Resistive Wall Mode Control in DIII-D

by
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for
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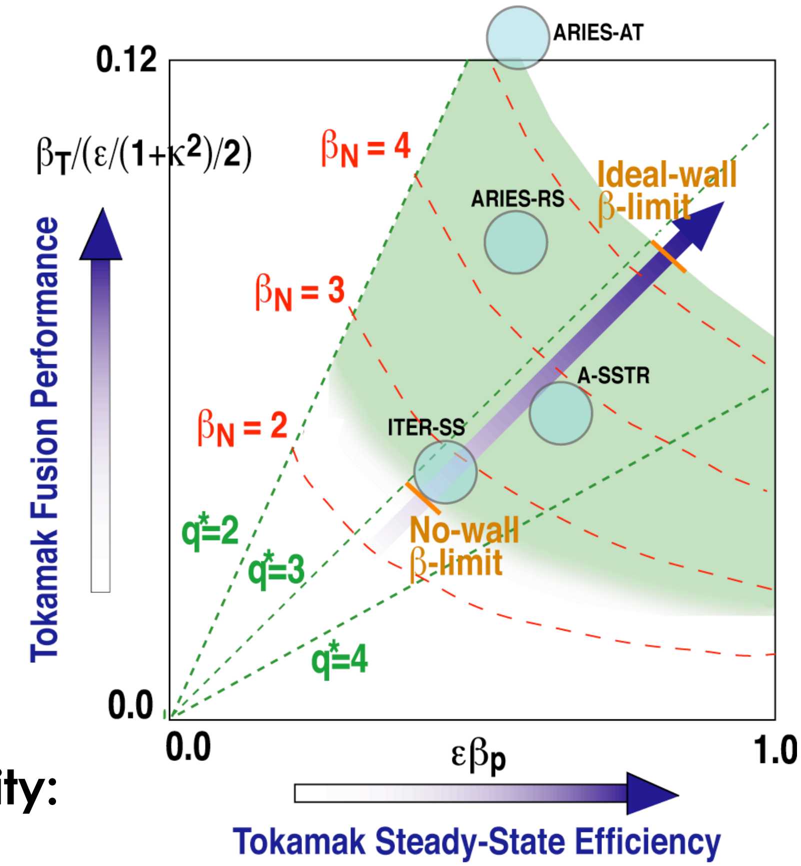

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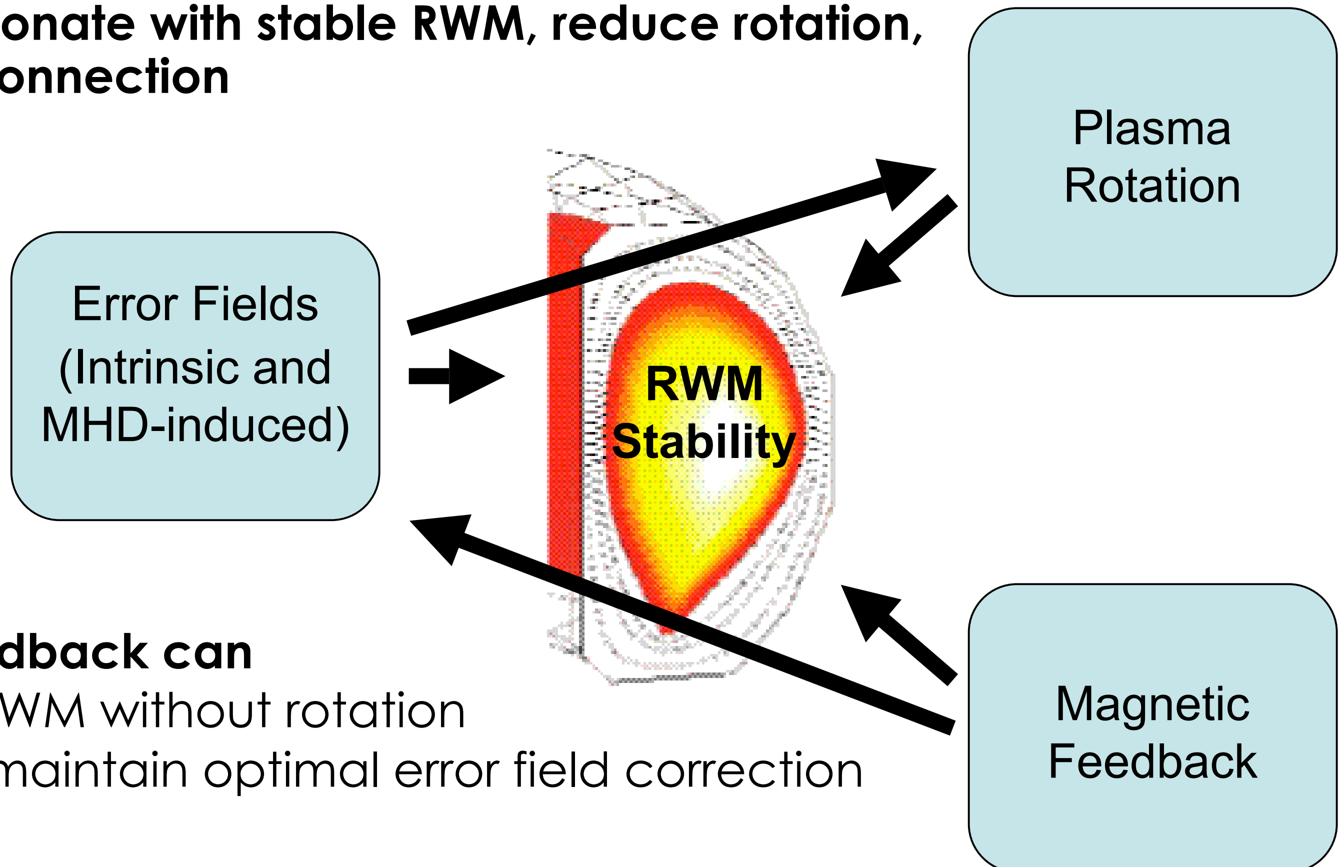
RWM Stabilization Involves Complex Interaction of Rotation, Error Fields, and Feedback

- **Plasma rotation stabilizes RWM, but stabilization is weak**
- **Error fields resonate with stable RWM, reduce rotation, can drive reconnection**

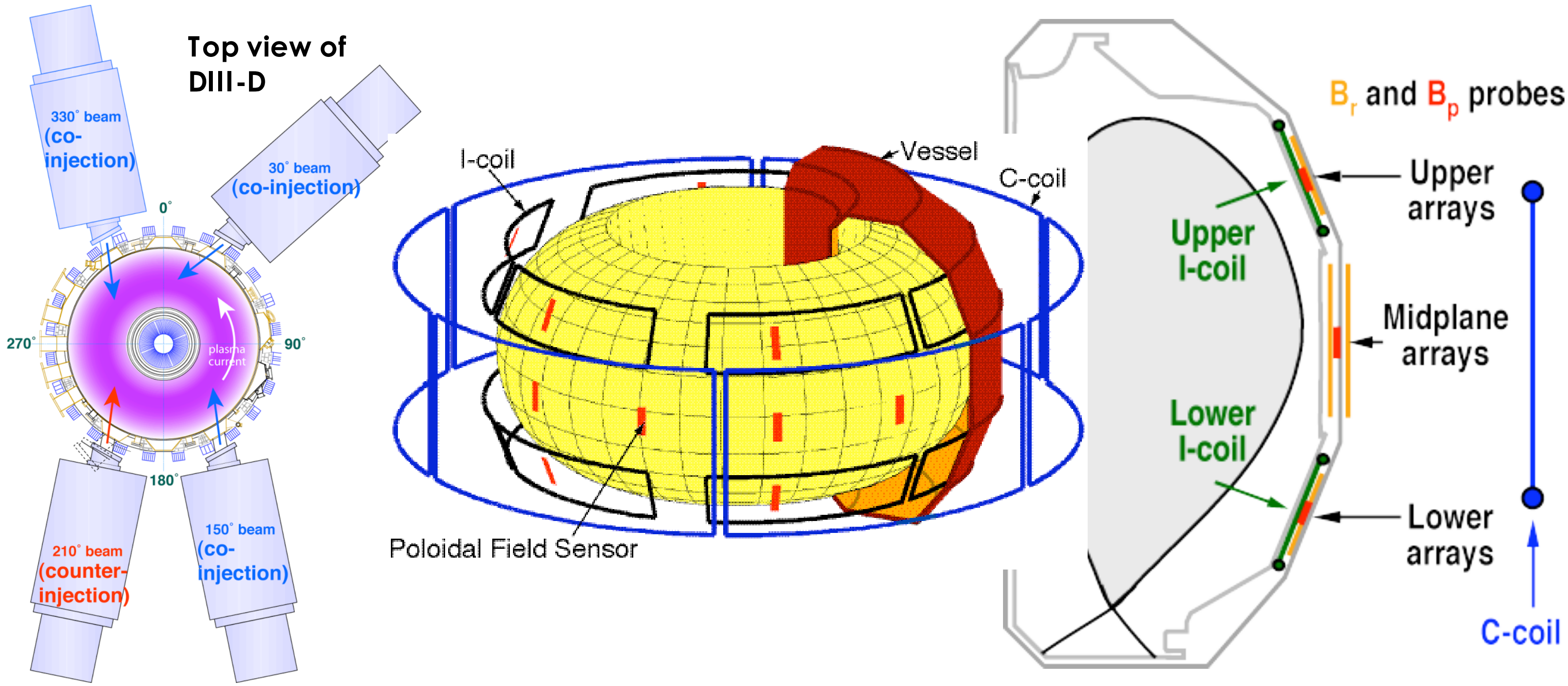


- **Magnetic feedback can**
  - Stabilize RWM without rotation
  - Find and maintain optimal error field correction

- **Requirements on feedback system can be relaxed if goal is to maintain rotational stabilization**

