Resistive Wall Mode and Plasma Stability at High β and Slow Rotation

by
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with
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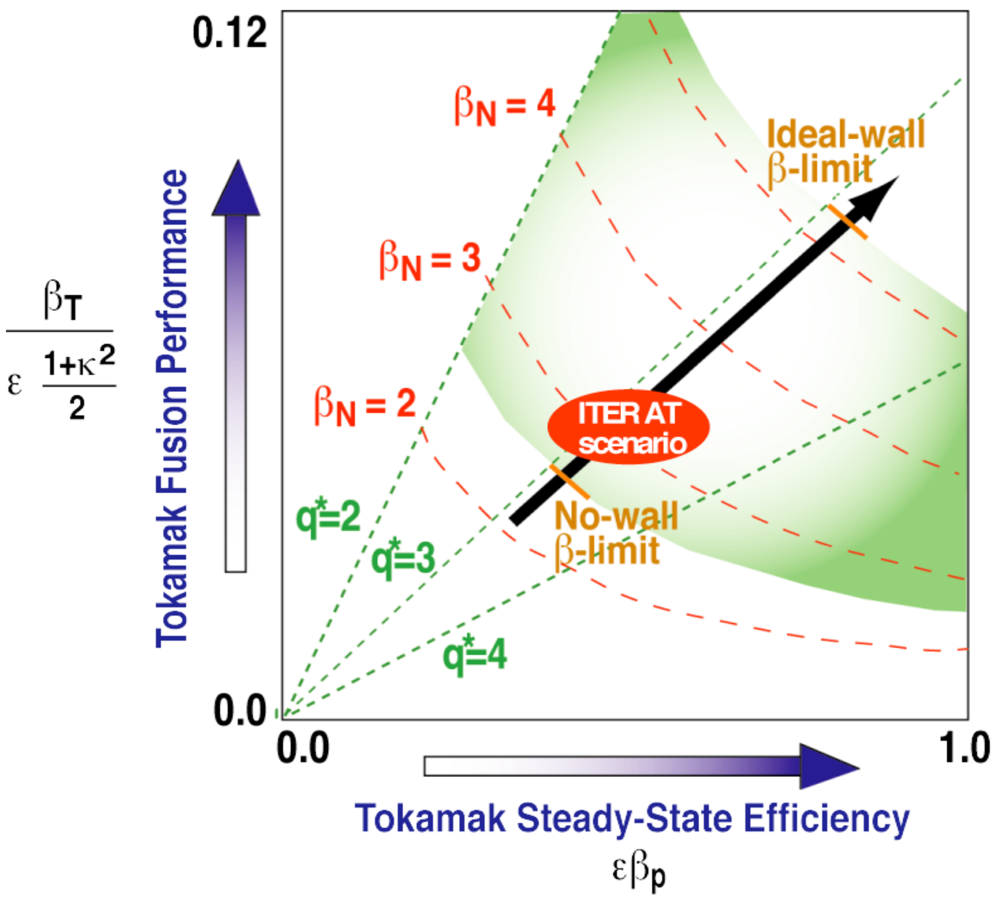

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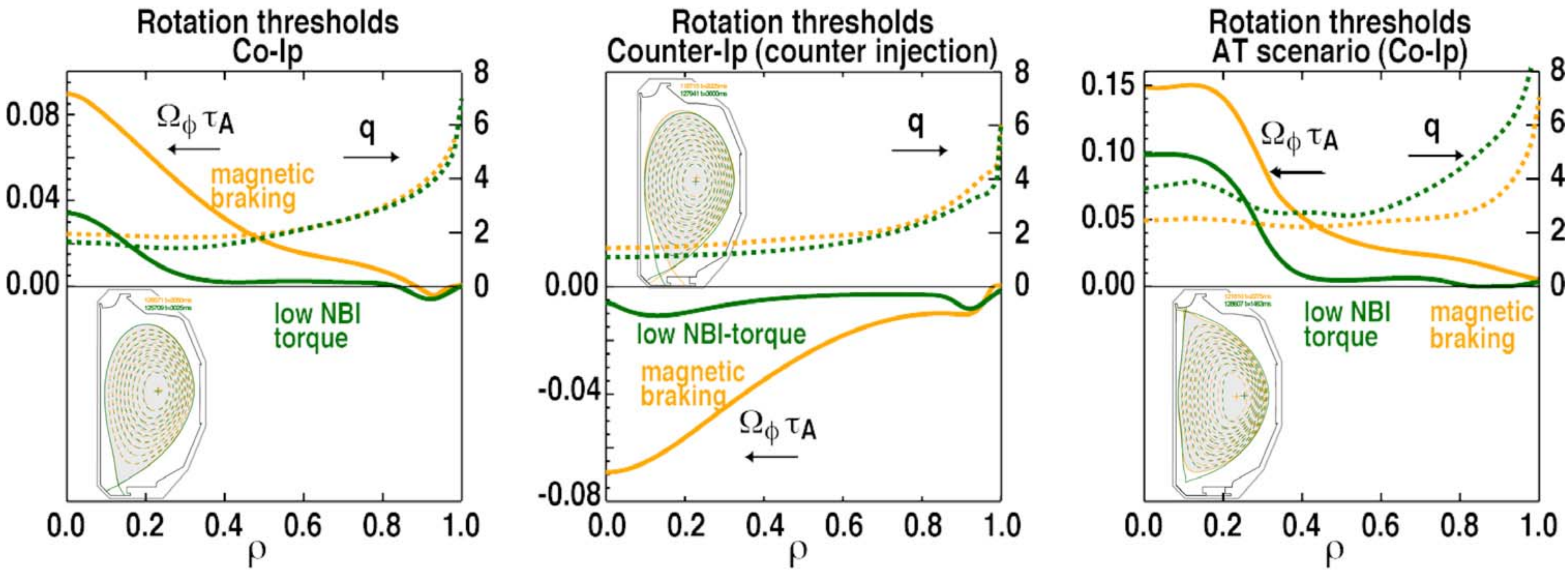
Outline/Main Results of 2007 DIII-D Experiments

