Stability and Control of Resistive Wall Modes in Low-Rotation Tokamak Plasmas

EX/7-1Ra: Active Control of Resistive Wall Modes in High Beta Low Rotation Plasmas

A.M. Garofalo[*]

for: G.L. Jackson,[†] R.J. La Haye,[†] M. Okabayashi,[‡] H. Reimerdes,[*] E.J. Strait,[†] M.S. Chu,[†] E.J. Doyle,[¶] J.R. Ferron,[†] C.M. Greenfield,[†] R.J. Groebner,[†] Y. In,[§] R.J. Jayakumar,[△] M.J. Lanctot,[*] G. Matsunaga,[#] G.A. Navratil,[*] C.C. Petty,[†] J.T. Scoville,[†] W.M. Solomon,[‡] H. Takahashi,[‡] M. Takechi,[#] A.D. Turnbull,[†] and The DIII-D Team

EX/7-1Rb: Plasma Rotation and Wall Effects on Resistive Wall Mode in JT-60U

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for: G. Matsunaga,[#] T. Ozeki,[#] N. Aiba,[#] G. Kurita,[#] A. Isayama,[#] Y. Koide,[#] Y. Sakamoto,[#] T.Fujita,[#] Y. Kamada,[#] and the JT-60U Team

Presented by A.M. Garofalo[*]

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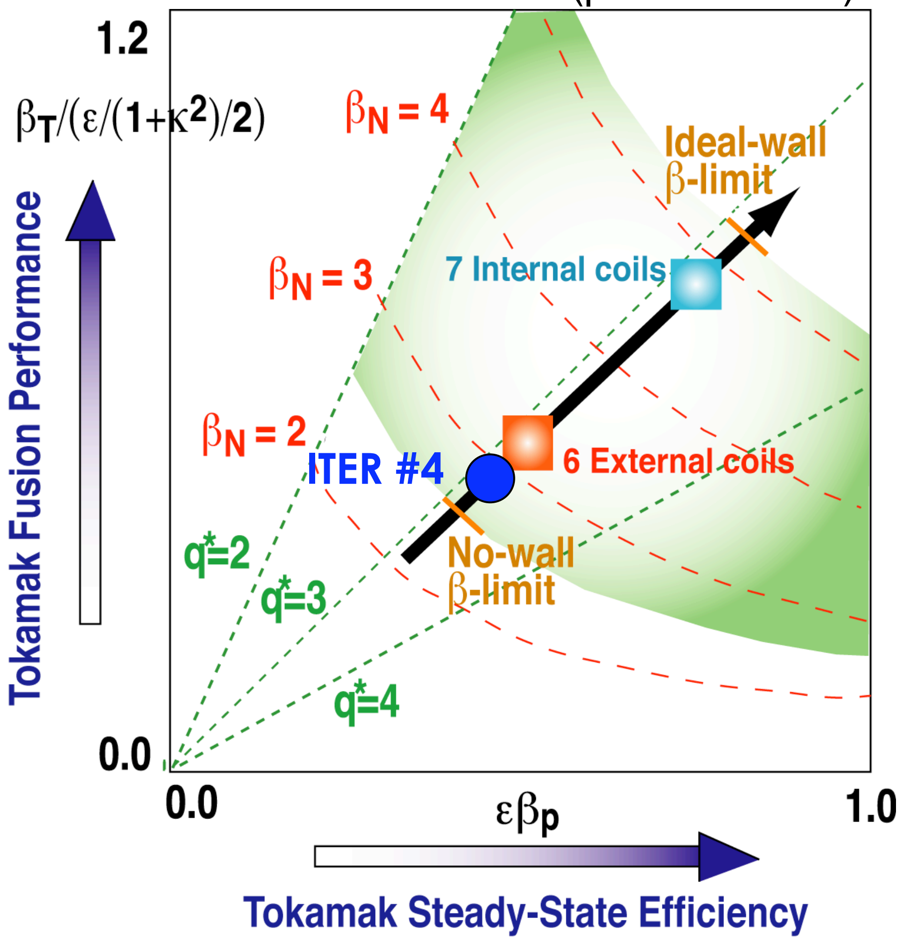
Resistive Wall Mode Stabilization is Needed for Steady State Tokamak Operation at High Fusion Performance

- **ITER Steady-State scenario (#4) requires Resistive Wall Mode stabilization**
  - Target: $\beta_N \sim 3$, above the no-wall stability limit $\beta_N^{\text{no-wall}} \sim 2.5$
- **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)



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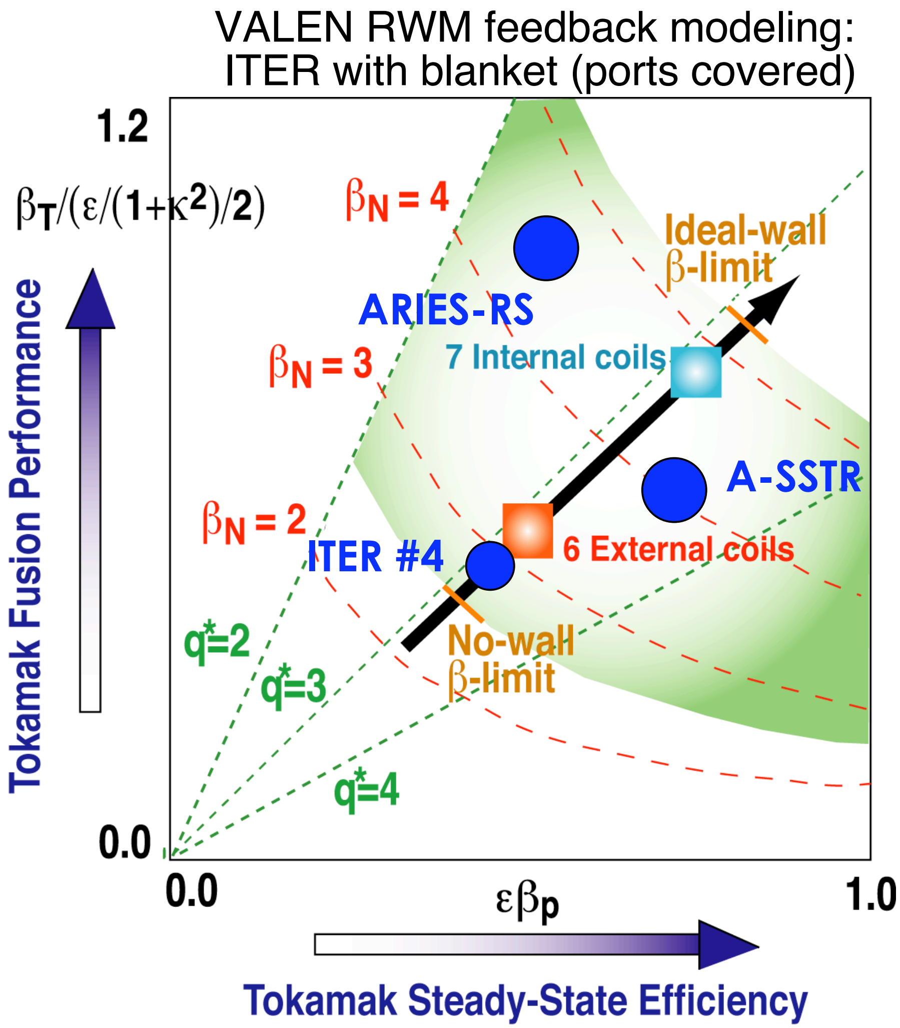
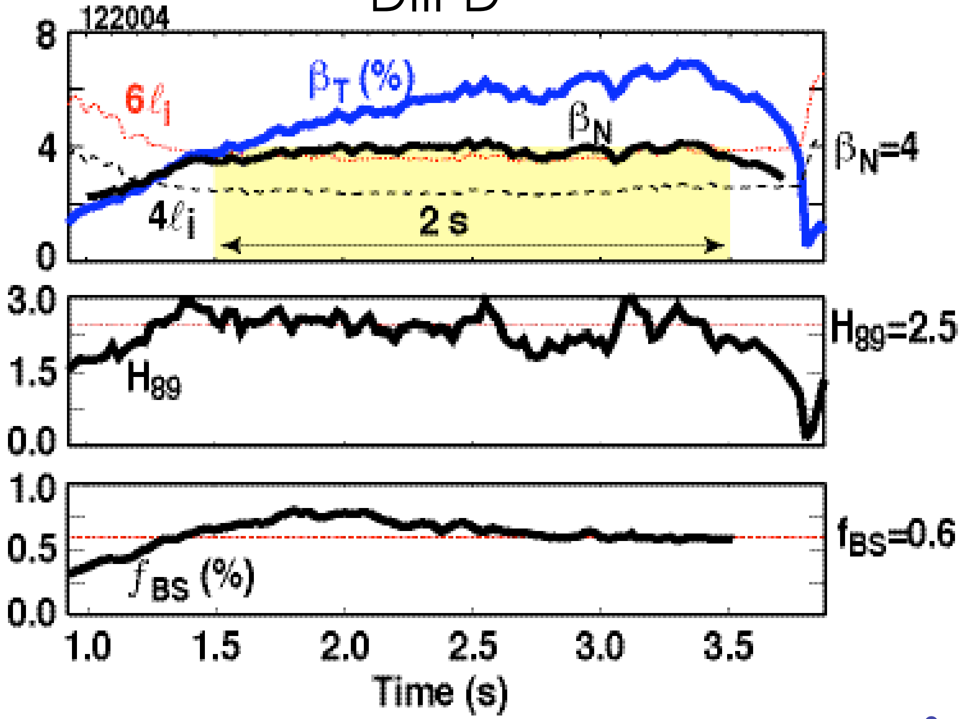
- **Sufficient plasma rotation could stabilize RWM up to ideal-wall β_N limit**
- **Present ITER design of external error field correction coils is predicted to allow RWM feedback stabilization if plasma rotation is not sufficient**
- **Improved design for RWM stabilization could allow studies of scenarios approaching advanced tokamak reactor concepts, i.e. $\beta_N > 4$**

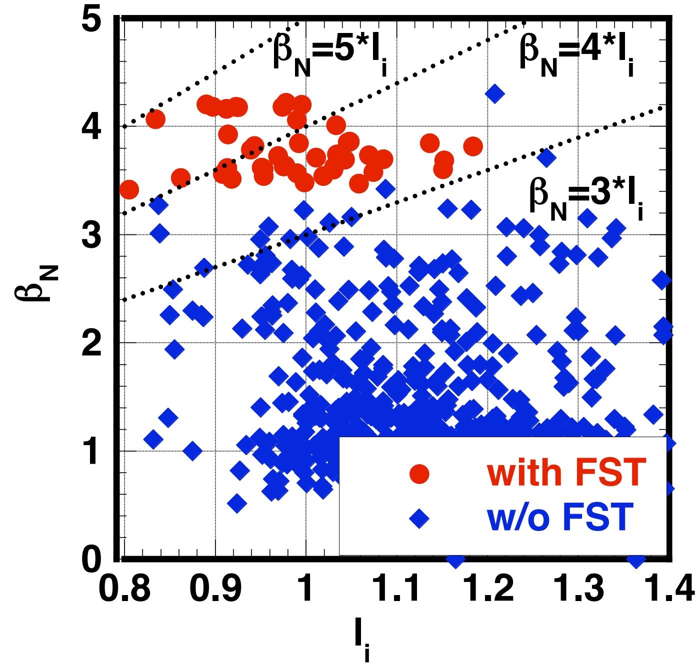


RWM Stabilization by Rotation Allows Demonstration of High Performance Tokamak Regimes

