Resistive Wall Mode Control in DIII-D

by

Andrea M. Garofalo[1]

for

G.L. Jackson[2], R.J. La Haye[2], M. Okabayashi[3], H. Reimerdes[1], E.J. Strait[2], R.J. Groebner[2], Y. In[4], M.J. Lanctot[1], G.A. Navratil[1], W.M. Solomon[3], H. Takahashi[3], and the DIII-D Team

[1]*Columbia University, New York, New York*
[2]*General Atomics, San Diego, California*
[3]*Princeton Plasma Physics Laboratory, Princeton, New Jersey*
[4]*FAR-TECH, Inc., San Diego, California*

presented at the
Workshop on Active Control of MHD Stability: Active MHD control in ITER

Princeton Plasma Physics Laboratory, Princeton, New Jersey
November 6 - 8, 2006

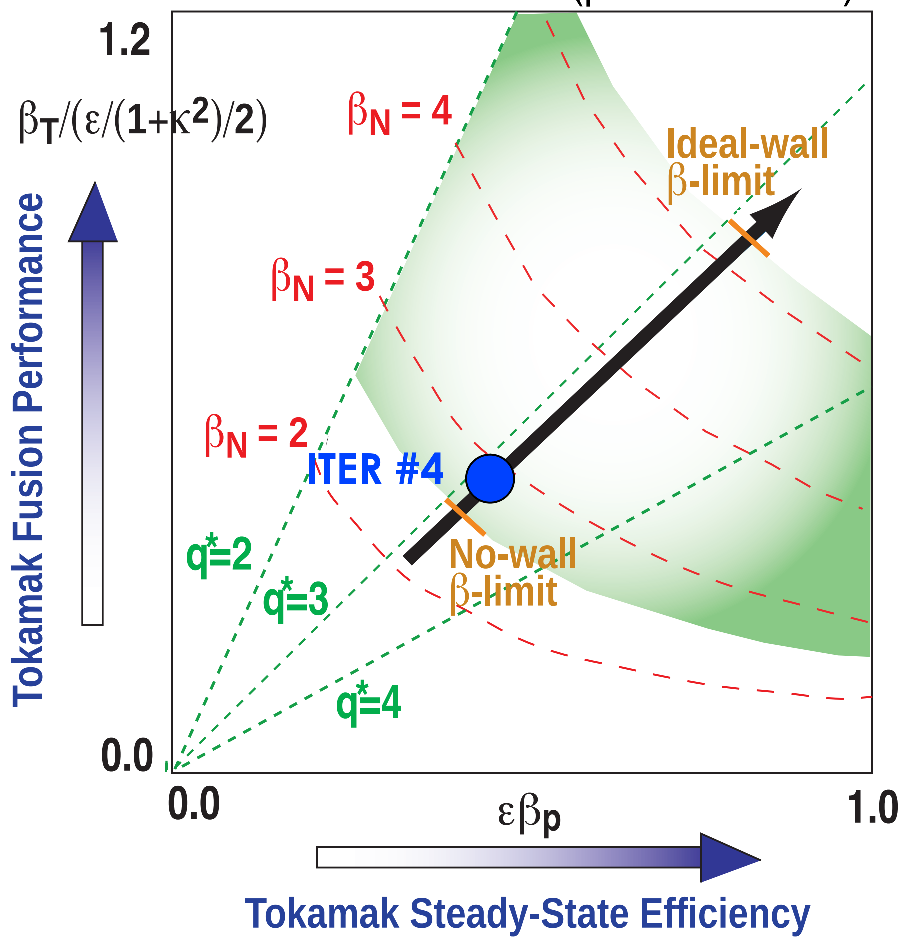
DIII-D NATIONAL FUSION FACILITY SAN DIEGO

Columbia University

Resistive Wall Mode Stabilization is Needed for Steady State Tokamak Operation at High Fusion Performance

- **ITER Steady-State scenario (#4) requires Resistive Wall Mode stabilization**
  - Target: $\beta_N \sim 3$, above the no-wall stability limit $\beta_N^{no\text{-}wall} \sim 2.5$
- **Sufficient plasma rotation could stabilize RWM up to ideal-wall β_N limit**

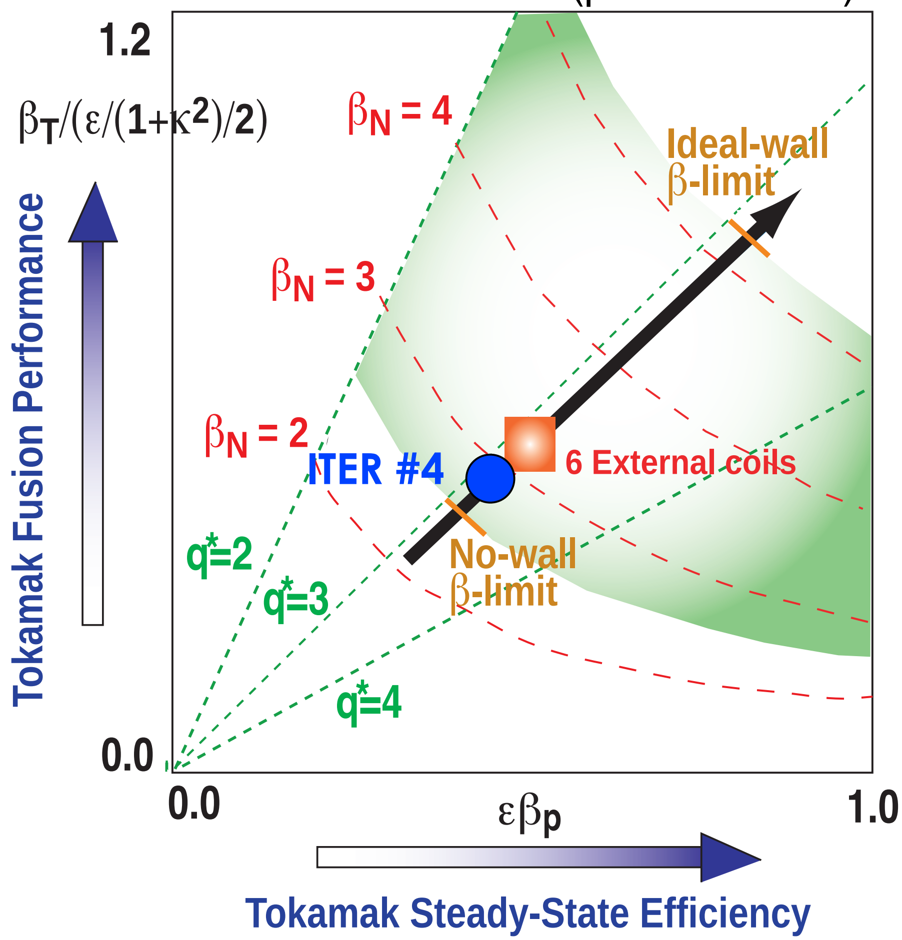
VALEN RWM feedback modeling: ITER with blanket (ports covered)



Resistive Wall Mode Stabilization is Needed for Steady State Tokamak Operation at High Fusion Performance

- **ITER Steady-State scenario (#4) requires Resistive Wall Mode stabilization**
  - Target: $\beta_N \sim 3$, above the no-wall stability limit $\beta_N^{no\text{-}wall} \sim 2.5$
- **Sufficient plasma rotation could stabilize RWM up to ideal-wall β_N limit**
- **Present ITER design of external error field correction coils is predicted to allow RWM feedback stabilization if plasma rotation is not sufficient**

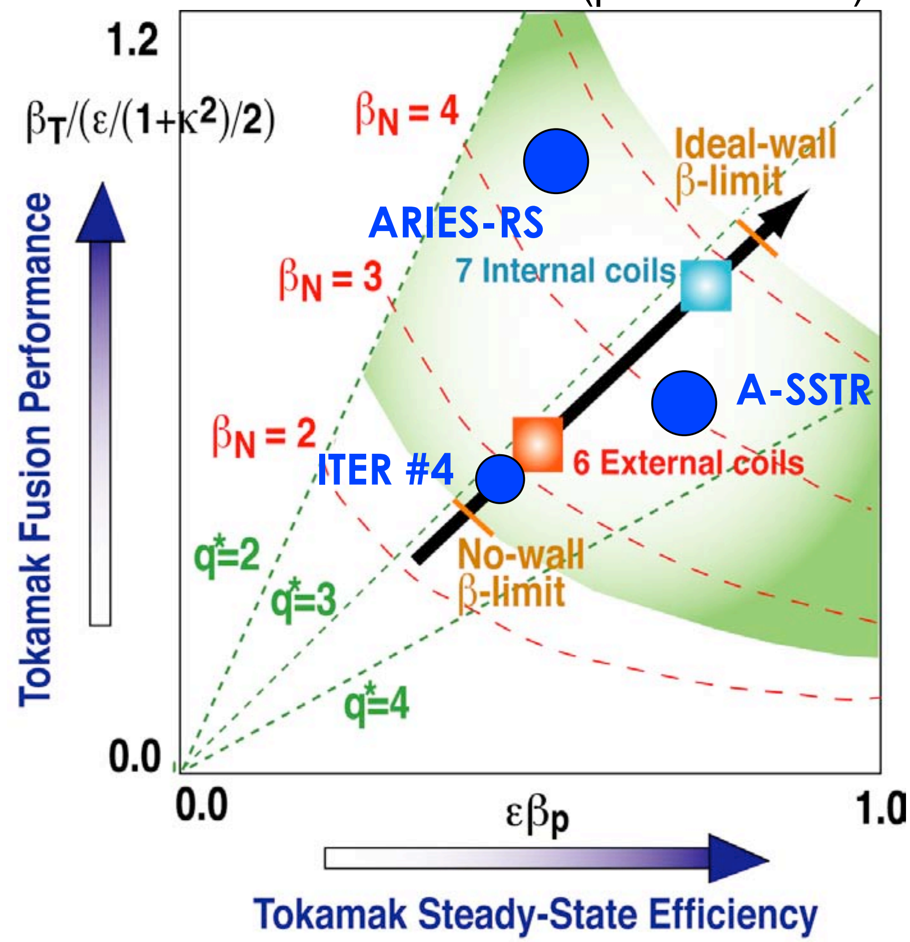
VALEN RWM feedback modeling: ITER with blanket (ports covered)



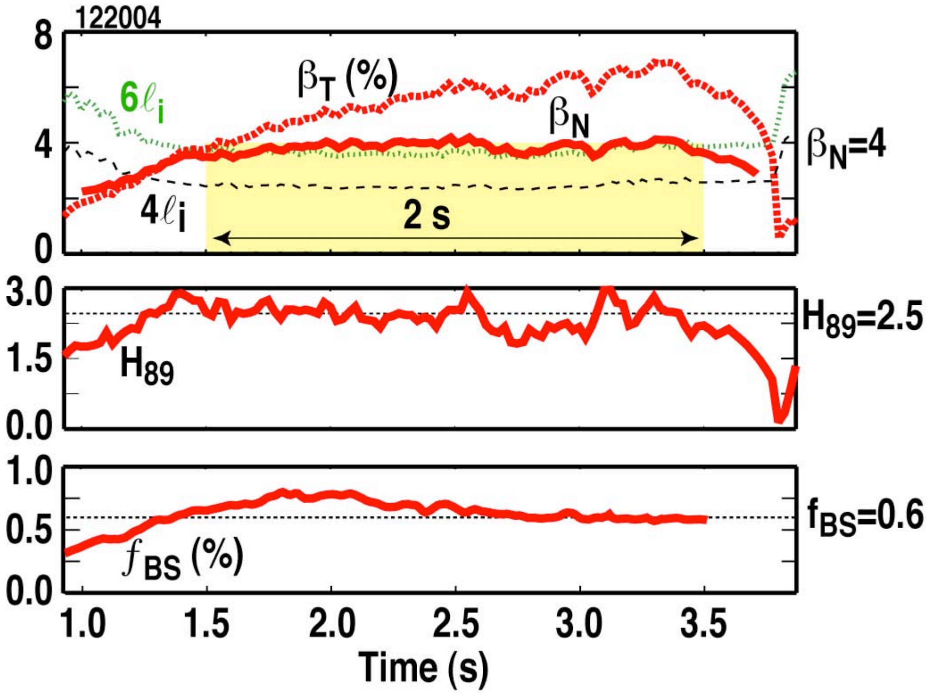
Resistive Wall Mode Stabilization is Needed for Steady State Tokamak Operation at High Fusion Performance

- **ITER Steady-State scenario (#4) requires Resistive Wall Mode stabilization**
  - Target: $\beta_N \sim 3$, above the no-wall stability limit $\beta_N^{no\text{-}wall} \sim 2.5$
- **Sufficient plasma rotation could stabilize RWM up to ideal-wall β_N limit**
- **Present ITER design of external error field correction coils is predicted to allow RWM feedback stabilization if plasma rotation is not sufficient**
- **Improved design for RWM stabilization could allow studies of scenarios approaching advanced tokamak reactor concepts, i.e. $\beta_N > 4$**

VALEN RWM feedback modeling: ITER with blanket (ports covered)

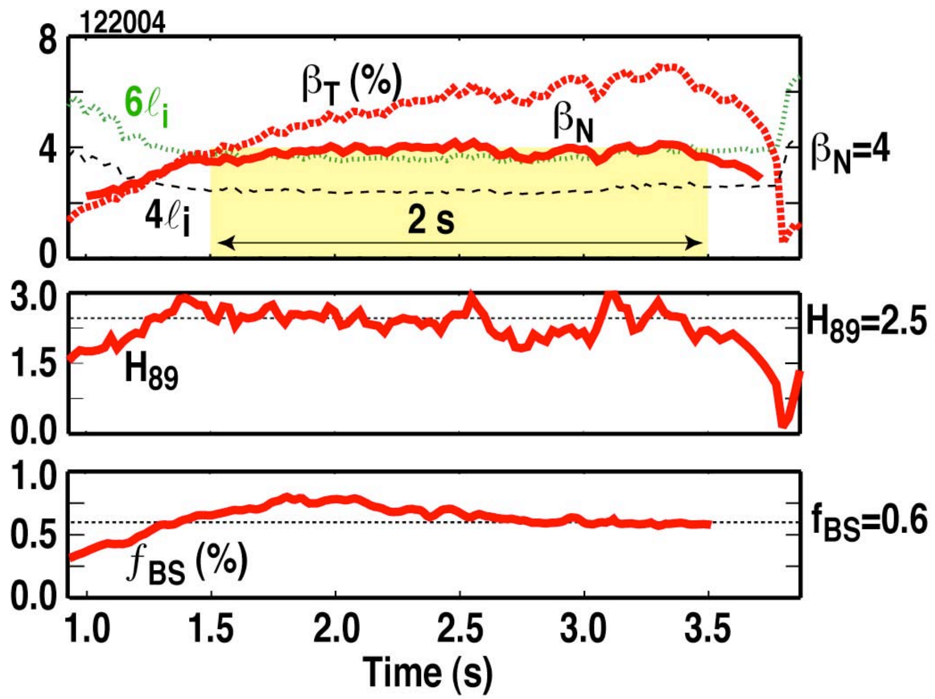


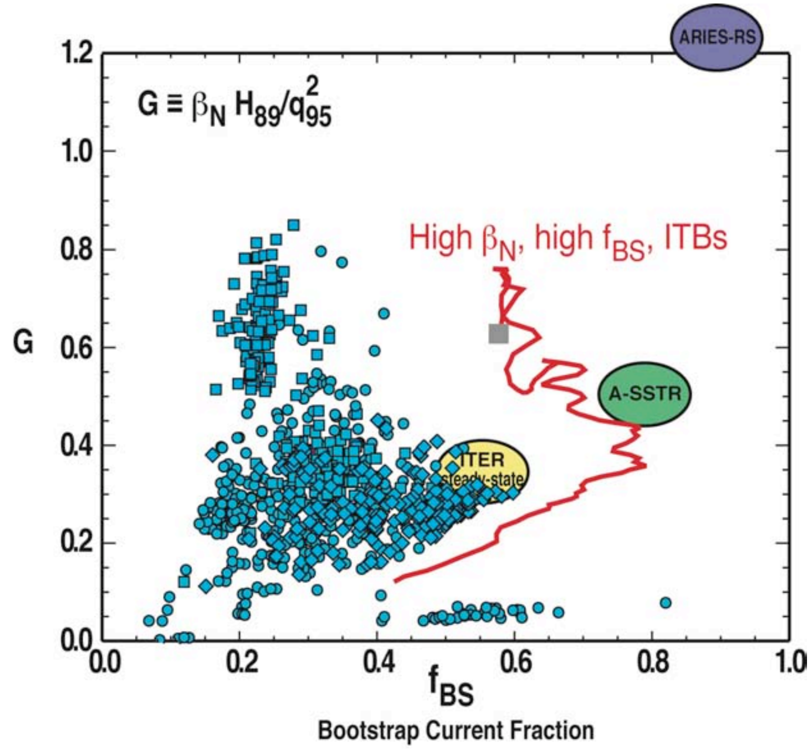
RWM Stabilization by Rotation Allows Demonstration of High Performance Tokamak Regimes



