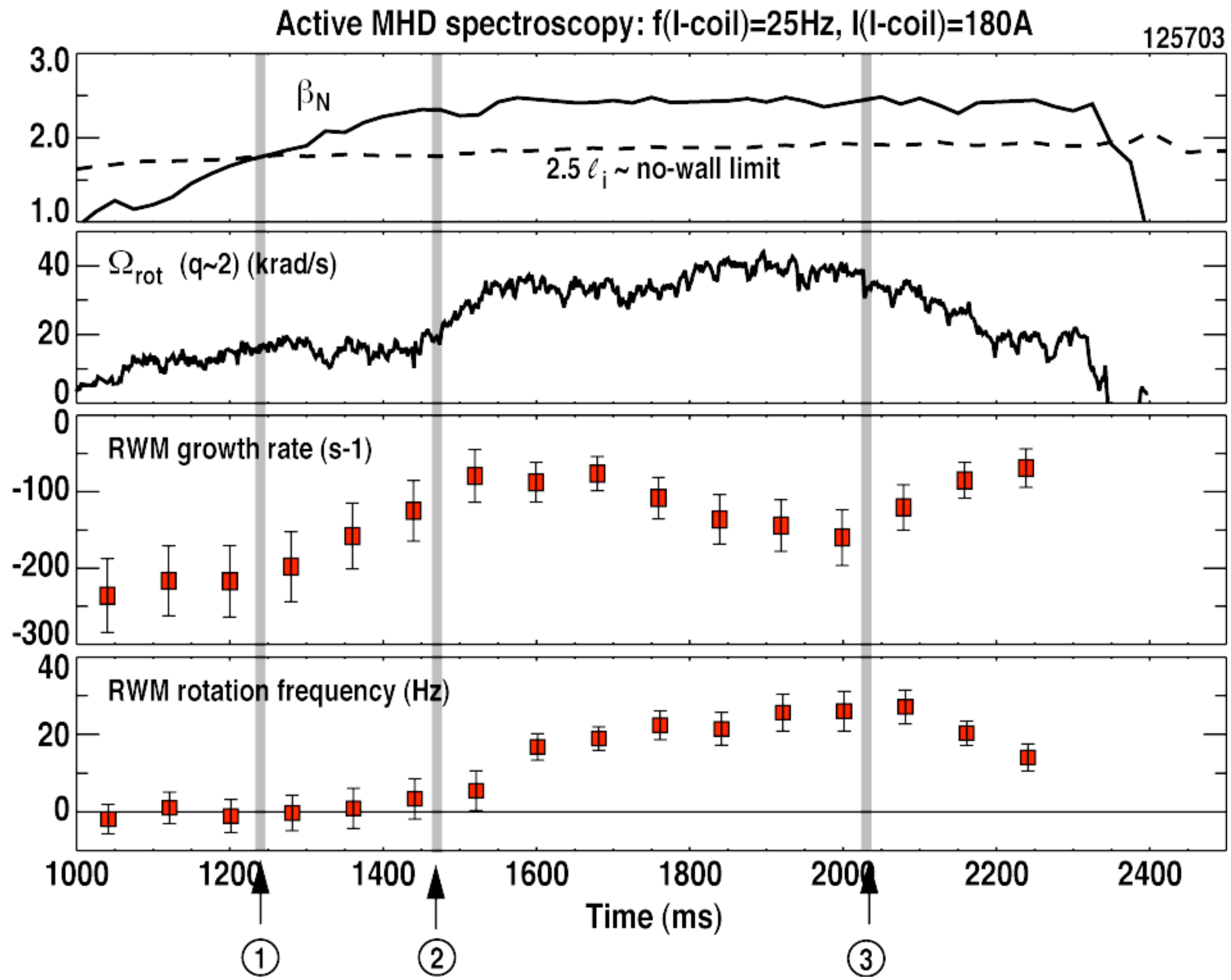
2. **Rotation increases**
   - Mode rotation increases, too
3. **Rotation decreases at constant beta**
   - Mode rotation decreases
   - Damping decreases



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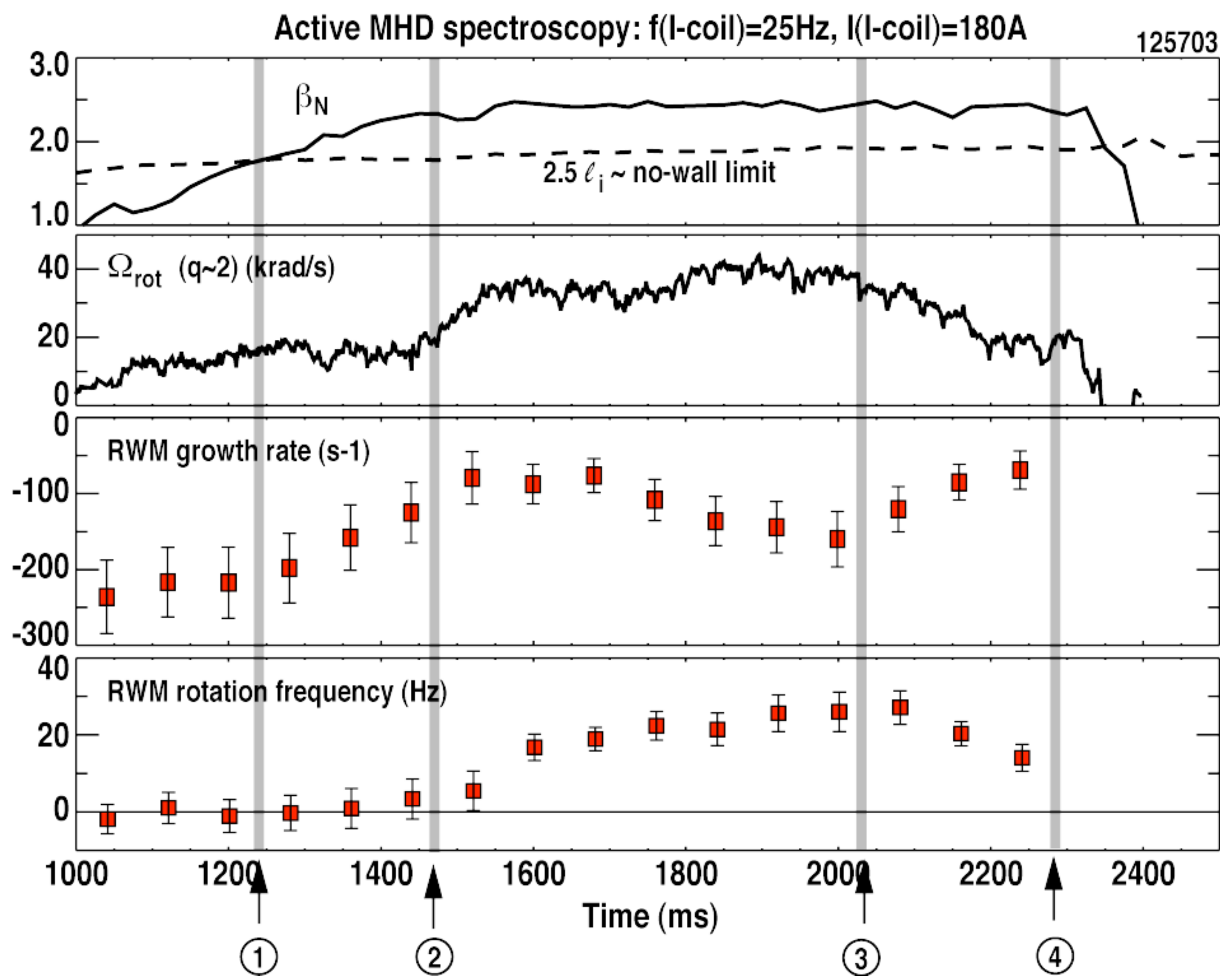
4. Onset of rotating mode