DIII-D Has a Unique Set of Tools for RWM Stabilization Studies

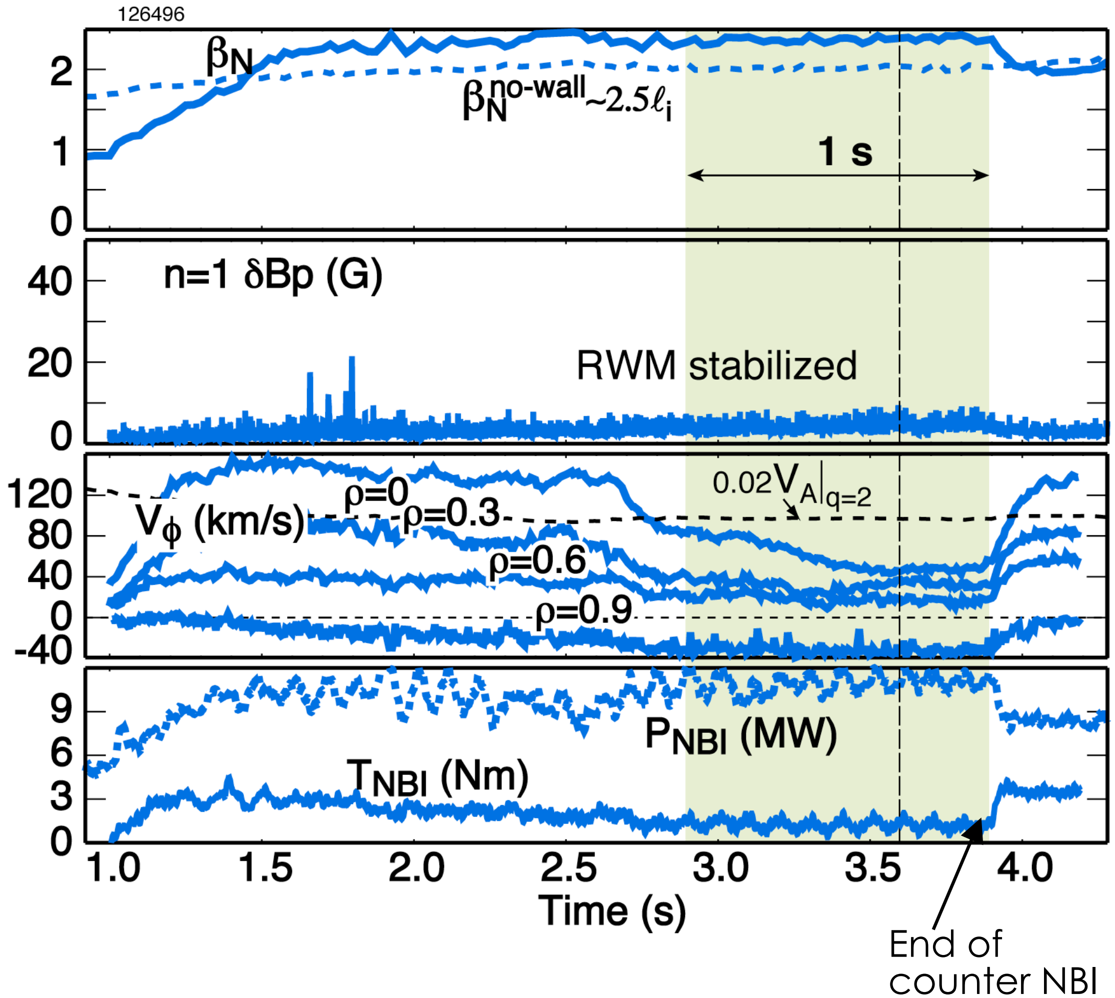
- Independent control of heating and rotation by 12.5 MW co-Ip neutral beam injection (NBI), 5 MW counter-Ip NBI
- Two sets of non-axisymmetric coils
- Extensive magnetic diagnostics
- Conducting wall close to plasma
- Fast, flexible digital control system



Summary/Main Results

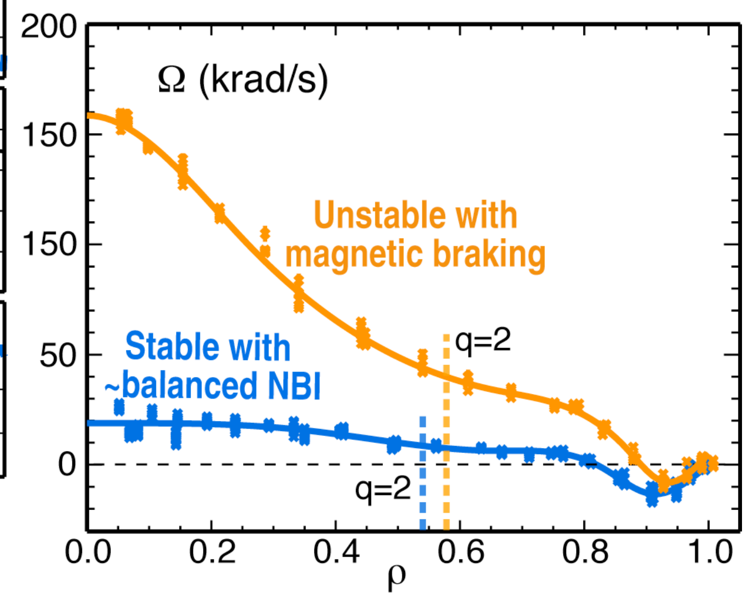
- **RWM stabilization by slow plasma rotation was extended to advanced tokamak regime ($\Omega\tau_A$<0.6% at q=2)**
  - $\beta_N > 4\ell_i$, $q_{min} > 2$
- **Reduction of n=1 error field is critical in obtaining stability at low rotation**
  - Marginally stable RWM lowers threshold of tolerable error 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
- **Low-β, current driven RWMs may be optimal target for studies of direct feedback stabilization**

2006: RWM Stabilization at Slow Rotation Observed by Reducing the Injected Torque With Minimized Error Fields



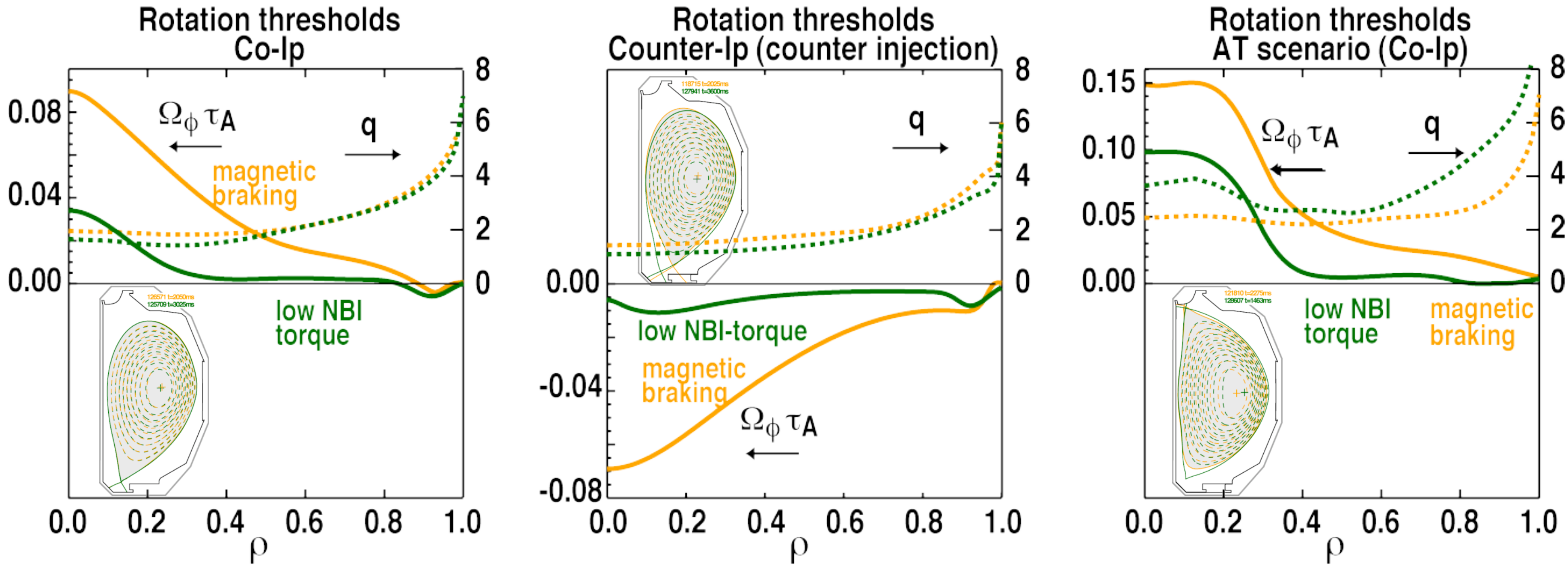
A proposed explanation:

- **Counter NB injection increases the (negative) edge rotation, provides stability with slow rotation at q=2**



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**



- **In high triangularity plasmas, near-balanced NBI reduces the plasma rotation at all minor radii**

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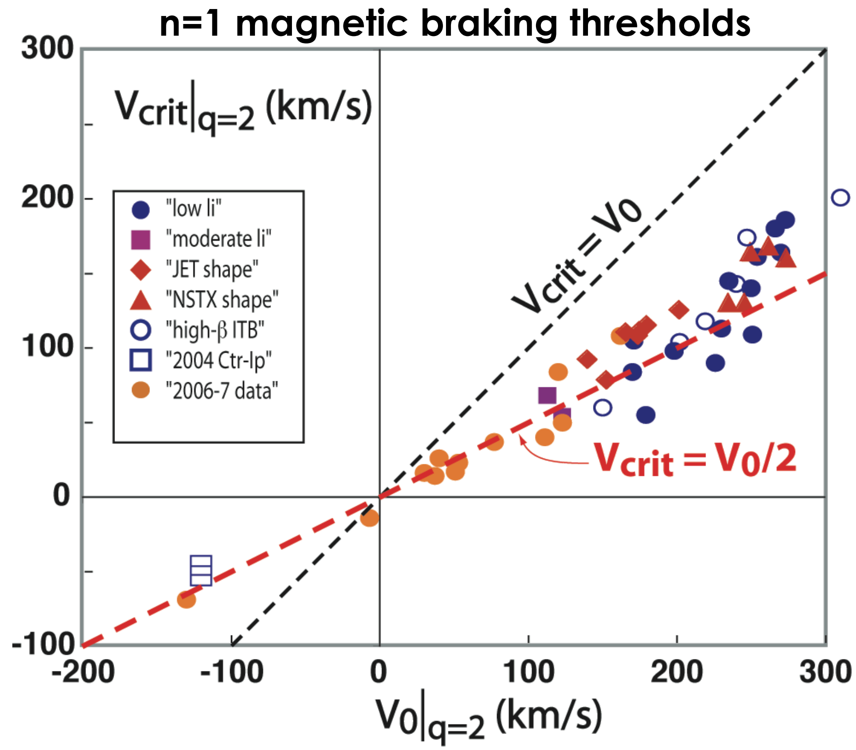
- High rotation thresholds