DIII-D



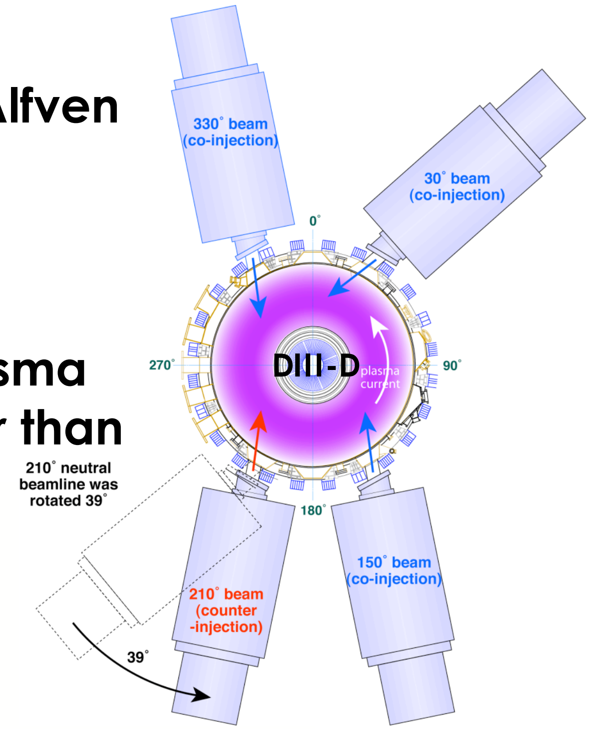
JT-60U

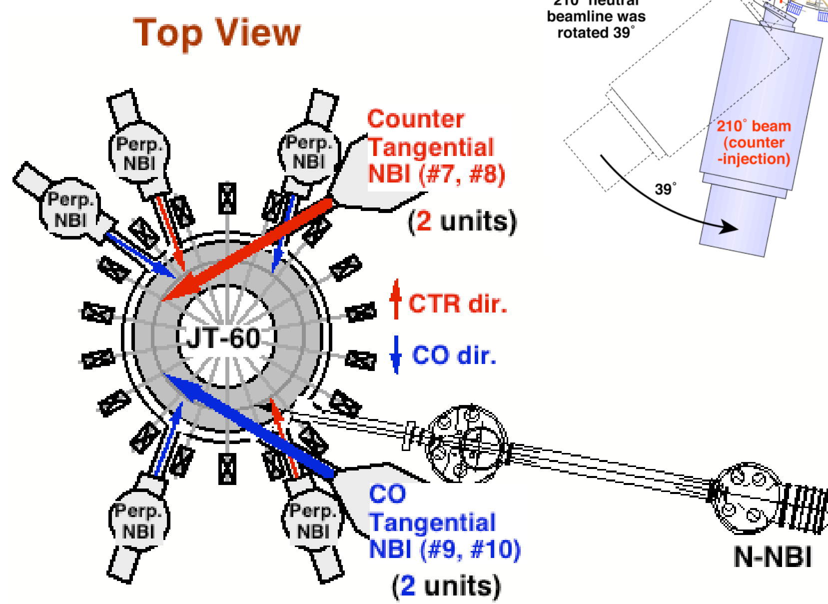


- **High β, β_N, high bootstrap current fraction, high energy confinement sustained simultaneously in DIII-D**
  - RWM feedback -> sustained high plasma rotation
- **High β_N achieved with ferritic steel tiles in JT60U**
  - Reduced ripple loss -> higher confinement and rotation with smaller plasma-wall separation

Will RWM Stabilization by Rotation Work in ITER?

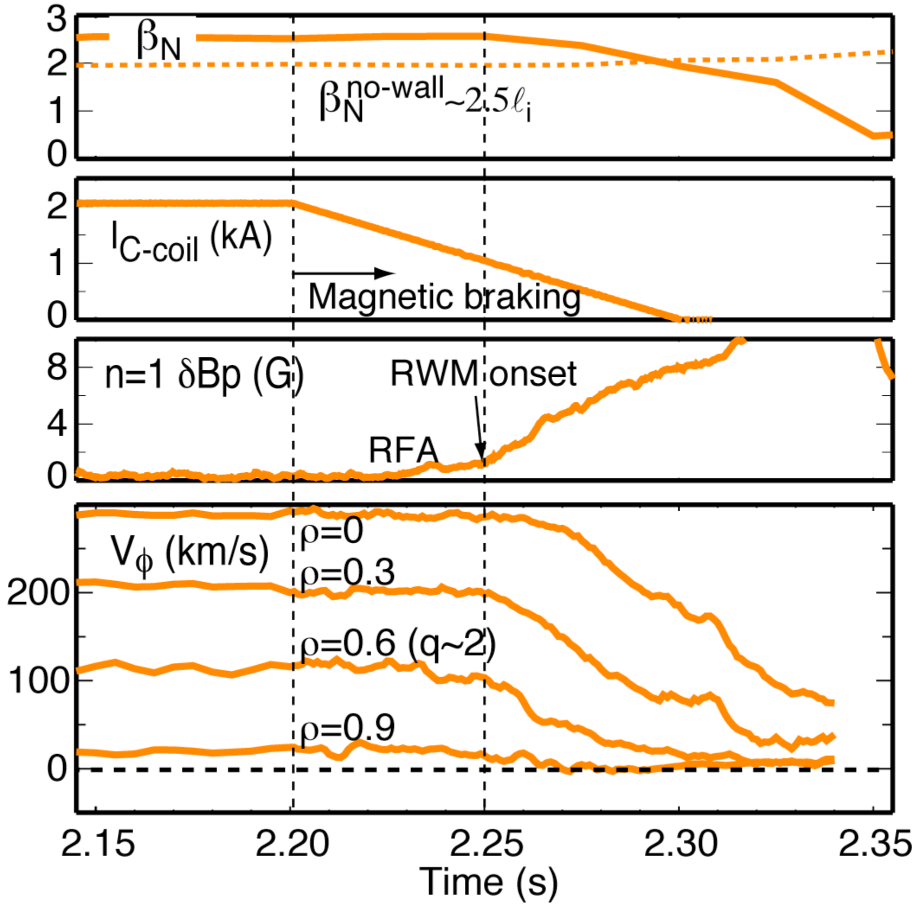
- **Until recently, it was believed that RWM stabilization required mid-radius plasma rotation ~O(1%) of the Alfven frequency, Ω_A**
  - This level of rotation may not be realized in ITER
- **Recent experiments using balanced neutral beam injection (NBI) in DIII-D and JT-60U show that the plasma rotation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



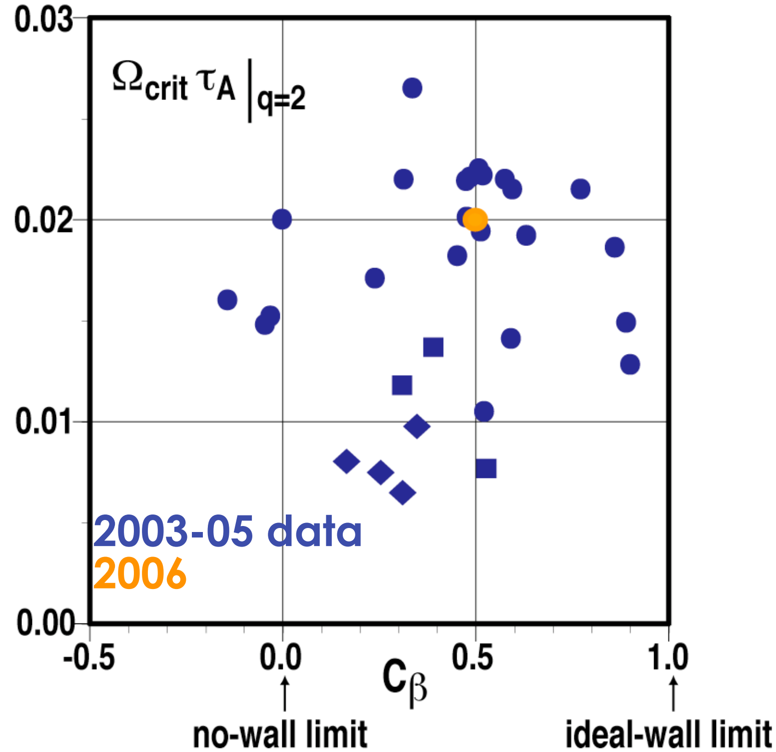


Previously, RWM Rotation Thresholds Were Measured Through Magnetic Braking by n=1 External or Intrinsic Fields

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

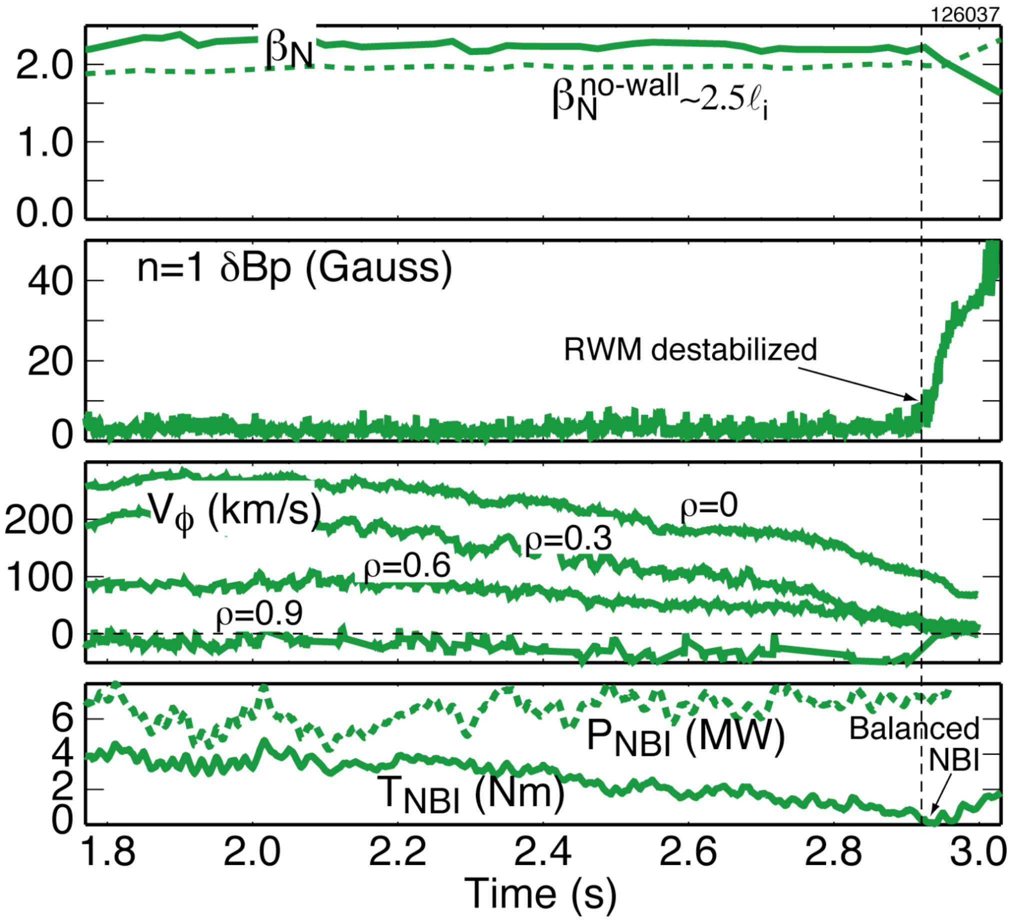


  - Critical rotation frequency Ω_{crit} at q = 2 surface ranges from 0.7 to 2.5% of local Ω_A