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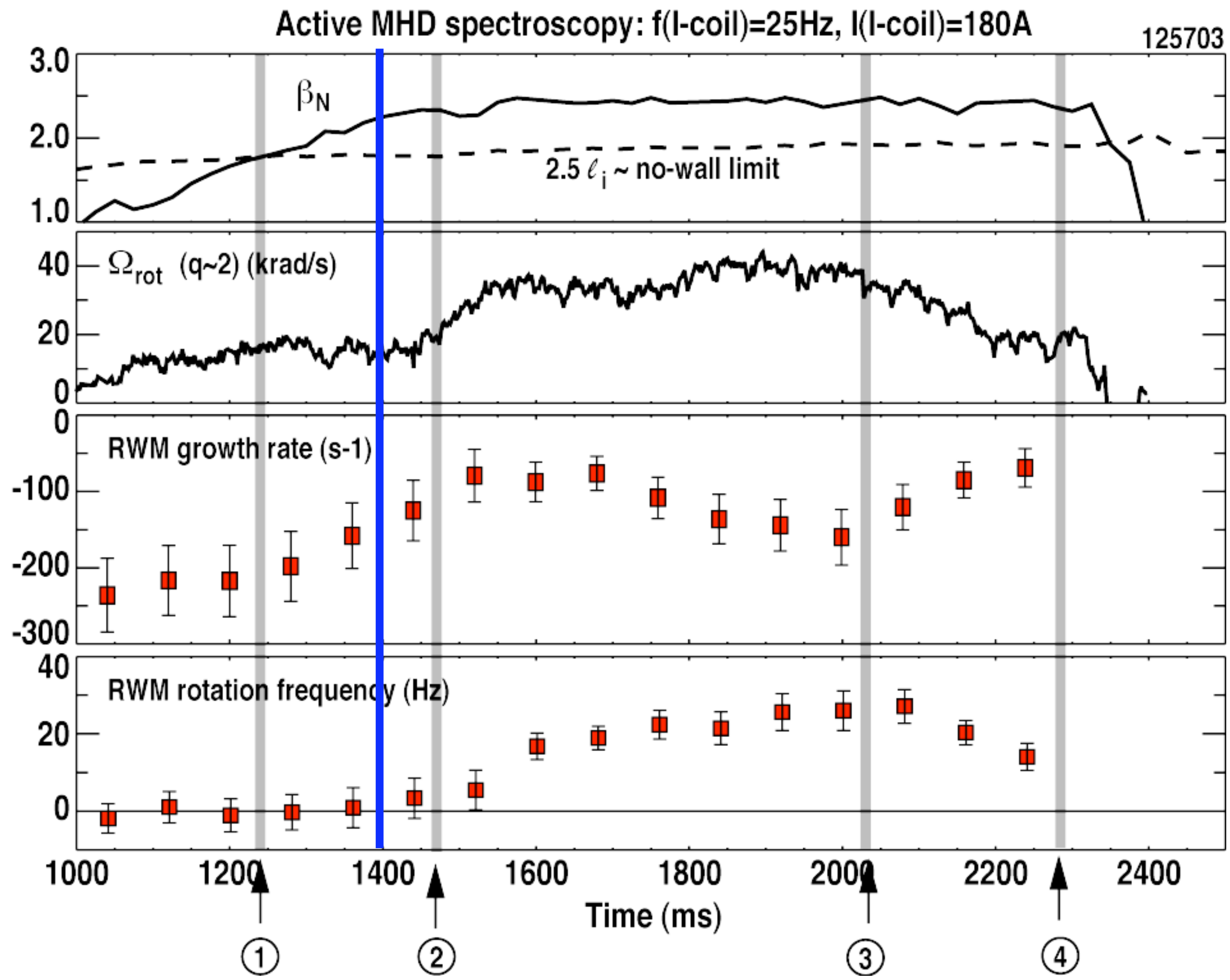

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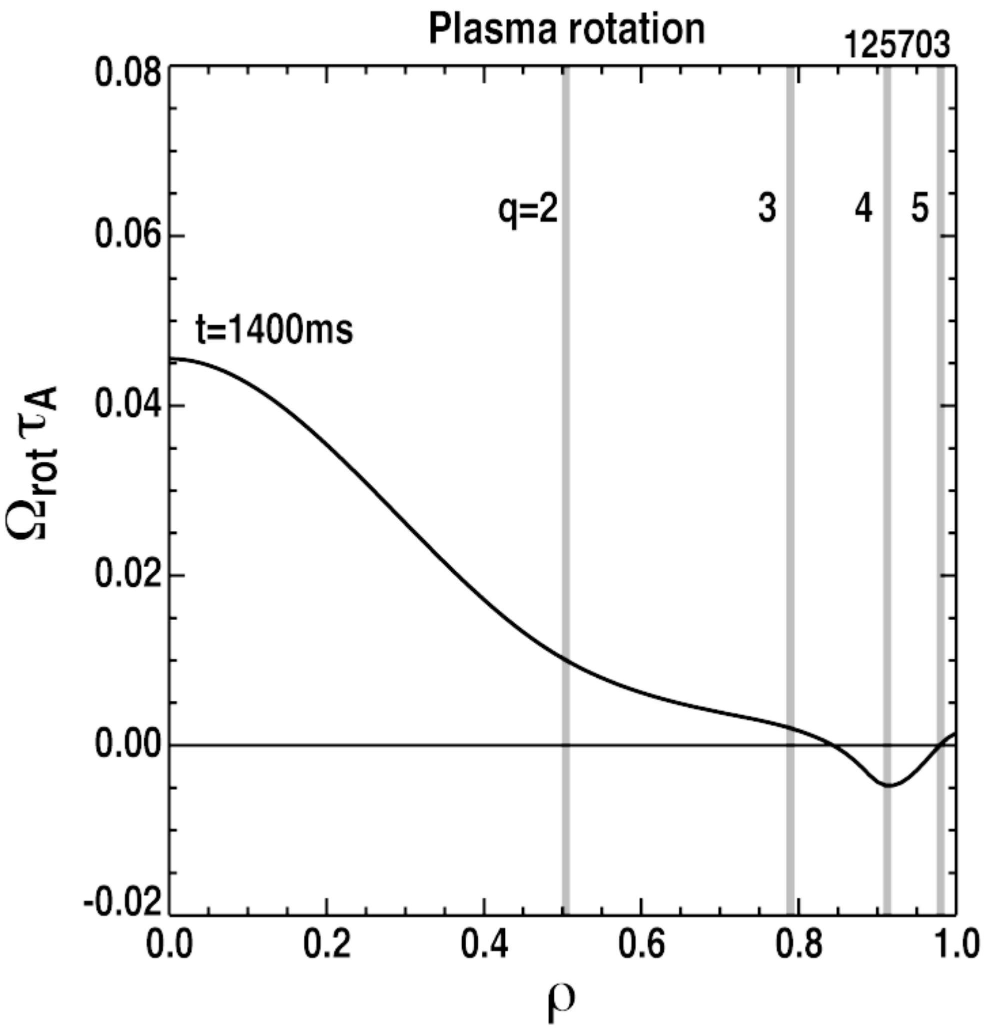
RWM stabilized despite near zero mode frequency