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

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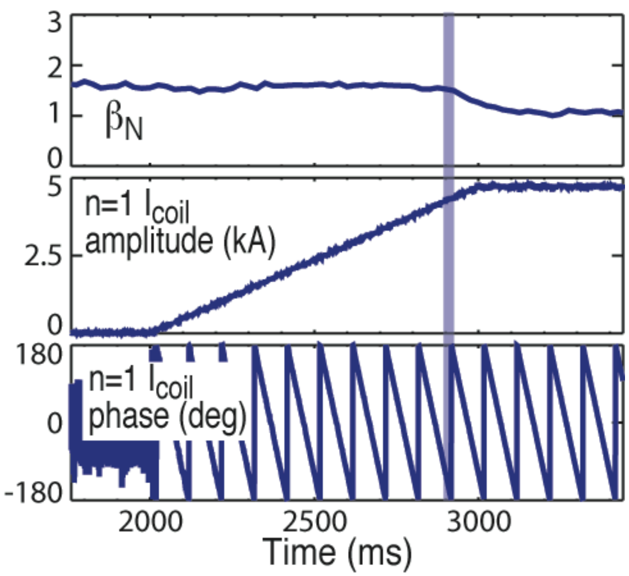
Magnetic Reconnection at q=2 Surface Observed Below Rotation Threshold

- **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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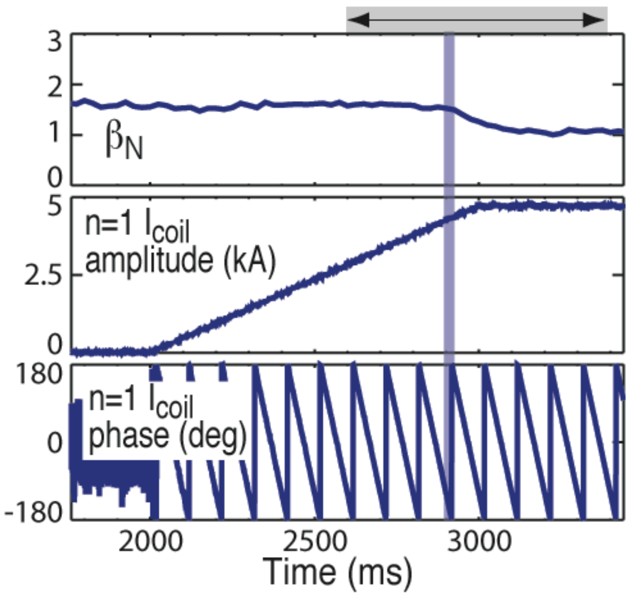

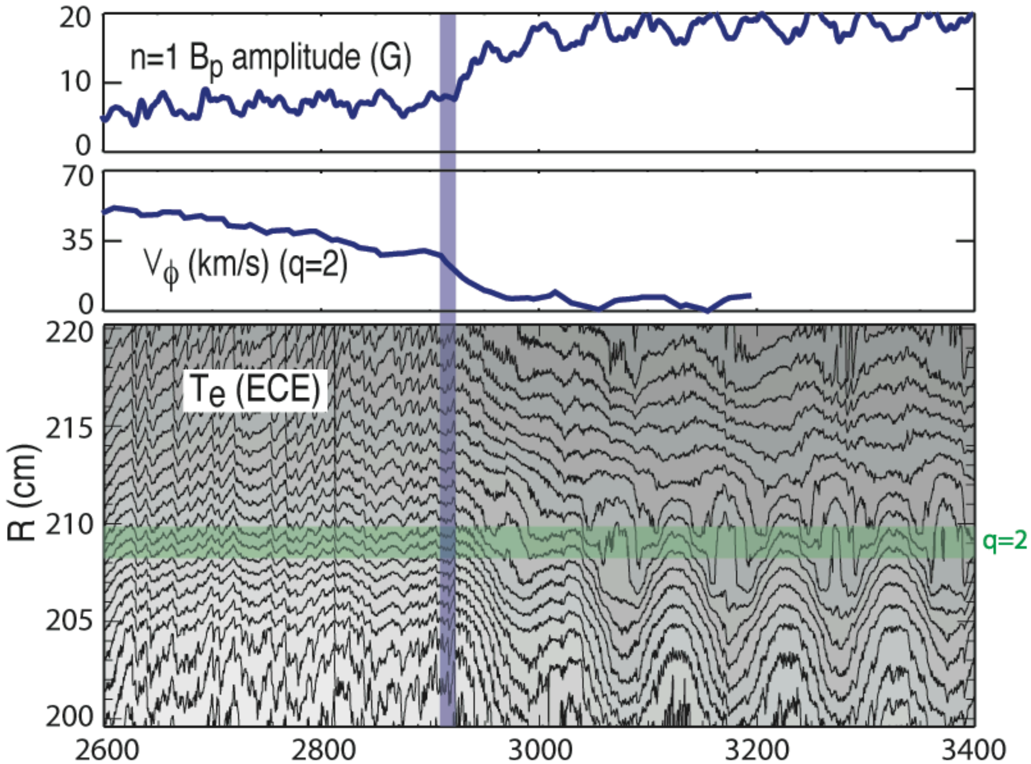

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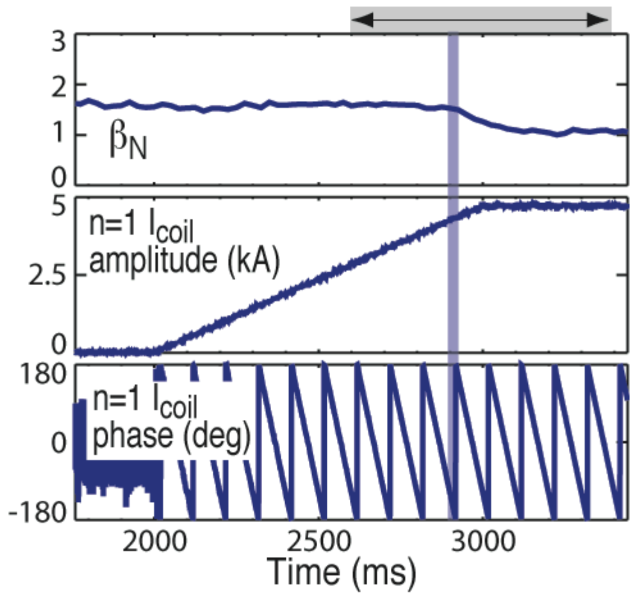
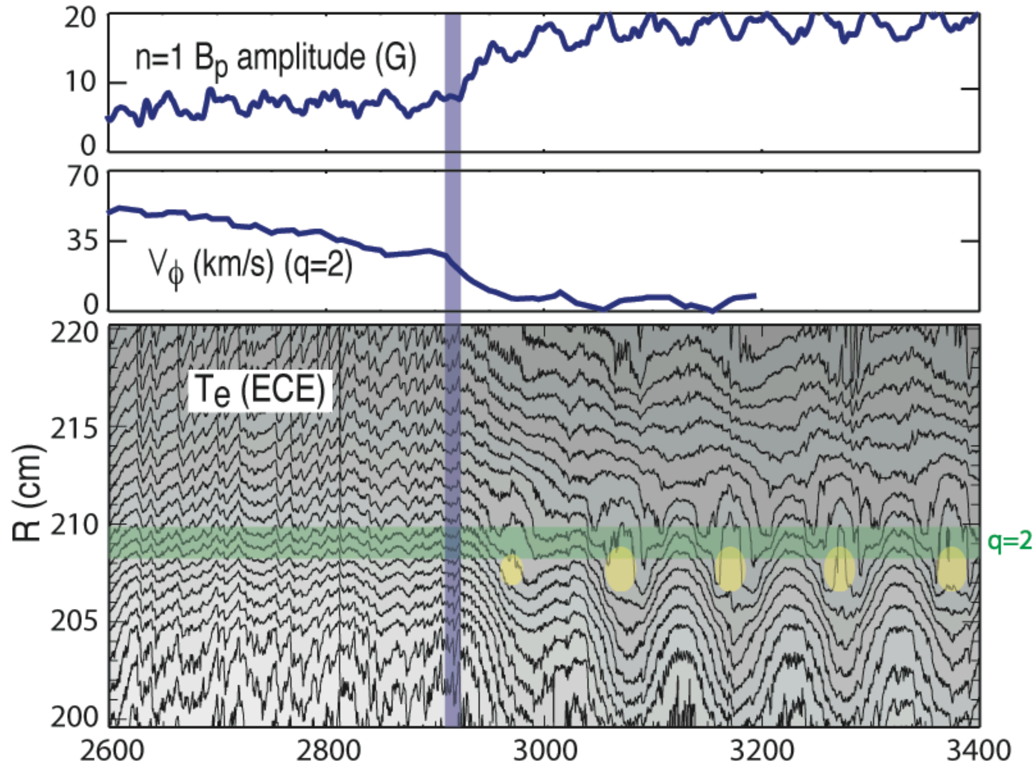
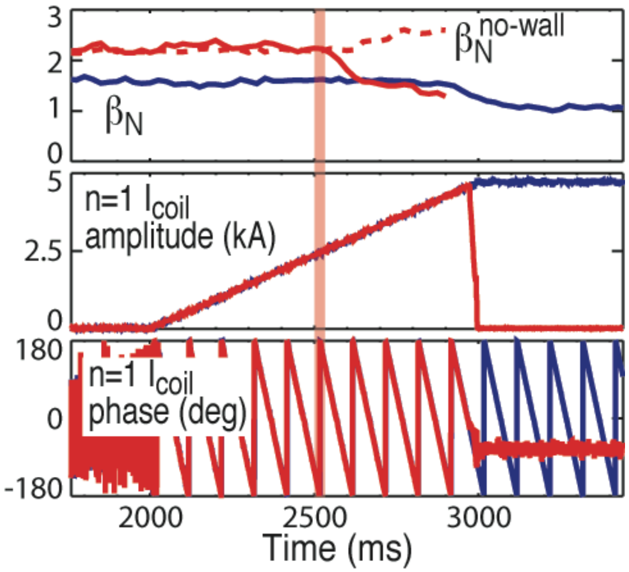