- **Observation of RWM stabilization by slow plasma rotation extended to advanced tokamak regime**
  - $\beta_N > 4\ell_i$, $q_{min} > 2$
- **Reduction of n=1 error field is critical in obtaining stability at low rotation**
  - Marginally stable RWM lowers threshold of tolerable error fields in ITER
- **Linear kinetic theory predicts stability even below the observed low rotation threshold**
  - Observed stability threshold may not be RWM stability threshold
- **Magnetic feedback can increase stability against dynamic disturbances, such as large ELMs**
  - Feedback quickly restores axisymmetry and avoids locking

RWM Stabilization by Slow Plasma Rotation Observed in Advanced Tokamak Regime

- **Threshold rotation for stability observed with:**
  - **High NBI torque and increased n=1 error field for magnetic braking**
  - **Low NBI torque and minimized n=1 error field**



- **Stability at low rotation requires optimal correction of n=1 error fields**

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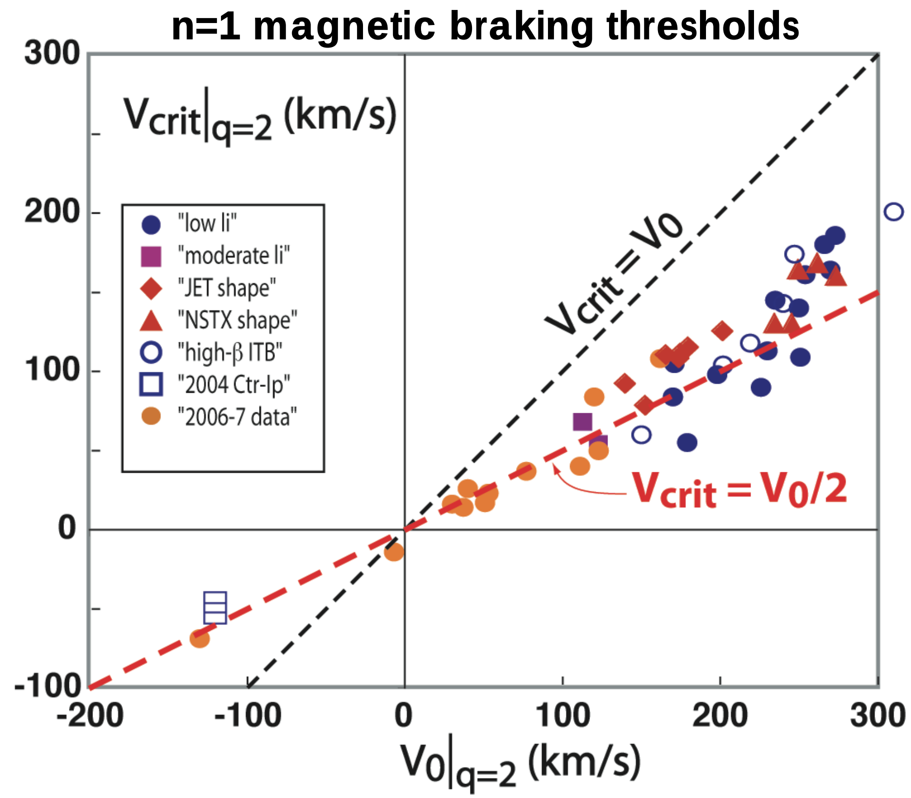
- High rotation thresholds

Resonant Magnetic Perturbations Introduce a Threshold Rotation for Stability

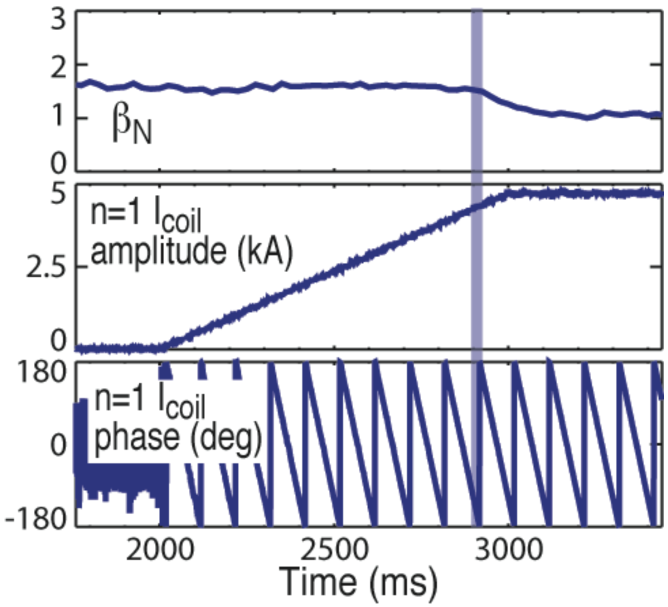
- **Threshold V_{crit} depends on unperturbed rotation V_0**
  - $V_{crit} = \frac{V_0}{2}$
- **Threshold V_{crit} independent of β**
- **Consistent with "induction motor" model of error field-driven reconnection [Fitzpatrick, *Phys. Plasmas*, 1998]**