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

t (ms)	γ_{RWM} (s^{-1})	ω_{RWM} (Hz)
1400	-140	**2±5**



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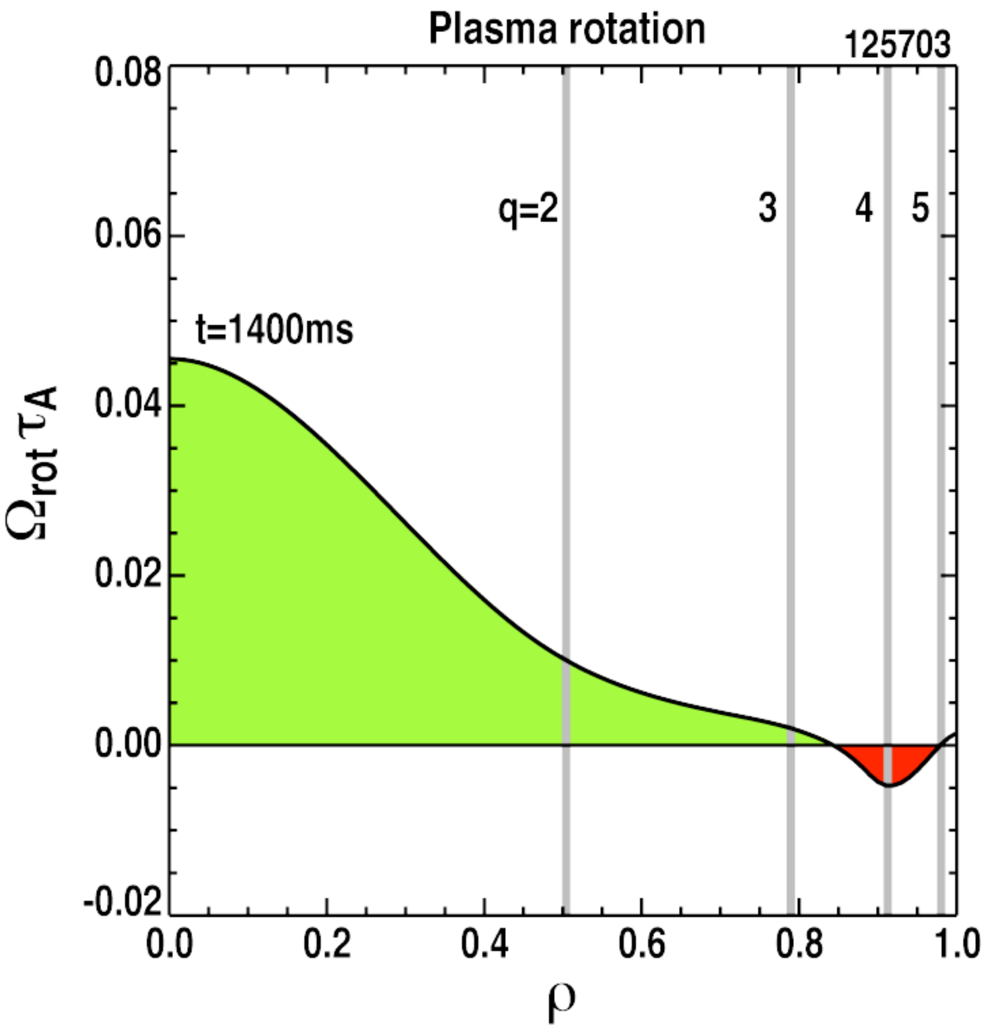

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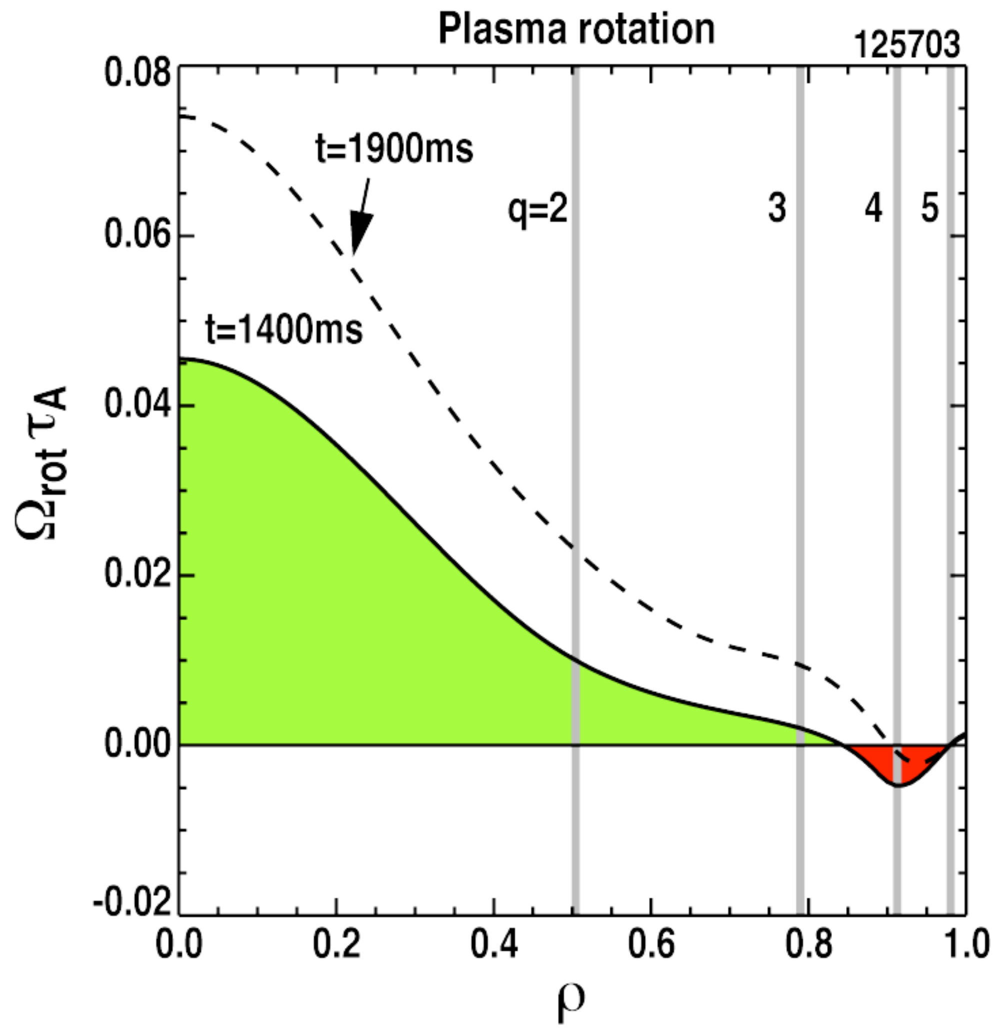
1400	-140	**2±5**
1900	-140	25±5



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Can theory explain the new low RWM stabilization rotation threshold?

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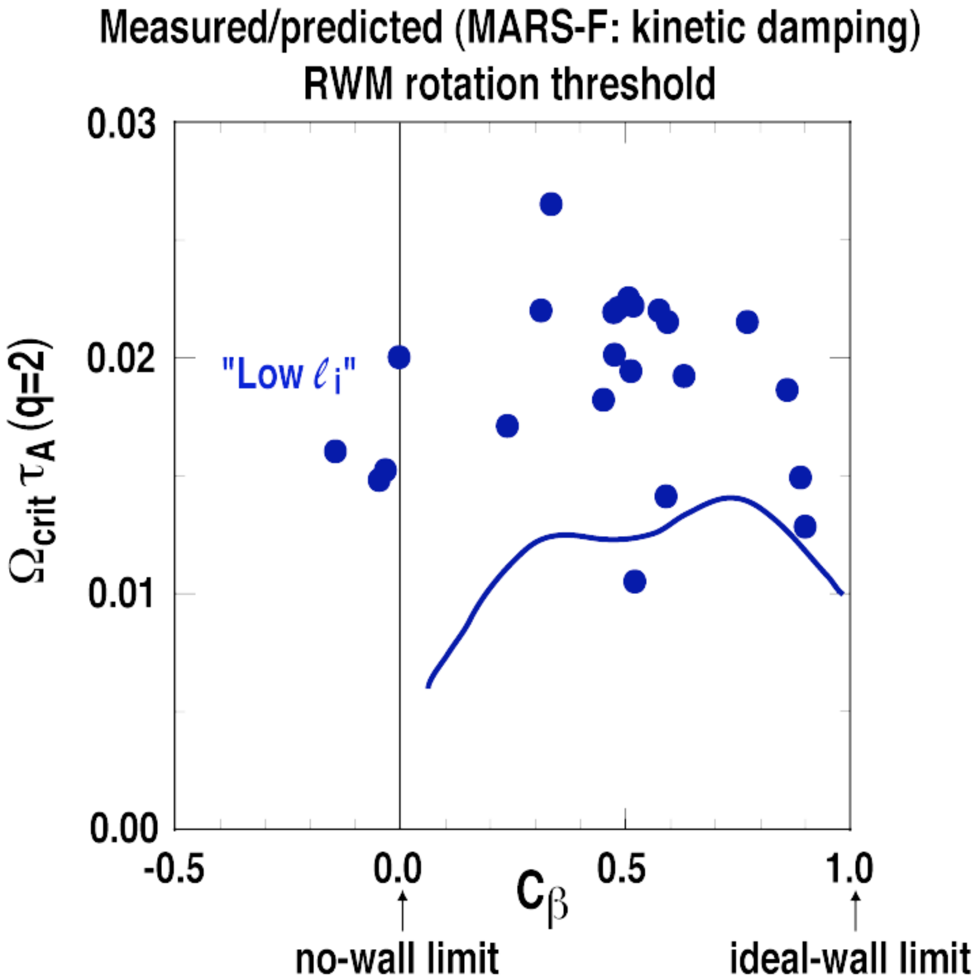
  [La Haye et al, Nucl. Fusion 2004]
  – Kinetic damping underestimates Ω_{crit} by ~30%