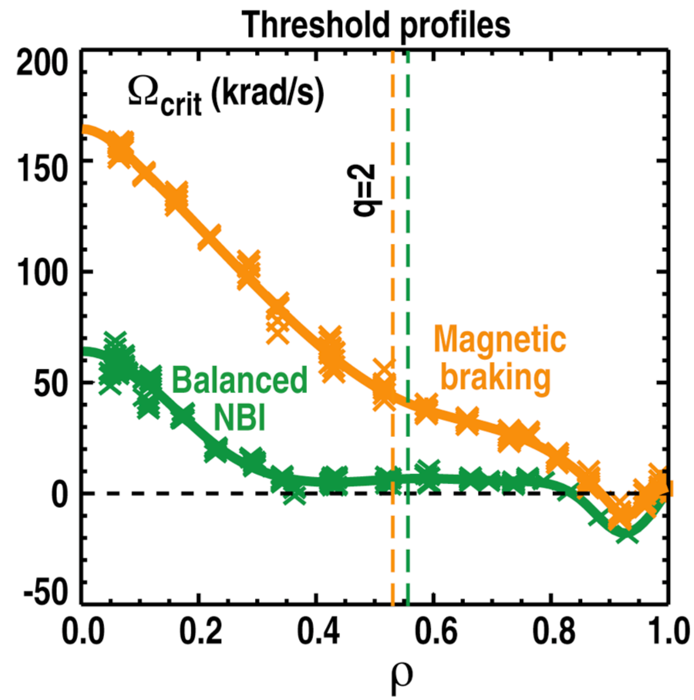
Much Slower Rotation Before RWM Onset is Observed by Reducing the Injected Torque With Minimized Error Fields

- **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



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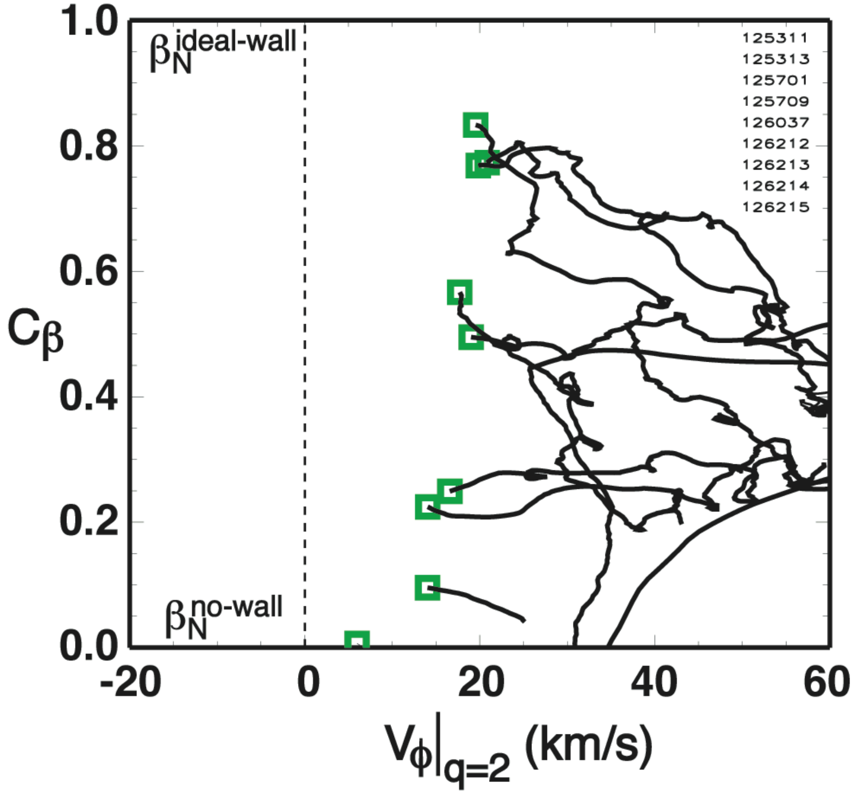
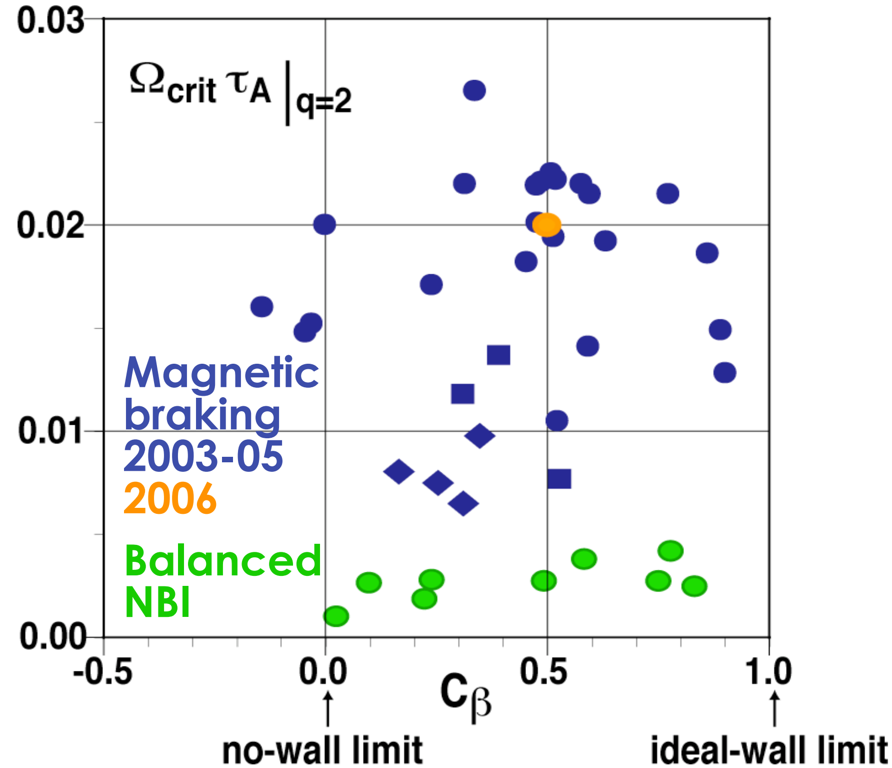
Weak β-Dependence is Observed for Rotation Thresholds Measured With Minimized Error Fields





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

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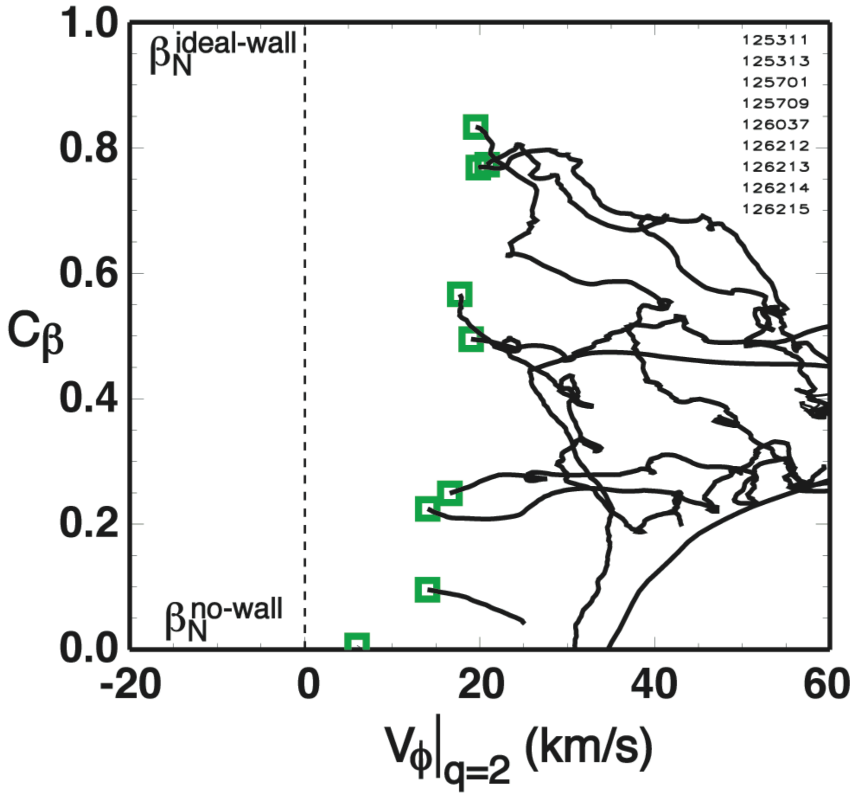
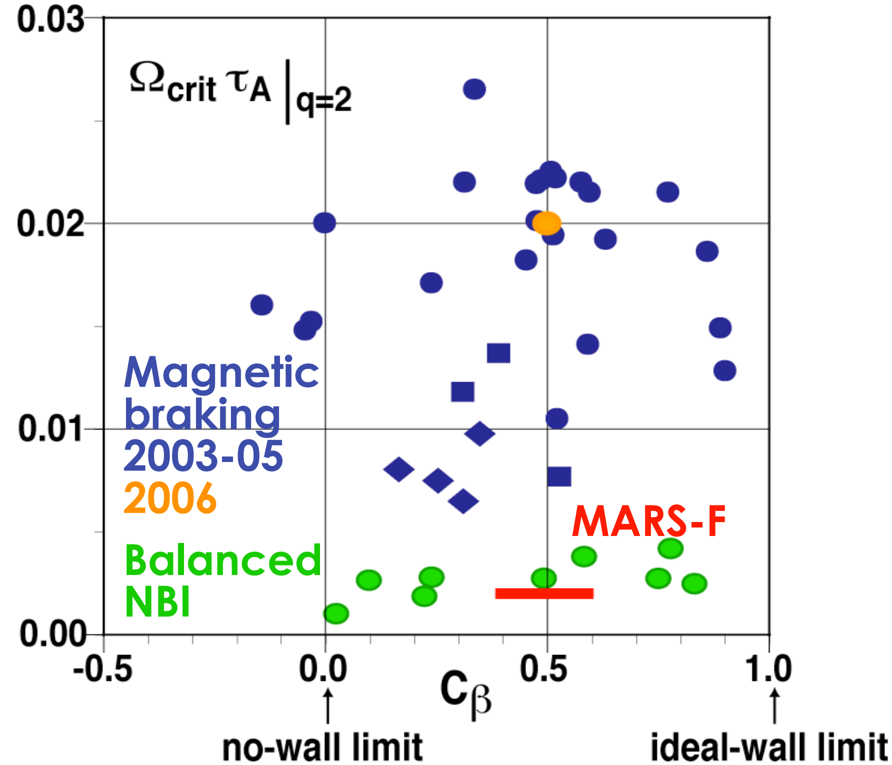
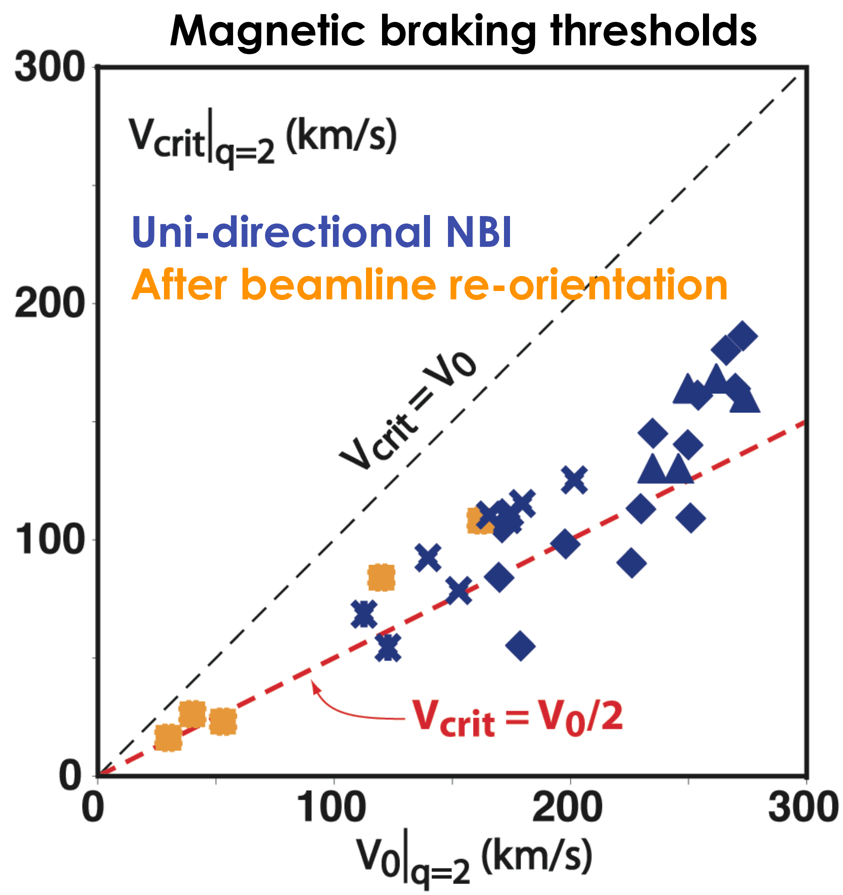




