Dependence of Confinement and Stability on Variations in the External Torque in the DIII–D Tokamak

by
T.C. Luce[£]

for
K.H. Burrell,[£] R.J. Buttery,[‡] J.C. DeBoo,[£] J.R. Ferron,[£]
A.M. Garofalo,[*] P. Gohil,[£] D.A. Humphreys,[£] G.L. Jackson,[£]
R.J. Jayakumar,[§] J.E. Kinsey,[¶] R.J. La Haye,[£] G.R. McKee,[#]
M. Okabayashi,[†] C.C. Petty,[£] P.A. Politzer,[£] H. Reimerdes,[*] D.J. Schlossberg,[#]
J.T. Scoville,[£] M.W. Shafer,[#] W.M. Solomon,[†] E.J. Strait[£], F. Volpe[¢]

[£]General Atomics, San Diego, California.
[*]Columbia University, New York, New York.
[†]Princeton Plasma Physics Laboratory, Princeton, New Jersey.
[‡]EURATOM/UKAEA Association, Culham, United Kingdom.
[¶]Lehigh University, Bethlehem, Pennsylvania.
[§]Lawrence Livermore National Laboratory, Livermore, California.
[#]University of Wisconsin, Madison, Wisconsin.
[¢]Max Planck Gesellschaft, Germany.

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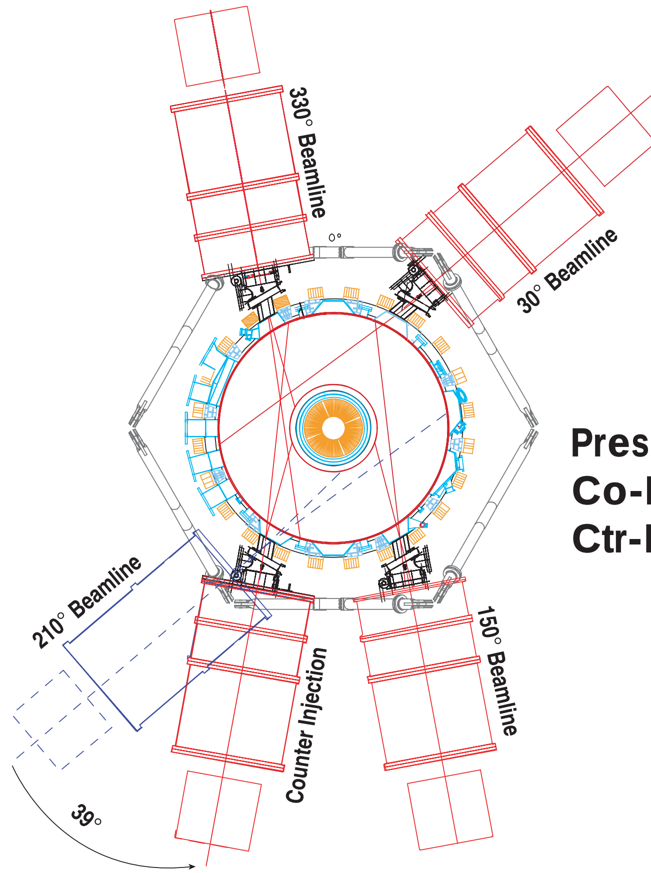
Reorientation of One Neutral Beam Line Allows Experiments to Test the Effects of Rotation on Confinement and Stability

- Effects on energy confinement (L-mode, H-mode, Hybrid)
- Measurements of momentum confinement
- Simultaneous control of rotation and stored energy
- Effects on the L-H transition power threshold
- Changes in tearing mode onset and saturated amplitude
- New insight into rotational stabilization of resistive wall modes