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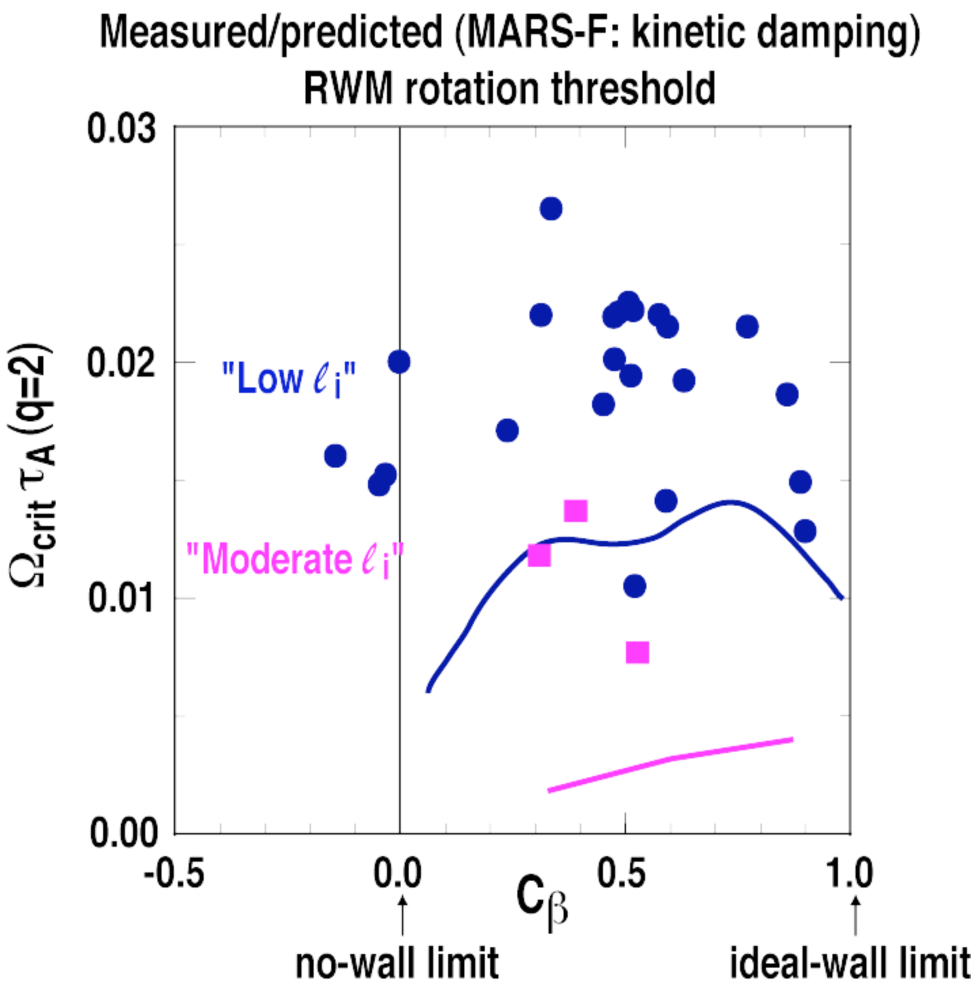

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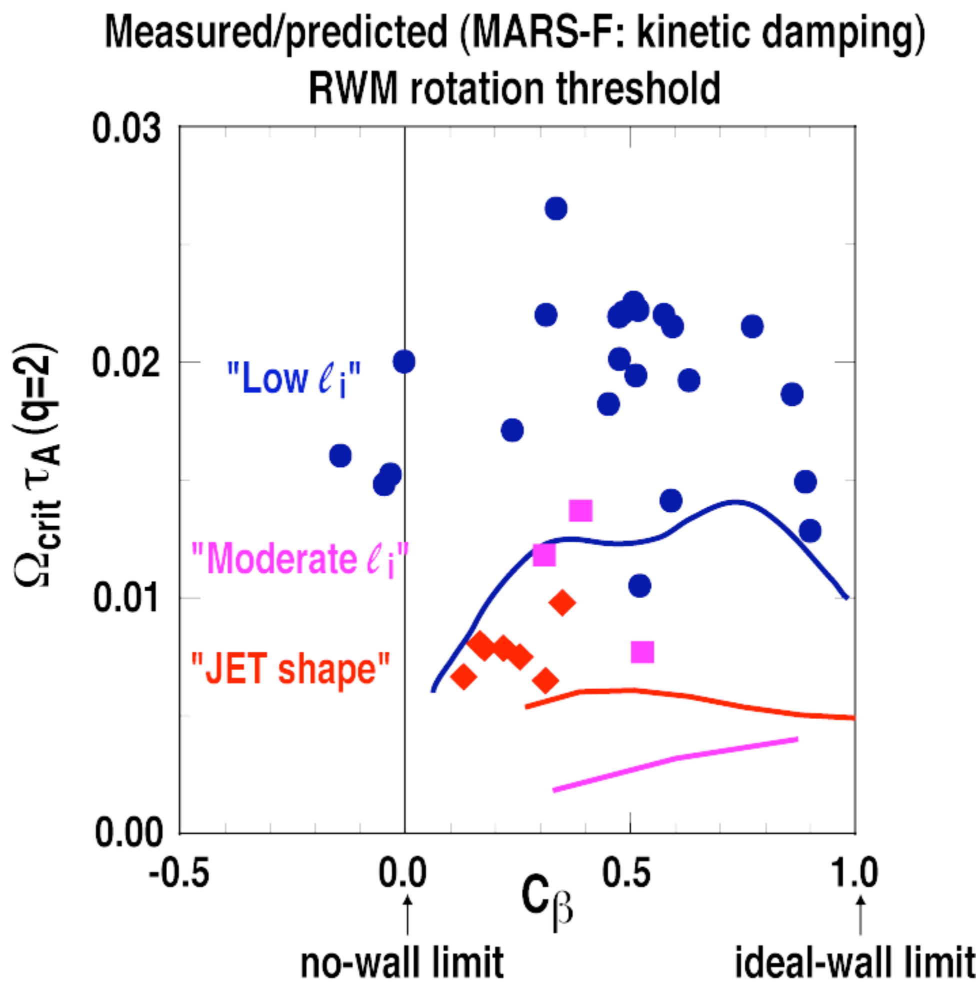

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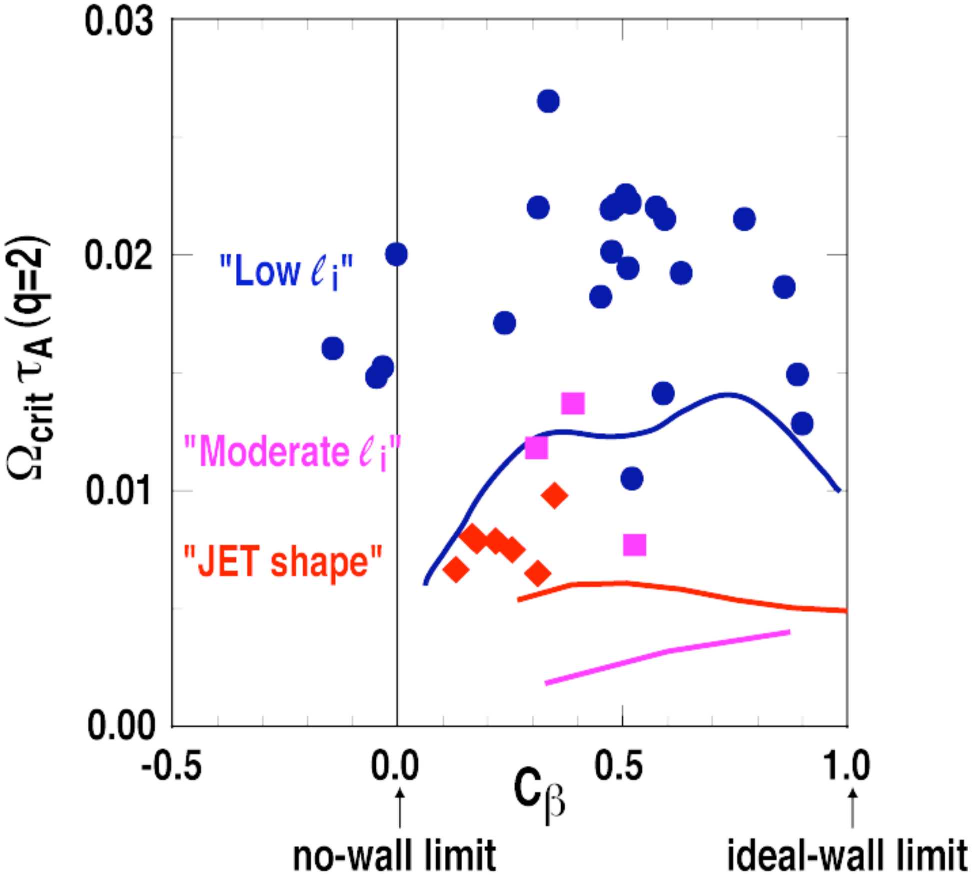
Measured/predicted (MARS-F: kinetic damping) RWM rotation threshold