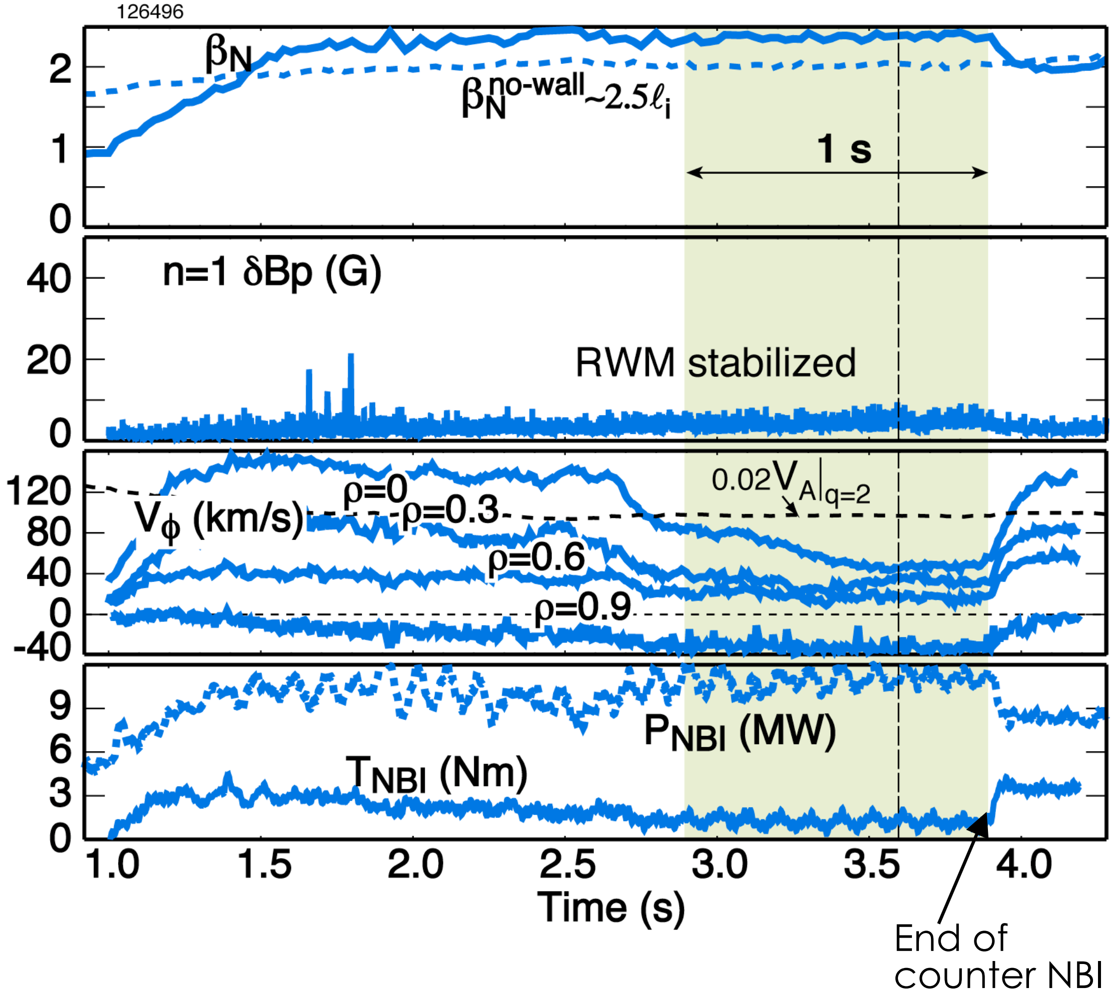
- RWM onset (❐) observed when V_ϕ at *q*=2 is ~10-20 km/s, or ~0.3% of local V_A
- Ideal MHD with dissipation implemented in MARS-F (kinetic damping model [Bondeson and Chu]) predicts slow rotation threshold for balanced NBI plasmas

High Threshold Measured With Magnetic Braking May Correspond to Entrance Into Forbidden Band of Rotation

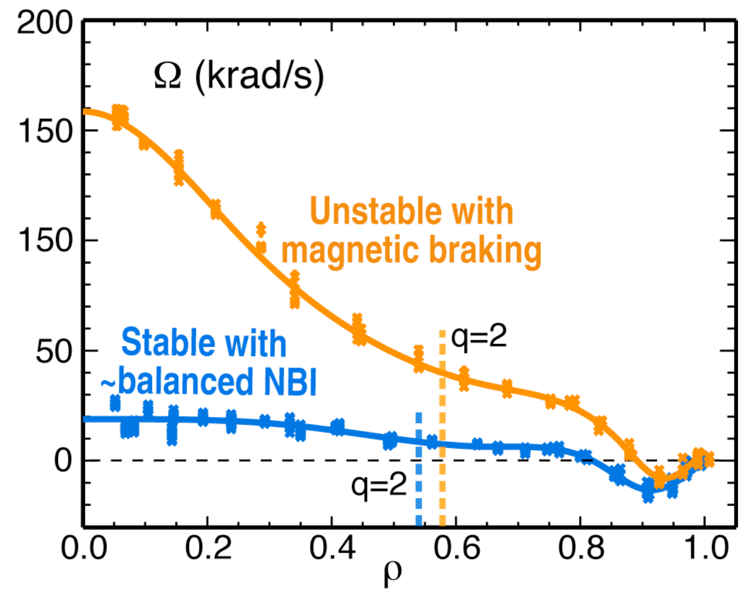
- **Increasing static non-axisymmetric field leads to bifurcation in torque-balance equilibrium of plasma**
  - Rotation must jump from a high value to essentially locked
- **"Induction motor" model of error field-driven reconnection [Fitzpatrick]:**
  - Plasma rotation at critical point, V_{crit}~1/2 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**



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



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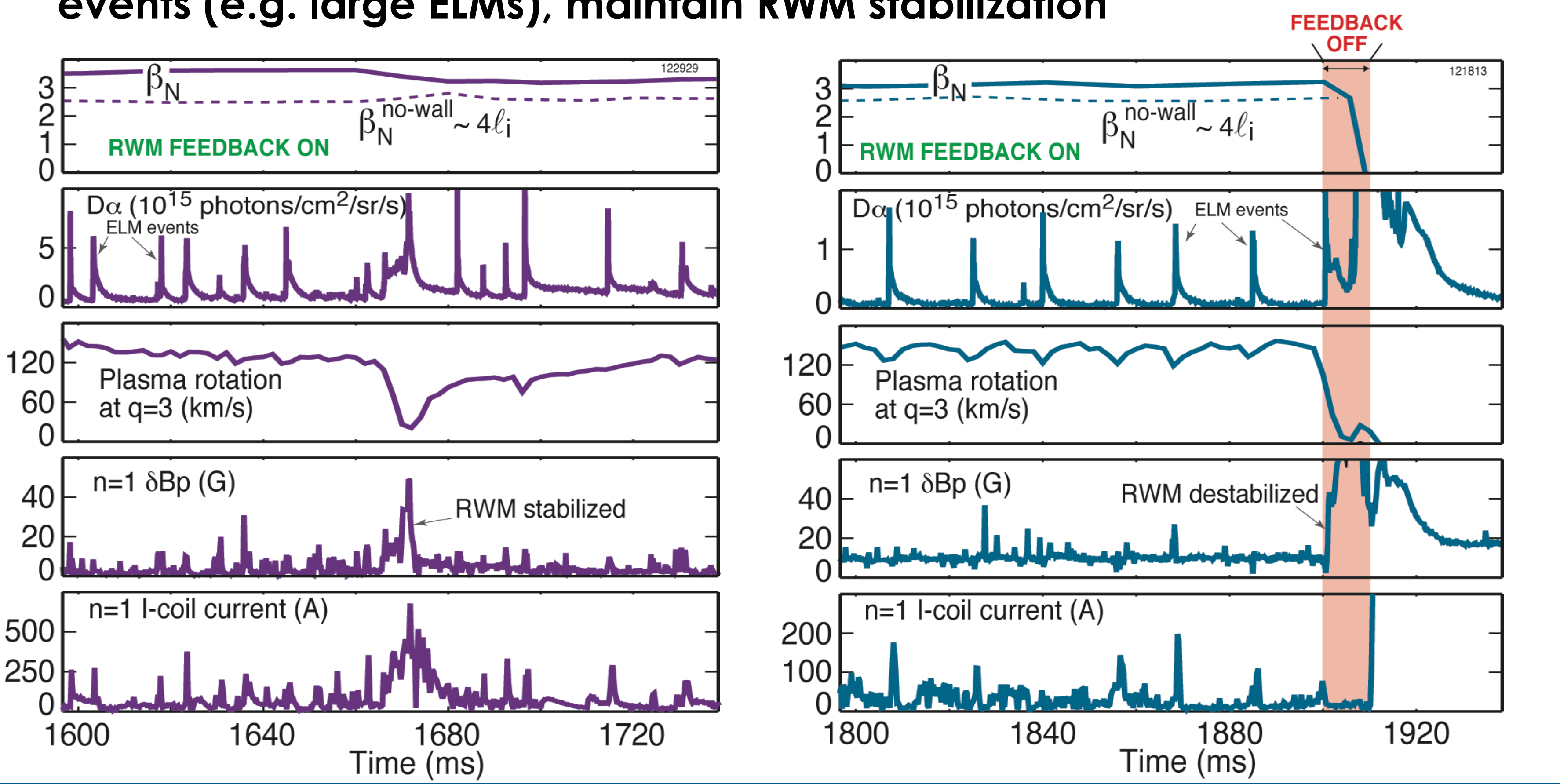
In High Performance Plasmas, Active RWM Feedback Is Required