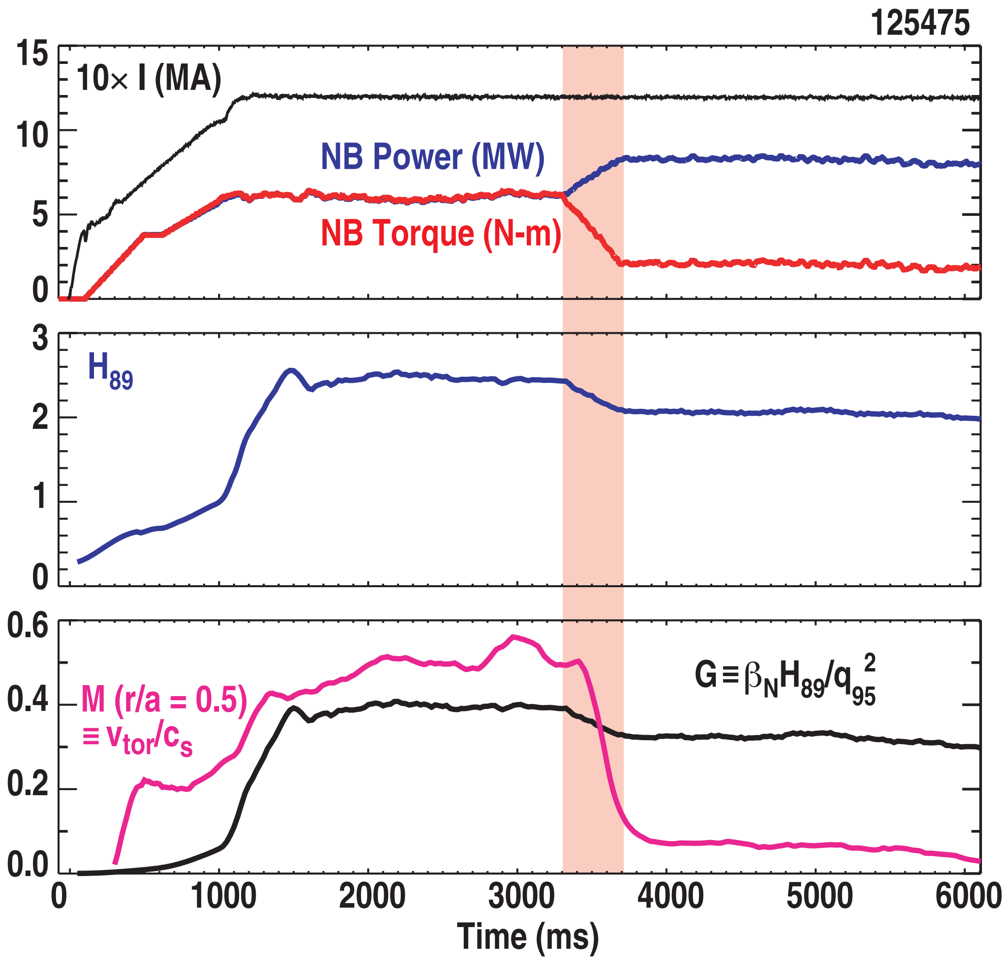
Plan View of DIII–D Tokamak



Present capability:
Co-NBI 12.5 MW
Ctr-NBI 5 MW

Caveat: Fueling and NBCD profiles also change. These effects must be factored into the conclusions