At High β, Plasma Response Reduces Tolerable Error Field

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



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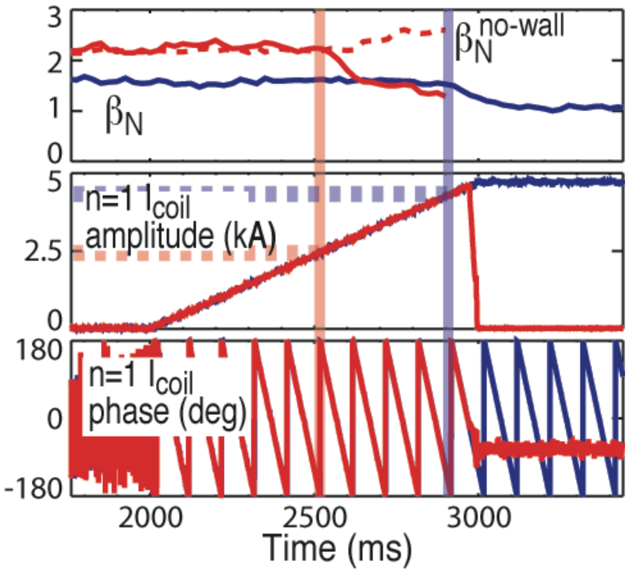

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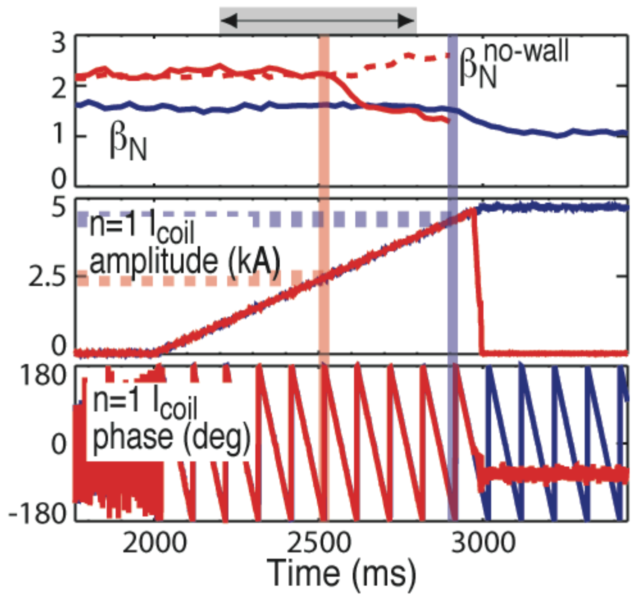
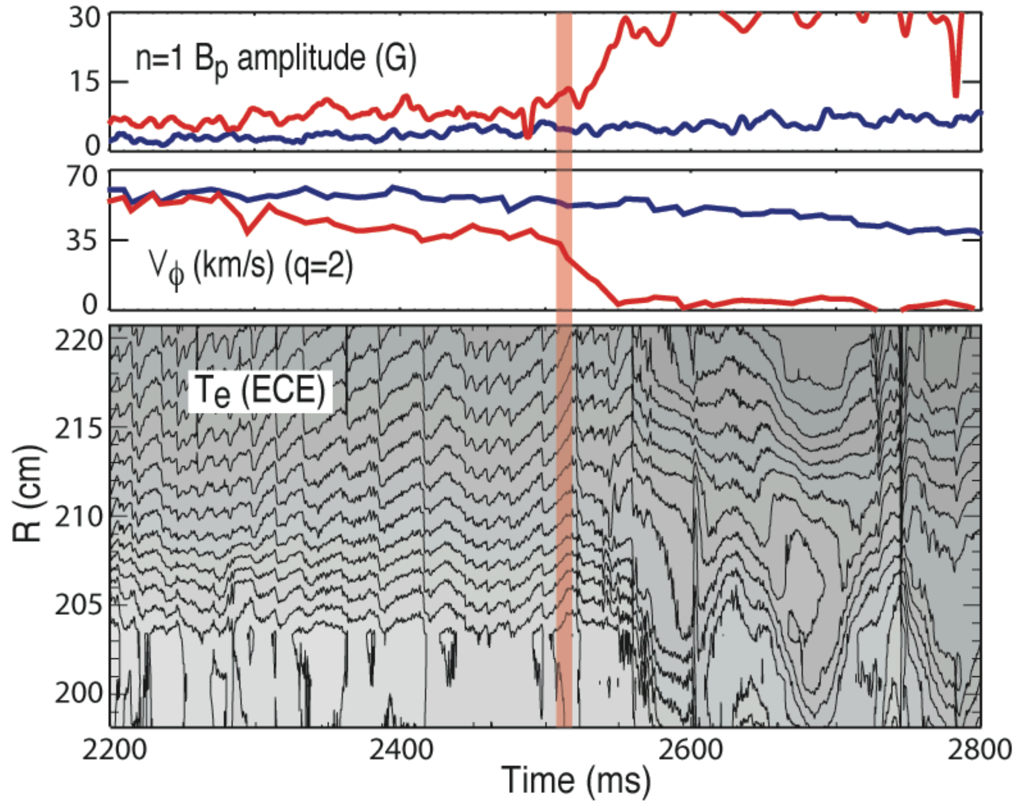
- **Marginally stable RWM amplifies error field**
  [Reimerdes, JP8.081]
  - Plasma response ~2x





- Low rotation thresholds

Threshold Without Magnetic Braking Too Low to Neglect Diamagnetic Rotation/difference Between Ion Species

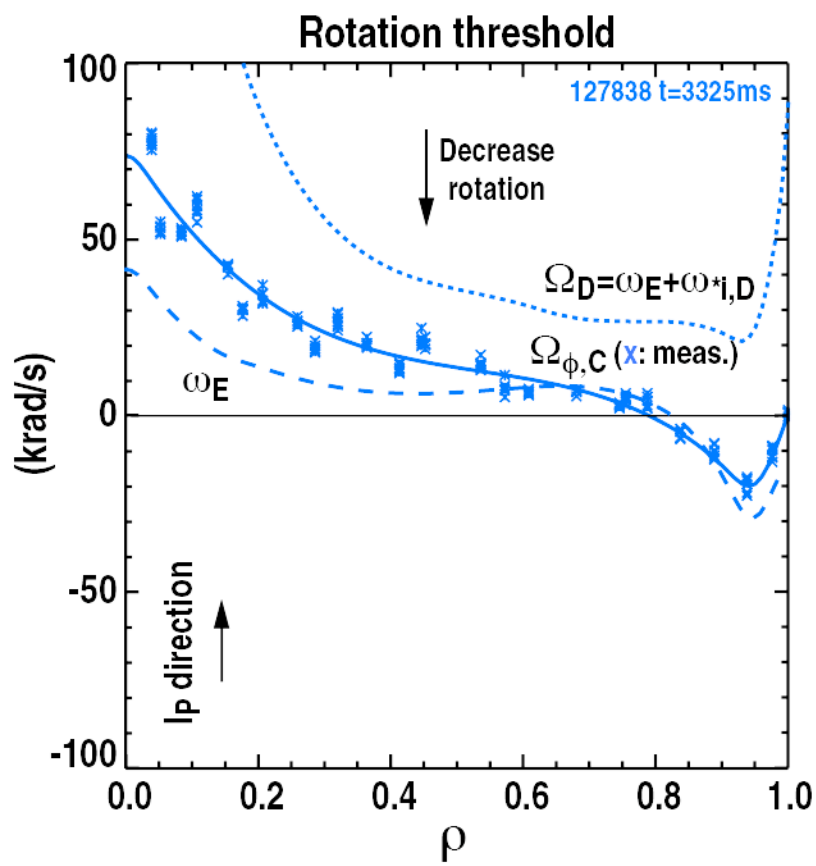
- **Charge exchange recombination (CER) spectroscopy measures carbon impurity rotation**

- **$\Omega_\phi = V_\phi / R$ is not a flux function**
  - Assume $\nabla \cdot \mathbf{V} = 0$, V_r=0 and force balance

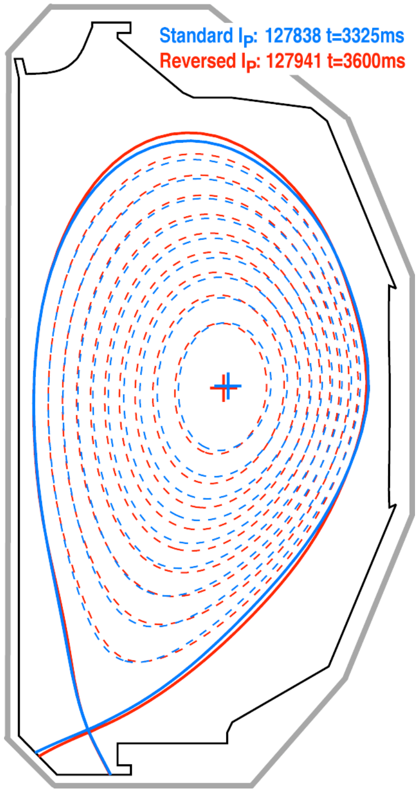
    $$\mathbf{V} = k(\psi)\mathbf{B} + R\Omega(\psi)\mathbf{e}_\phi$$