- **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**



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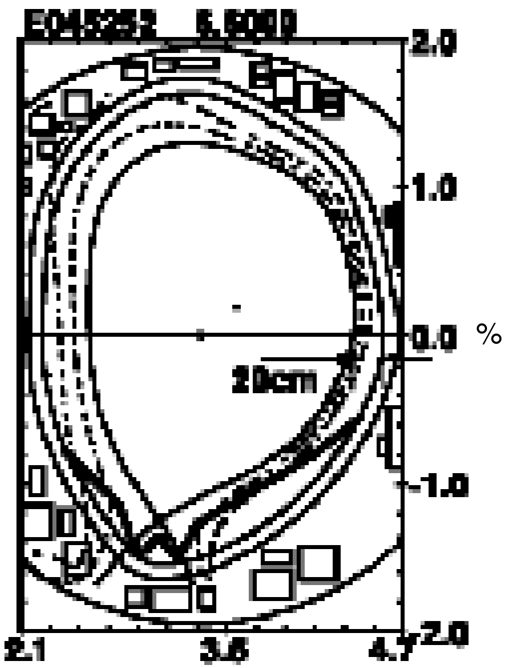
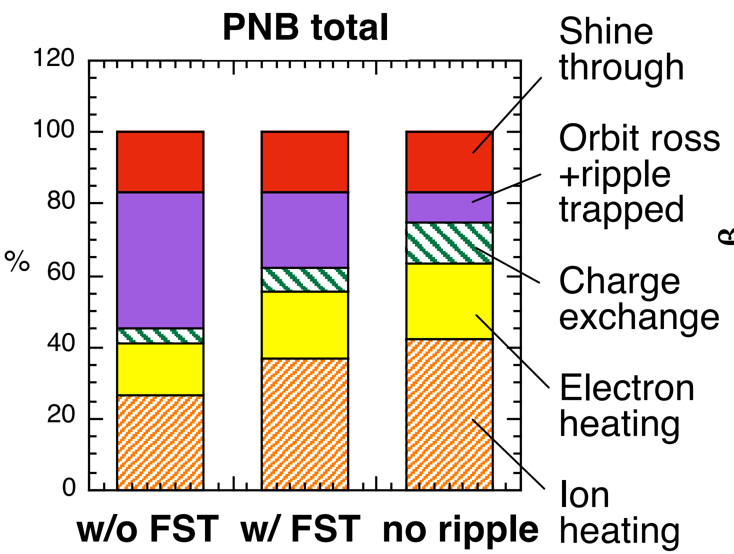
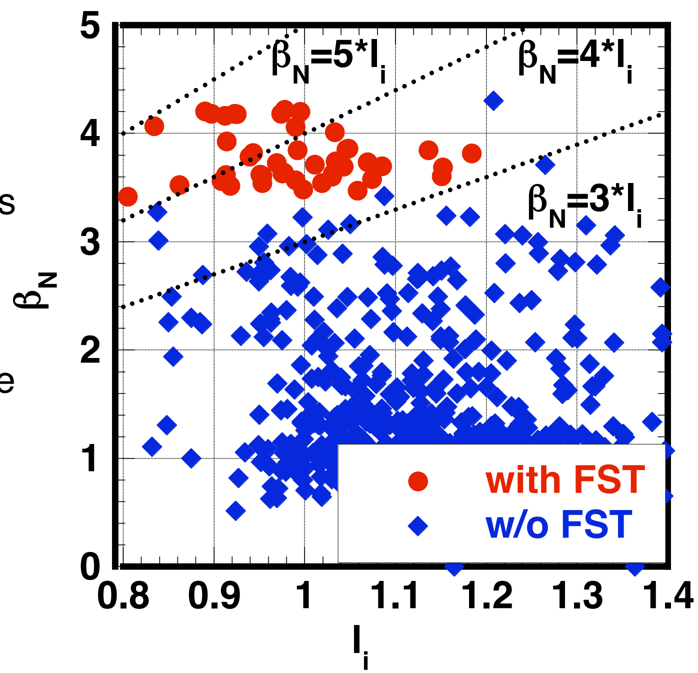
Ferritic Steel Tiles (FST) lead to high beta on large JT-60U plasmas

JT-60U

- Before installing ferritic steel tiles, few large plasmas reached the ideal beta limit, however it is difficult to exceed it due to lack of NB power.
- The net NB power with FST is 1.34 times larger than that w/o FST due to reduction of ripple loss.
- Increase net power of ~3.5 MW corresponding to 2 tangential beams.
  - --> Change rotation by one-way tangential NB injection.
- Achieved high β_N~4.2 exceeding ideal limit at l_i<1.2 and V_p>70m^3 (β_N~3.4 w/o FST).



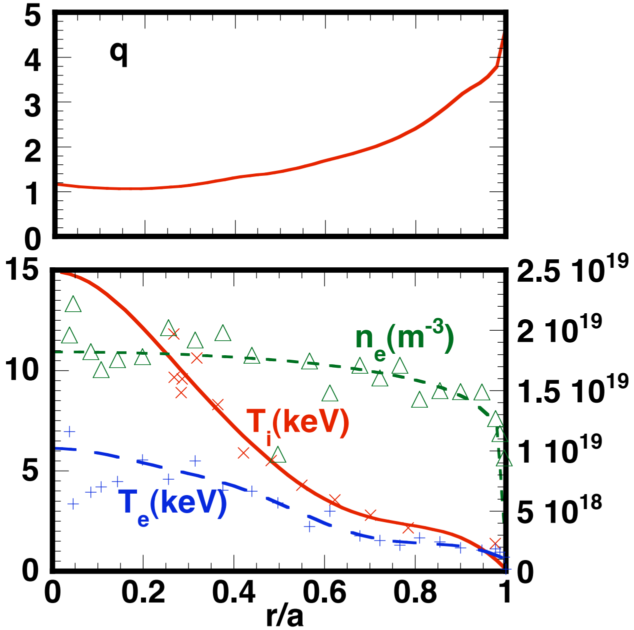


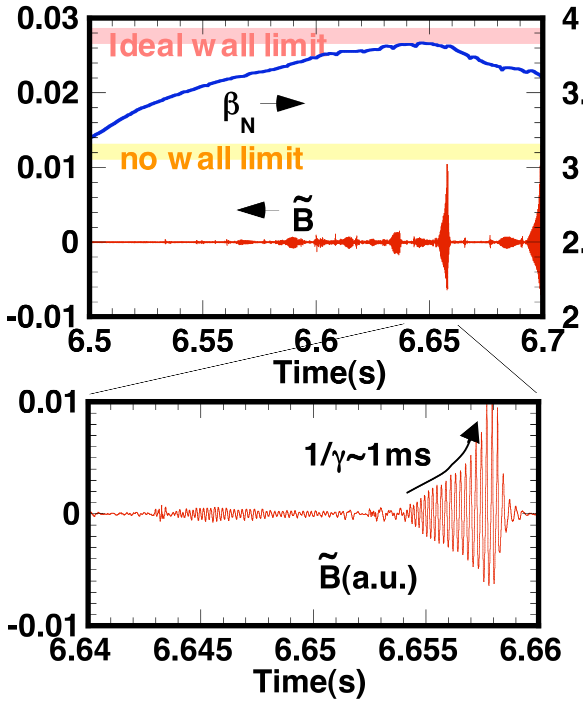


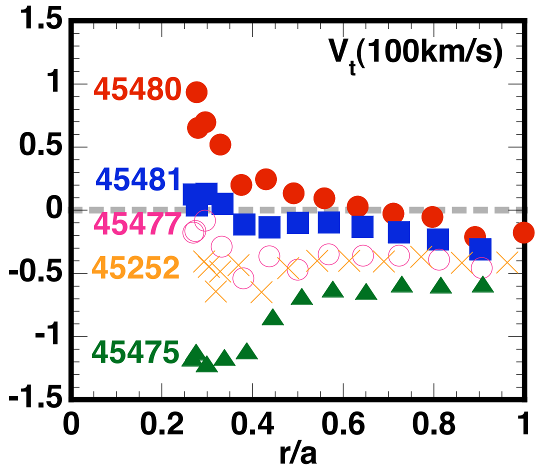
β_N is restricted by the MHD instability

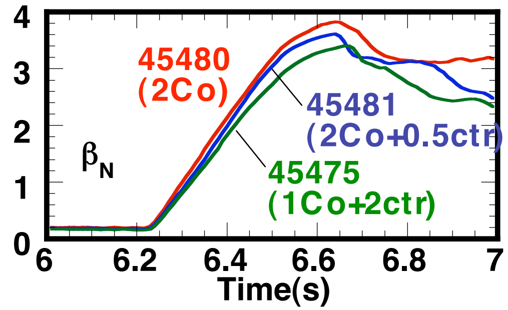
JT-60U

- B_t=1.575, I_p=0.9MA, q_{min}~1.1, q_{95}~3.5,d/a~1.2
- High β_p-H mode plasma (ITB&ETB)
- The n=1 (m~3) mode appears at high beta region.
- The mode grows with growth time $1/\gamma$ ~1ms before collapse.
- Frequency of the mode is ~1-5 kHz
- Highest beta is obtained with co-rotation
- Confinement is best for the co-rotation plasma



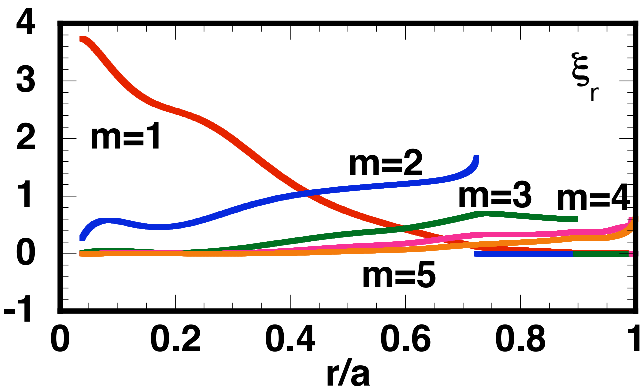


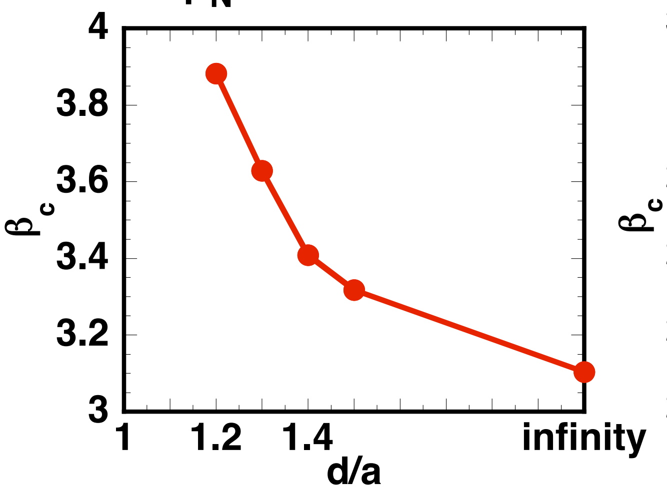


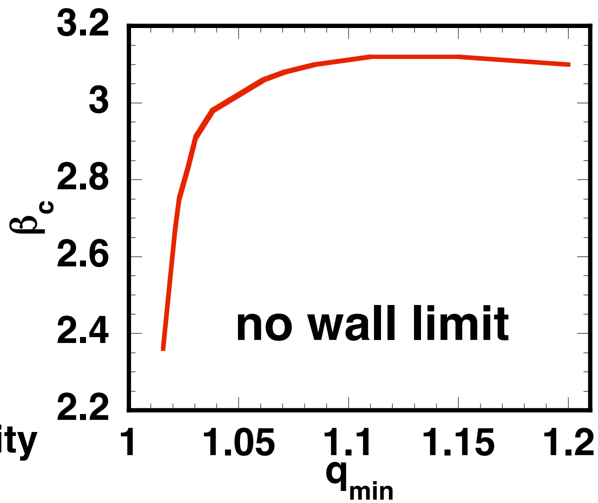


β_N is determined by the ideal wall limit. (MARG2D code)