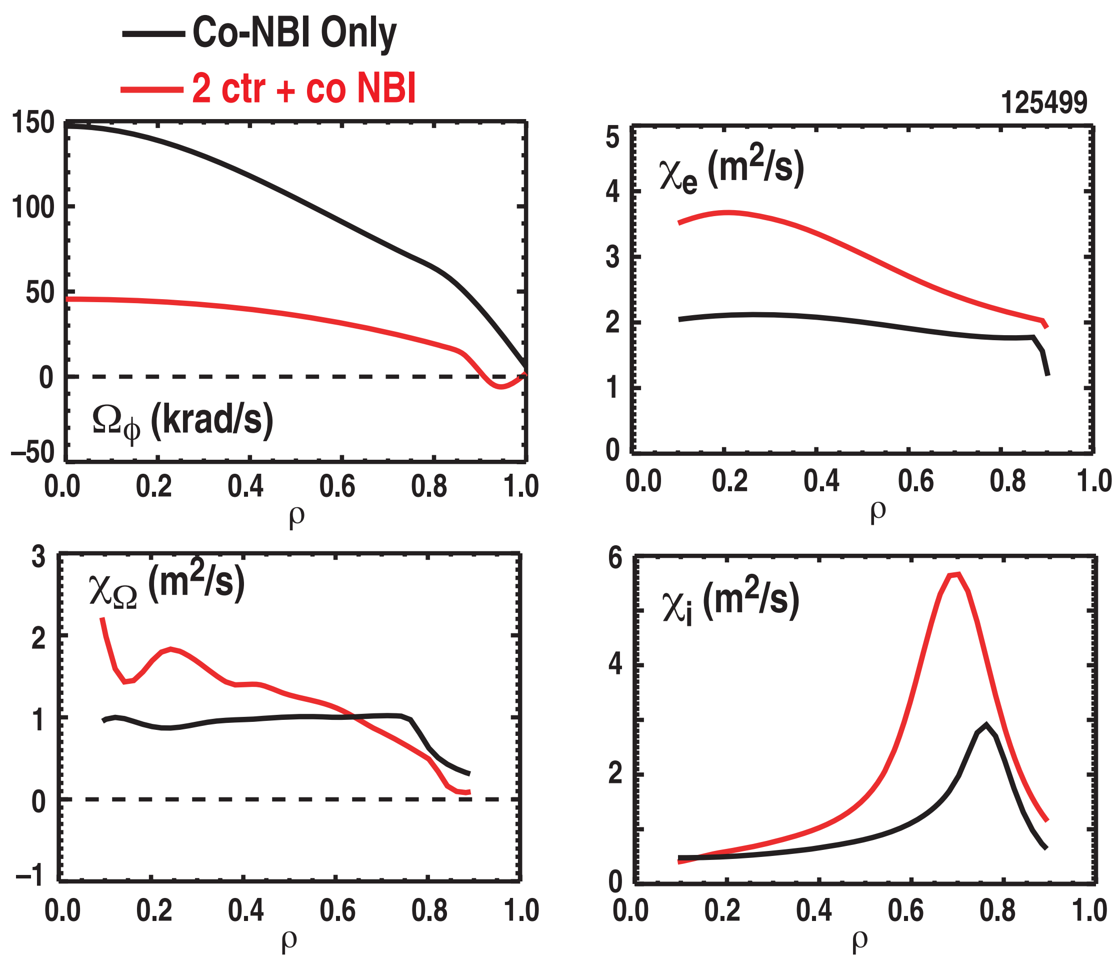
Hybrid Scenario Demonstrated at Low Rotation With Modest Reduction in Confinement



- Low rotation obtained with 1.5 ctr-injection sources + co-injection in feedback control ($\beta_N = 2.6$)
- Sawteeth do not appear ($q_{95} = 4.0$)
- Performance not yet optimized (pressure limit, lowest q_{95} without sawteeth)

Effect of Changes in Torque Seen Across the Entire Radial Profile

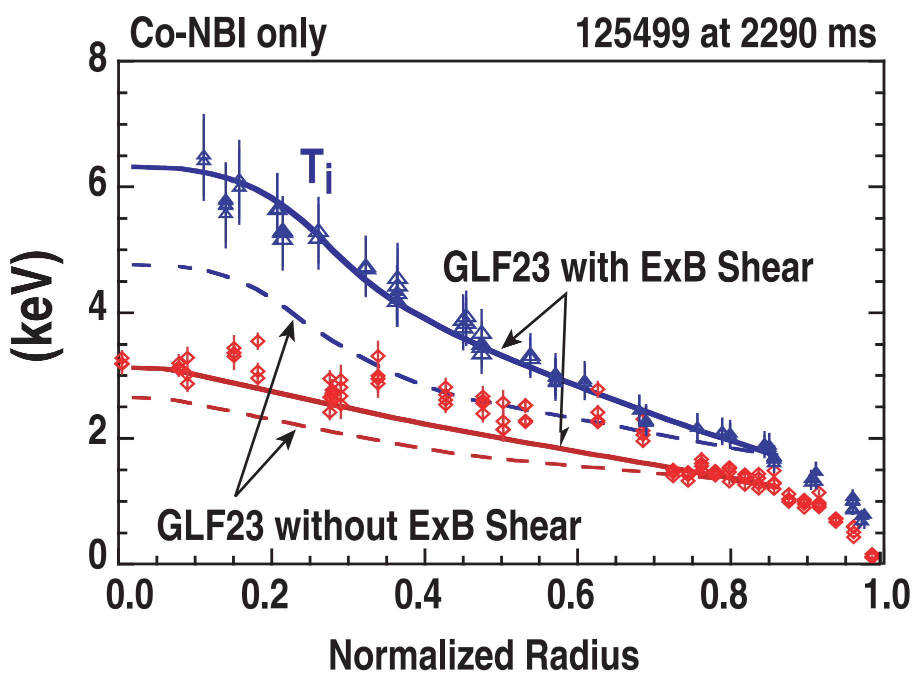
- Toroidal rotation changes at all radii
- Momentum transport ascribed exclusively to diffusive momentum flux