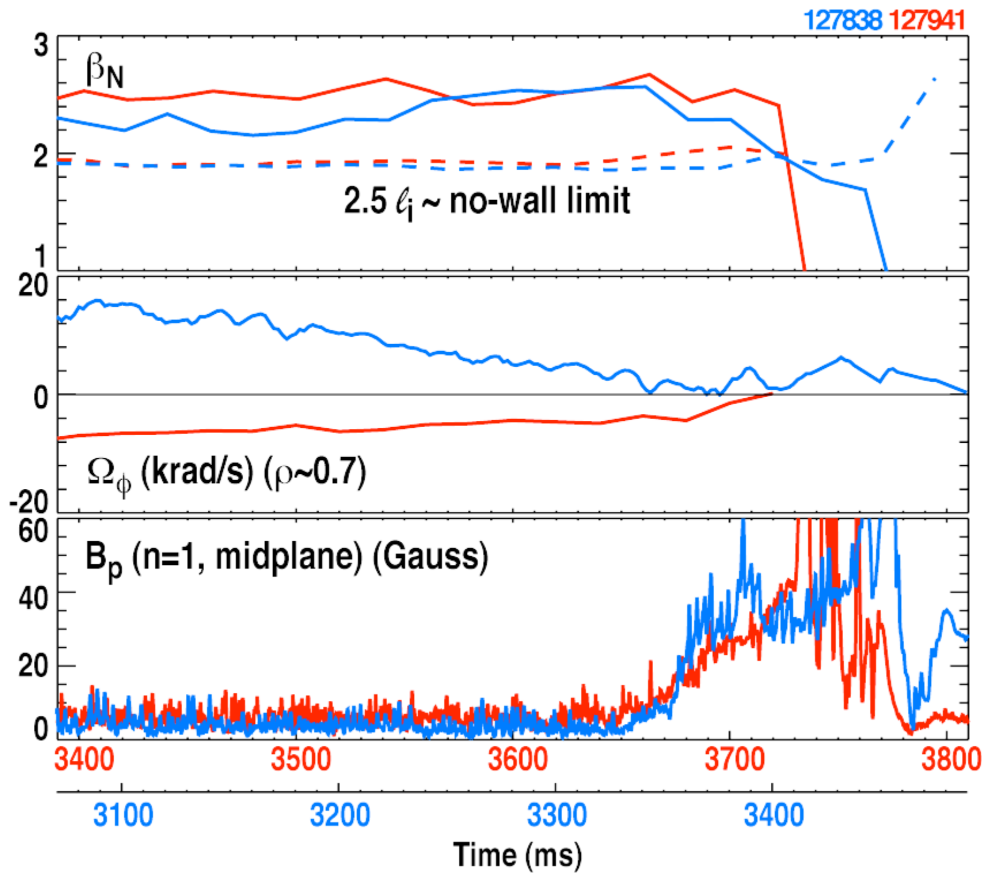
  - Poloidal flow leads to $k \neq 0$
- **Radial force balance links species *j* via the radial electric field E_r**

$$\Omega_j = \underbrace{\frac{E_r}{RB_\theta}}_{\omega_E} - \underbrace{(Z_j n_j e)^{-1}\frac{dP_j}{d\psi}}_{\omega_{*i,j}}$$



Role of rotation components studied by comparing thresholds in co- and counter-rotating plasmas

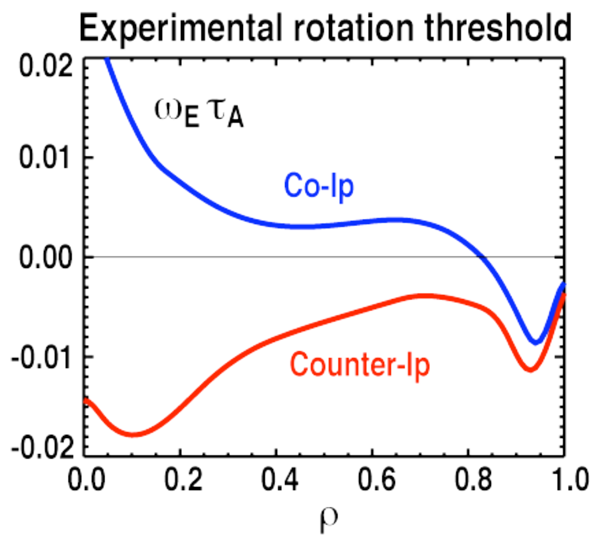


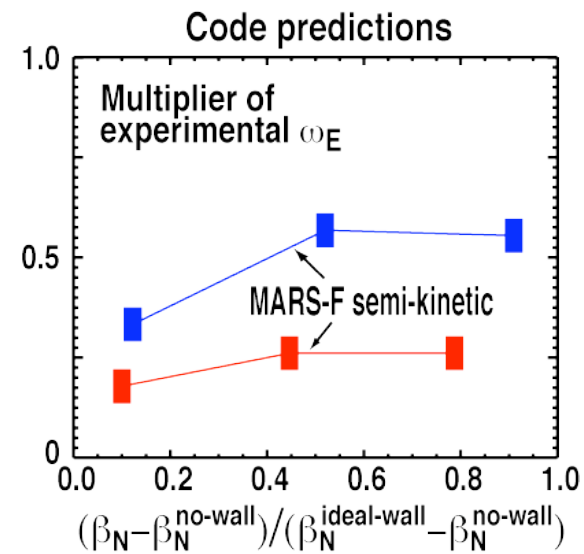


- **NBI torque ramp-downs in similar co-rotating (with respect to I_P) and counter-rotating plasmas lead to RWM onsets**

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

- **Use ω_E rotation for model-exp comparison (toroidal flow due to radial electric field)**





- **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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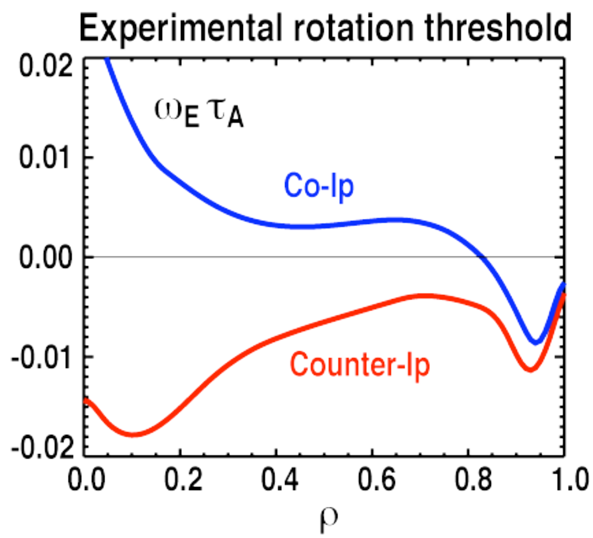
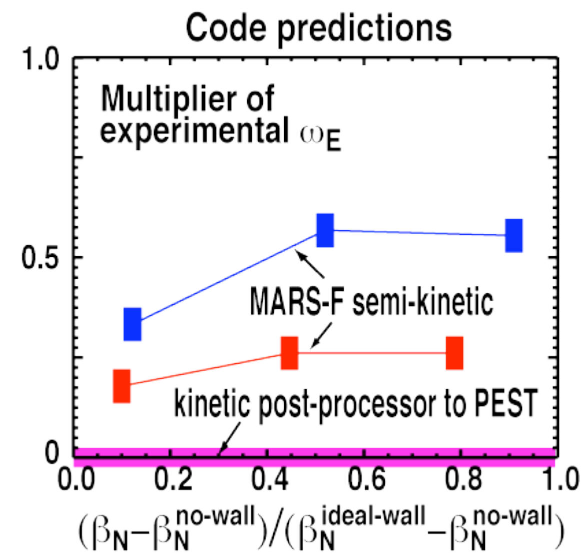


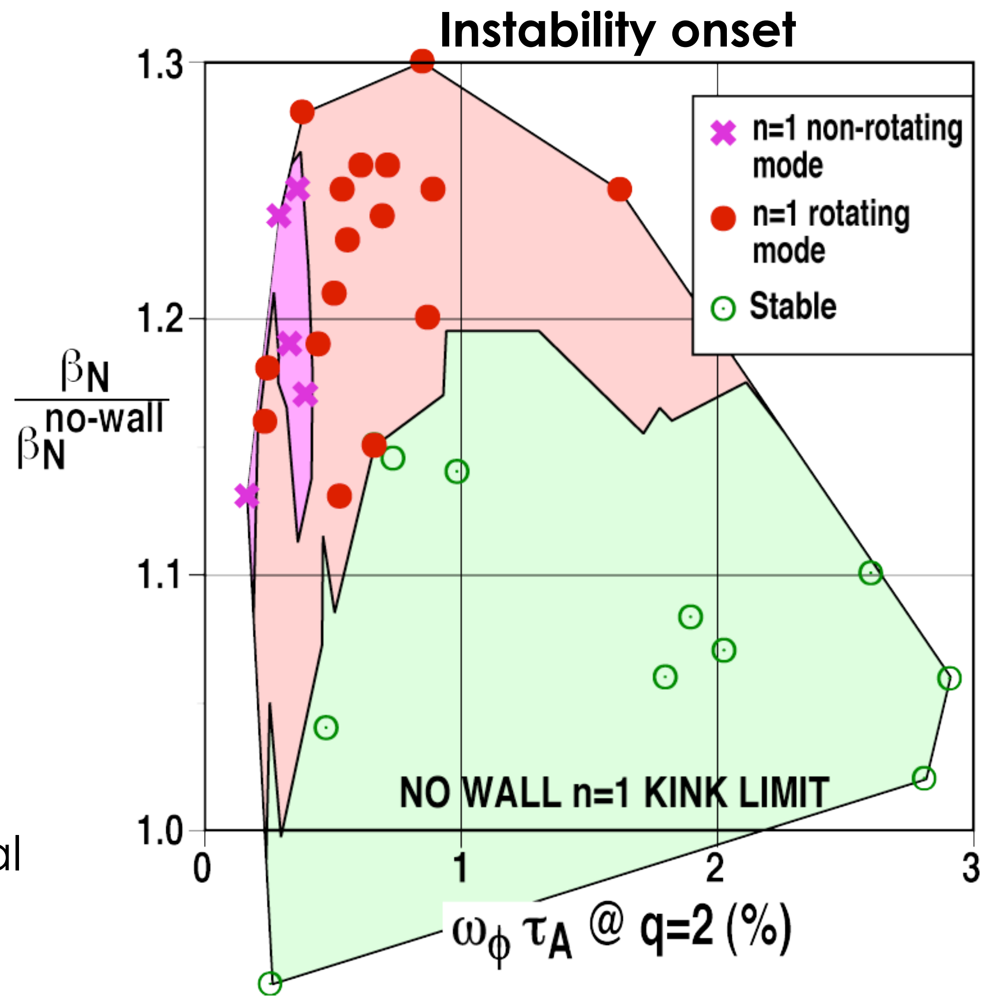


- **Semi-kinetic damping model in MARS-F predicts stability with ~1/2 of experimental rotation threshold**
  - Resonance with transit frequency of passing particles, bounce frequency of trapped particles [Bondeson & Chu, *Phys. Plasmas* 1996]
- **Adding resonance with trapped particle precession drift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