- **High β, β_N, high bootstrap current fraction, high energy confinement sustained simultaneously for 2 s in DIII-D**

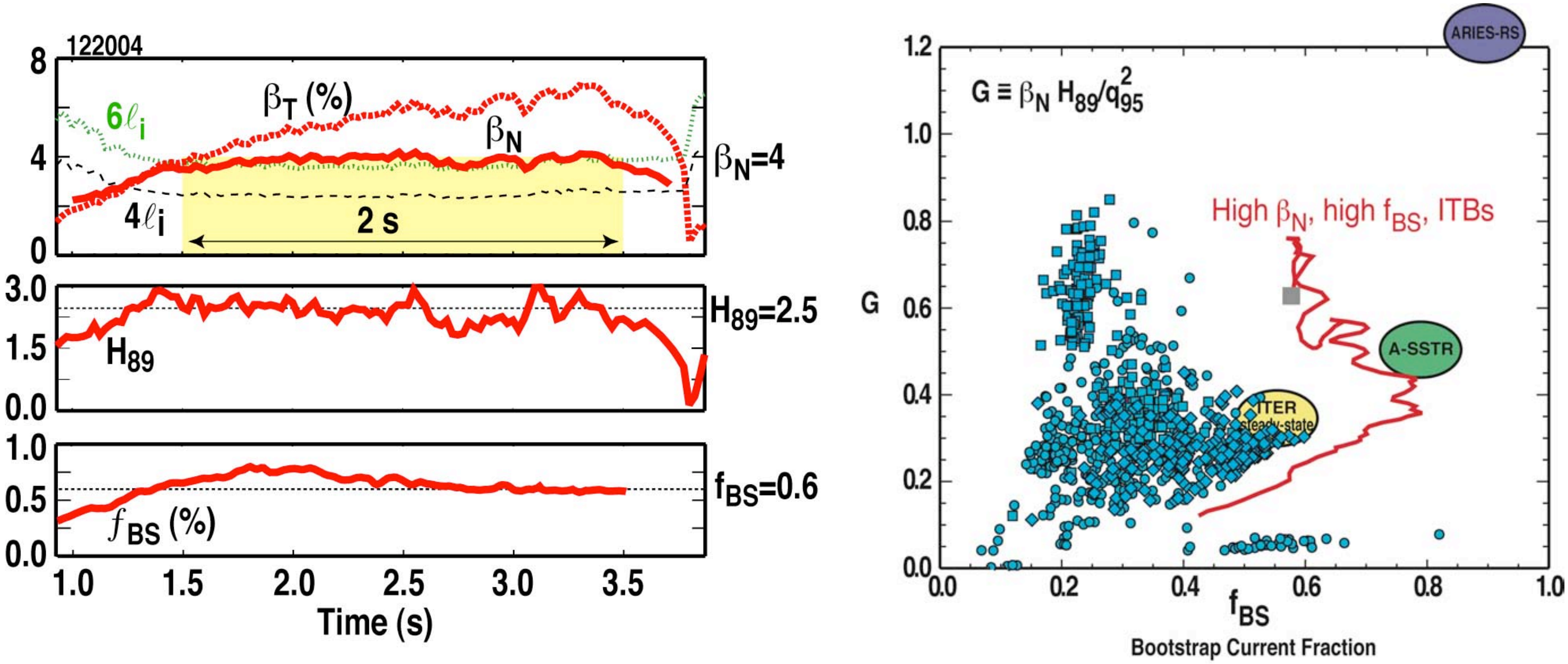
RWM Stabilization by Rotation Allows Demonstration of High Performance Tokamak Regimes





- **High β, β_N, high bootstrap current fraction, high energy confinement sustained simultaneously for 2 s in DIII-D**

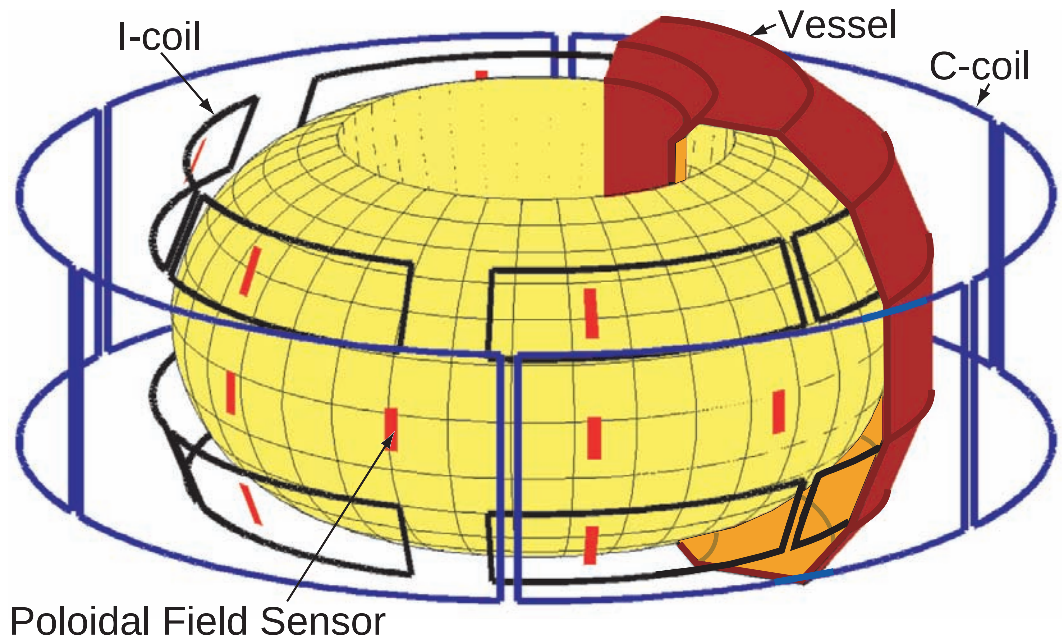
RWM Stabilization by Rotation Allows Demonstration of High Performance Tokamak Regimes



- **High β, β_N, high bootstrap current fraction, high energy confinement sustained simultaneously for 2 s in DIII-D**
- **Multiple control tools needed, including**
  - Simultaneous ramping of plasma current and toroidal field
  - Simultaneous feedback control of error fields and RWM

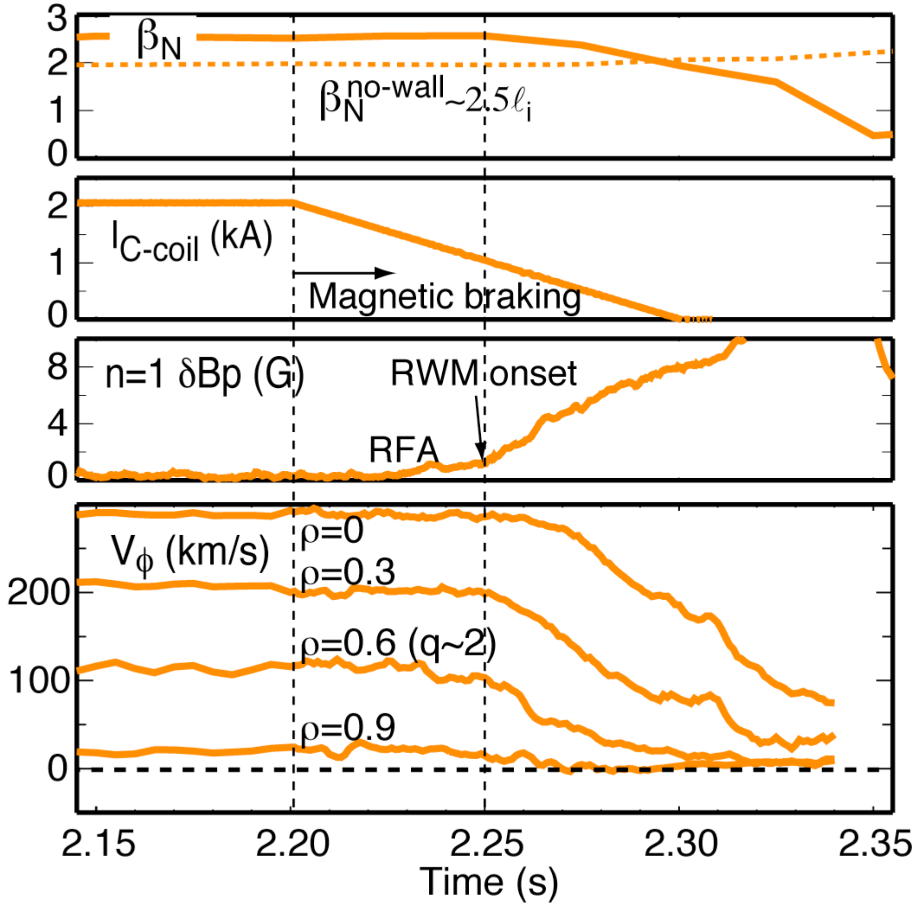
Plasma Rotation Control is Needed to Explore Regime of High Beta and Low Rotation

- **Plasma rotation is sufficient to stabilize RWMs in most DIII-D scenarios with all co-injected neutral beams (same direction as I_p)**
  - Unidirectional NB heating in high beta plasmas applies strong torque
  - Difficult to test RWM feedback control under realistic reactor conditions
- **Resonant and non-resonant magnetic braking to reduce the rotation have disadvantages**
  - Feedback system tends to respond to applied resonant braking field
  - Fine control is difficult: rotation tends to lock
  - Once locked, braking field may excite islands in the plasma

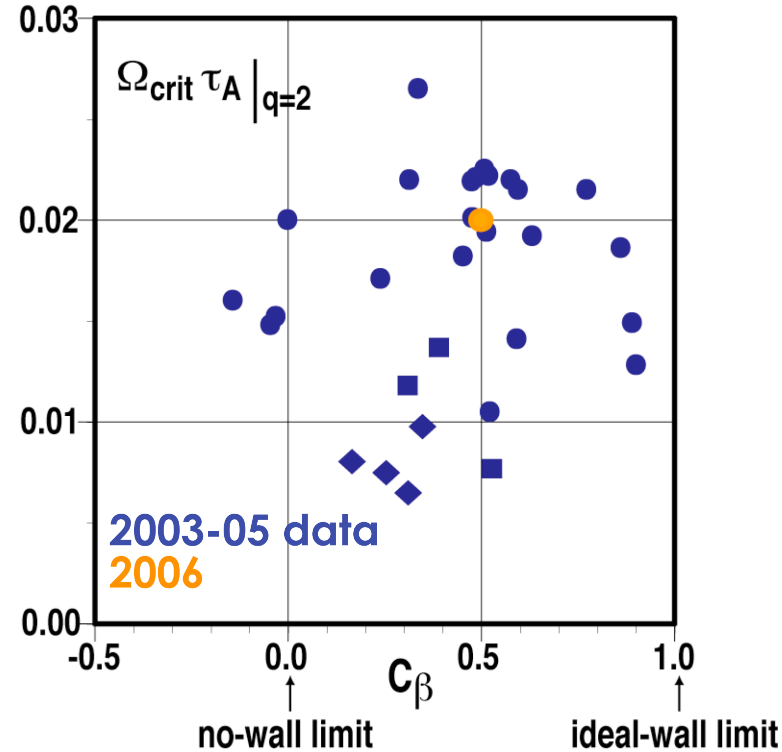


Magnetic Braking Using n=1 External or Intrinsic Fields Yields RWM Rotation Thresholds ~O(1%) of Ω_A (q=2 or 3)

- **DIII-D using only uni-directional NBI:**
  - Magnetic braking is applied by removing the empirical correction of the intrinsic n=1 error field

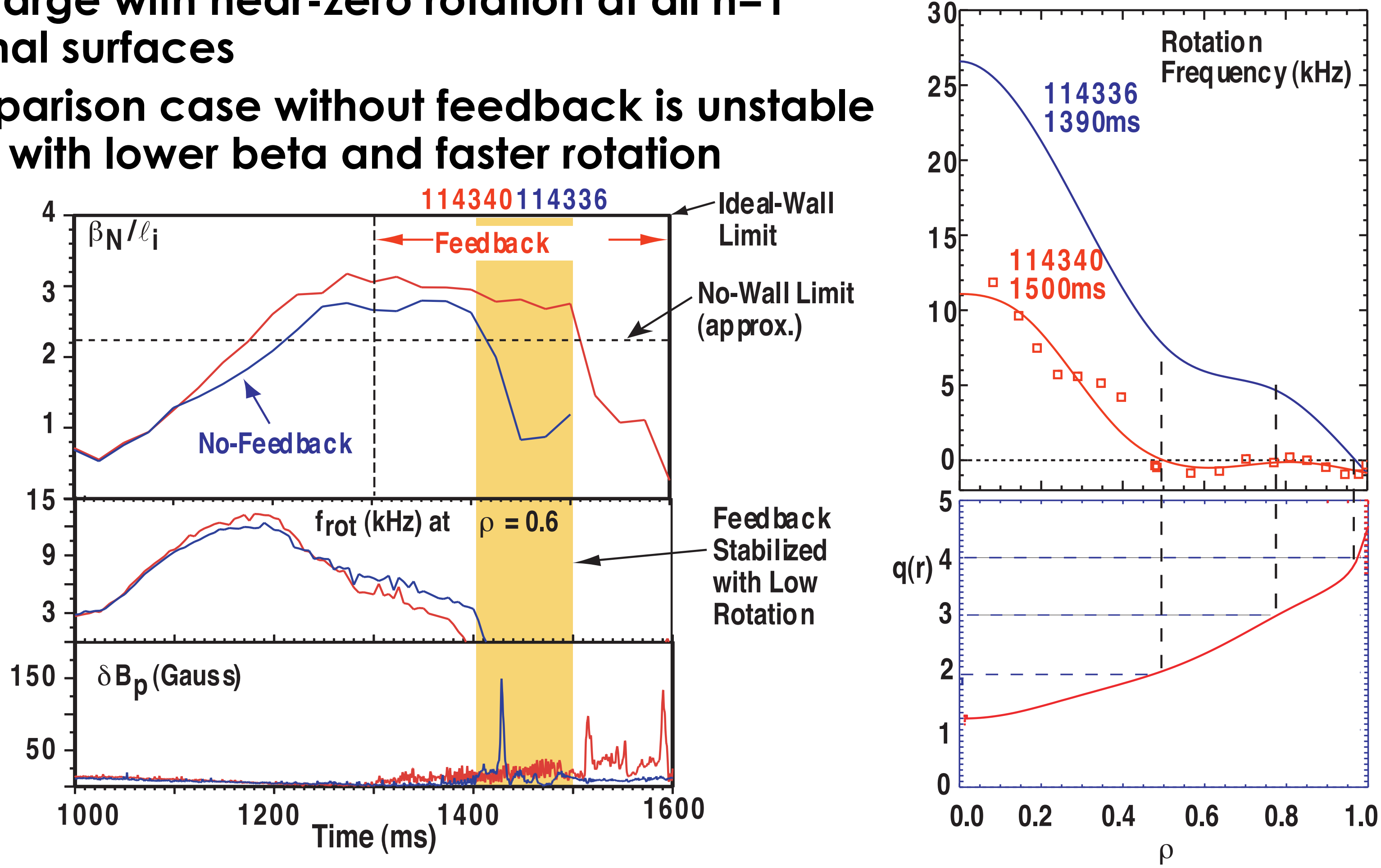


  - Critical rotation frequency Ω_{crit} at q = 2 surface ranges from 0.7 to 2.5% of local Ω_A