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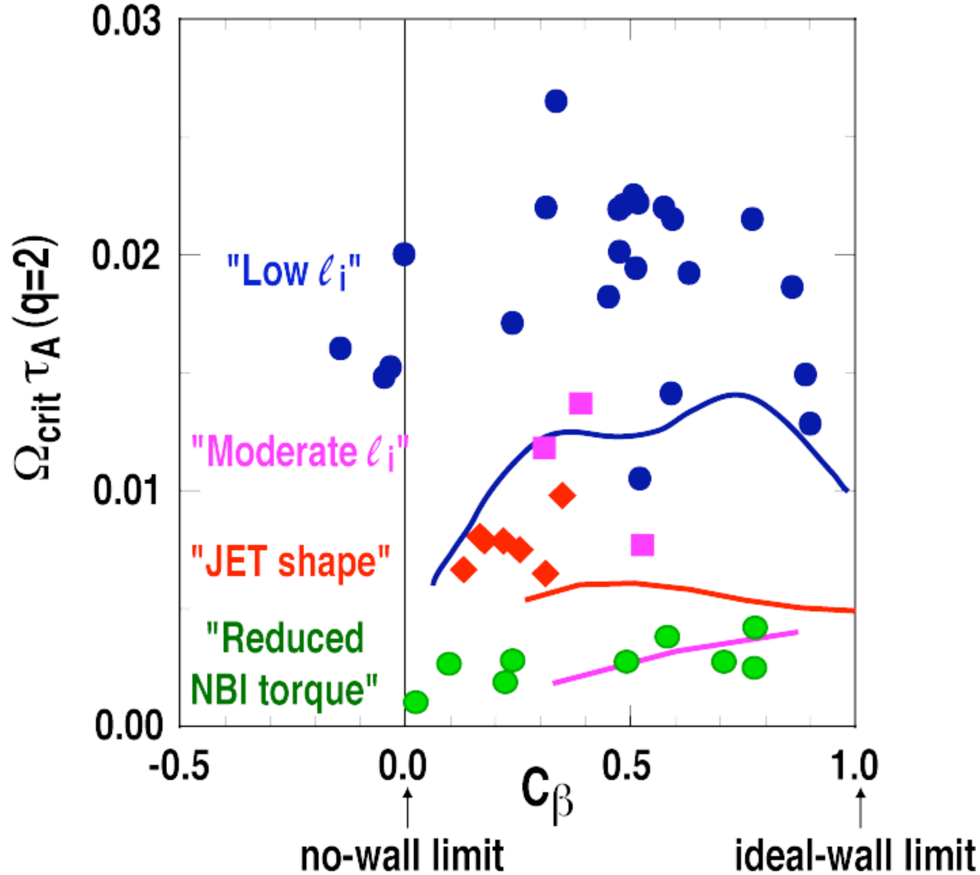

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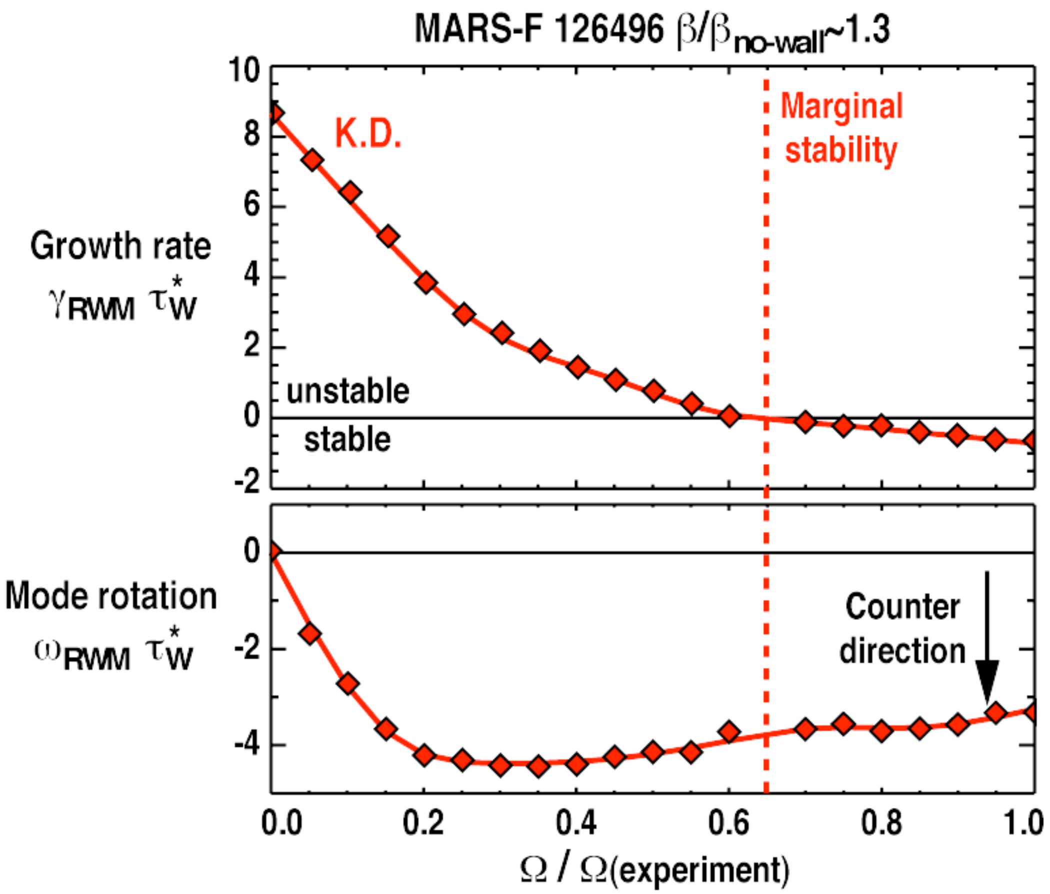