- The dominant poloidal component is m=1 due to strong ITB at r/a~0.2.
- The mode is stabilized by the wall and ideal wall limit is β_N~3.9 for the plasma at d/a=1.2 when no wall limit is β_N~3.1.
  - -->Beta reaches ideal wall limit
- Current profile is determined by competition between current diffusion and increasing bootstrap current
- Small q_{min}(~1.0) for small and ctr rotation plasmas due to small bootstrap current.
  - --> Critical beta decrease at q_{min}<1.1. (q_{min}~1.08 at highest beta plasma).
  - --> Small ideal wall limit.
- The critical beta is affected by the peripheral plasma current.
  - --> Small current ramp down before NB injection to reduce edge current.
  - -->Achieved highest beta β_N~4.2.

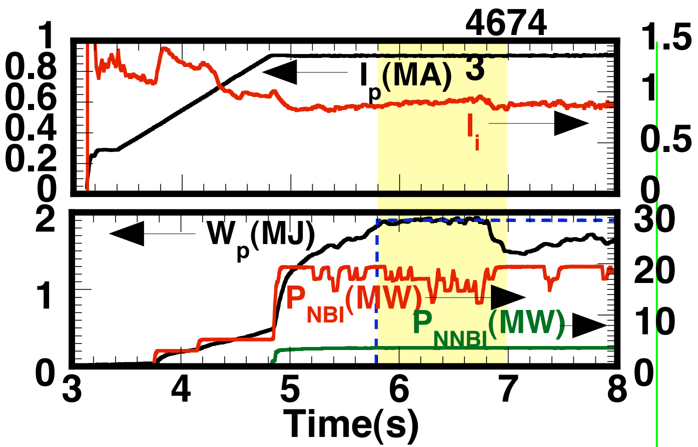


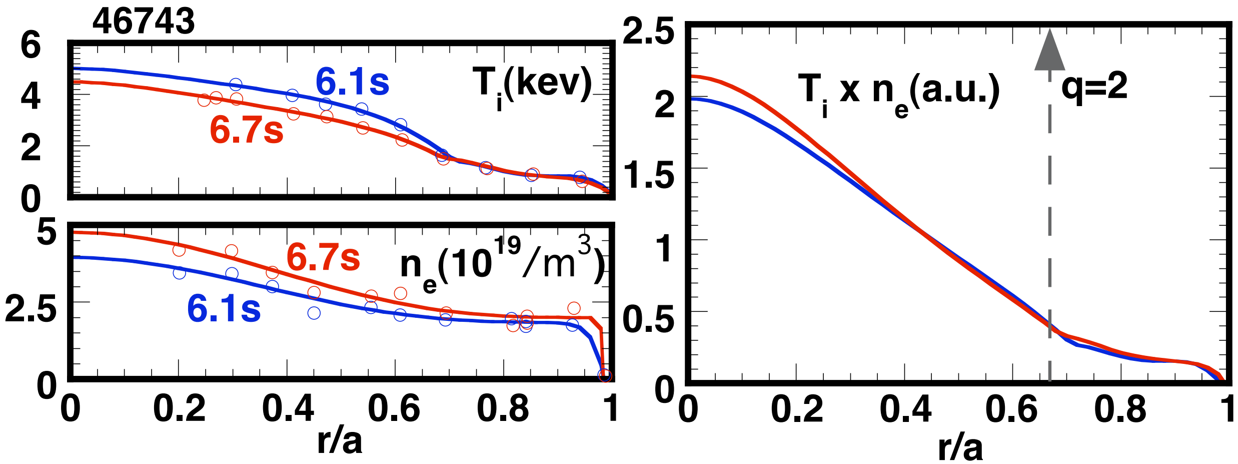


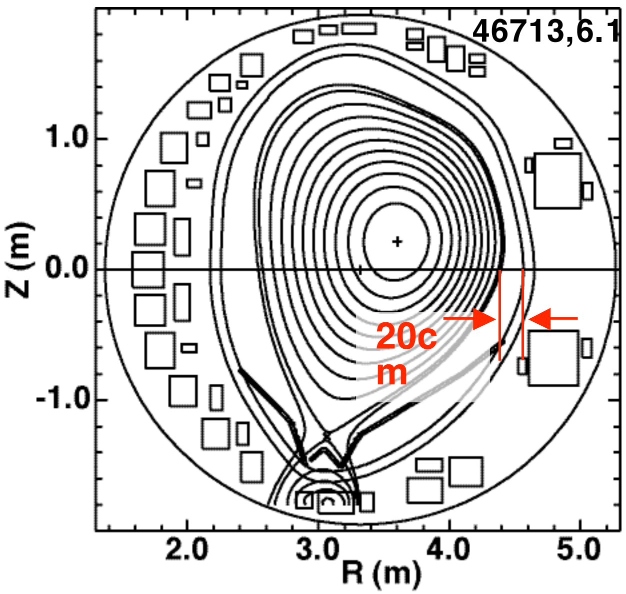


RWM experiment for critical rotation

- B_t=1.575 T, I_p=0.9 MA, q_{min}~1.2, q_{95}~3.5
- d/a~1.2
- To increase q_{min}, pre-NB is injected during current ramp up
- β_N is kept constant and change the tangential NB from ctr-NB to co-NB.
- Pressure and current profile is also kept constant



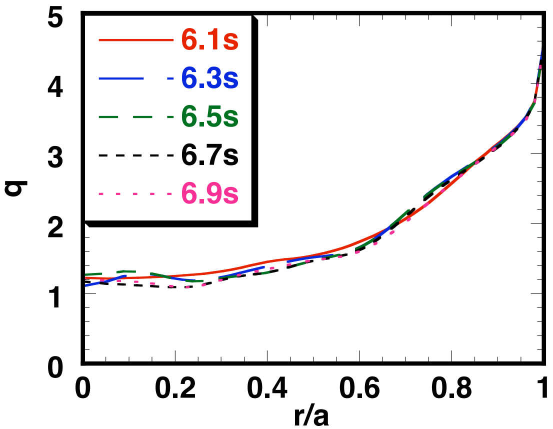


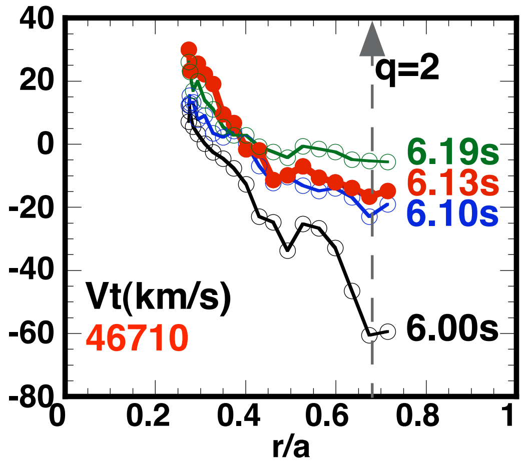


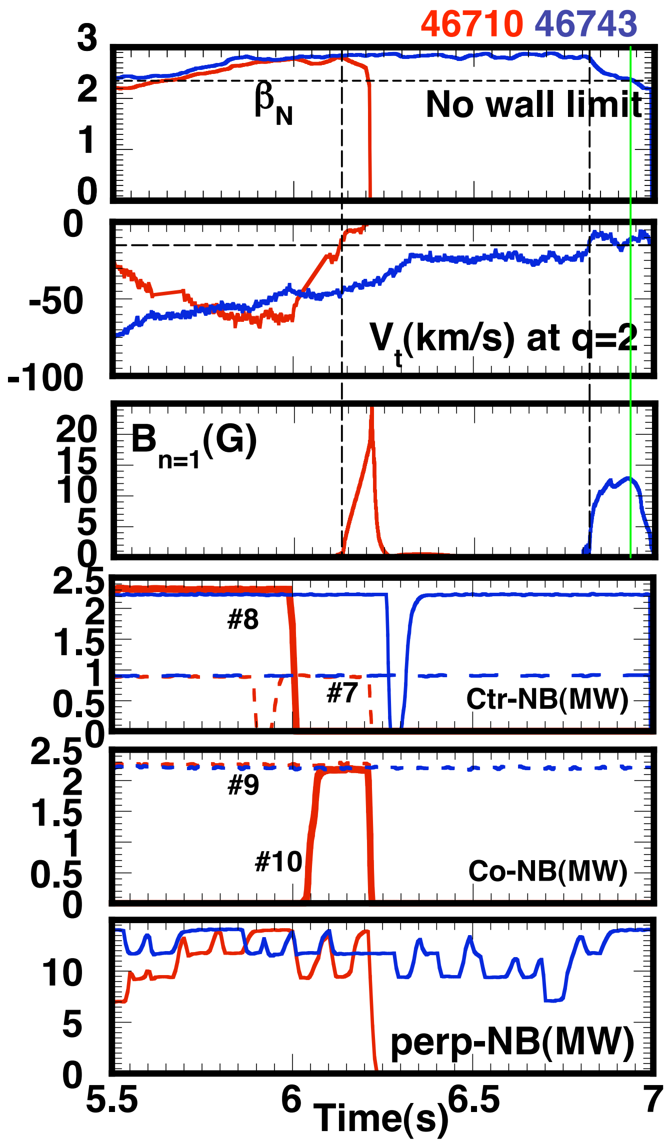
RWM is suppressed by plasma rotation

JT-60U

- β_N is kept constant and change the tangential NB from ctr-NB to co-NB.
- Rotation can be controlled by changing tangential NB combination
- Disruption or collapse occurs at Vt~10 km/s ->n=1 mode grow with 1/γ ~10 ms .
- The mode suppressed after $\beta_N < \beta_{N\ \text{no-wall limit}}$
- To investigate the effect of beta on critical rotation, we change the constant β_N.