Resonant Braking Provides Demonstration of Transient Feedback Stabilization at Low Rotation

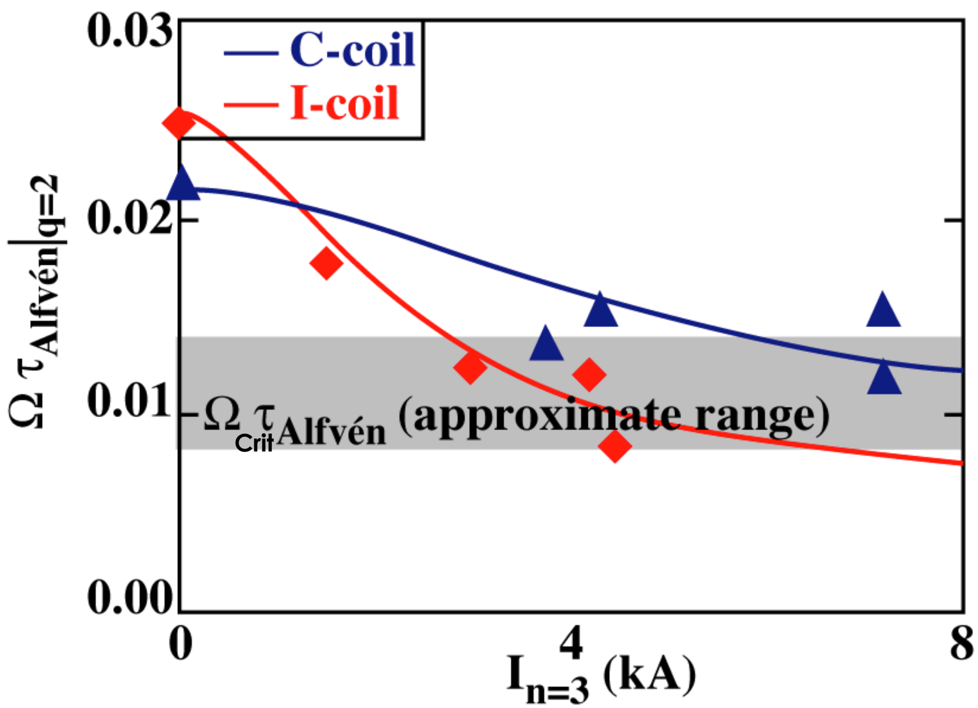
- **I-coil feedback sustains beta (for ~$30\tau_w$) in discharge with near-zero rotation at all n=1 rational surfaces**
- **Comparison case without feedback is unstable even with lower beta and faster rotation**



DIII-D NATIONAL FUSION FACILITY

Non-Resonant n=3 Braking Did Not Give Access to the Low-rotation Regime

- **n=3 magnetic braking can create large drag torque**
- **RWM remains stable when correction of n=1 error field is optimal (DEFC)**



$$dL/dt = T_{NB} - L/\tau_M - k(\Omega - \Omega_D)\, I^2_{n=3}$$

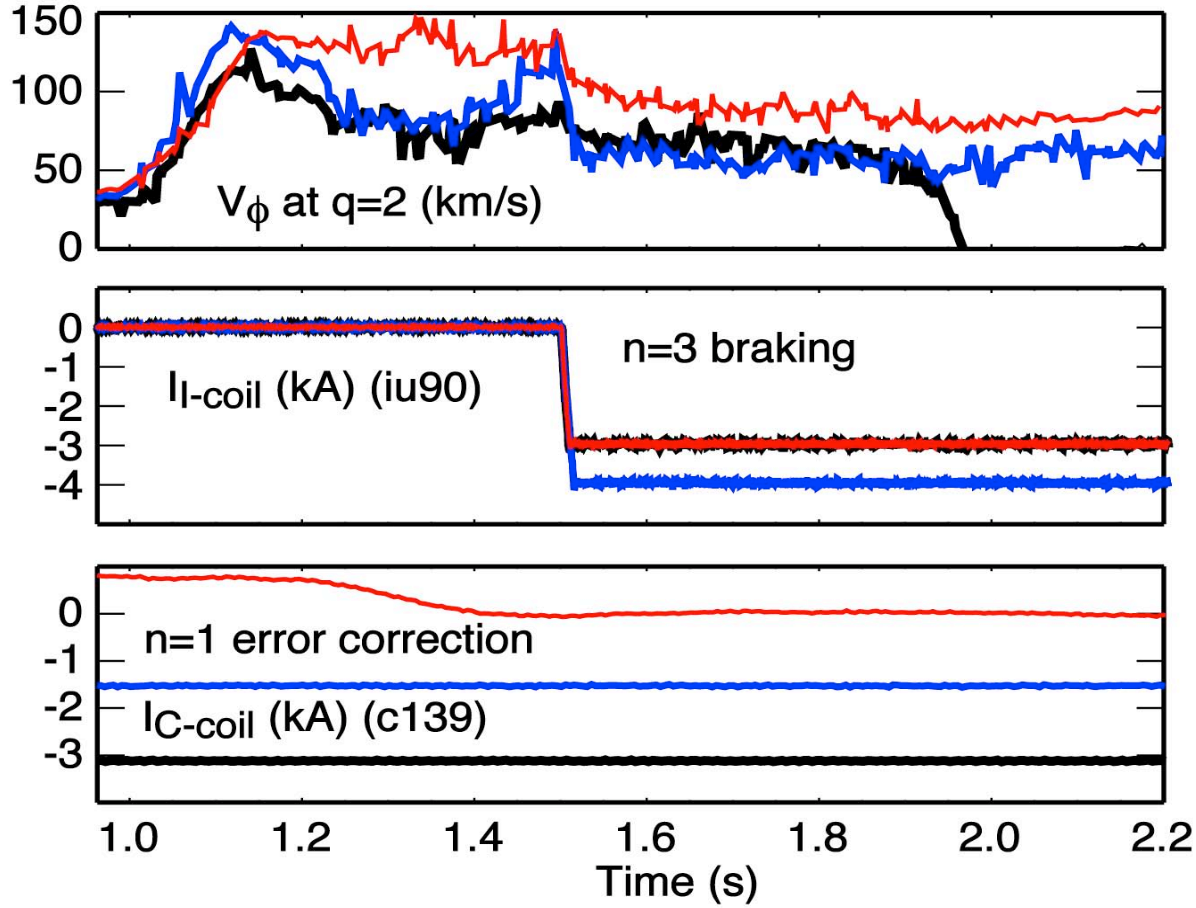
- **Braking effect saturates as braking field is increased**
- **Saturated rotation agrees with neoclassical toroidal viscosity model**

$$\Omega_D \sim 2/3 \nabla T_i /(Z_i e B_\theta R)$$

  - K.C. Shaing, S.P. Hirshman and J.D. Callen, Phys. Fluids **29**, 521 (1986)

Non-Resonant n=3 Braking Can Give Access to Unstable RWM, If n=1 Error Correction Is Non-optimal

- C-coil used for n=1 error field correction (red=optimal)
- I-coil used for n=3 magnetic braking



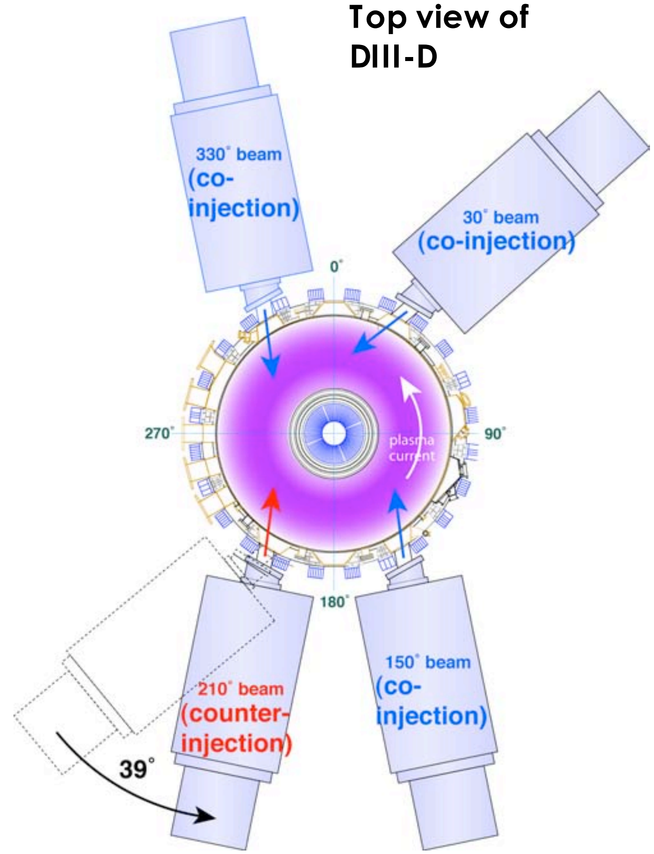
- Small n=1 error field introduced accidentally (one C-coil pair)
- RWM onset observed for sufficiently large n=3 and n=1 error field

DIII-D NATIONAL FUSION FACILITY

Balanced injection provides effective rotation control without magnetic perturbations

- **Magnetic braking experiments suggested that RWM stabilization requires mid-radius plasma rotation ~O(1%) of the Alfven frequency, Ω_A**
  - This level of rotation may not be realized in ITER
- **Recent experiments using balanced NBI in DIII-D (and JT-60U) show that the plasma rotation needed for RWM stabilization is much slower than previously thought**
  - ~O(0.1%) of Ω_A
  - Such a low rotation should be achievable in ITER
- **Even with sufficient rotation, active feedback may still be needed, but the system requirements could be reduced**

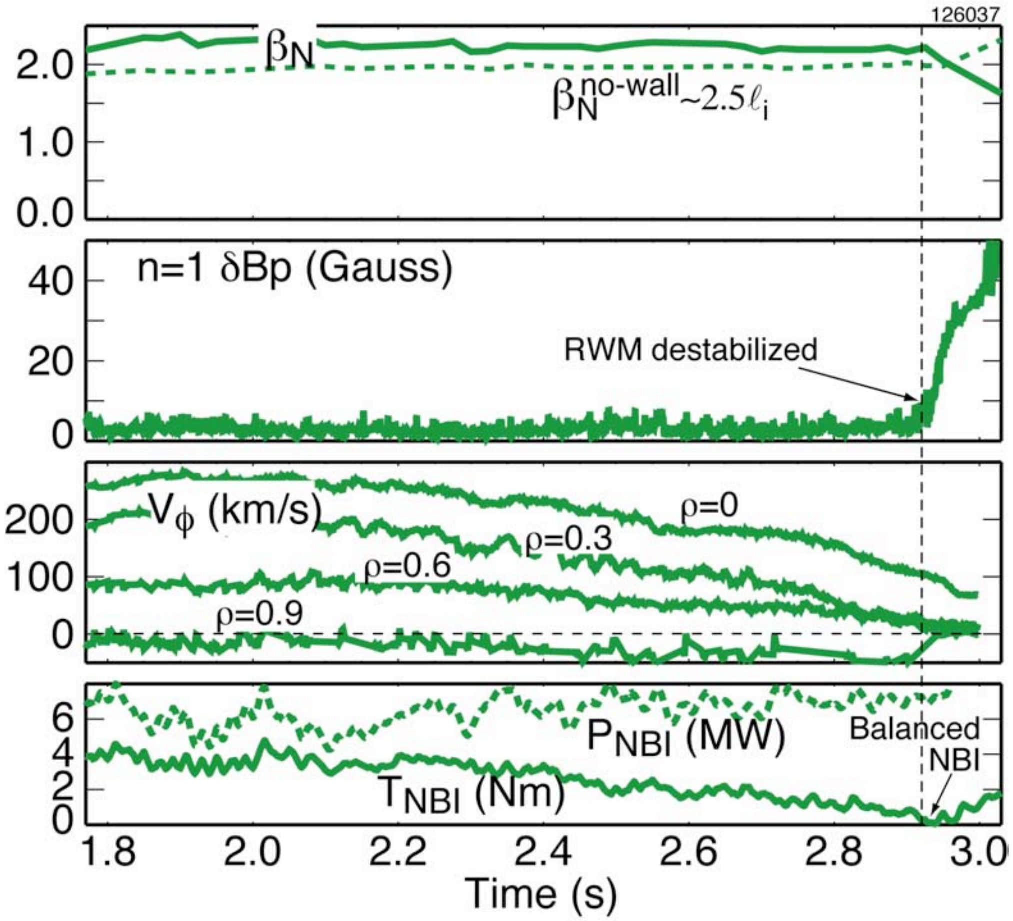
Top view of DIII-D



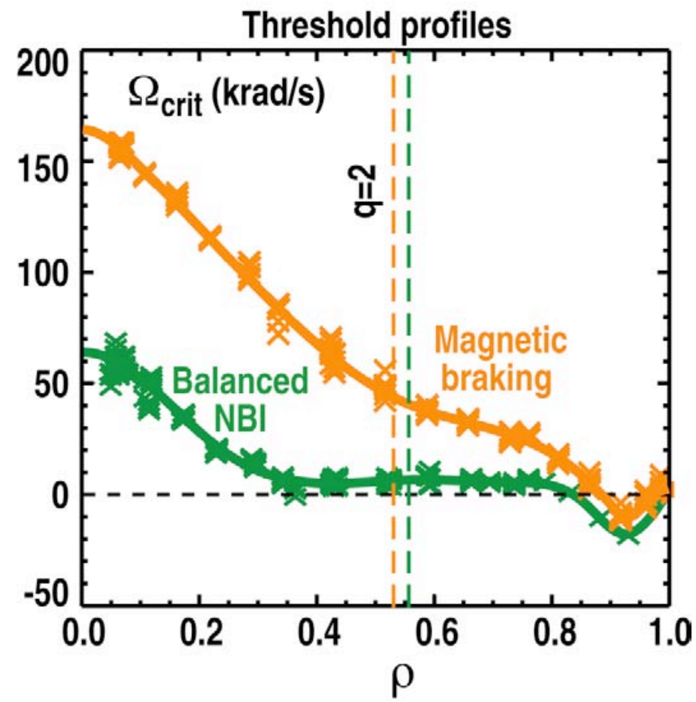
210° neutral beamline was rotated 39°

Much Slower Rotation Before RWM Onset is Observed by Reducing the Injected Torque With Minimized Error Fields