- Increasing static resonant error field beyond threshold amplitude (-> V_{crit}) leads to loss of torque balance, rotation collapse
- Error field (shielded at high rotation) unimpeded from causing magnetic reconnection at low rotation

Magnetic Reconnection at q=2 Surface Observed Below Rotation Threshold

- **Controlled braking experiments using n=1 resonant field with slowly increasing amplitude (constant NBI torque)**
  - Slowly rotating (10 Hz) to move island past ECE detector



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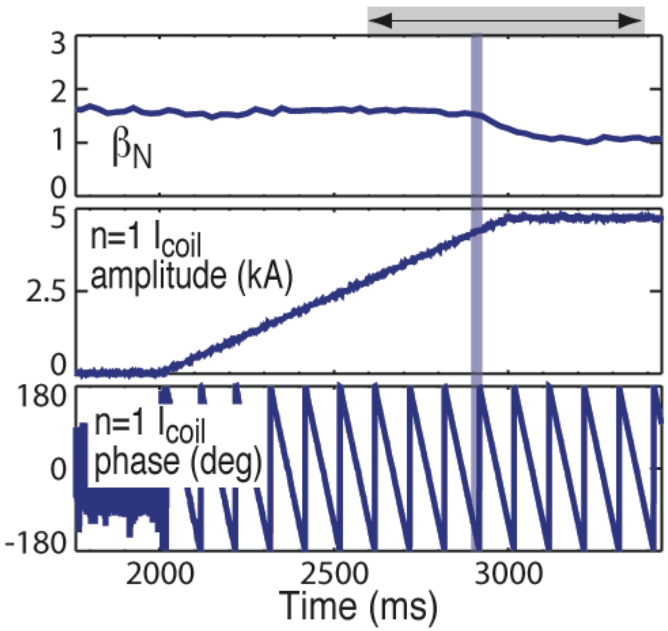