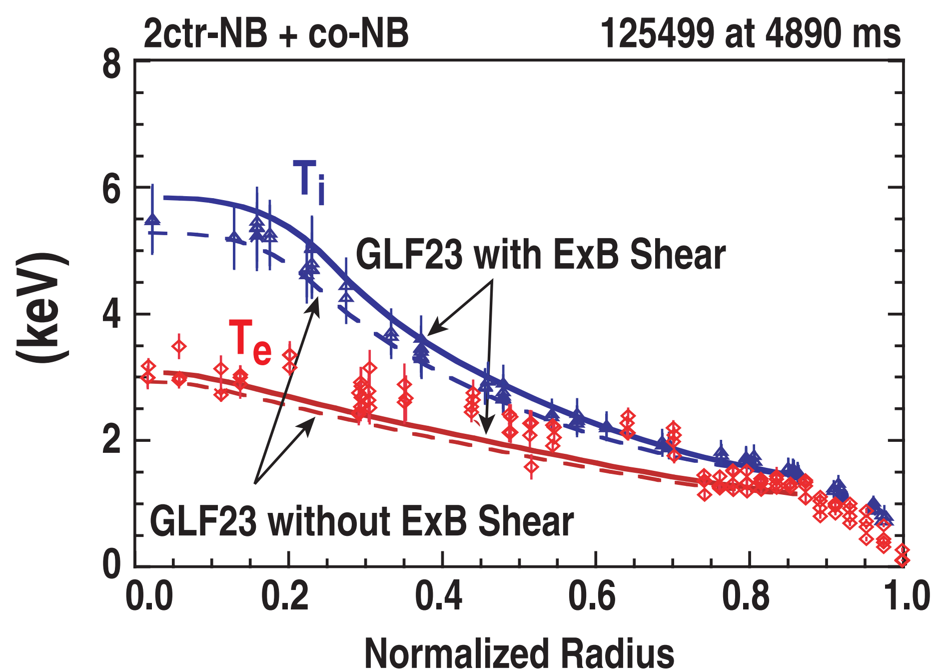


- Fractional increase in electron heat transport is highest in the center
- Fractional change in ion heat transport is highest around $\rho = 0.7$

Changes in E×B Shear Can Explain the Effect of Torque on Energy Confinement

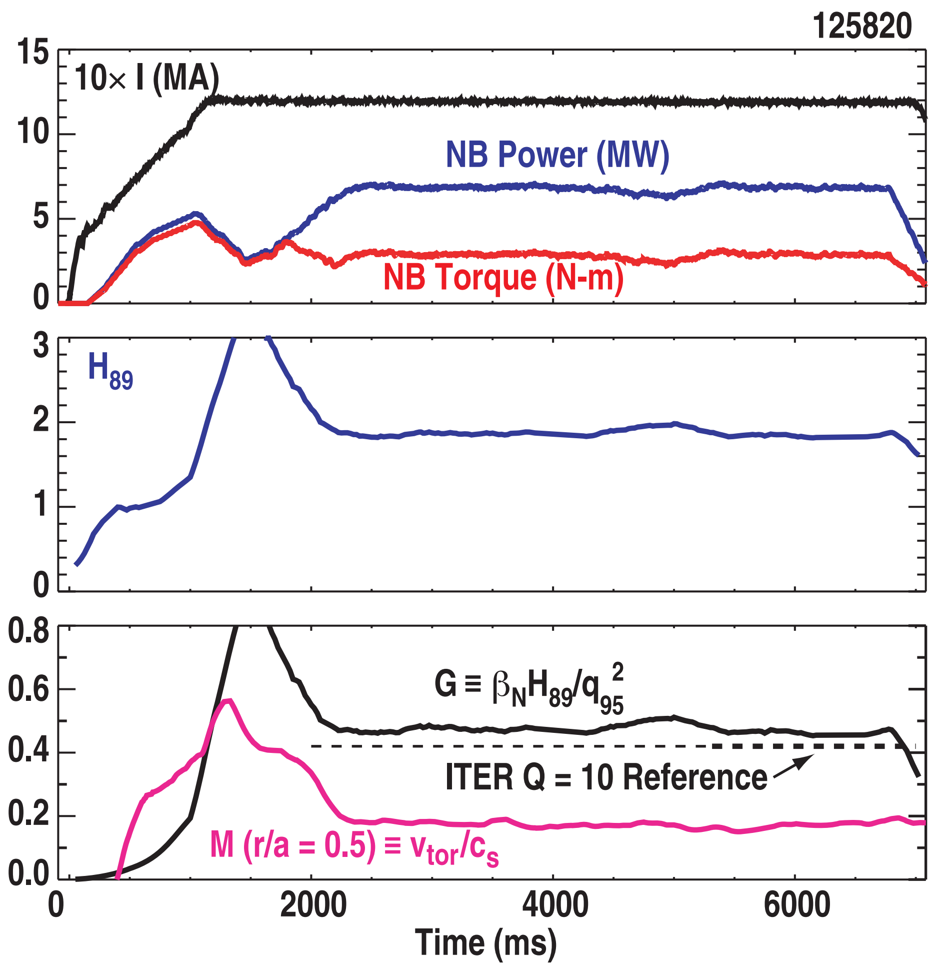
- With high toroidal rotation, E×B shear required in to reproduce measured profiles
- At low rotation, E×B shear is much less important