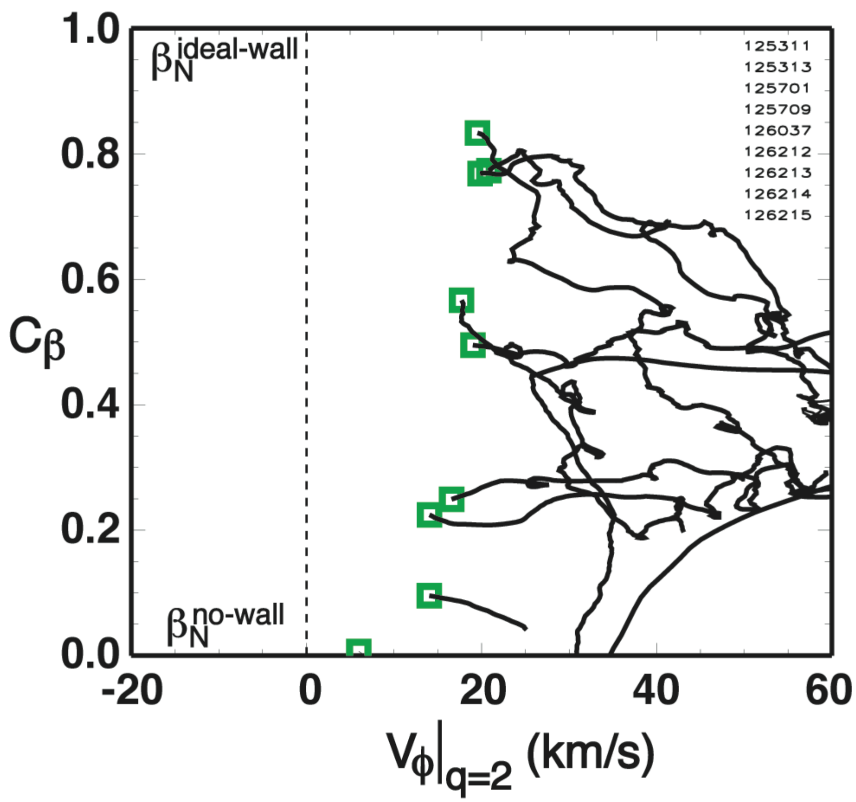
- **DIII-D using a varying mix of co and counter NBI:**

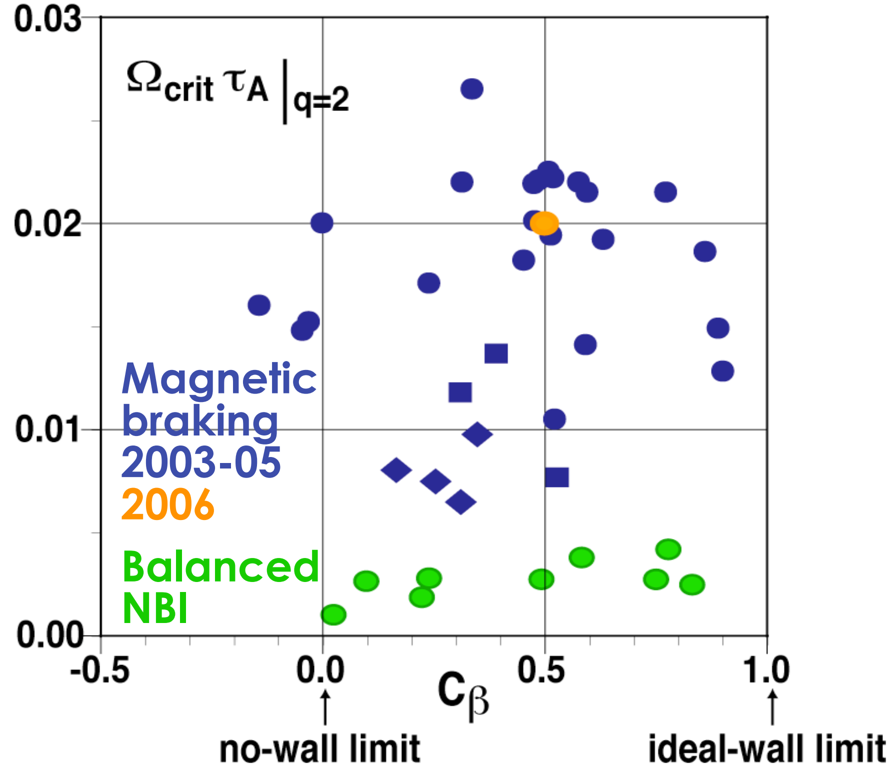


  - Plasma rotation is reduced uniformly for ρ<0.9
  - Ω_{crit} at q = 2 is ~7x slower than measured with magnetic braking



Weak β-Dependence is Observed for Rotation Thresholds Measured With Minimized Error Fields

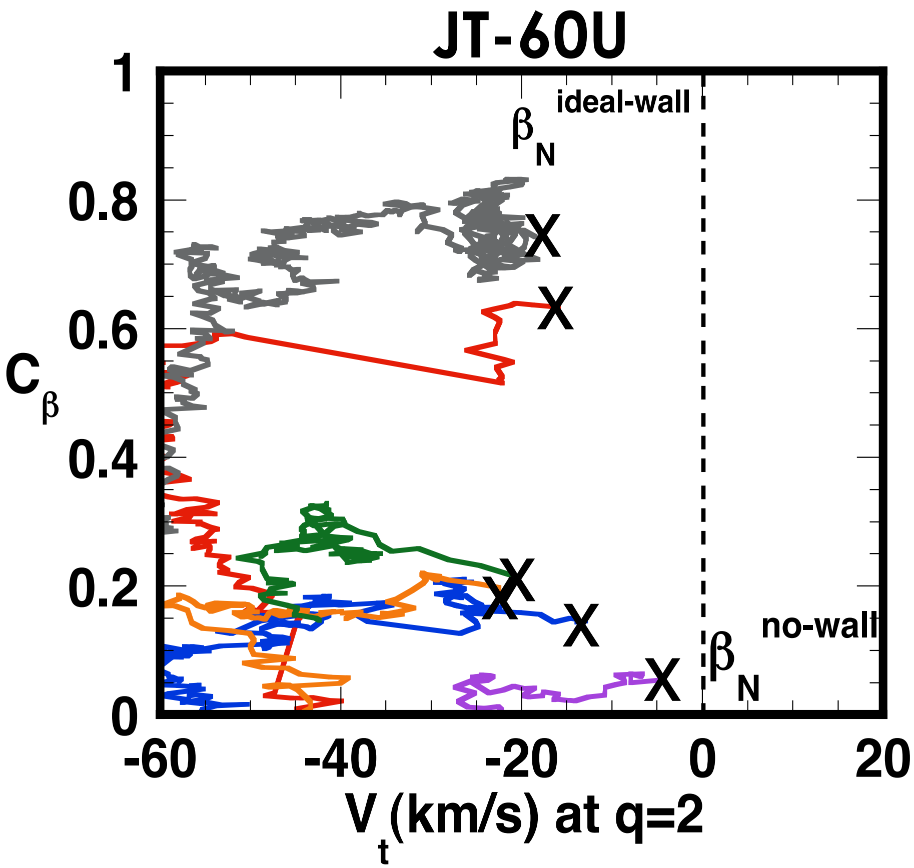


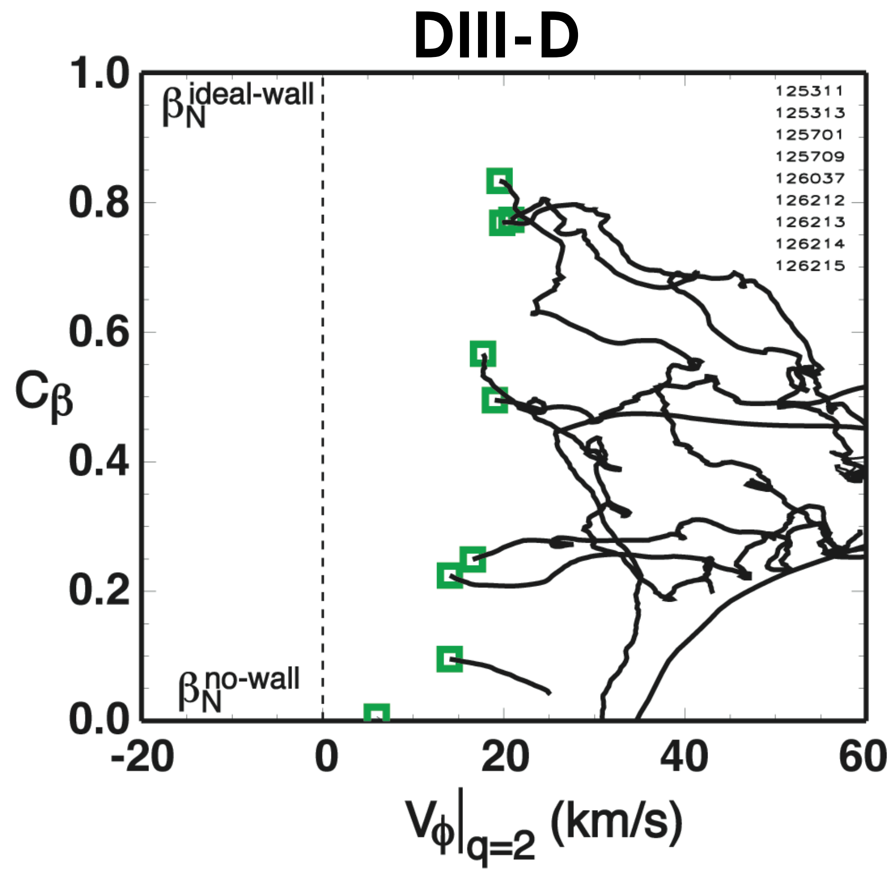


- RWM onset (□) observed when V_ϕ at q=2 is ~10-20 km/s, or ~0.3% of local V_A

Independent, Simultaneous Discovery of Low RWM Rotation Thresholds in DIII-D and JT-60U

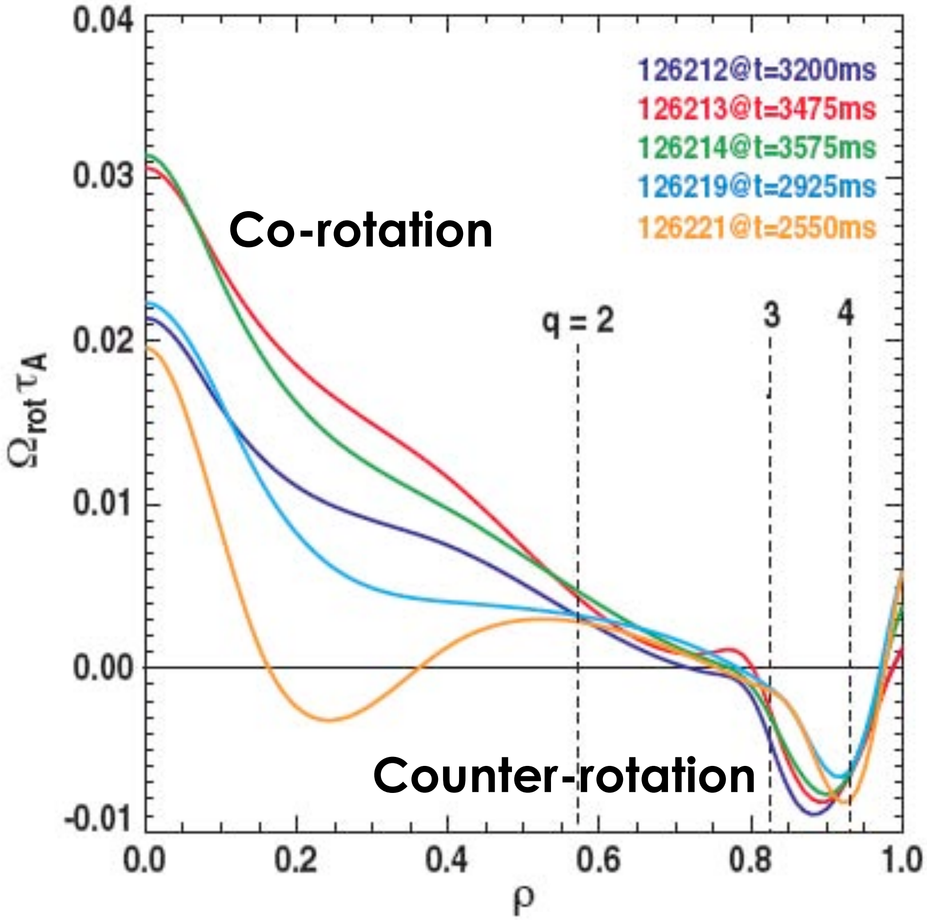
[Takechi, IAEA FEC 2006]



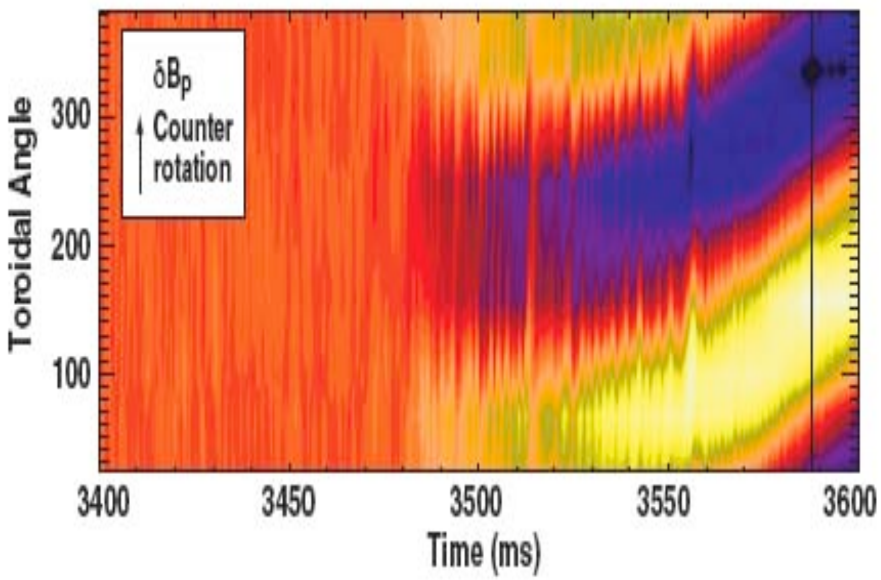


Profiles at RWM Onset Suggest Rotation in the Outer Region of the Plasma Is Important

- **Central rotation seems uncorrelated with RWM onset**

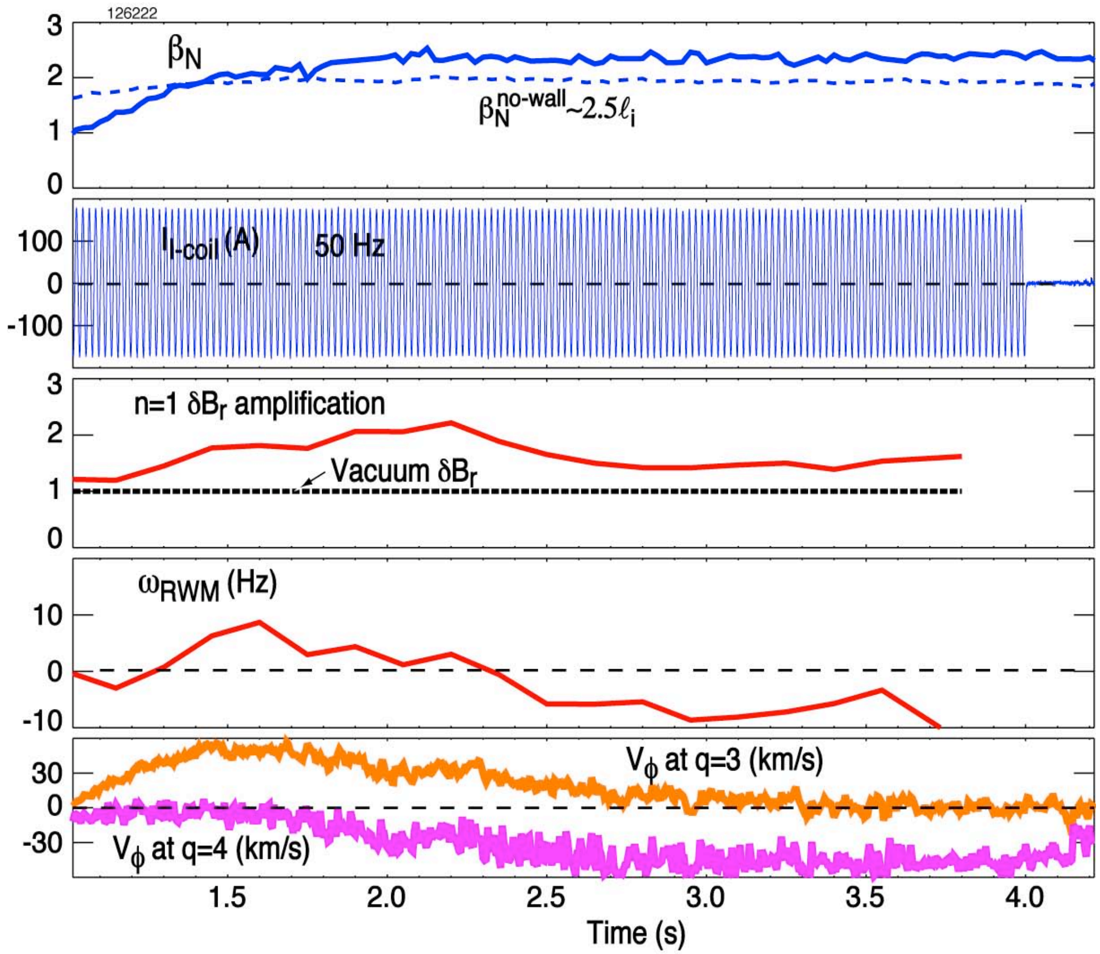


- **Negative mode rotation at onset suggests strong interaction near plasma edge**