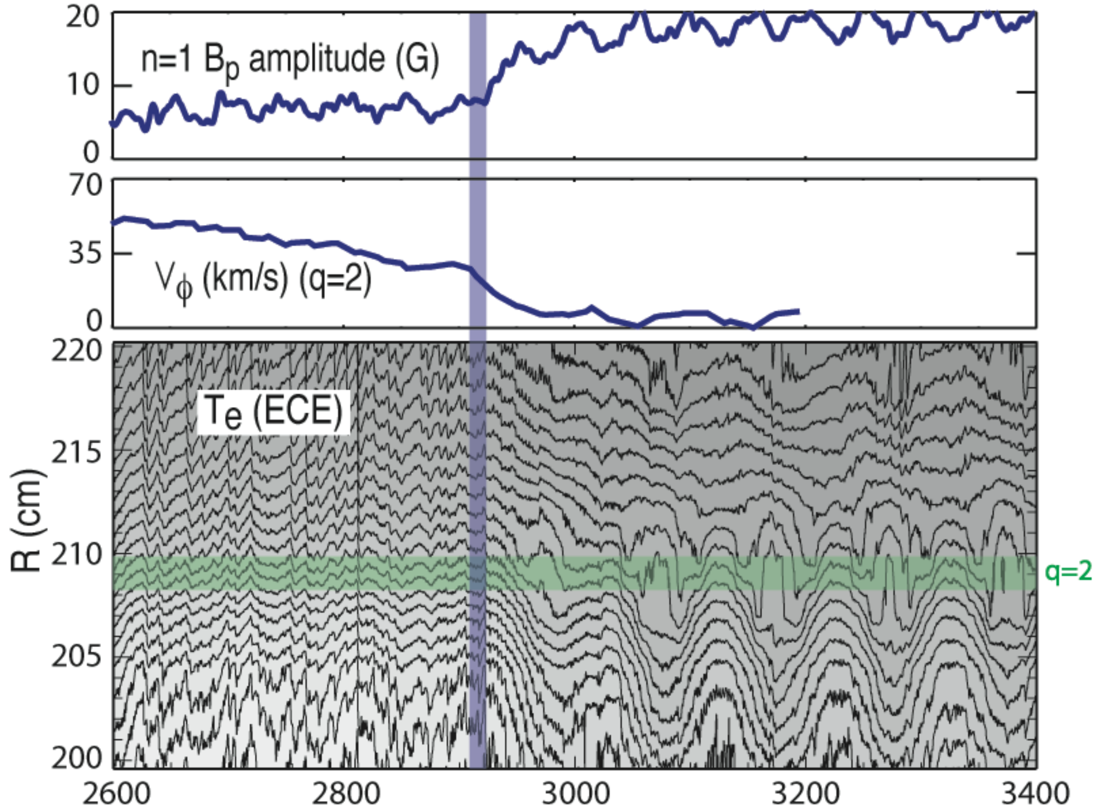

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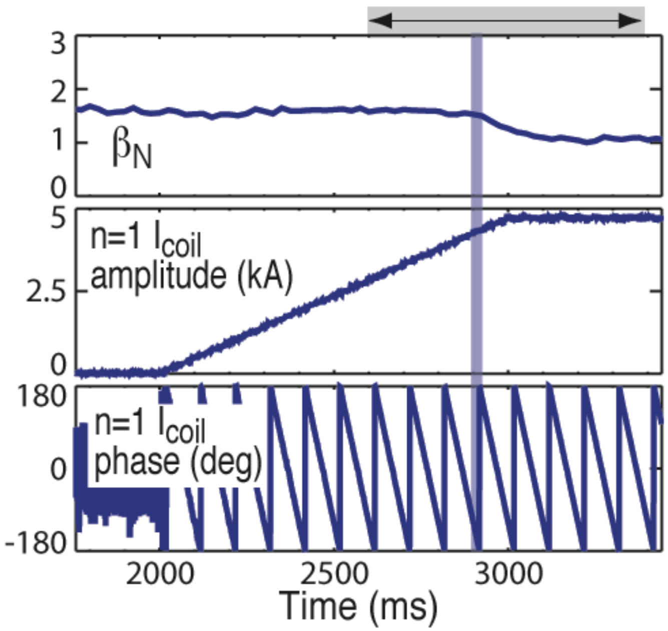
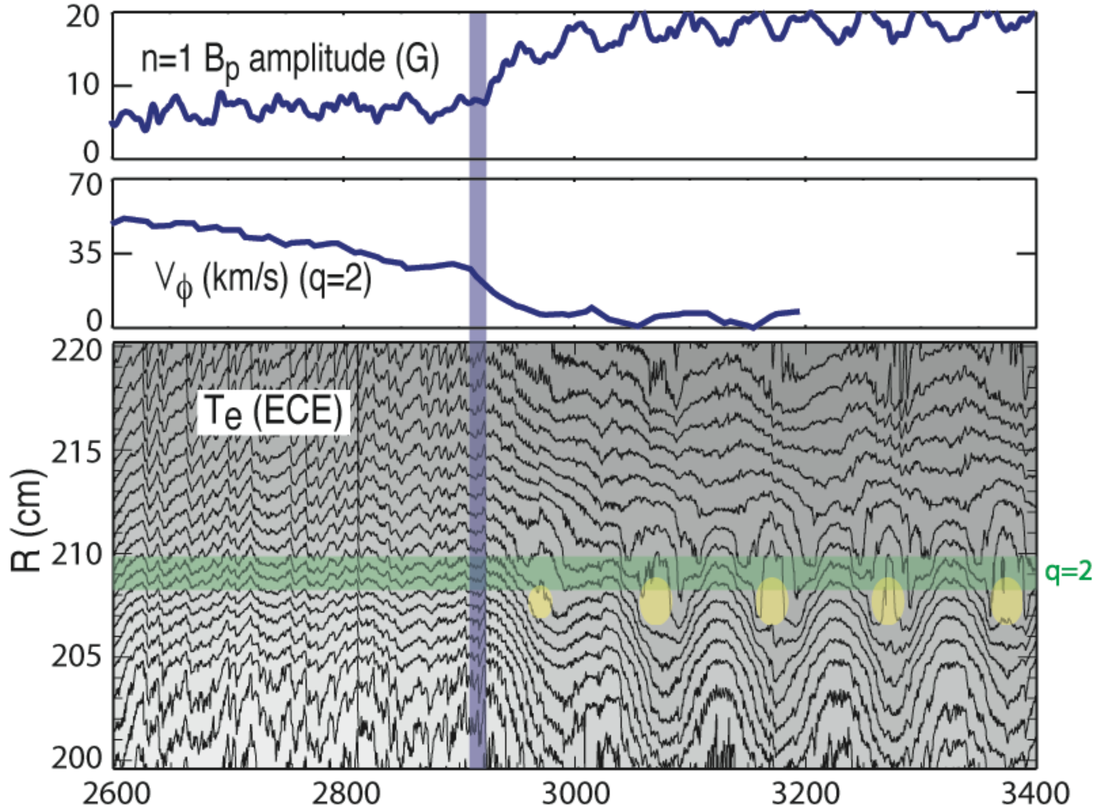
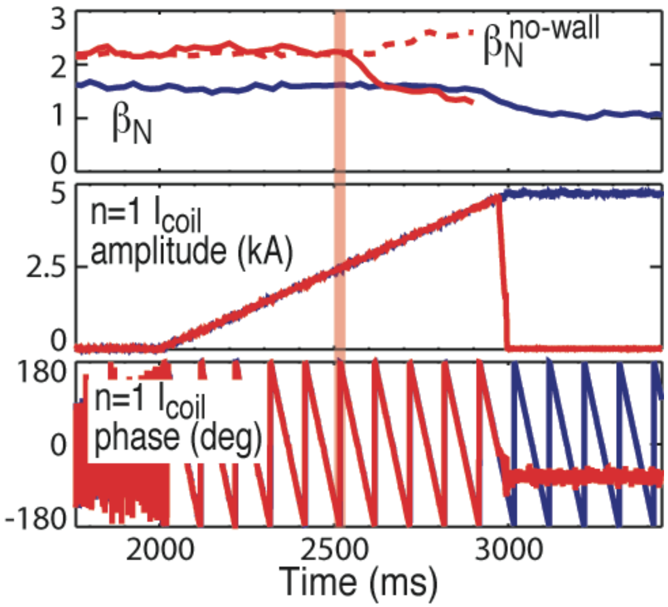