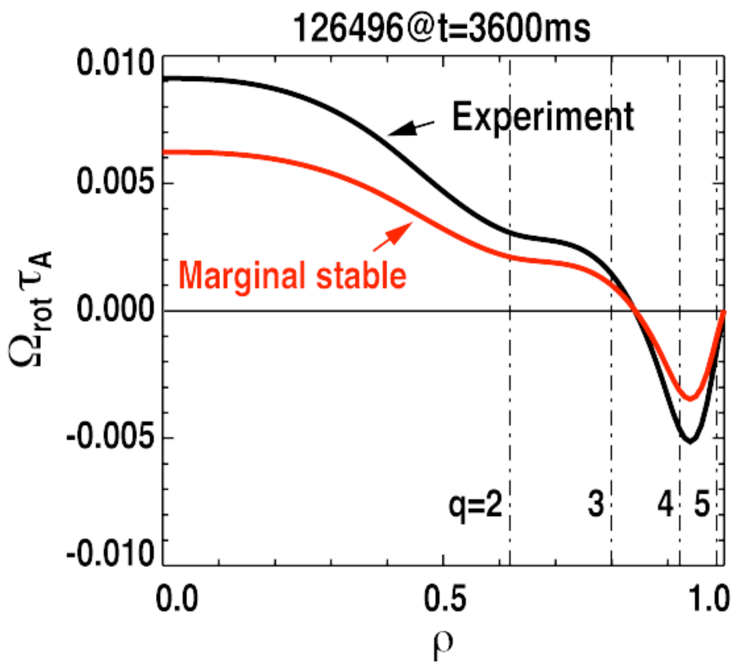

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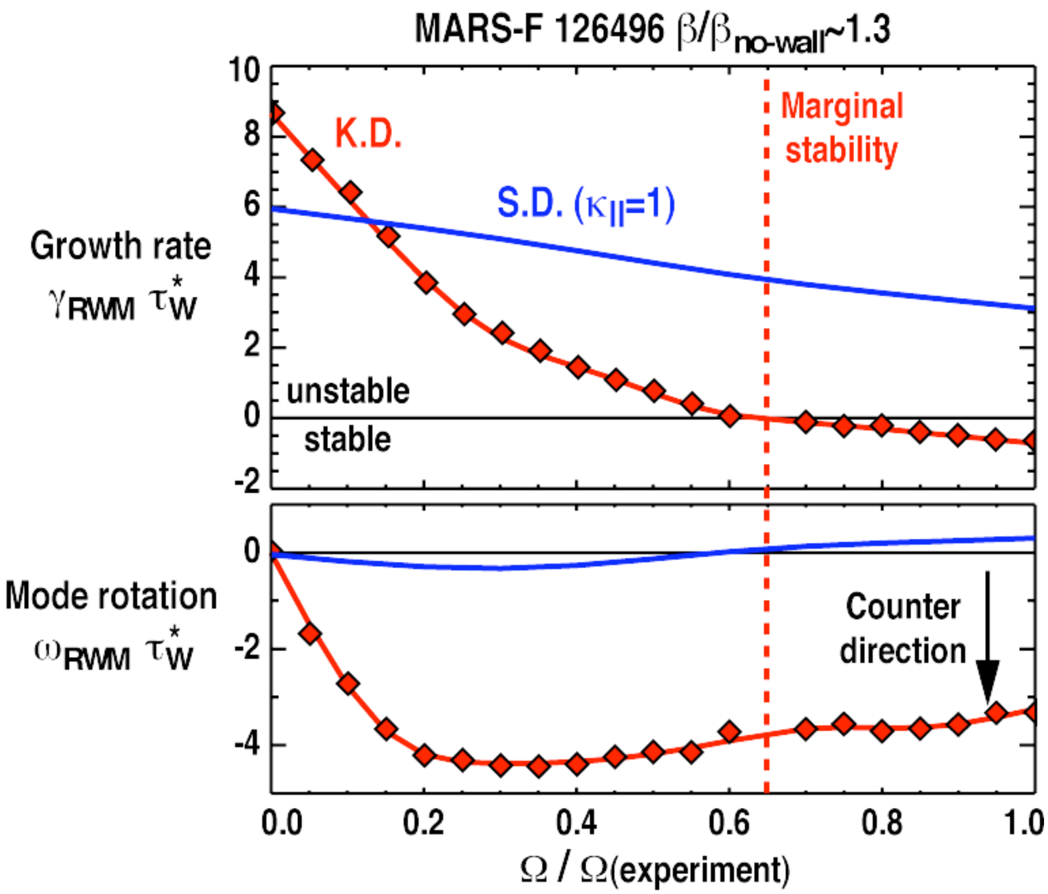

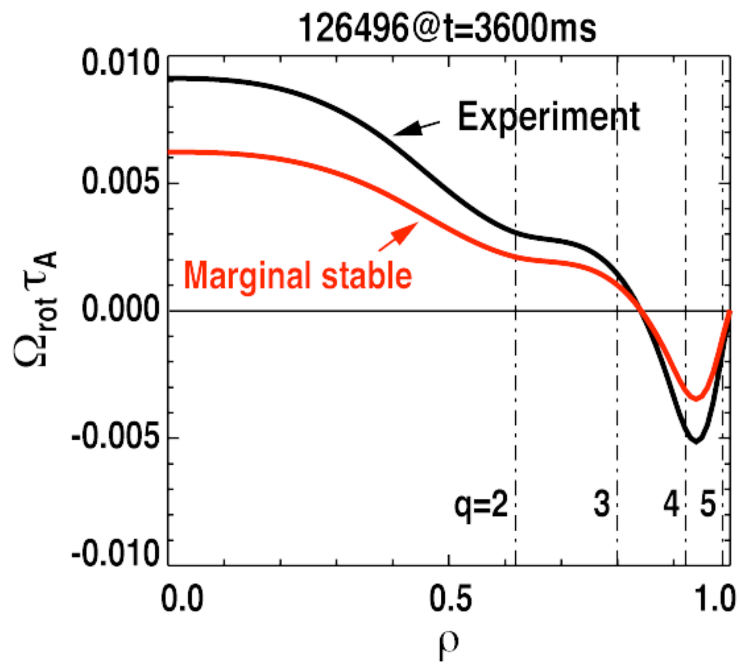

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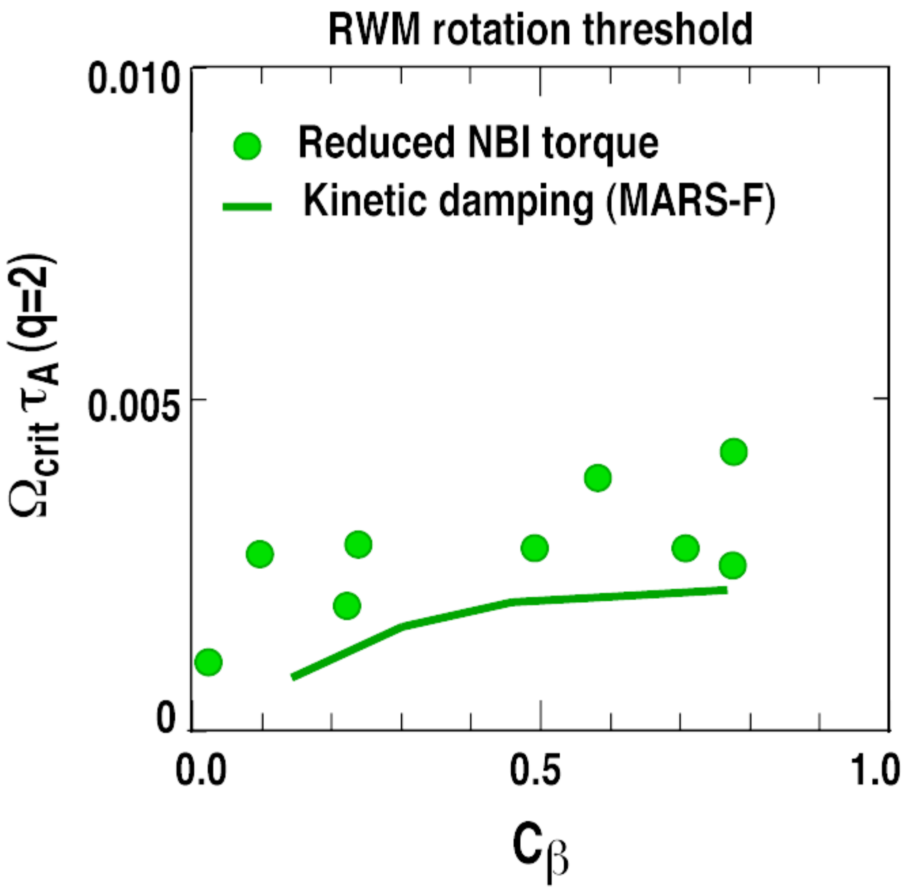

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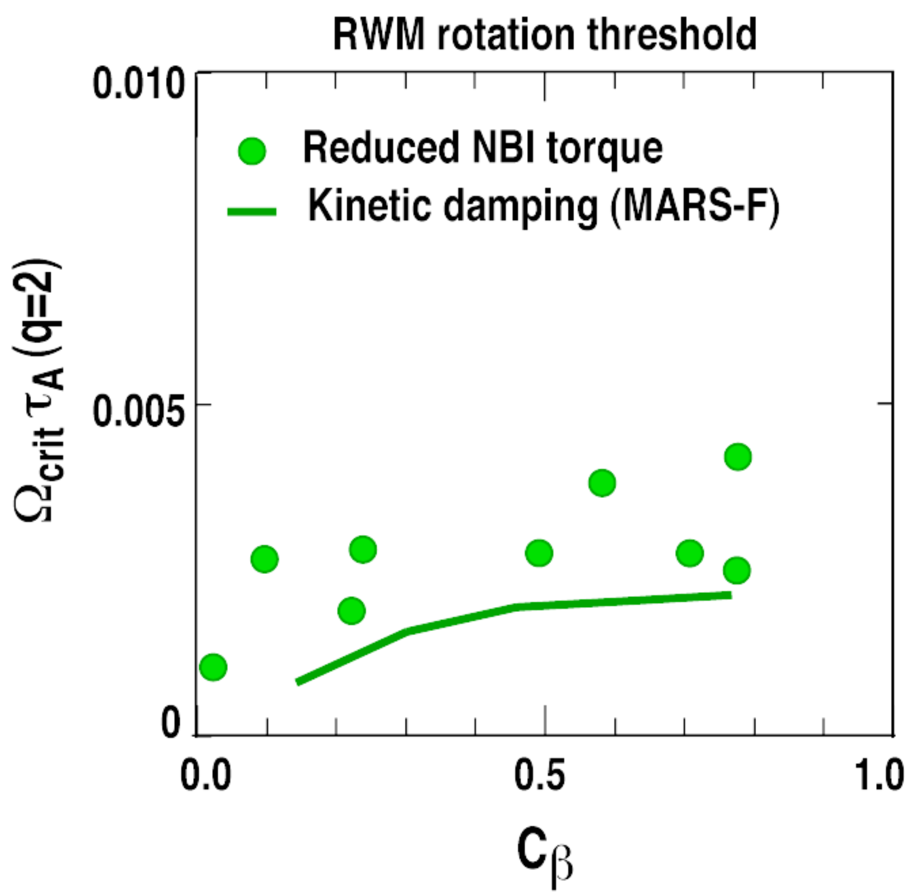
Kinetic damping model in surprisingly good agreement with observed β-dependence of RWM rotation threshold