DIII-D NATIONAL FUSION FACILITY

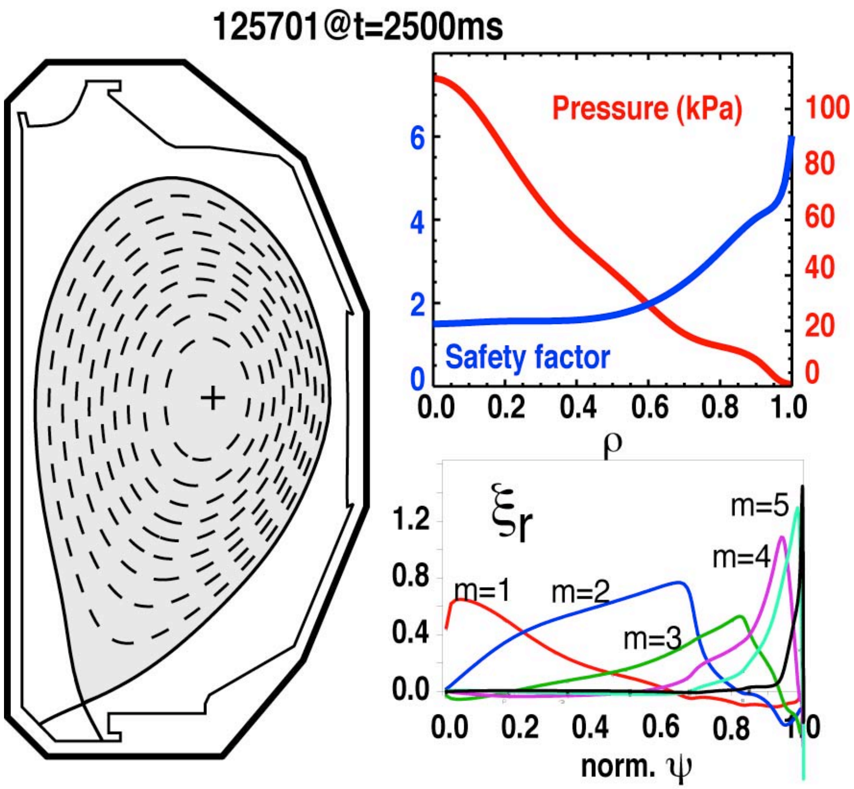
MHD Spectroscopic Measurements With Varying Plasma Rotation Shows Importance of Edge Rotation



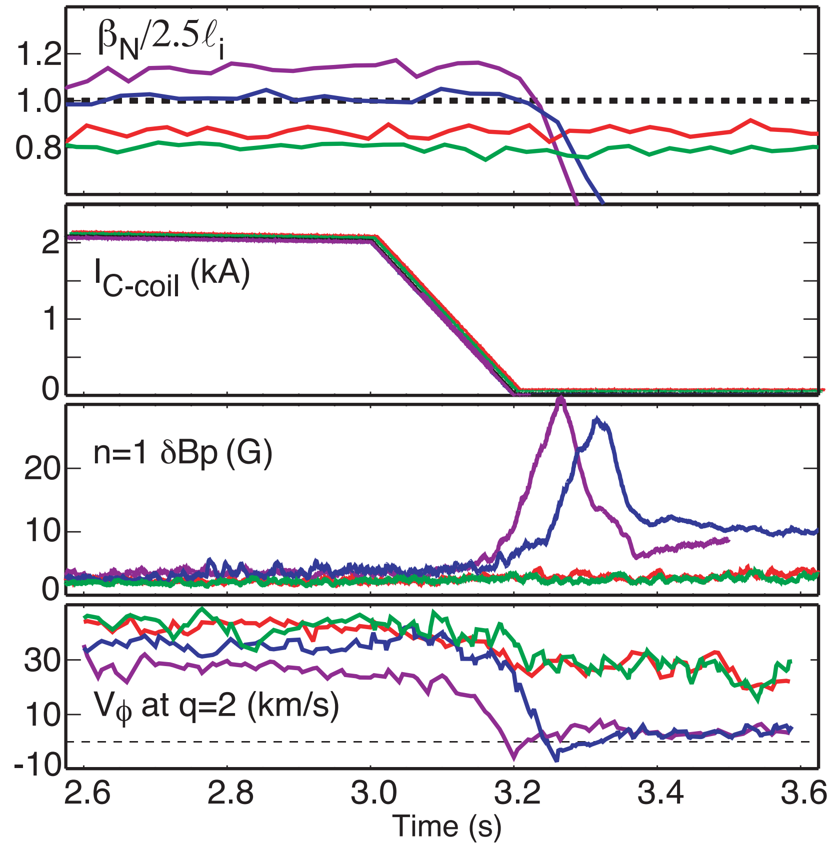
- **Natural rotation frequency of stable RWM, ω_{RWM}, obtained from measurements of plasma response at single frequency**
- **Plasma rotation varied with nearly constant β_N**
- **ω_{RWM} crosses zero when rotation between q=3 and q=4 crosses zero**

Sensitivity to Error Fields Confirms β_N Is Above No-Wall Limit

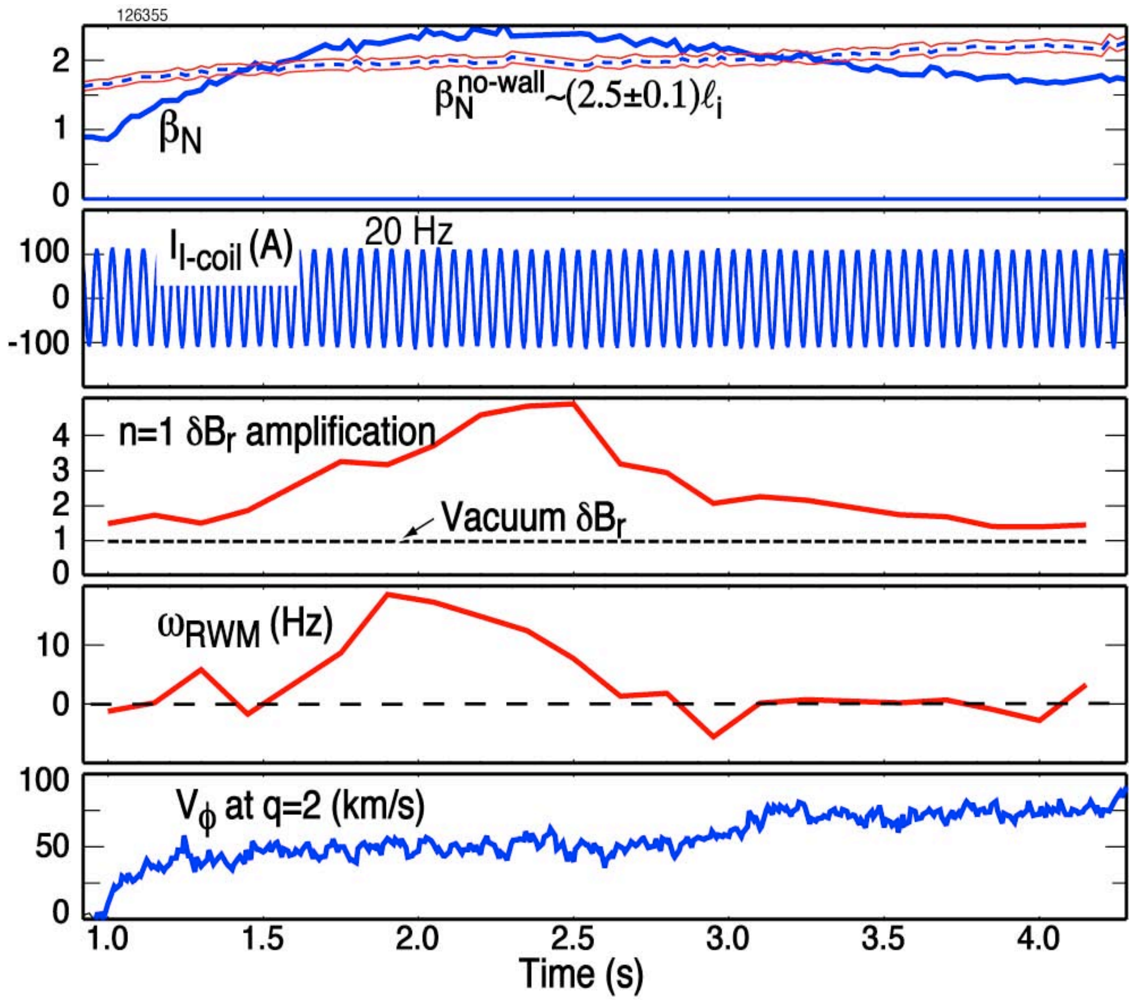
- **Ideal MHD stability calculations (DCON code and GATO code) predict $\beta_N^{no\text{-}wall} \approx (2.5\pm0.1)\ell_i$**



- **Sensitivity to field asymmetries brackets $\beta_N^{no\text{-}wall}$ between $2.3\ell_i$ and $2.5\ell_i$, consistent with stability calculations**



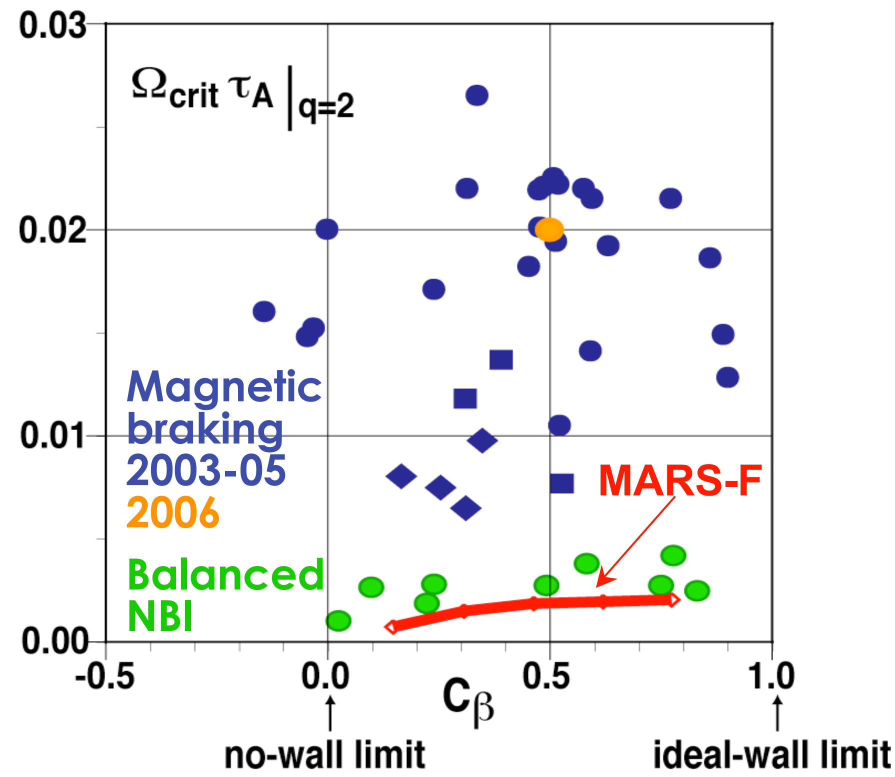
MHD Spectroscopic Measurements With Varying β_N Explain Sharp Threshold of Sensitivity to Error Fields



- **Natural rotation frequency of stable RWM, ω_{RWM}, obtained from measurements of plasma response at single frequency**
  - β_N varied with nearly constant high plasma rotation
- **ω_{RWM} ~0 when $\beta_N \leq \beta_N^{no\text{-}wall}$**
- **No momentum exchange between mode and static non-axisymmetric field when natural rotation frequency of RWM is zero**

Ideal MHD With Kinetic Damping Model of Dissipation Is Consistent With New Low Threshold Rotation

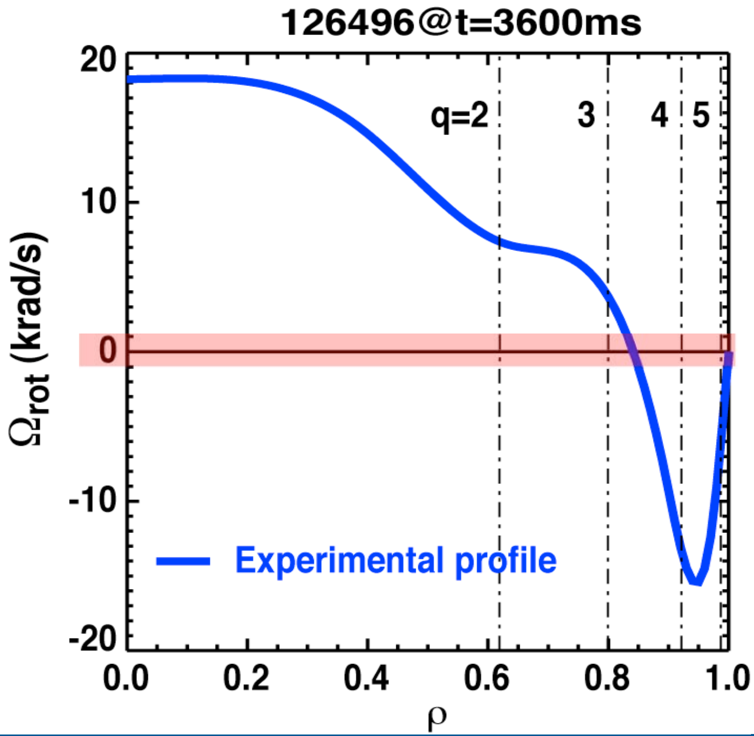
- **Marginal stability predicted with 70% of experimental rotation profile for balanced NBI plasmas**
  - Kinetic damping model [Bondeson and Chu] implemented in MARS-F