At High β, Plasma Response Reduces Tolerable Error Field

- **Higher β_N ($\geq \beta_N^{no\text{-}wall}$), nearly same NBI torque**



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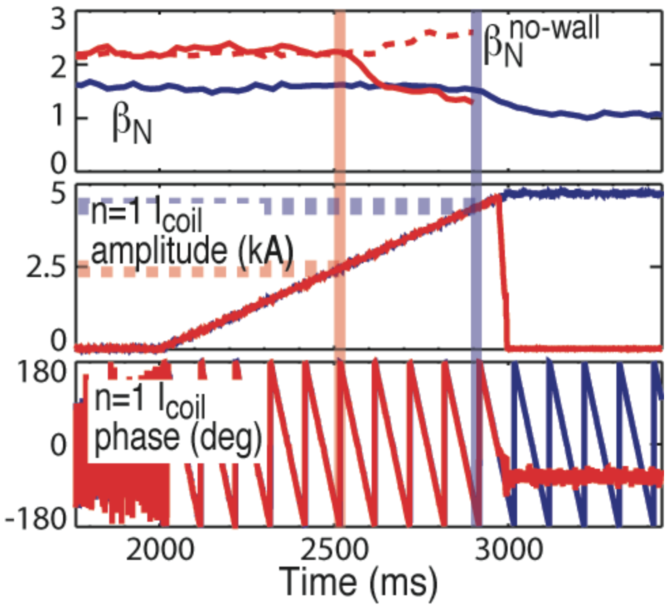
- β_N drop occurs at ~1/2 error field amplitude



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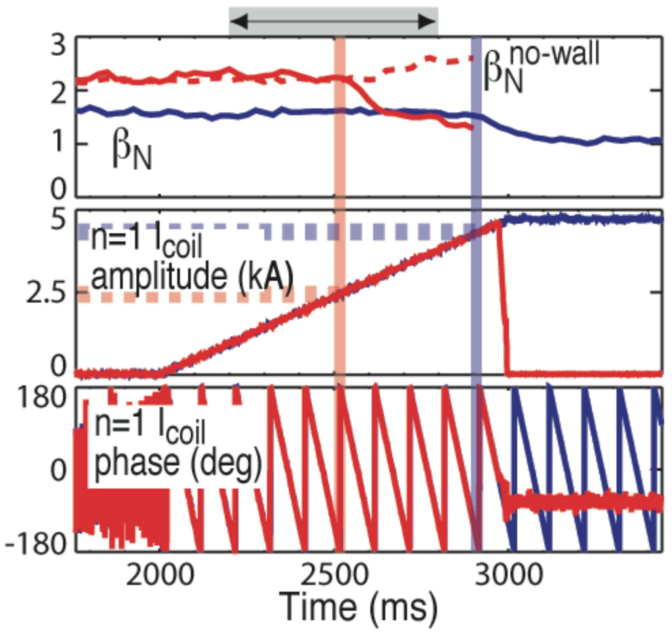
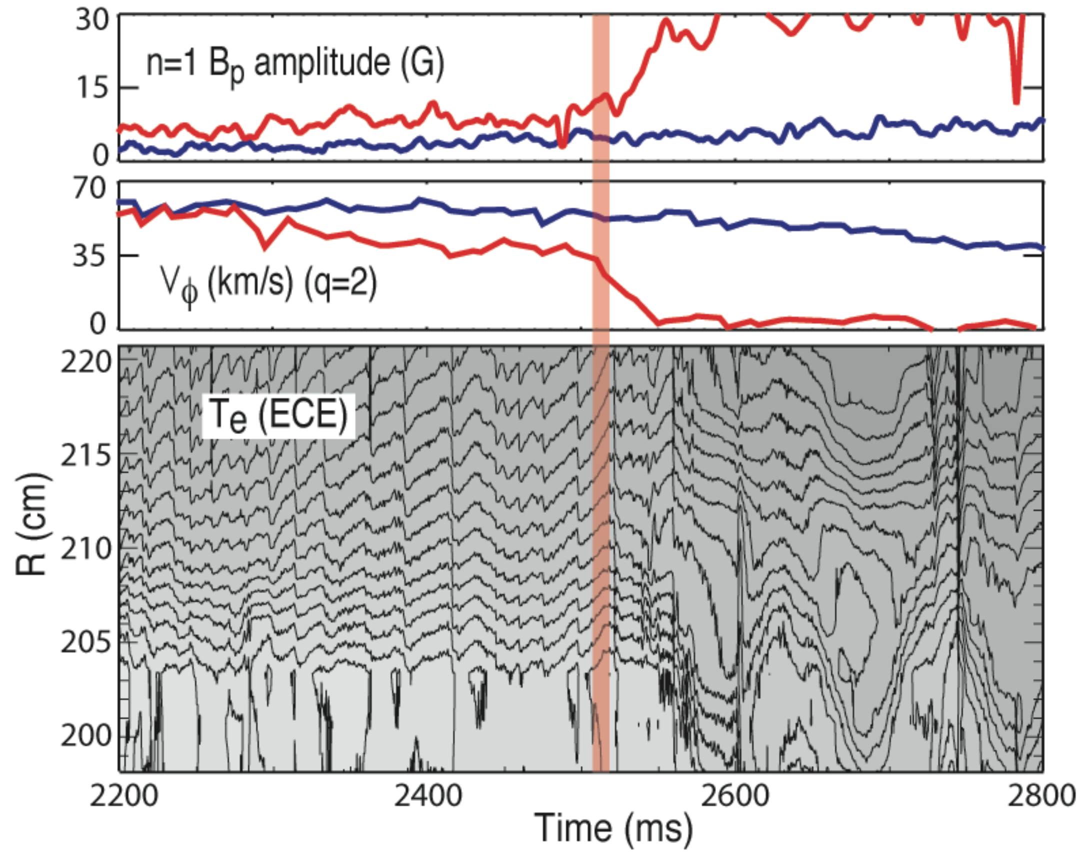
- **Higher β_N ($\geq \beta_N^{no\text{-}wall}$), nearly same NBI torque**
- **β_N drop occurs at ~1/2 error field amplitude**
- **Marginally stable RWM amplifies error field** **[Reimerdes, JP8.081]**
  - Plasma response ~2x