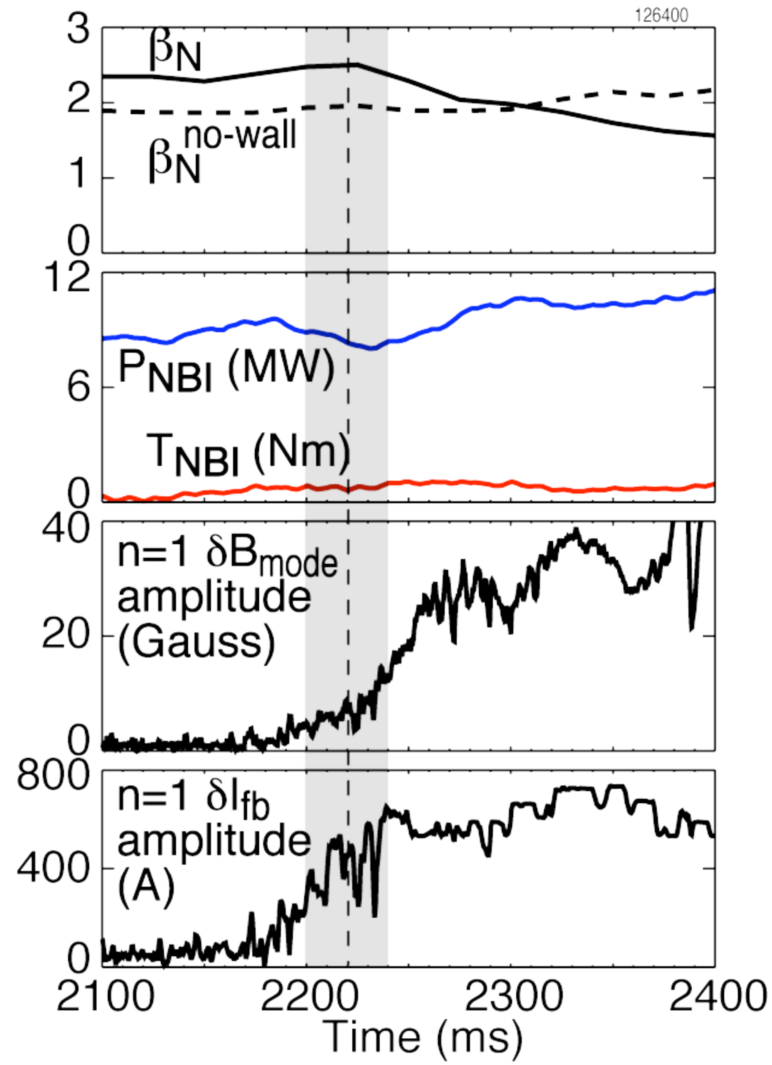
- **Tearing mode is more unstable**
  - Tearing mode rotates with plasma before it locks
- **Error field threshold for forced reconnection is lower**
- **Uncertainty on nature of non-rotating limiting instability**
  - Could be RWM
  - Could be TM, non-rotating if the plasma rotation is ~zero
  - Could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



- RWM feedback on non-rotating n=1 mode at low rotation

Effect of Feedback at Low Rotation Suggests Target Instability Is Not an RWM

- **Near balanced NBI**
- **Beta collapse caused by n=1 mode non-rotating at onset**
- **Mode grows against feedback field (gain too low?)**



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- **Near balanced NBI**
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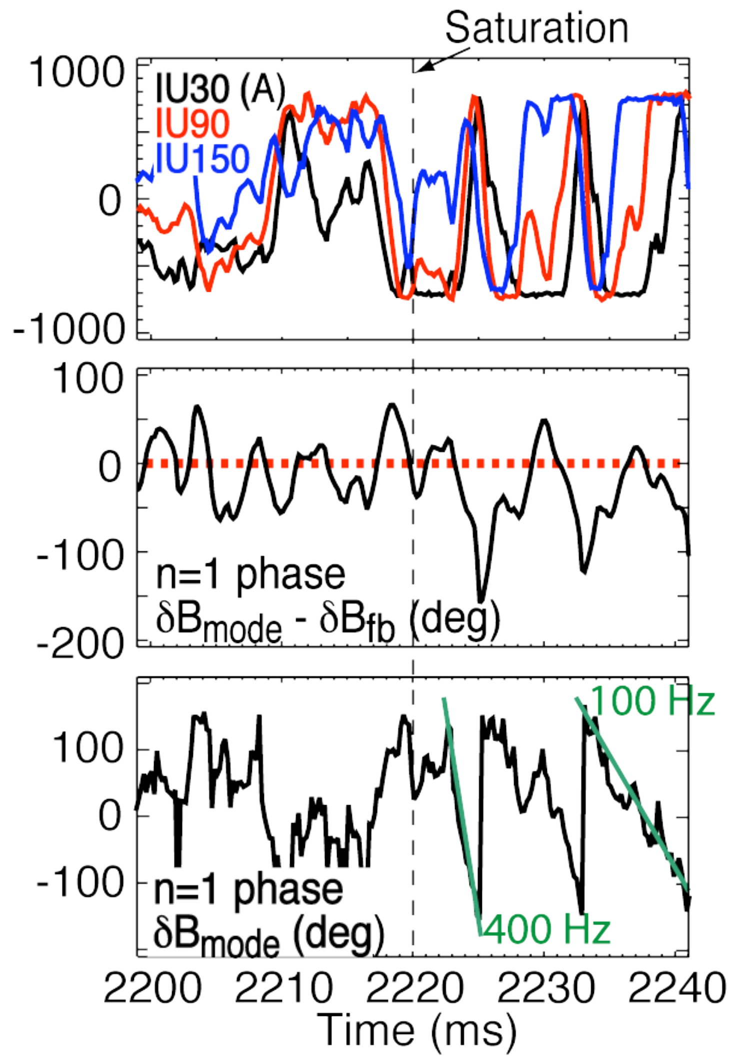
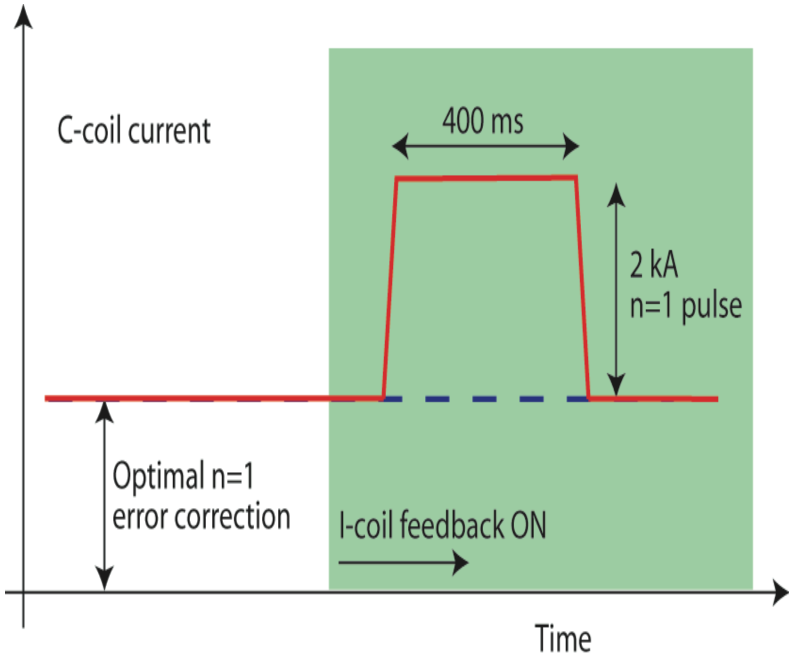
- **Mode grows against feedback field (gain too low?)**
- **Shortly after the feedback currents begin to saturate, the mode the mode initiates a continuous rotation.**
  - Initial rotation ~400 Hz >> $1/\tau_w$
- **Mode grows while it rotates rapidly, suggesting that this mode is not an RWM**



- RWM feedback for dynamic error field correction

RWM feedback is routinely used to optimize correction of ~static error field in high β DIII-D plasmas

- **Dynamic Error Field Correction (DEFC): feedback senses and opposes increase in plasma response as beta increases above the no-wall limit**
  - In a rapidly rotating plasma, RWM response to externally applied error field is toroidally shifted in direction of plasma rotation
- **Does the feedback simply correct the RWM response to the error field, or does it actually correct the error field that drives the response?**
  - Use C-coil to apply a known error field
  - Use I-coil in closed loop RWM feedback to carry out dynamic error field correction (DEFC)
  - Iterative solution: feedback output serves as a programmed offset for the I-coil currents in the next discharge, to minimize feedback error



Simple Model:
With Large Enough Gain, Feedback Cancels Error Field

- Complex numbers representing amplitude and toroidal phase of n=1 radial field evaluated at wall:
  - ❑ $\mathbf{B_{EF}}$ = external error field (constant)
  - ❑ $\mathbf{B_{FB}}$ = field applied by feedback coils
  - ❑ $\mathbf{B_{PR} = \alpha\ (B_{EF} + B_{FB})}$ = plasma response to total external field ($B_{EF} + B_{FB}$)
    - ➢ where α is complex to allow for toroidal phase shift between external field and plasma response
- Suppose that feedback coils are driven by a <u>real</u> gain **G**
- Assume that sensors see only plasma response
  - – That is, sensors are decoupled from error field and coil field
  - ❑ $\mathbf{B_{FB} = -G\ B_{PR} = -G\ \alpha\ (B_{EF} + B_{FB})}$
- Solving for B_{FB}:
  - ❑ $\mathbf{B_{FB} = -G\ \alpha\ B_{EF} / (1 + G\ \alpha)}$
- **For G α >> 1, $\mathbf{B_{FB}}$ approaches –$\mathbf{B_{EF}}$**
  - – That is, with large enough gain, the applied field cancels the error field
  - – This happens <u>even though</u>
    1. the sensors do not detect the error field, only the plasma response
    2. the plasma response has an arbitrary toroidal phase shift

Larger Gain and Iteration on Offset Currents Help Feedback Cancel the Applied Error

I-coil feedback using poloidal field sensors at outer midplane
(only detect plasma response)
Proportional time constant, τ_p=100 ms (longer τ_p allows higher stable G_p)
Proportional gain: G_p=20, and G_p=100