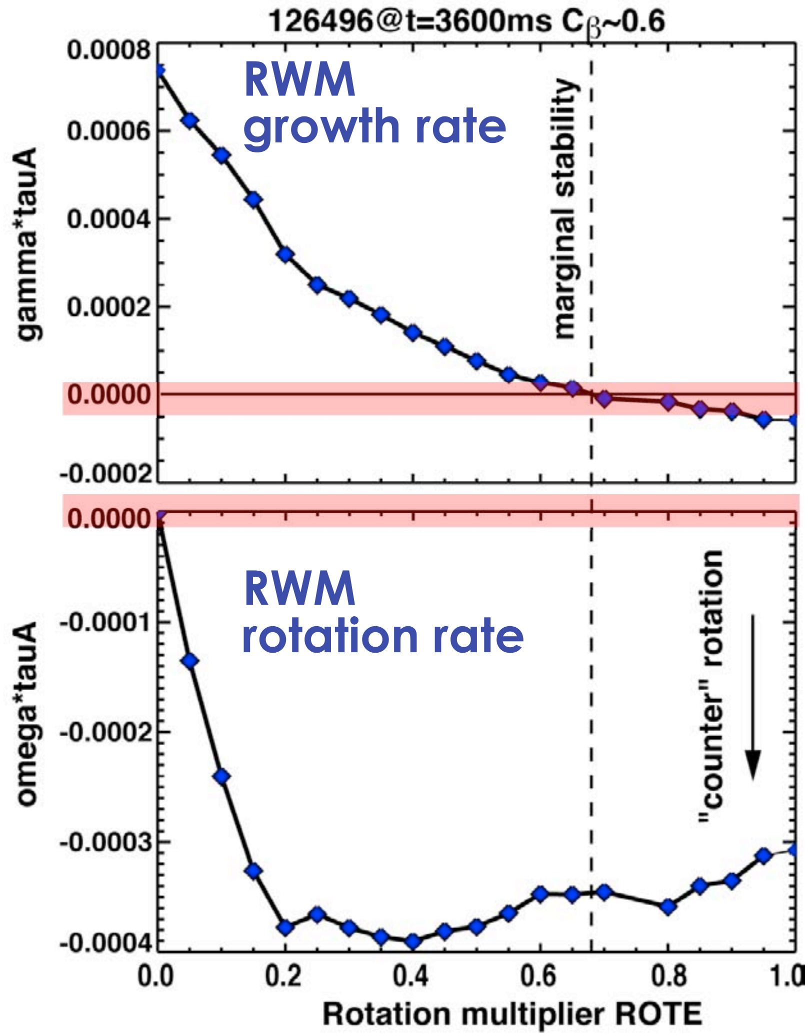


- **Sound wave damping model needs at least 300% of experimental rotation profile for marginal stability**

MARS-F With Kinetic Damping Model Suggests Importance of Plasma Rotation Near the Edge

- **Experimental rotation profile is scaled to find marginal stability**
  - RWM growth rate γ_{RWM} and mode rotation frequency ω_{RWM} are normalized to growth rate without rotation
- **RWM rotates in direction of plasma edge**

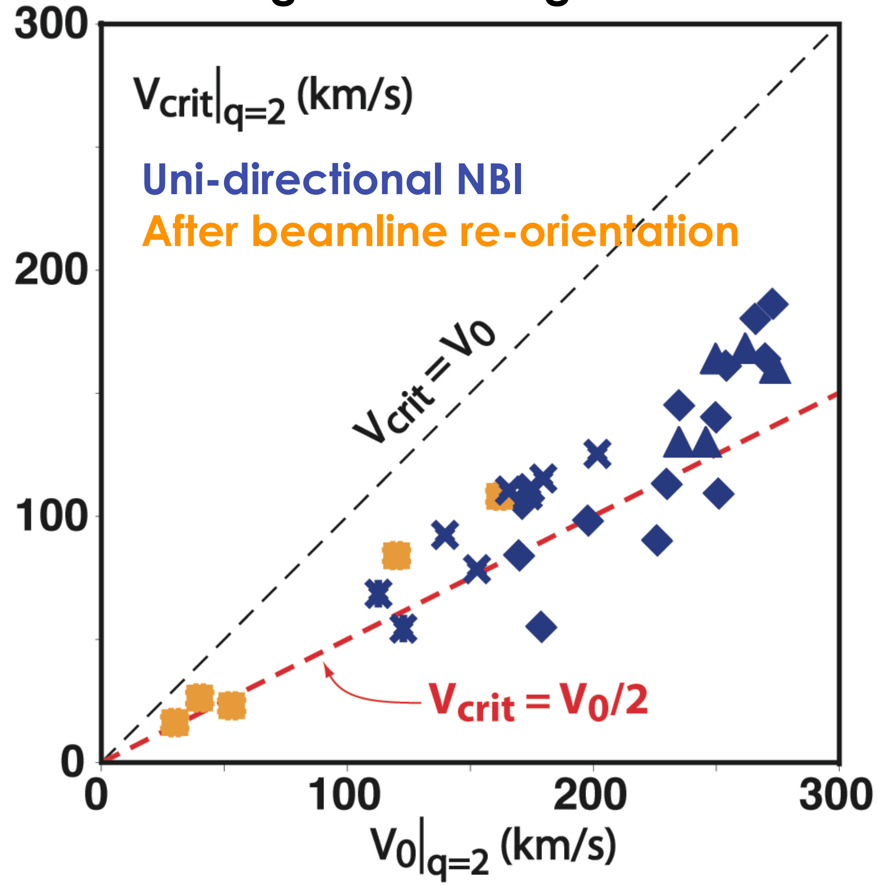




High Rotation Threshold Measured With Magnetic Braking Is Consistent With Torque-balance Equilibrium Bifurcation

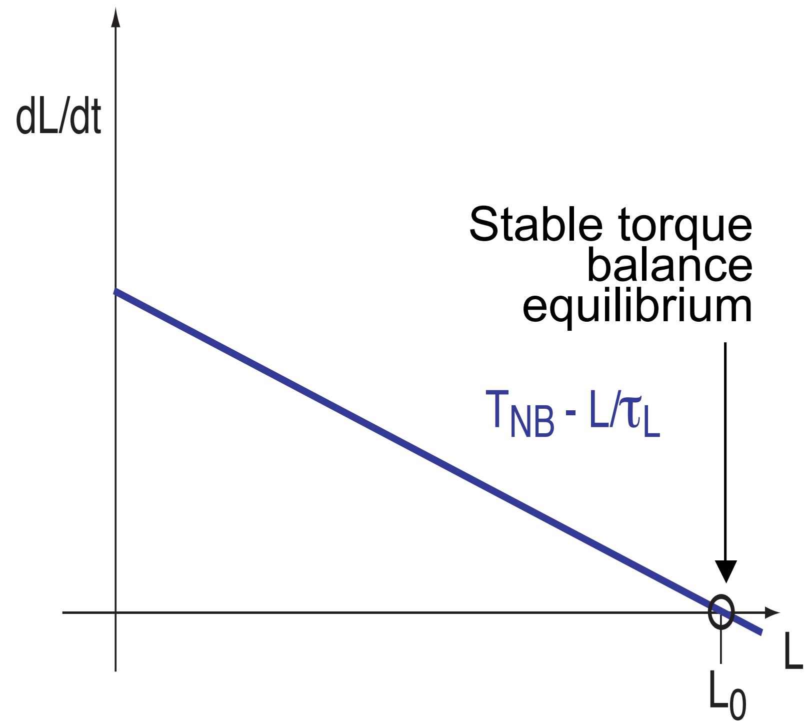
- **Increasing static resonant error field (n=m/q) leads to bifurcation in torque-balance equilibrium of plasma**
  - Rotation must jump from a high value to essentially locked
- **“Induction motor” model of error field-driven reconnection [Fitzpatrick]:**
  - Plasma rotation at critical point, V_{crit}~1/2 of unperturbed rotation, V_0
- **Lower neutral beam torque gives lower V_0, therefore a lower V_{crit} at entrance to “forbidden band of rotation”**

Magnetic braking thresholds



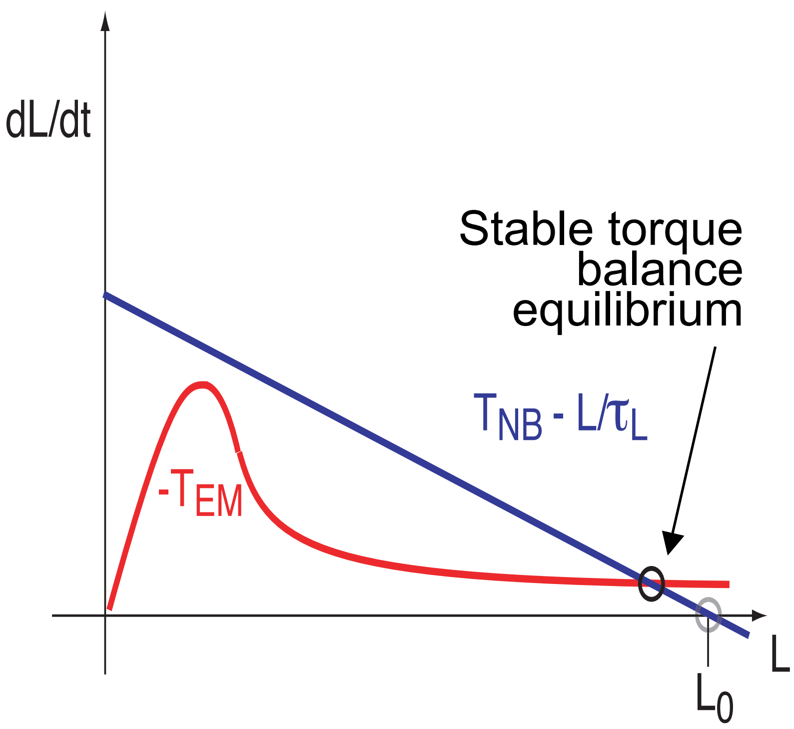
"Forbidden Band" of Rotation Results in a Higher Effective Rotation Threshold for RWM Onset

- **With no error field, torque balance requires NB torque = viscous torque**



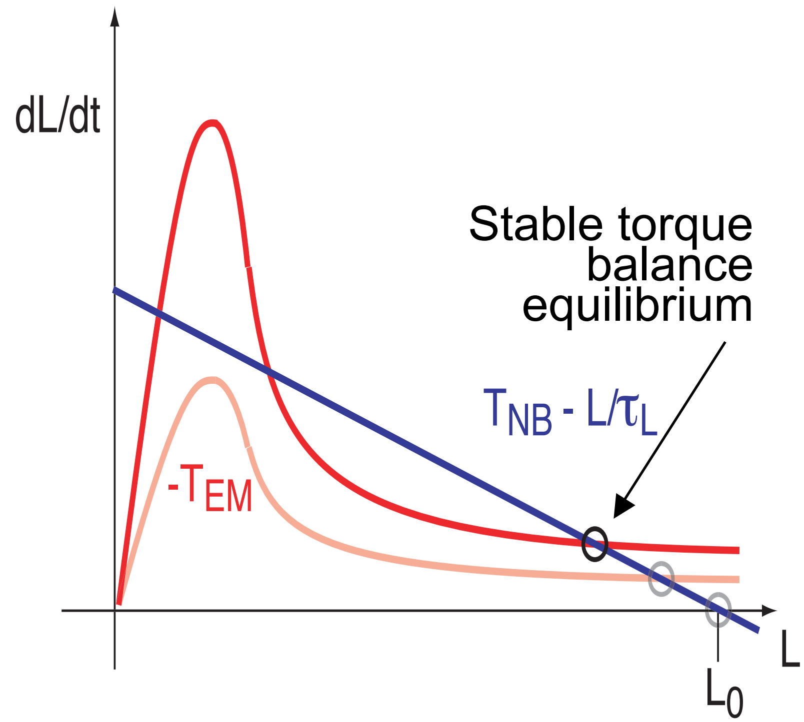
"Forbidden Band" of Rotation Results in a Higher Effective Rotation Threshold for RWM Onset

- **With uncorrected error field, resonant field amplification by stable RWM leads to large electromagnetic torque**



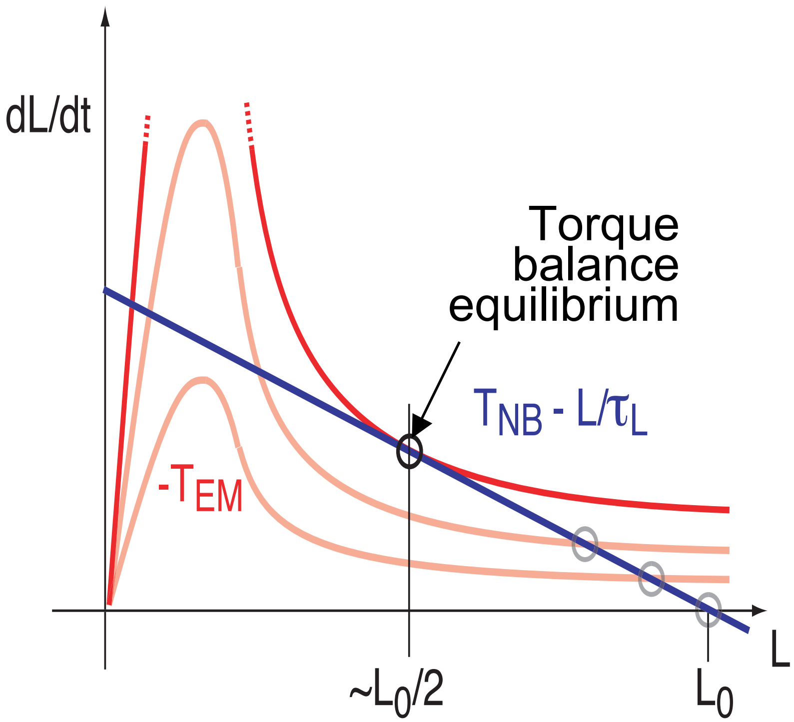
"Forbidden Band" of Rotation Results in a Higher Effective Rotation Threshold for RWM Onset

- **With uncorrected error field, resonant field amplification by stable RWM leads to large electromagnetic torque increasing with beta above no-wall limit**



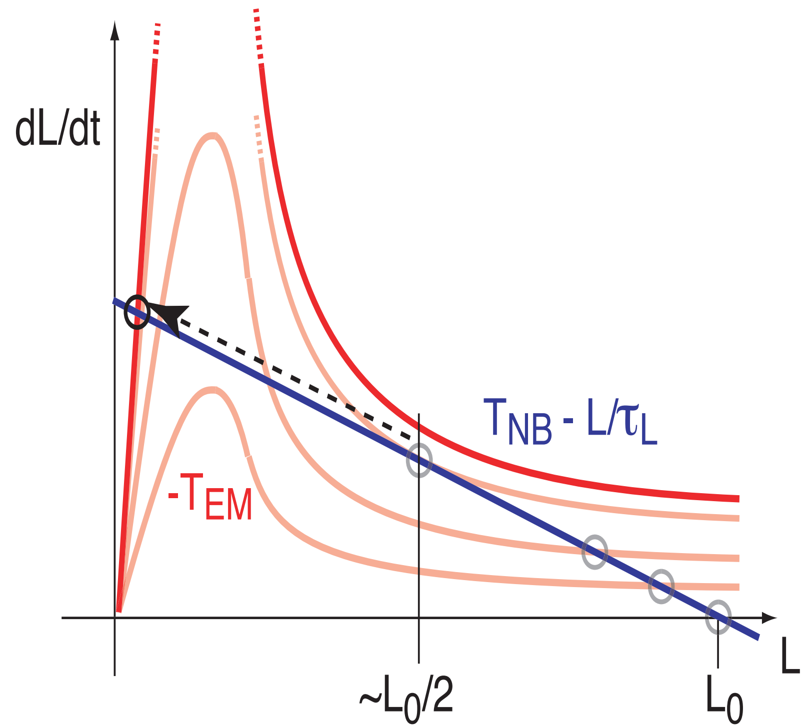
"Forbidden Band" of Rotation Results in a Higher Effective Rotation Threshold for RWM Onset

- **With uncorrected error field, resonant field amplification by stable RWM leads to large electromagnetic torque increasing with beta above no-wall limit**