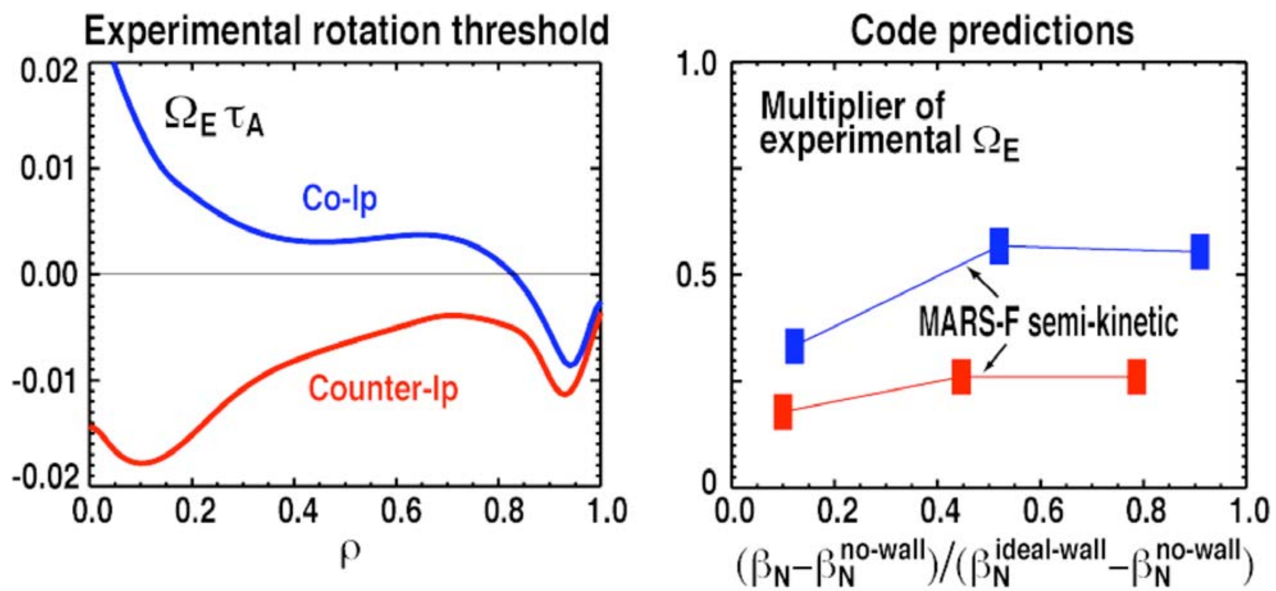




- Low rotation thresholds

Kinetic Damping Models Predict Stability Even with Rotation Below the "Small" Experimental Threshold

- **Use Ω_E rotation for model-exp comparison (toroidal flow due to radial electric field)** **[Strait, JP8.083]**



- **Semi-kinetic damping model in MARS-F predicts stability with ~1/2 of experimental rotation threshold**
  - Resonance with transit frequency of passing particles, bounce frequency of trapped particles [Bondeson & Chu, *Phys. Plasmas* 1996]

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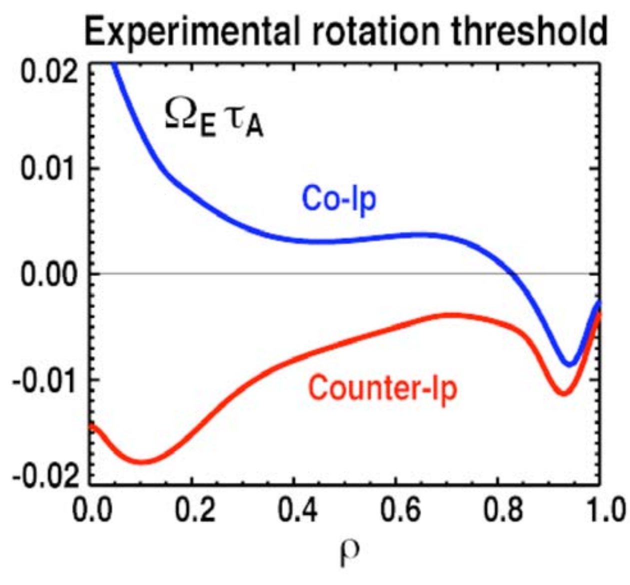
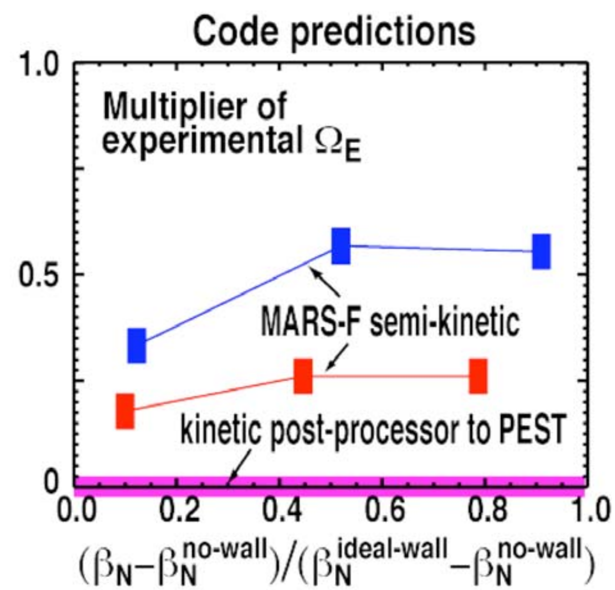