- **Kinetic damping predictions forms lower bound of observed rotation threshold**
- **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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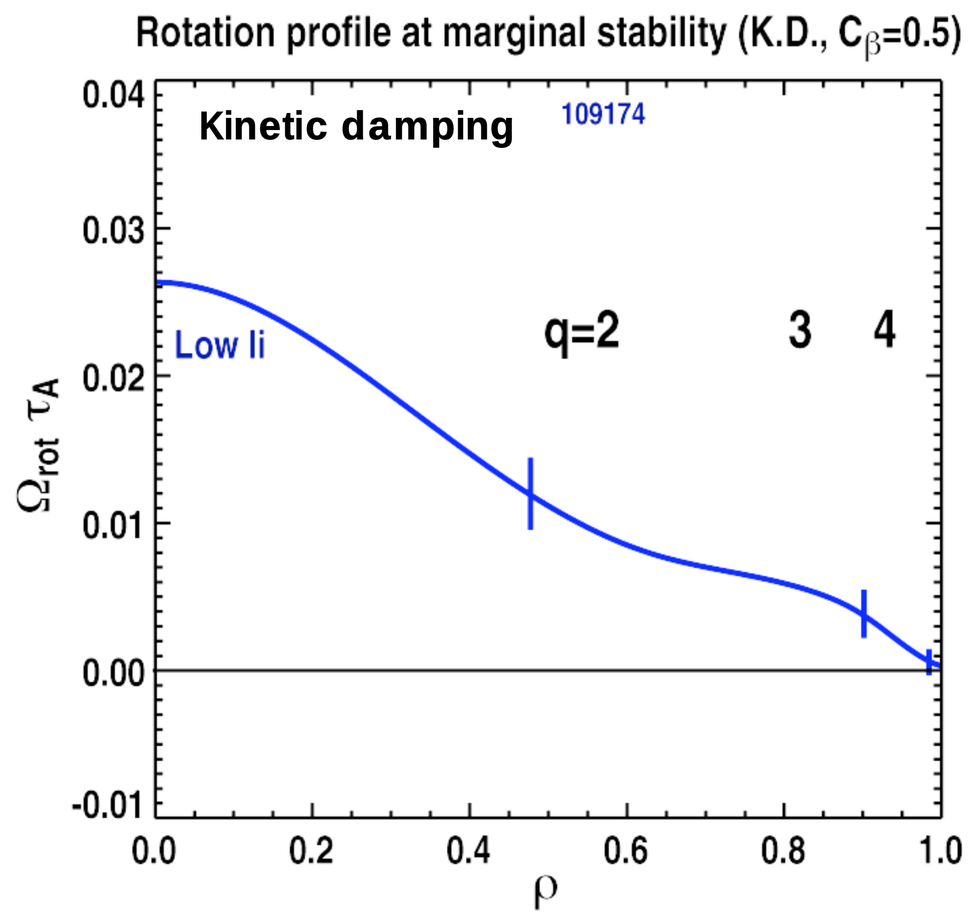
  - "High" critical rotation at q=2
  - Only 2 resonant surfaces with significant rotation



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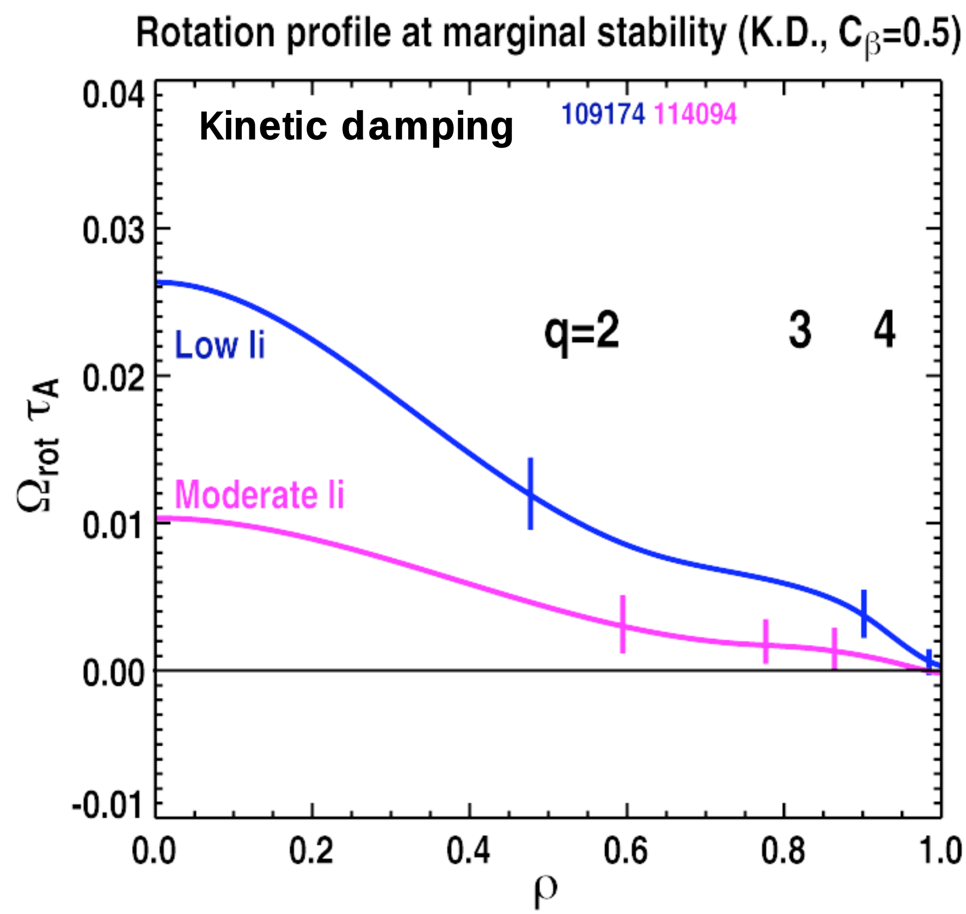