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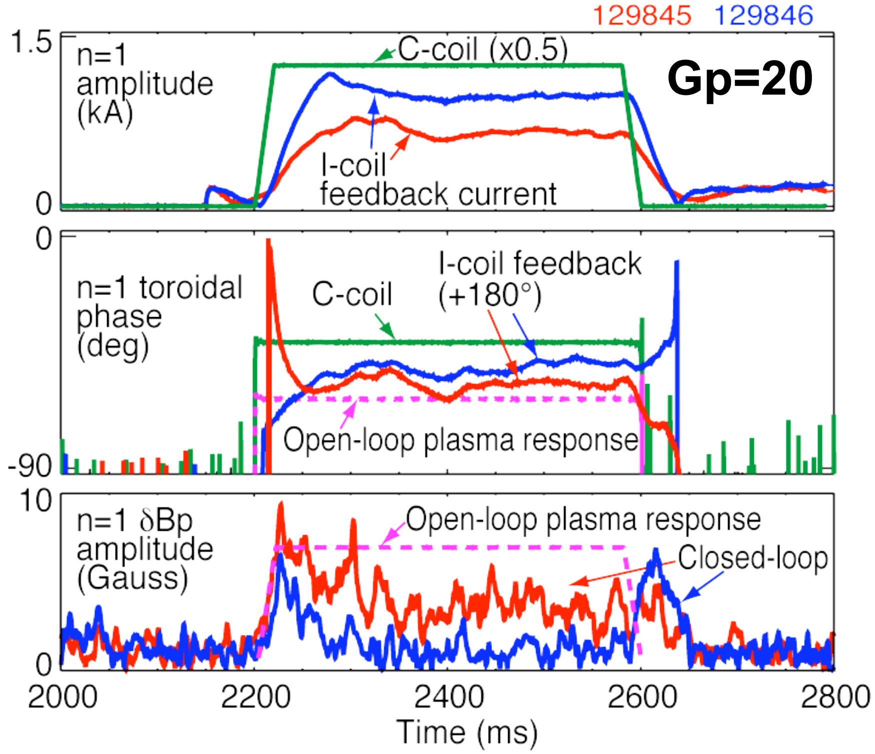
Red: pre-programmed I-coil current (feedback offset) = 0

Blue: feedback offset = time average of feedback current in correspondent discharge in red



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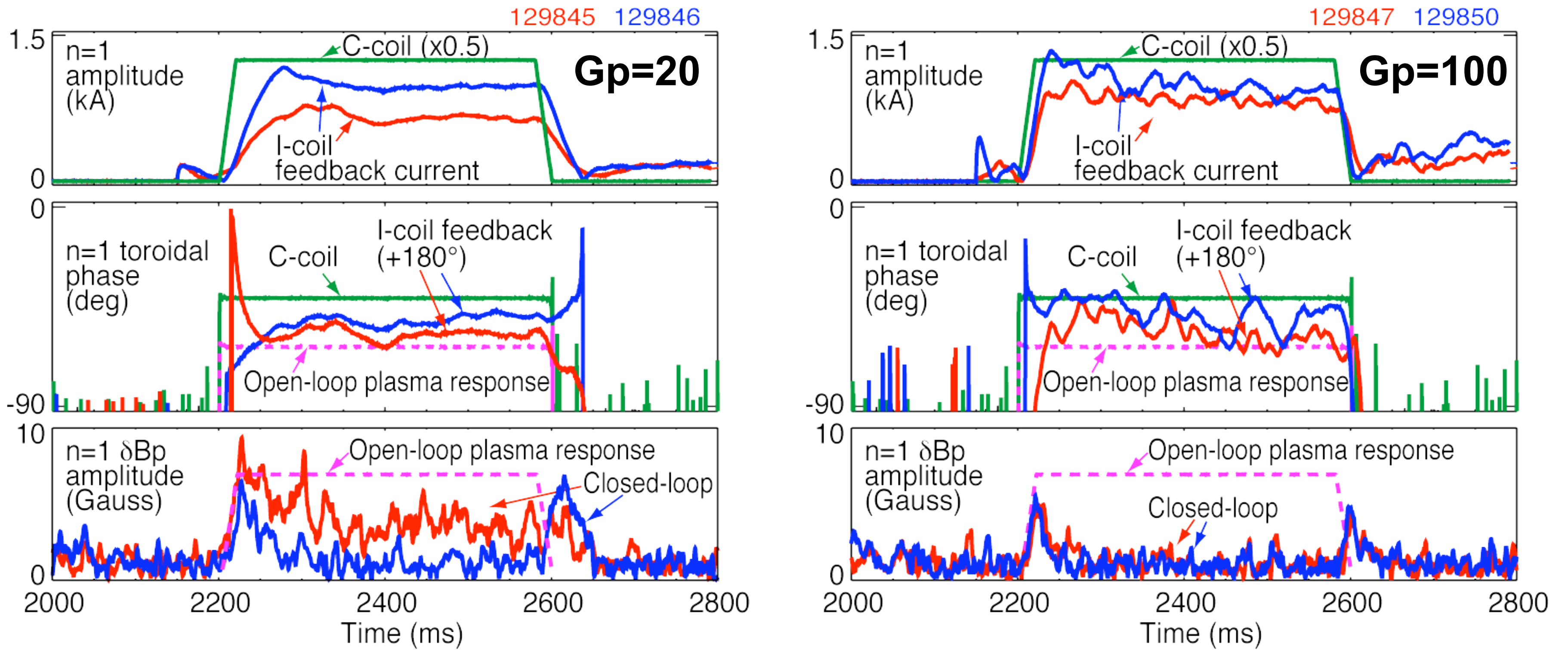
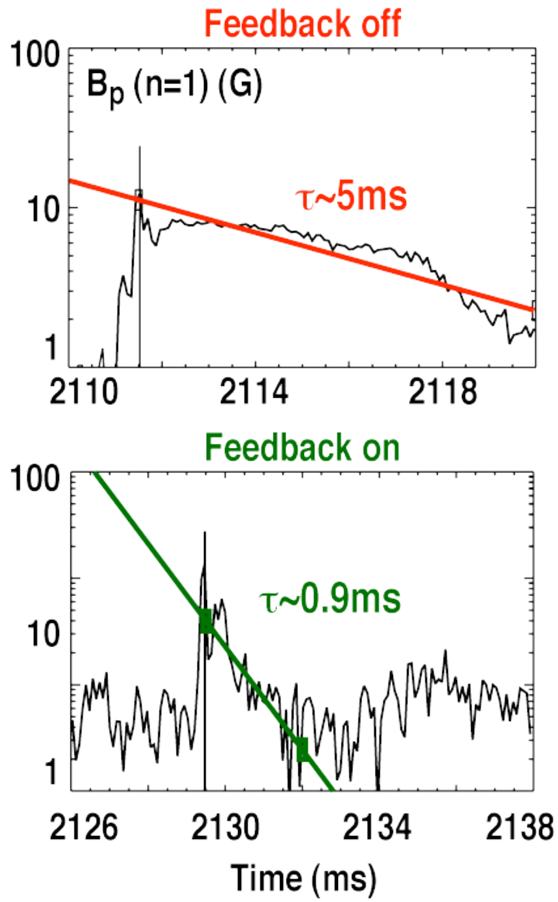
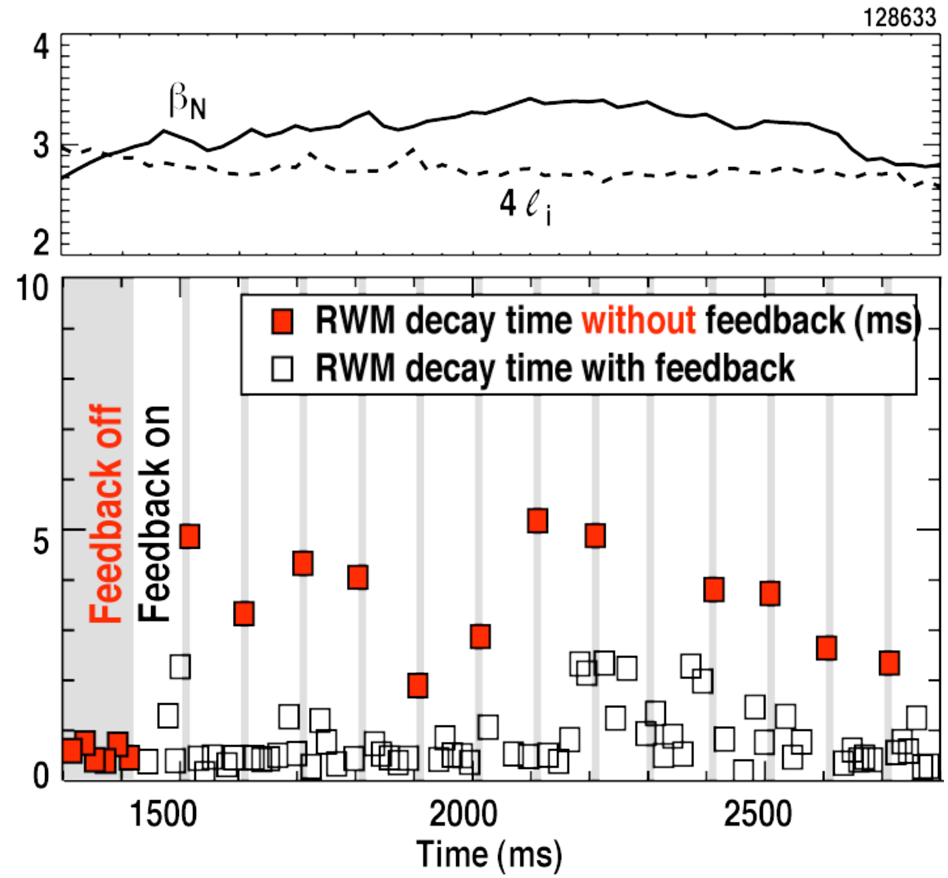


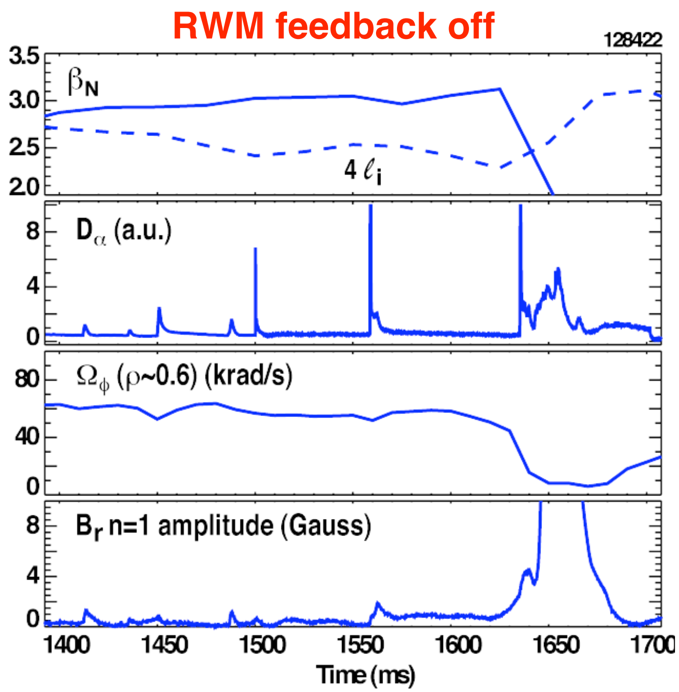
RWM Feedback Accelerates Damping of *N*=1 Perturbations Following ELMs