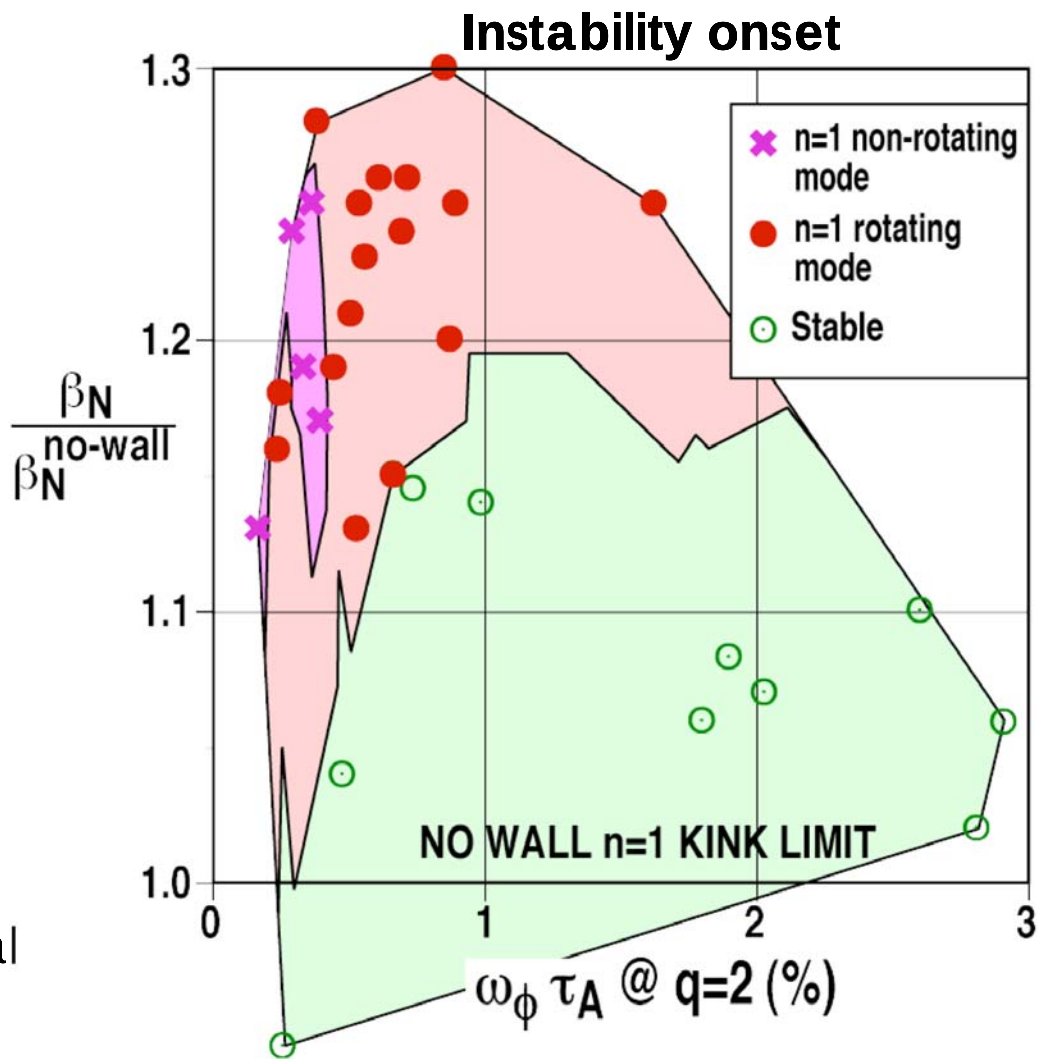


- **Semi-kinetic damping model in MARS-F predicts stability with ~1/2 of experimental rotation threshold**
  - Resonance with transit frequency of passing particles, bounce frequency of trapped particles [Bondeson & Chu, *Phys. Plasmas* 1996]
- **Adding resonance with trapped particle precession drift leads to stability even without rotation** **[Hu, GP8.116]**
  - [Hu&Betti, *PRL*, 2004]

Tearing Modes and Error Fields Make It Difficult to Test Prediction of RWM Stability Without Rotation