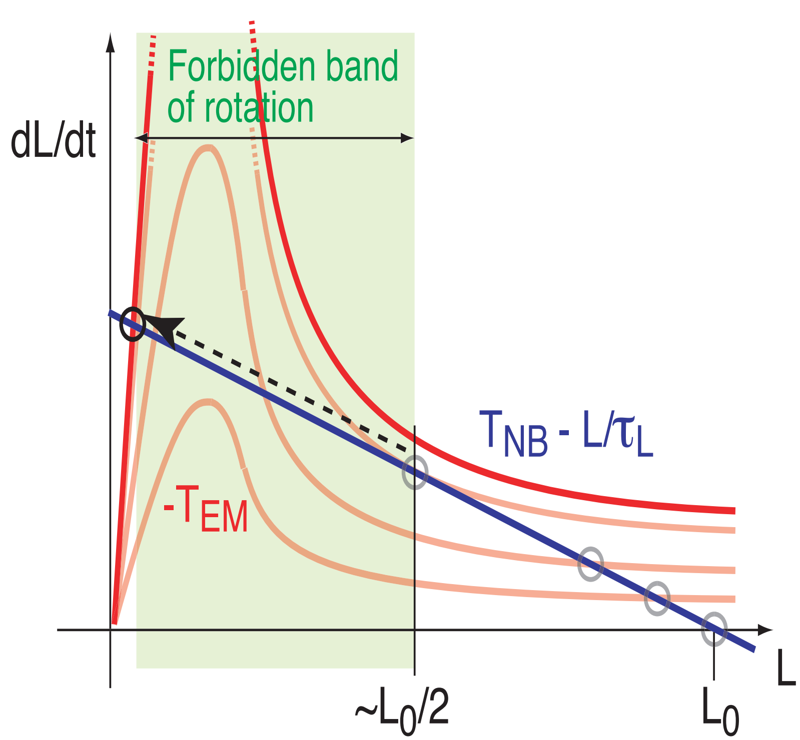
"Forbidden Band" of Rotation Results in a Higher Effective Rotation Threshold for RWM Onset

- **With uncorrected error field, resonant field amplification by stable RWM leads to large electromagnetic torque increasing with beta above no-wall limit**
- **As perturbation amplitude increases, torque balance jumps to low-rotation branch**



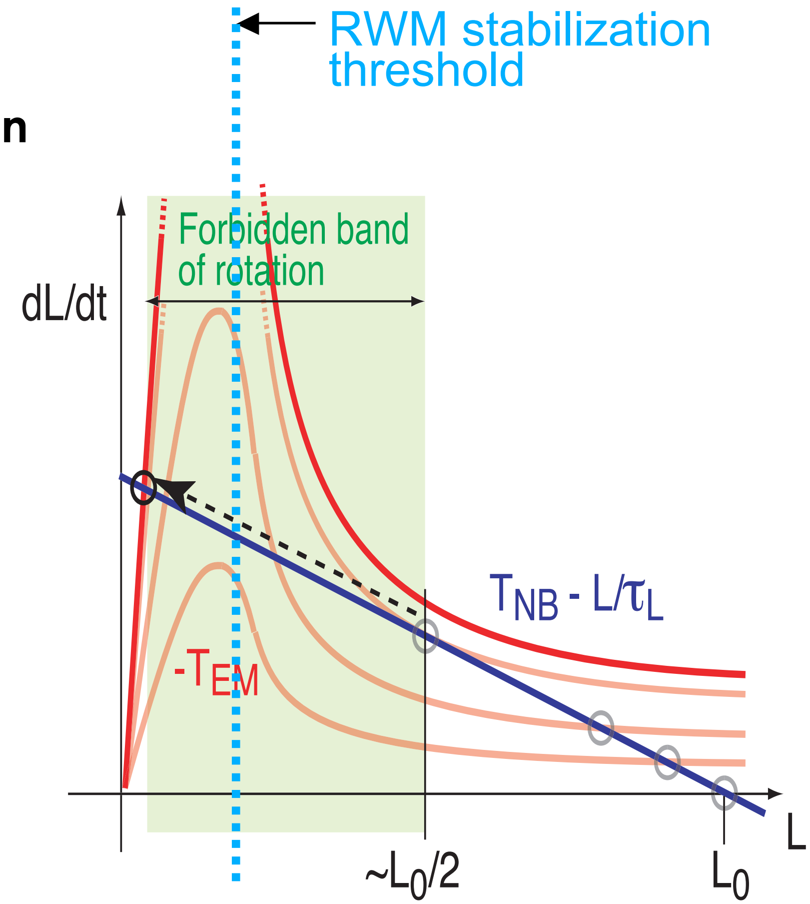
"Forbidden Band" of Rotation Results in a Higher Effective Rotation Threshold for RWM Onset

- **With uncorrected error field, resonant field amplification by stable RWM leads to large electromagnetic torque increasing with beta above no-wall limit**
- **As perturbation amplitude increases, torque balance jumps to low-rotation branch**



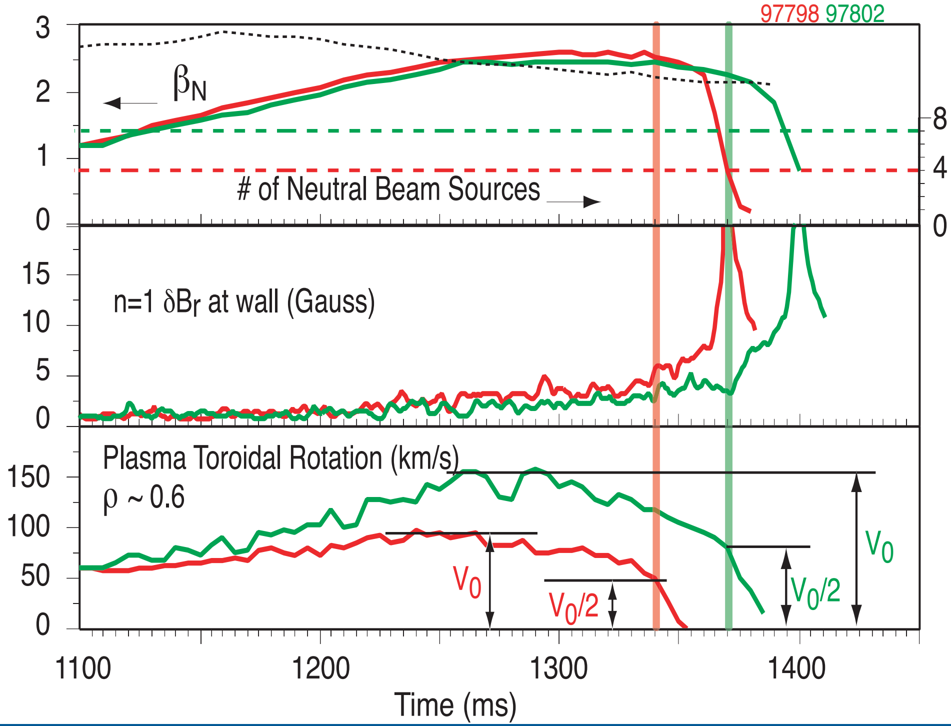
"Forbidden Band" of Rotation Results in a Higher Effective Rotation Threshold for RWM Onset

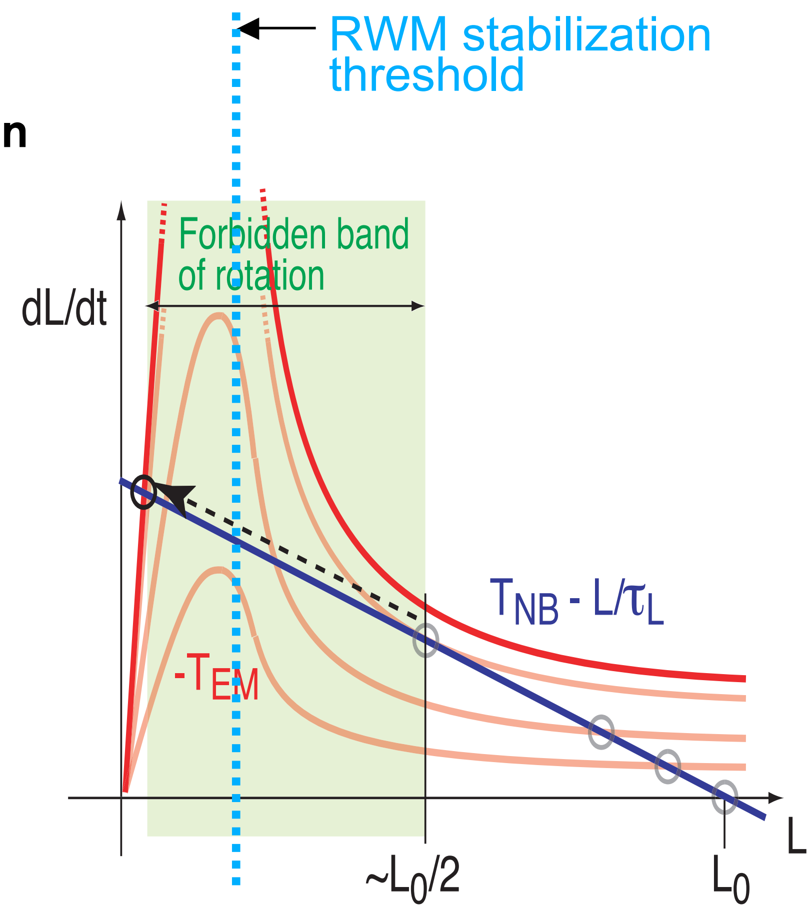
- **With uncorrected error field, resonant field amplification by stable RWM leads to large electromagnetic torque increasing with beta above no-wall limit**
- **As perturbation amplitude increases, torque balance jumps to low-rotation branch**
- **With large non-axisymmetric field, bifurcation of rotation occurs above RWM threshold**



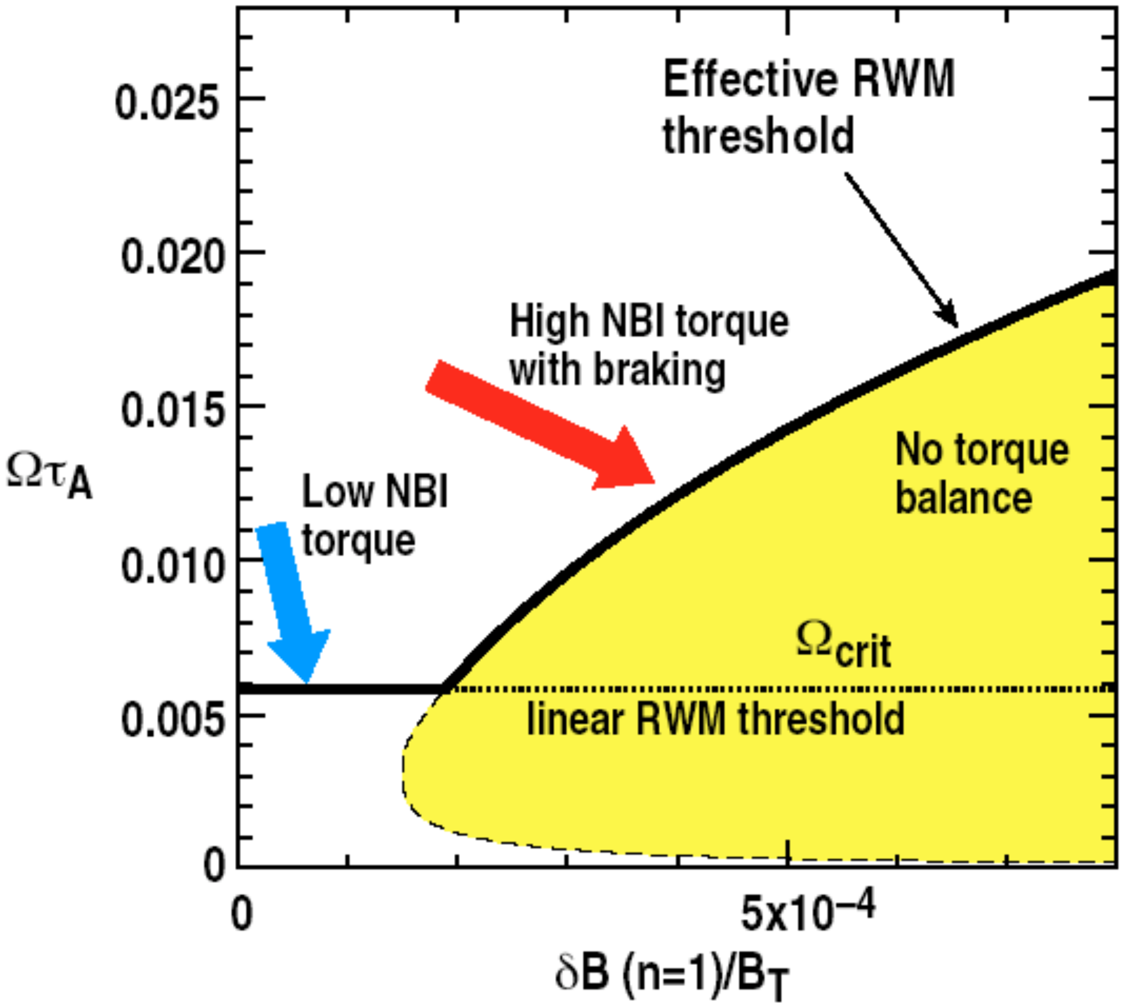
"Forbidden Band" of Rotation Results in a Higher Effective Rotation Threshold for RWM Onset

- **With uncorrected error field, resonant field amplification by stable RWM leads to large electromagnetic torque increasing with beta above no-wall limit**
- **As perturbation amplitude increases, torque balance jumps to low-rotation branch**
- **With large non-axisymmetric field, bifurcation of rotation occurs above RWM threshold**



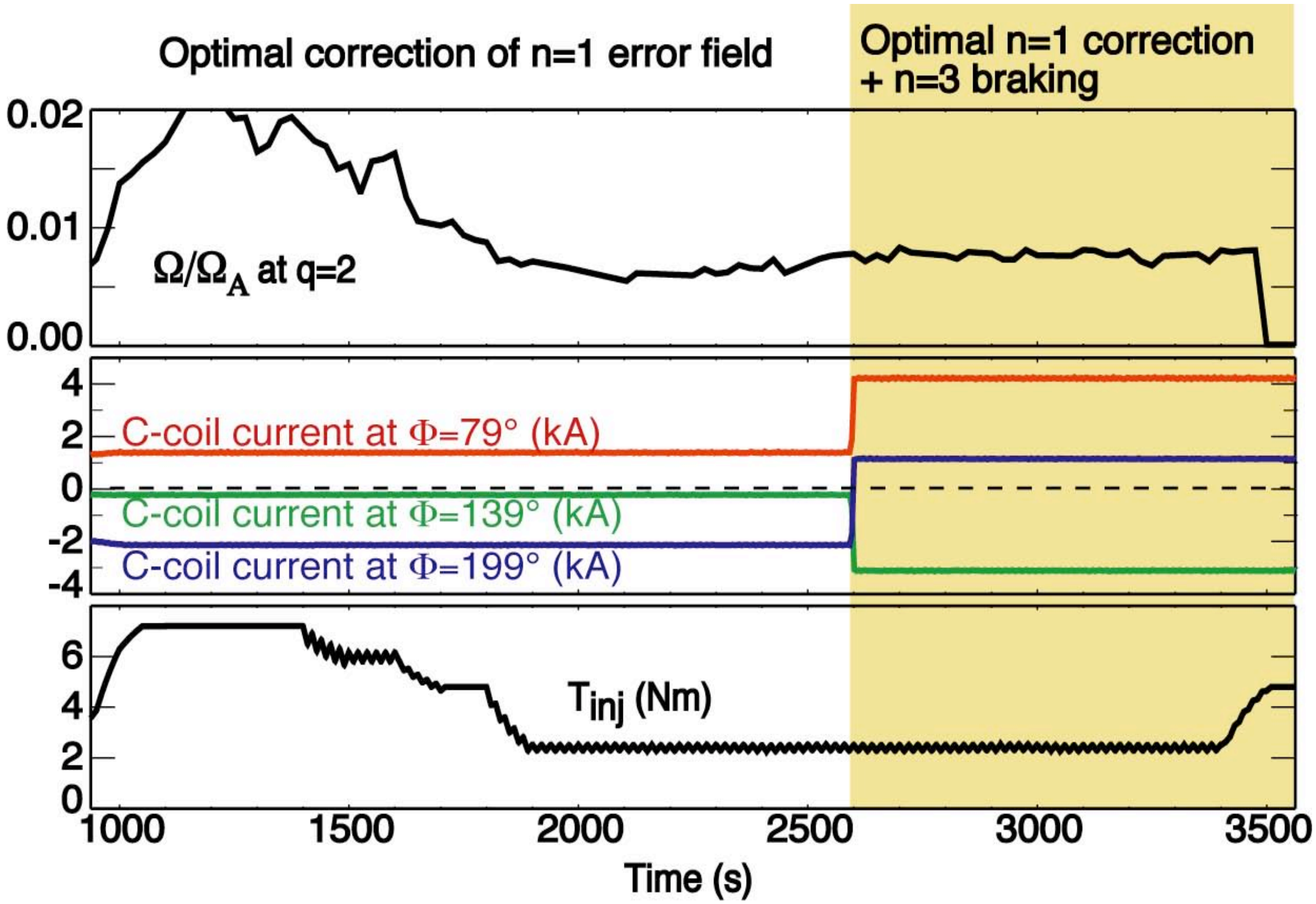


Recent Model by Fitzpatrick Includes RWM Dispersion Relation With Neoclassical Poloidal Viscosity