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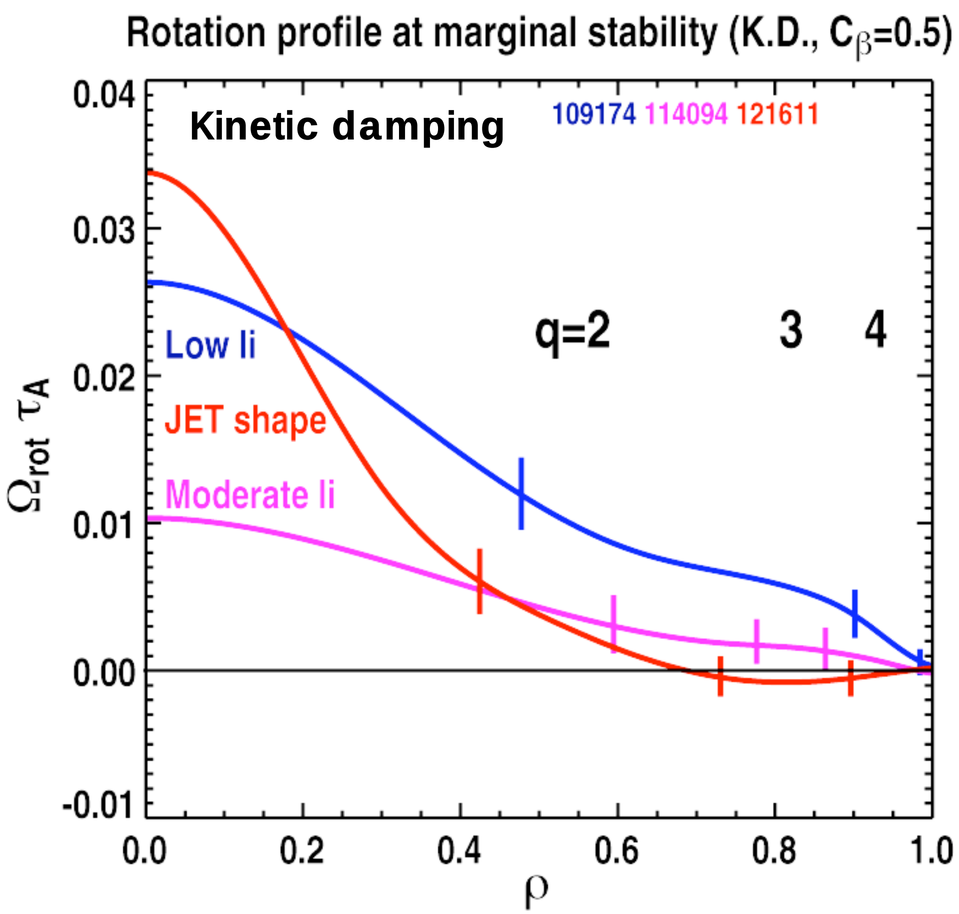

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- **"JET shape" plasmas**
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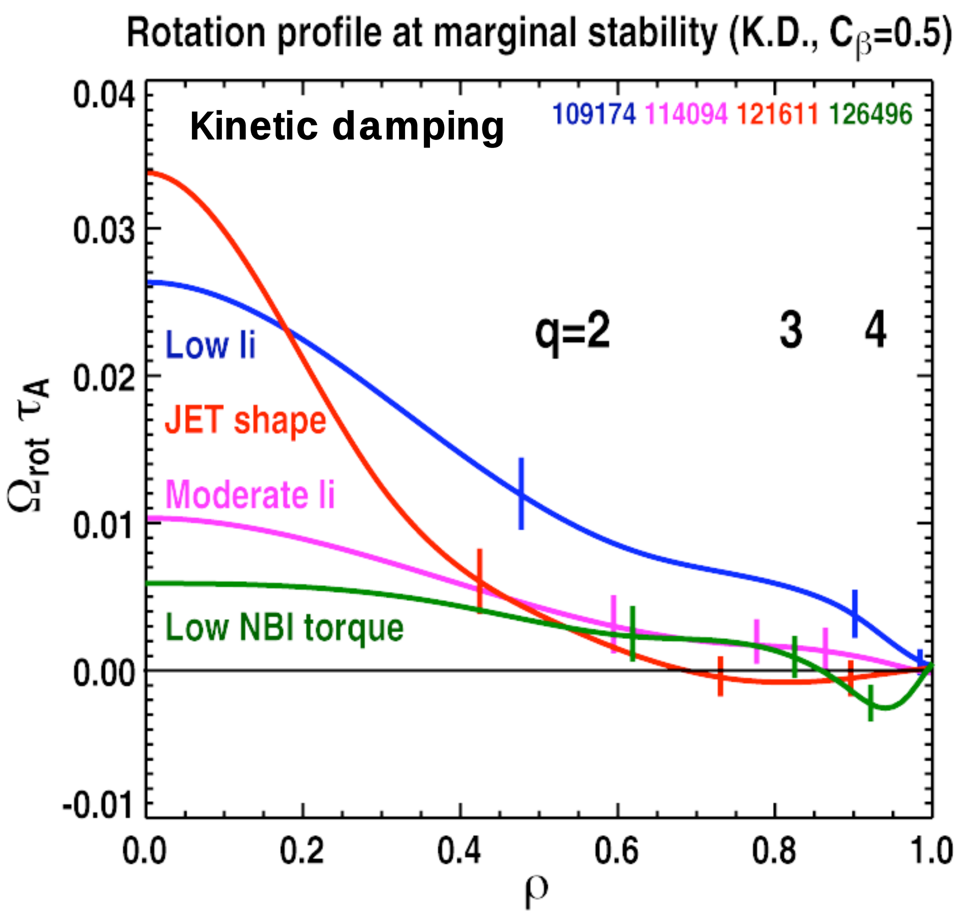
- **"Low NBI torque" plasmas**
  - "Lowest" critical rotation
  - 4 resonant surfaces with rotation



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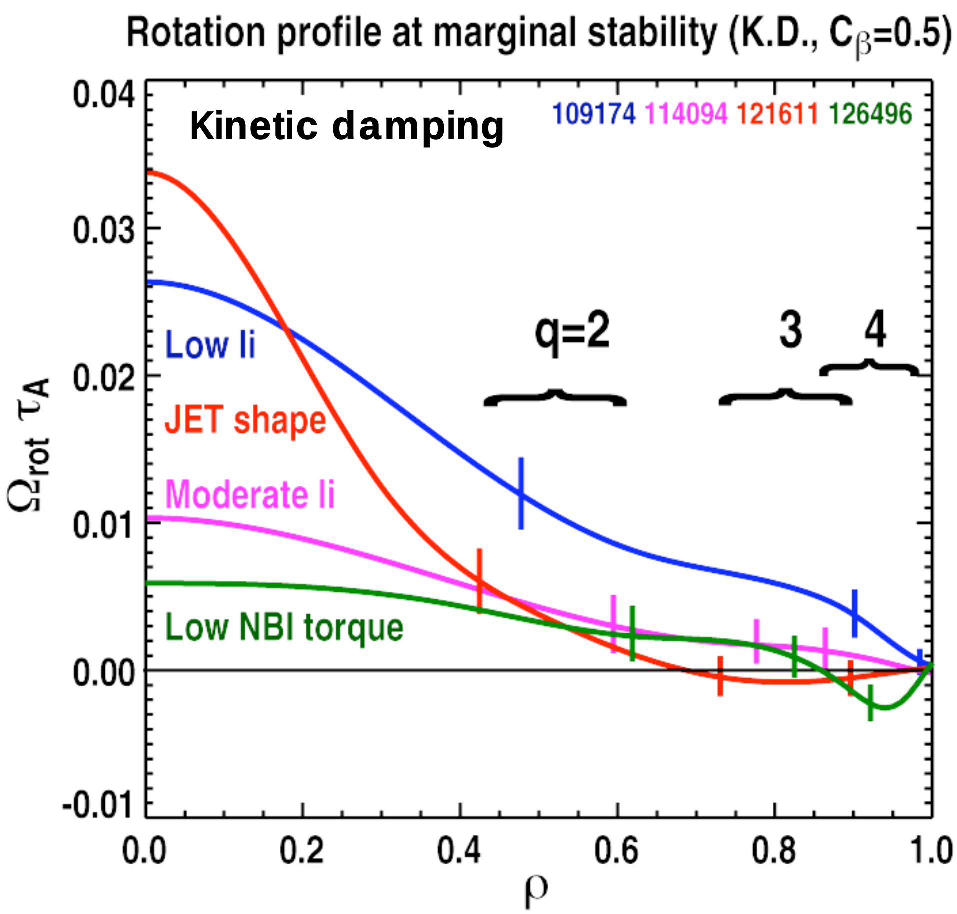

Weighted sum over rotation at all resonant surfaces may yield a better criterion for marginal stability

$\Omega_{crit}\tau_A$	q=2	q=3	q=4	q=5	$\sum(\lvert\Omega_{crit}\tau_A\rvert)_k$	$\sum(\lvert\Omega_{crit}\tau_A\rvert)_k q_k$	$\sum(\lvert\Omega_{crit}\tau_A\rvert)_k q_k^2$
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
JET shape	0.0060	0.0007	0.0007	0.0001	0.0075	**0.0174**	**0.0440**
Reduced T_{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
σ /mean	78%	72%	86%	120%	47%	36%	32%

- **Kinetic damping predictions of $\Omega_{crit}\tau_A$ 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 $\Omega_{crit}\tau_A \propto q^{-2}$
  - Displacement profile expected to play a significant role, too

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 $\Omega_{crit}\tau_A$=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**