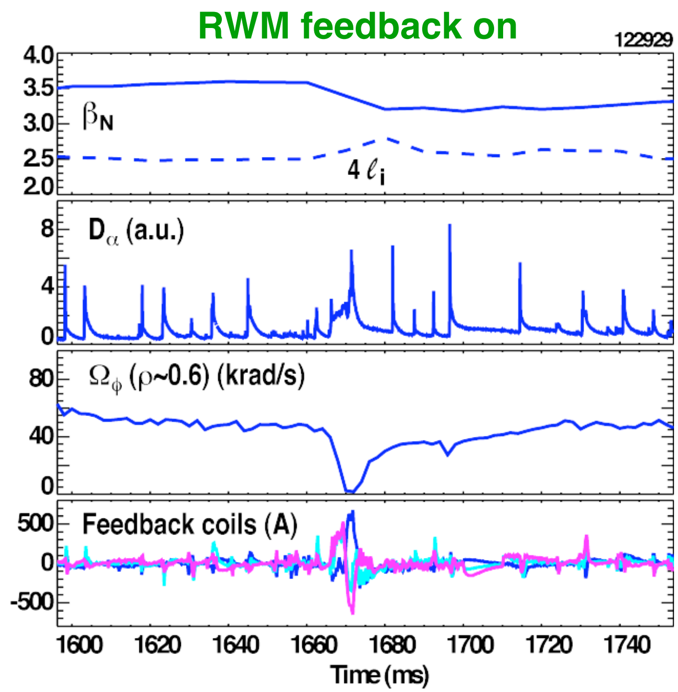
- **ELMs can couple resonantly to weakly damped RWM**
- **RWM feedback mitigates effect of transient perturbations**





Active RWM feedback improves reliability of operation at high β



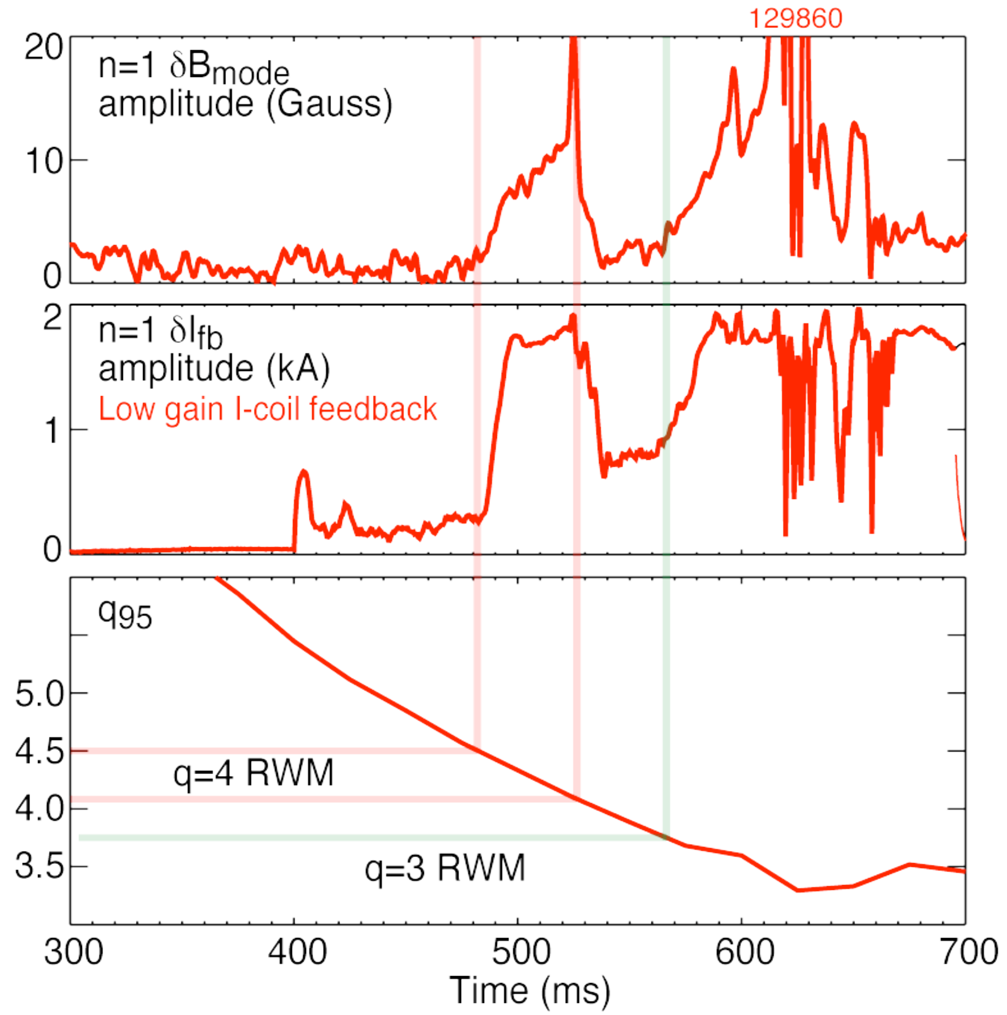


- **ELMs can trigger RWM in discharges stabilized by rotation**
  - Triggering is sporadic and criteria for ELM not known
  - Hypothesis: plasma generated *n*=1 perturbation increases effective threshold - similar to *n*=1 magnetic braking

- RWM feedback for direct mode stabilization

Low β, Current Driven RWMs May Give a Target for Direct Feedback Stabilization Studies

- **Purely current driven RWM destabilized in ohmic plasma**
  - Avoid rotation/kinetic stabilization at low-β and low rotation
  - First mode grows at q95 ~ 4.5, stable at q95 < 4
  - Second mode grows at q95 ~ 3.5, leads to thermal collapse
- **At low gain, feedback currents grow to saturation**



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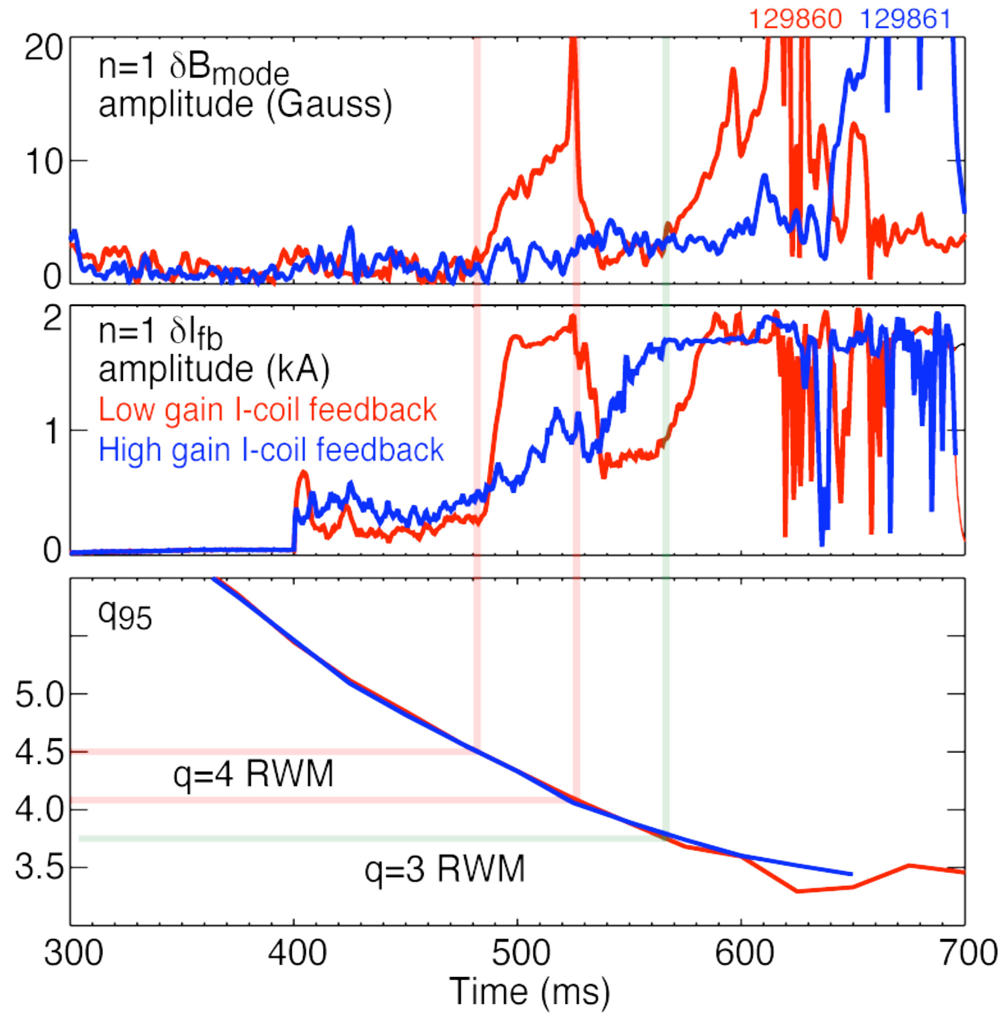
- **At low gain, feedback currents grow to saturation**
- **At twice the gain, first mode is stable with lower feedback currents**



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- **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
- **Low-β, current driven RWMs may be optimal target for studies of direct feedback stabilization**

DIII-D Experiments Show a Strong Synergy Between Feedback and Rotational Stabilization of the RWM

Even with optimal correction of the intrinsic magnetic field asymmetries:

- **Plasma rotation without magnetic feedback is not always sufficient to maintain RWM stabilization.**
  - In some advanced tokamak regimes, large ELMS or other MHD events can drive a weakly stable RWM to large amplitude, in some cases leading to strong resonant magnetic braking, rotation bifurcation, perturbation growth, magnetic reconnection, and beta collapse
  - Some magnetic feedback is necessary to quickly restore magnetic axisymmetry following these large MHD events, thus maintaining rotation and beta
- **In DIII-D experiments to date, magnetic feedback with plasma rotation approaching zero has not been shown sufficient to maintain stability**
  - Feedback is complicated by non-ideal plasma response
  - Some plasma rotation may be necessary to maintain an ideal-MHD-like plasma response against the penetration of residual error fields, or spurious fields from the feedback coils, or an RWM amplitude below the detection threshold