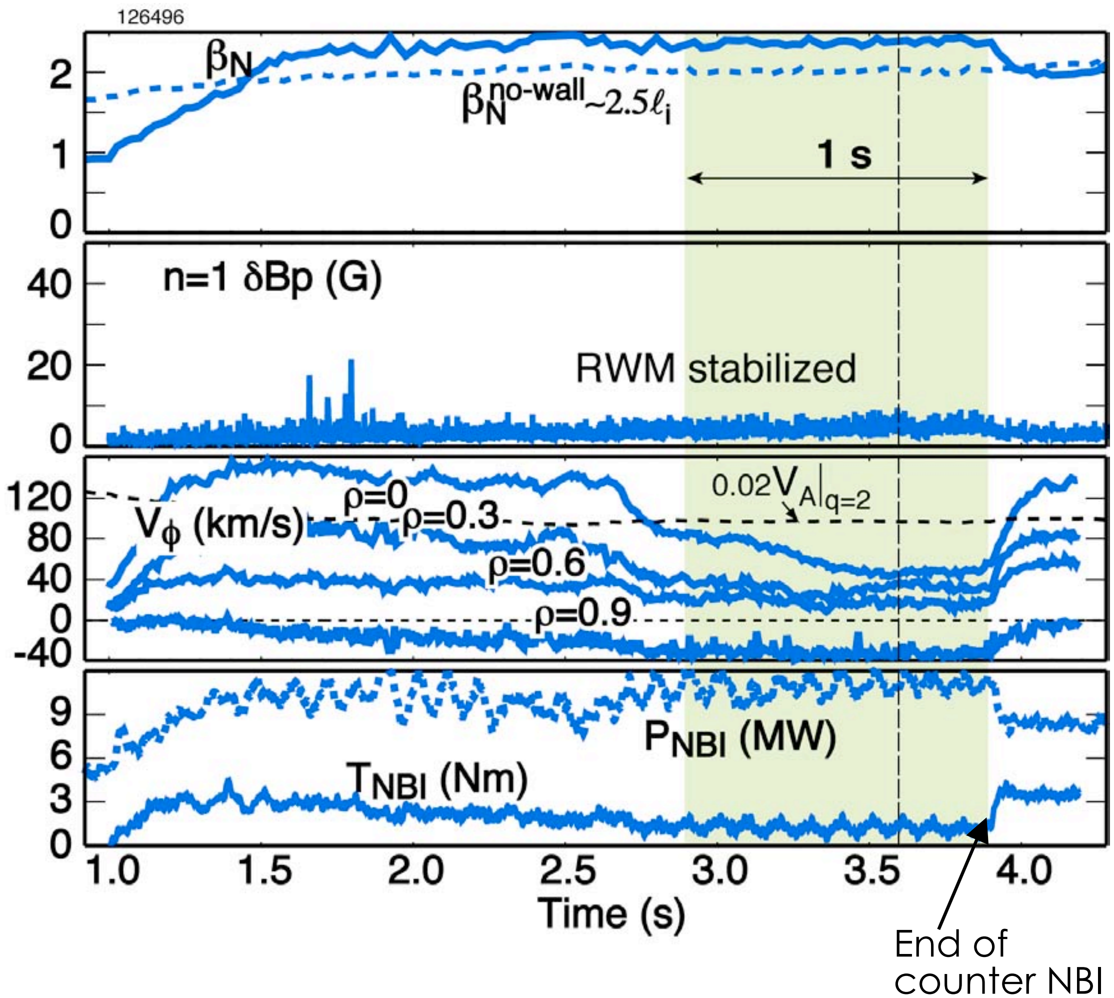
- "True" critical rotation for RWM is seen only when resonant error field is small
- Resonant surface is just outside plasma

Offset Rotation, Not Bifurcation, Observed With Non-resonant n=3 Braking and ~Balanced Injection

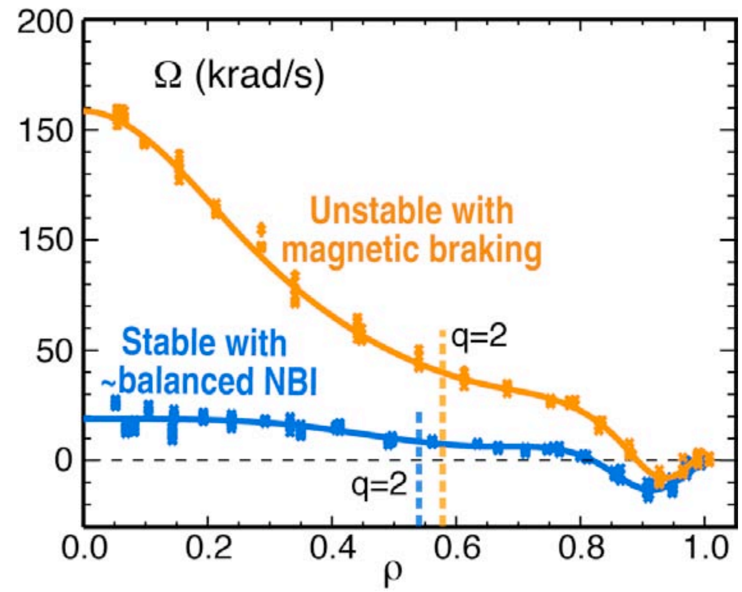


- $I_{n=3}$ > 3 kA has little effect on plasma rotation

With Optimal Error Field Correction, RWM Stabilization at Very Slow Plasma Rotation Sustained for >300 Wall Times



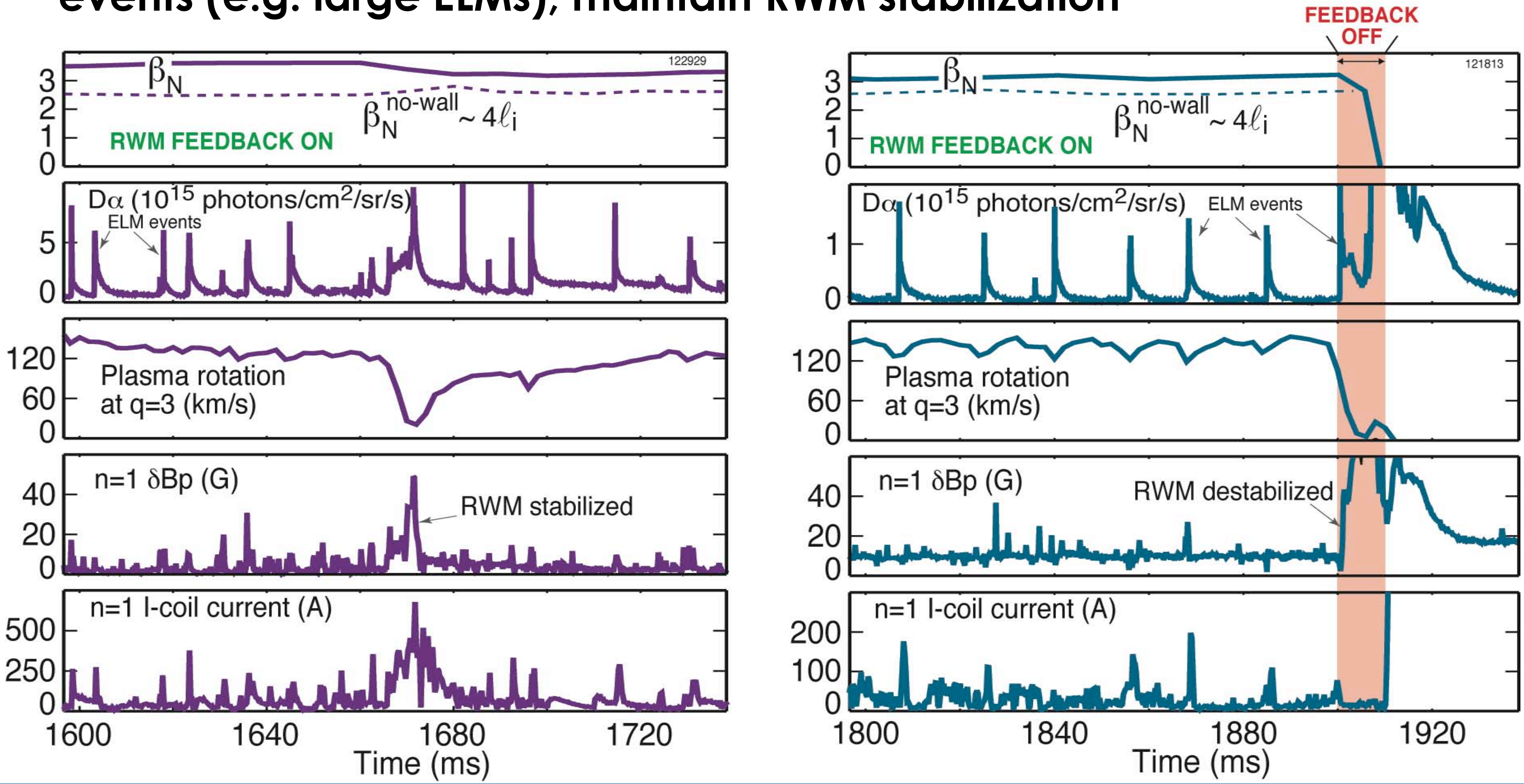
- **Plasma rotation at q=2 ~0.35% Ω_A just above Ω_{crit} is sufficient to sustain β_N above no-wall limit**



DIII-D NATIONAL FUSION FACILITY

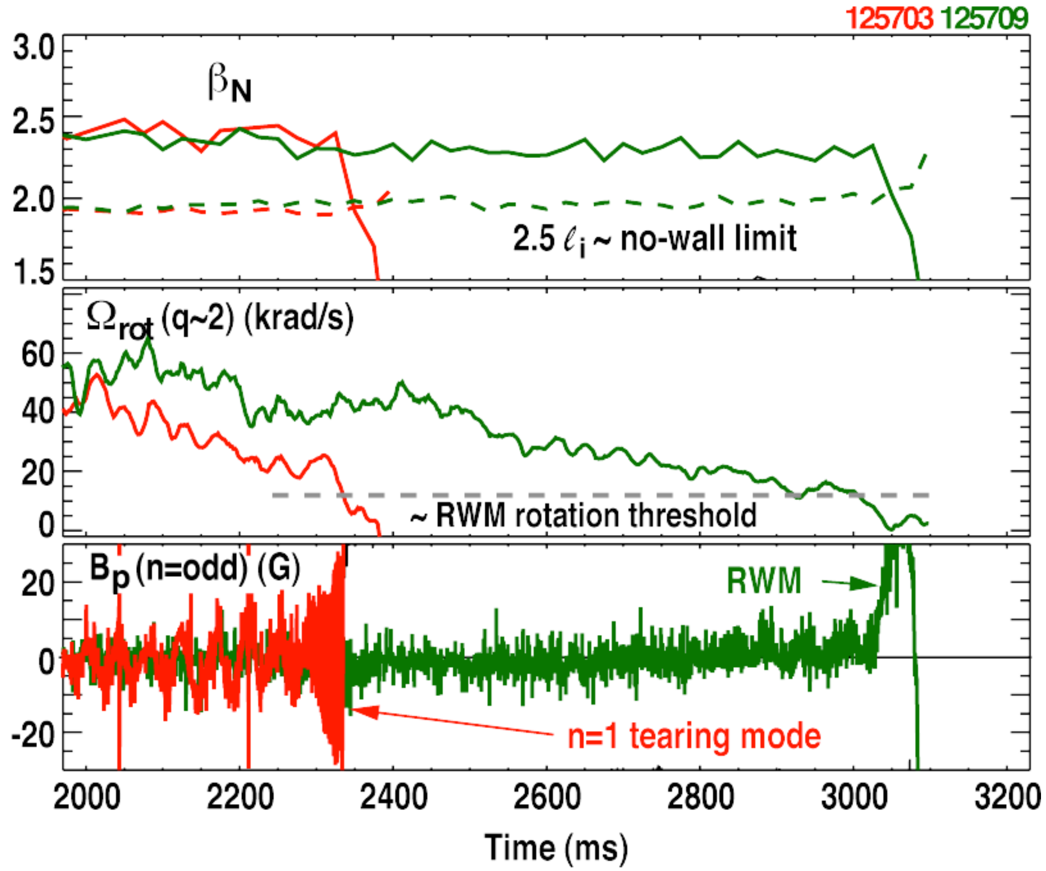
In High Performance Plasmas (Rapid Rotation) Active RWM Feedback Is Required

- **In DIII-D, high rotation is maintained with large, slow-varying n=1 currents in external coils for error field correction**
- **Smaller, faster-varying n=1 currents in internal coils respond to transient events (e.g. large ELMs), maintain RWM stabilization**



RWM Feedback at Slow Rotation More Difficult Than Anticipated

- **First attempts of RWM feedback not yet conclusive**
- **Onset of 2/1 tearing mode frequently observed near RWM onset**
  - High susceptibility to tearing in the vicinity of an ideal MHD stability limit
  - High susceptibility to penetration of resonant non-axisymmetric fields (RWM at amplitude below detection) at very slow rotation



RWM Stabilized With Near-balanced Neutral Beam Injection

- **The plasma rotation needed for RWM stabilization is much slower than previously thought –> $\Omega\tau_A$~0.3% at q=2**
  - Achieved with neutral beam line re-orientation in DIII-D:
    - Balanced neutral beam injection -> lower injected torque and plasma rotation with minimized non-axisymmetric fields
  - Such a slow rotation should be achievable in ITER
- **Resonant magnetic braking experiments overestimate the critical rotation**
  - Induction motor model of error field driven reconnection can explain observation of higher apparent thresholds
  - Non-resonant braking cannot slow rotation below RWM low threshold, consistent with NTV theory
- **Ideal MHD with dissipation (MARS-F with kinetic model) is consistent with experimental observations**
  - Edge plasma rotation may be crucial
- **Even with sufficient rotation, active RWM feedback is still needed**
  - System requirements for ITER could be reduced