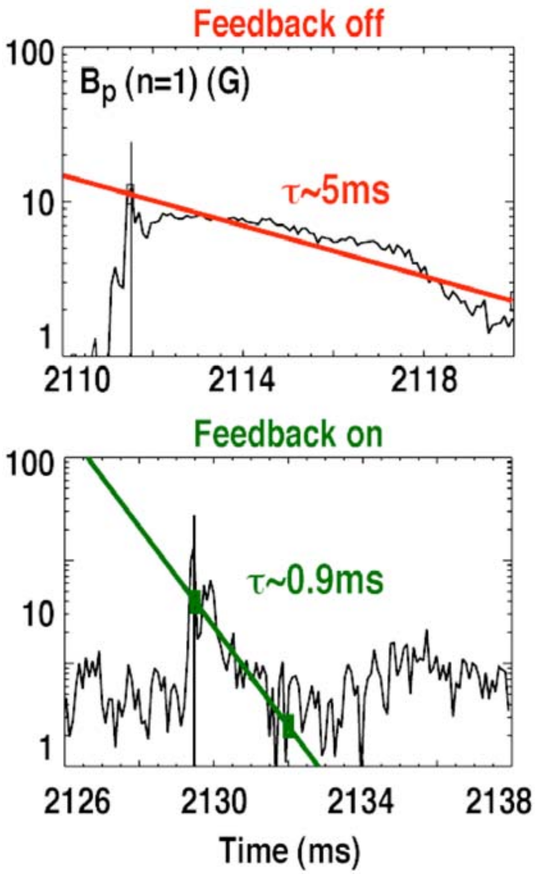
At high β and slow rotation:

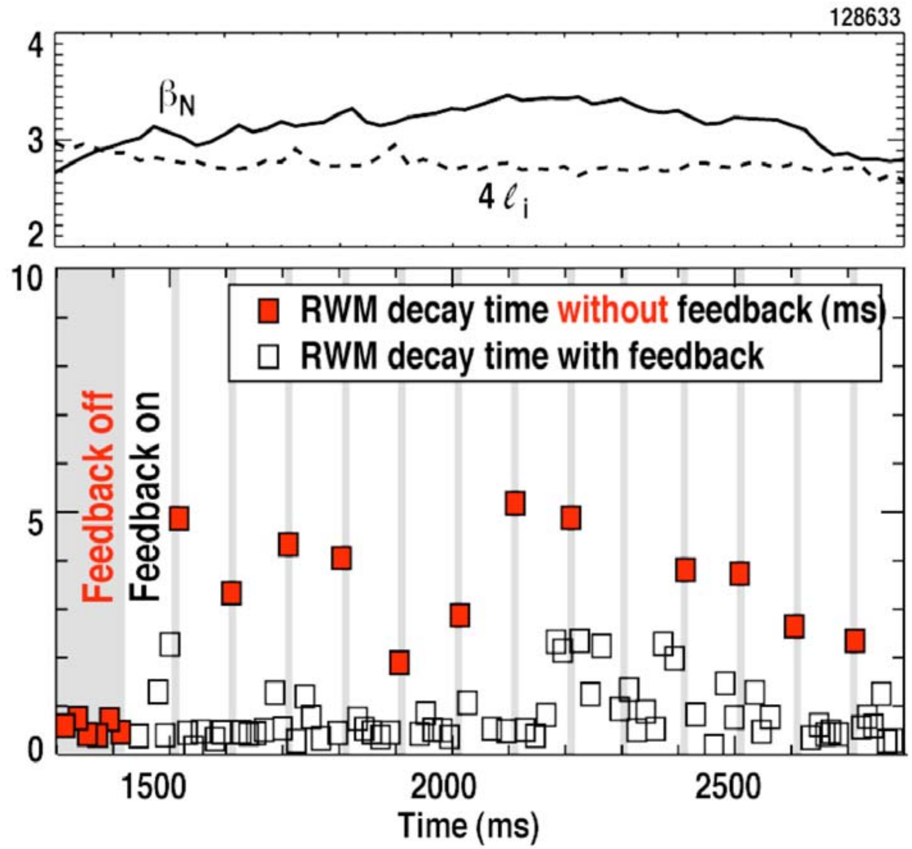
- **Tearing mode is more unstable [Buttery, UI1.003]**
  - Tearing mode rotates with plasma before it locks
- **Error field threshold for forced reconnection is lower**
- **Uncertainty on nature of non-rotating limiting instability**
  - Could be RWM
  - Could be TM, non-rotating if the plasma rotation is ~zero
  - Could be locked NTM "seeded" by forced reconnection due to residual uncorrected error fields



RWM Feedback Accelerates Damping of *n*=1 Perturbations Following ELMs

- **ELMs can couple resonantly to weakly damped RWM [Okabayashi, JP8.082, In, JP8.077]**
- **RWM feedback mitigates effect of transient perturbations, improves reliability of operation at high β**





Summary/Main Results

- **RWM stabilization by slow plasma rotation was extended to advanced tokamak regime ($\Omega\tau_A$<0.6% at q=2)**
  - $\beta_N > 4\ell_i$, $q_{min} > 2$
- **Reduction of n=1 error field is critical in obtaining stability at low rotation**
  - Marginally stable RWM lowers threshold of tolerable error fields in ITER
- **Linear kinetic theory predicts stability even below the observed low rotation threshold**
  - Observed stability threshold may not be RWM stability threshold
  - NTM stability, error field-driven “seed” island may be important
- **At higher rotation, magnetic feedback can maintain or quickly restore axisymmetry, and sustain stability in high-β regimes**
  - Slow feedback routinely used to minimize ~static error field
  - Fast feedback can correct transient perturbations due to ELMs