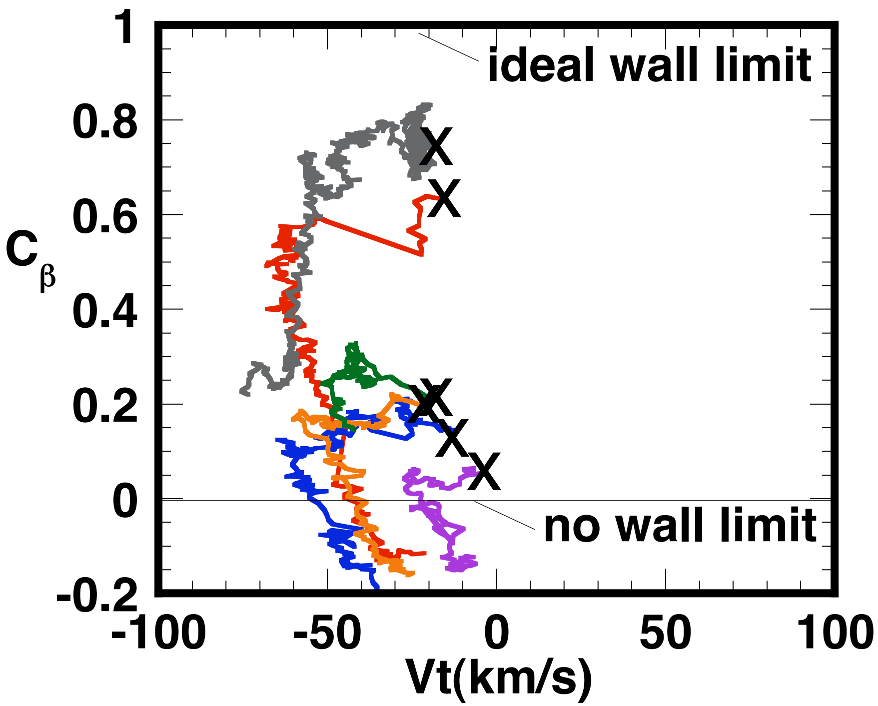


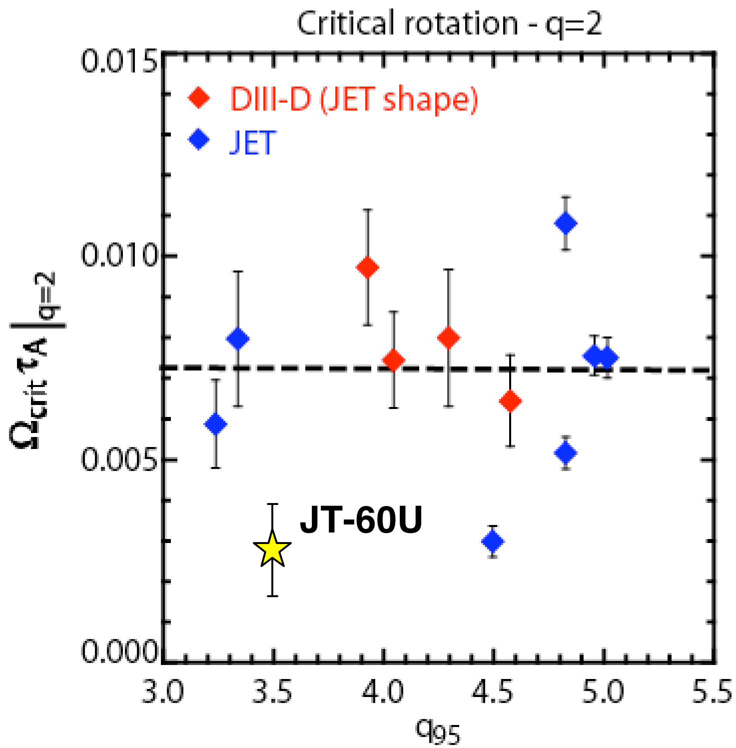




Critical Rotation

- Critical rotation V_c ~5-20km/s
- V_c/V_A~0.3% (q_{95}~3.5) is much smaller than previous DIIID and JET results using magnetic braking
  - Indicating importance of error field?
- V_c does not increase as C_β increase





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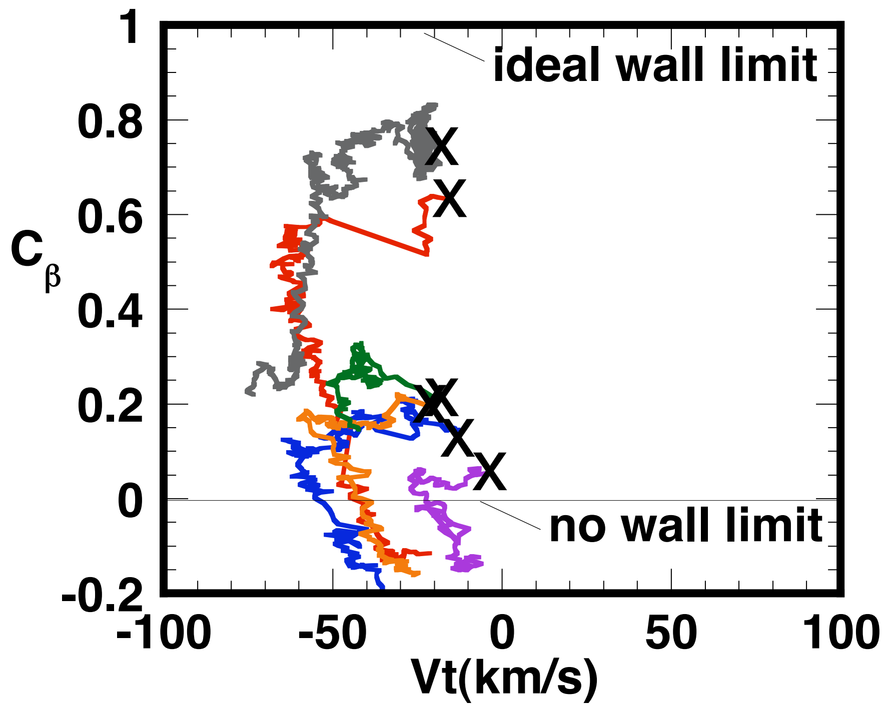
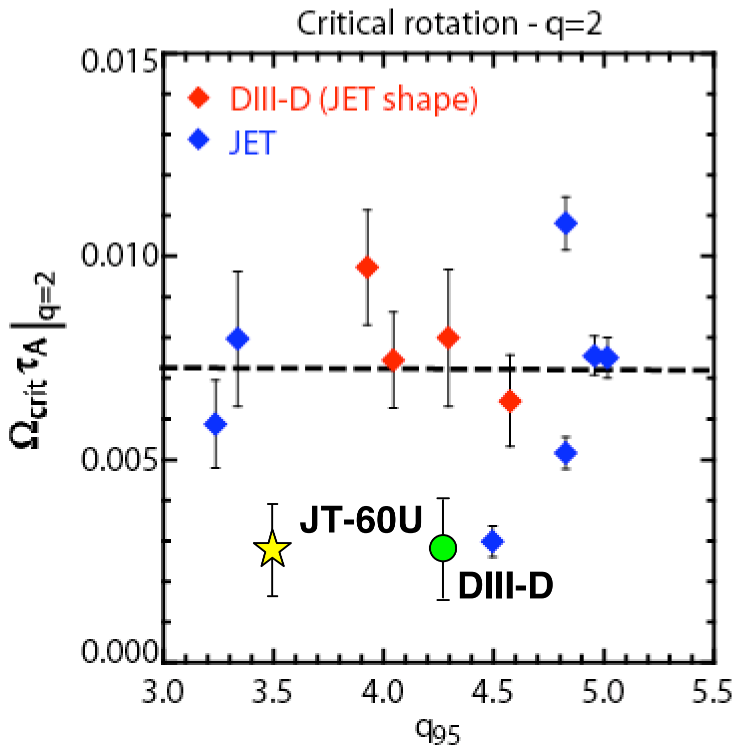
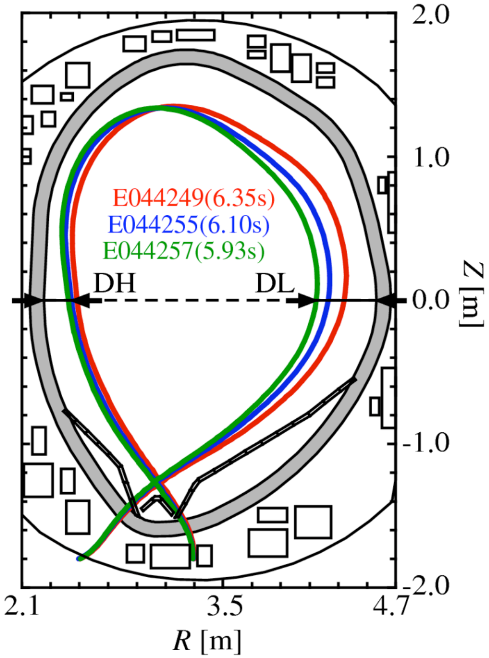


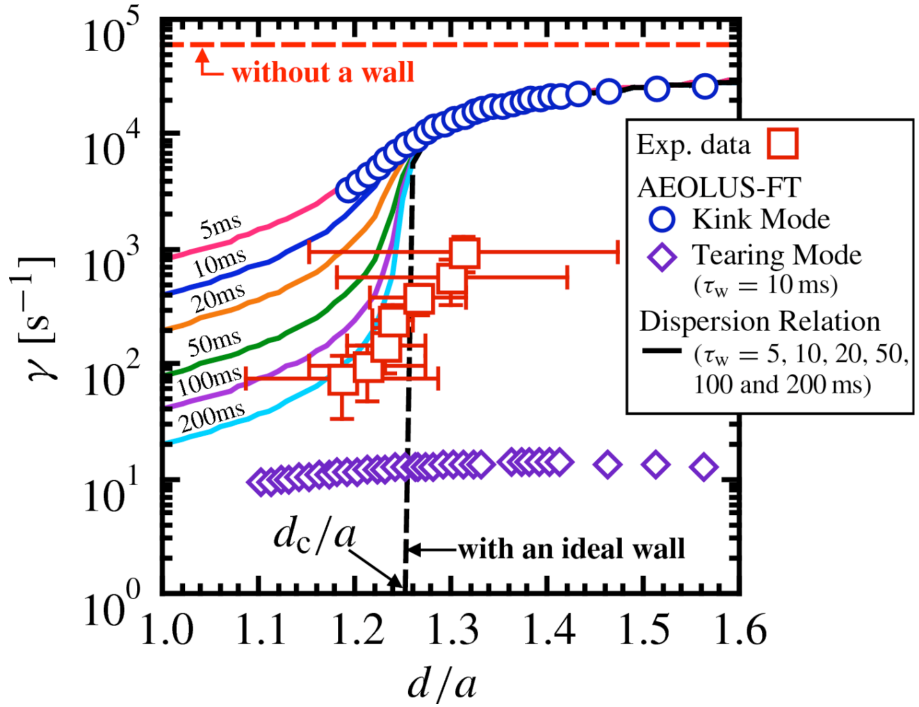


Current driven RWM experiment for wall effect

Experimentally obtained growth rates are consistent with RWM, wall stabilization effects were observed

- **AEOLUS-FT, which can take into account the resistivity of the wall, found 3/1 kink and 2/1 tearing branches.**
- **These modes have been observed in the region where the ideal MHD mode with ideal wall is stable.**
- **From the strong dependence, the observed modes can be identified as RWM.**





New Hardware Capabilities Allow Simultaneous Discovery of Low RWM Rotation Thresholds in DIII-D and JT-60U

- **The plasma rotation needed for RWM stabilization is much slower than previously thought –> $\Omega\tau_A$~0.3% in both tokamaks**
  - Achieved with neutral beam line re-orientation in DIII-D:
    - Balanced neutral beam injection –> lower injected torque and lower plasma rotation with minimized non-axisymmetric fields
  - Achieved with ferritic steel tiles in JT-60U:
    - Reduced ripple loss –> higher confinement and higher β with smaller plasma-wall separation
  - Such a slow rotation should be achievable in ITER
- **Ideal MHD with dissipation (MARS-F with kinetic model) is consistent with new threshold rotation profiles for RWM stabilization**
- **Even with sufficient rotation, active RWM feedback in ITER likely needed, but system requirements could be reduced**
- **RWM stabilization allows demonstration of high performance tokamak regimes (β_N~4)**

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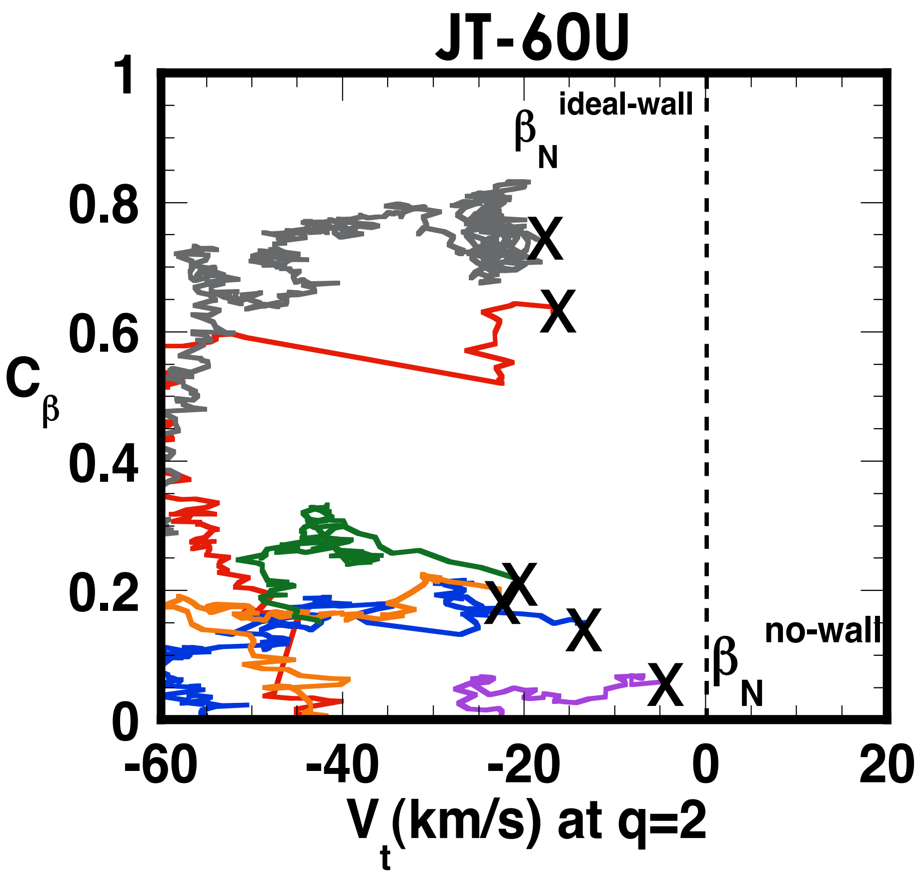
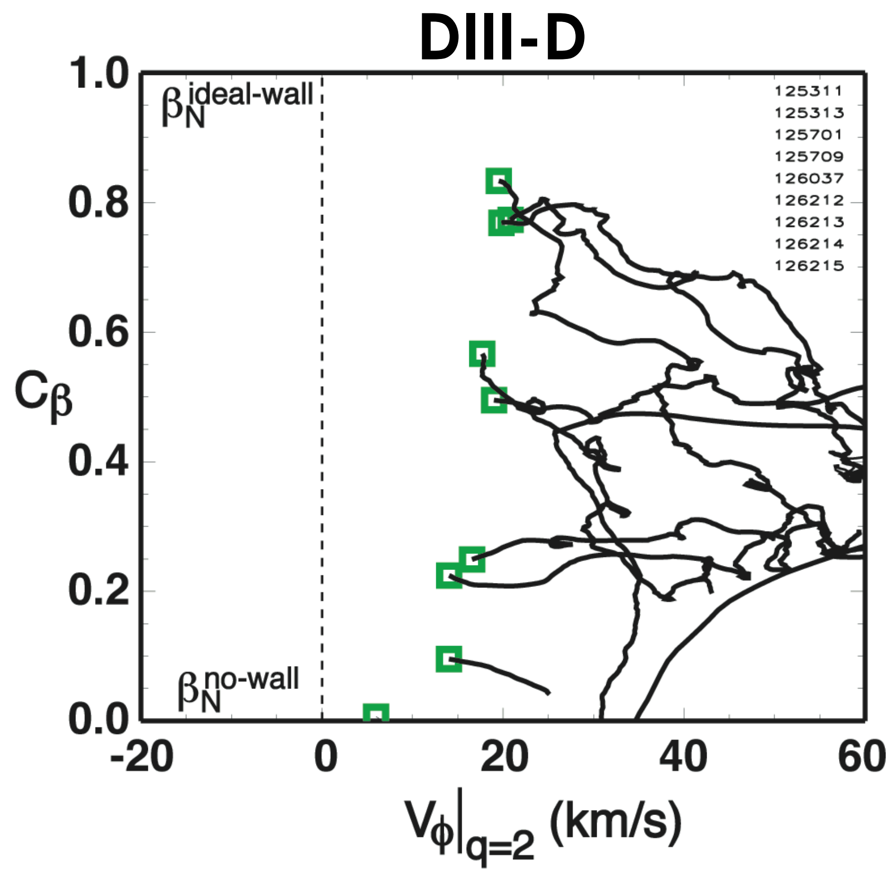
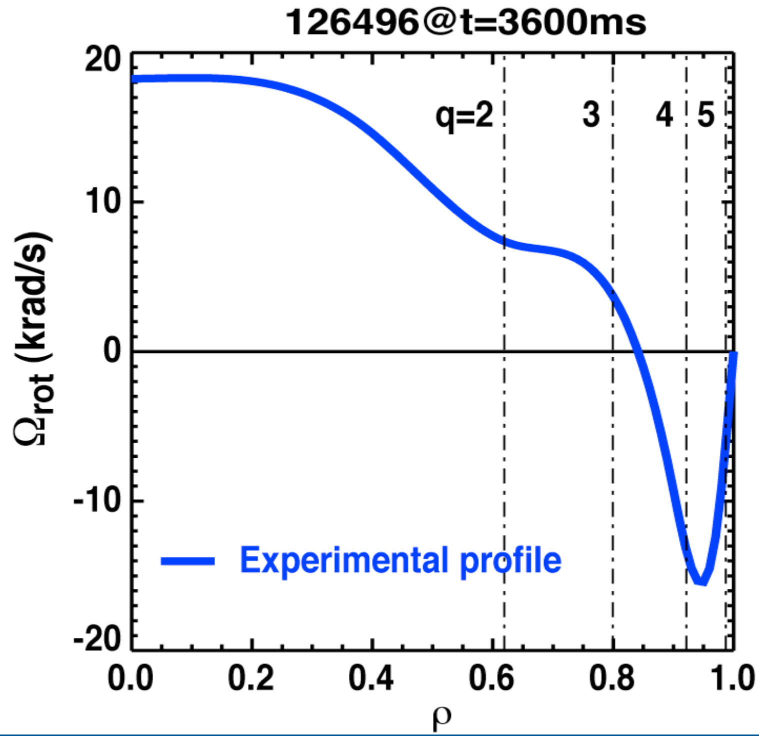
Independent, Simultaneous Discovery of Low RWM Rotation Thresholds in DIII-D and JT-60U

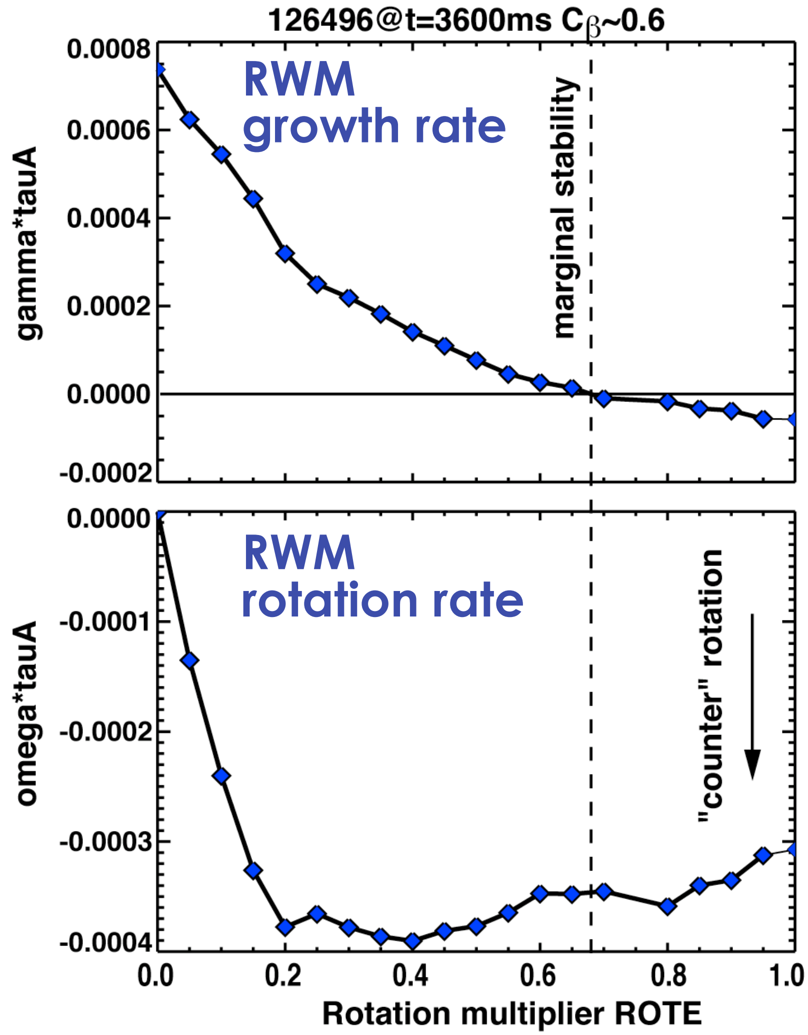




MARS-F Calculations Suggest Dominant Effect of Edge Plasma Rotation

- **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**





What Is the Right Criterion for Marginal Stability?

- **Rotation at q=2 surface: previously, kinetic damping model always underestimated rotation threshold**
  - Predicted both slow and fast thresholds (strong variation between scenarios)
- **Predictions are more uniform across scenarios if criterion is broadened to include all rational surfaces, weighted by q^2**

$\Omega_{crit}\tau_A$	q=2	q=3	q=4	q=5	$\Sigma\vert\Omega_{crit}\tau_A\vert_k$	$\Sigma\vert\Omega_{crit}\tau\vert_k q_k$	$\Sigma\vert\Omega_{crit}\tau_A\vert_k q_k^2$
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	0.0045	0.0013	0.0012	0.0006	0.0044	0.0086	0.0236
σ / mean	78%	72%	86%	120%	47%	36%	32%

"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 non-axisymmetric field 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**