- Uses measured density, toroidal rotation, and current profiles

Advanced Inductive Discharges Achieve Conditions Consistent with Q > 10 in ITER With Low Rotation



- β_N = 2.7 (feedback controlled), q_{95} = 3.3
- Transition to low rotation occurs at the initiation of the high β_N phase
- High performance at low rotation maintained for > 4 τ_R
- Extrapolates to Q > 10 in ITER at 15 MA for several common scalings:

ITER89-P:	Q = 10.3
IPB98y2:	Q = 10.2
DS03:	Q = ∞ (even with 7% lower H_{DS03})

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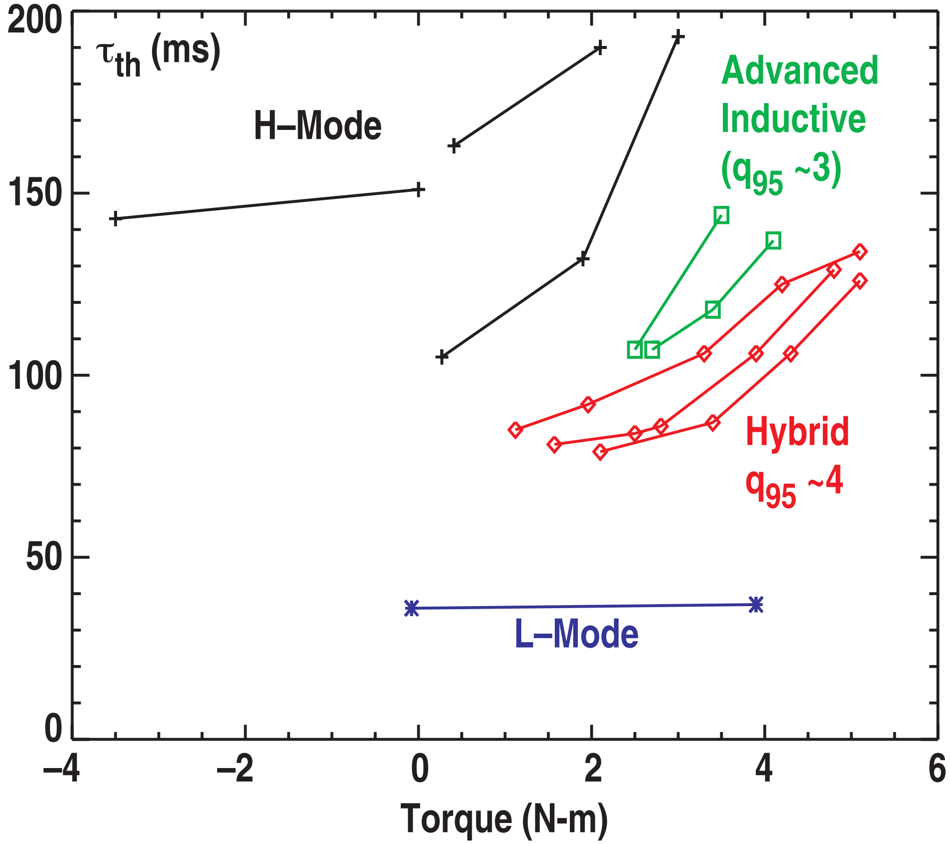
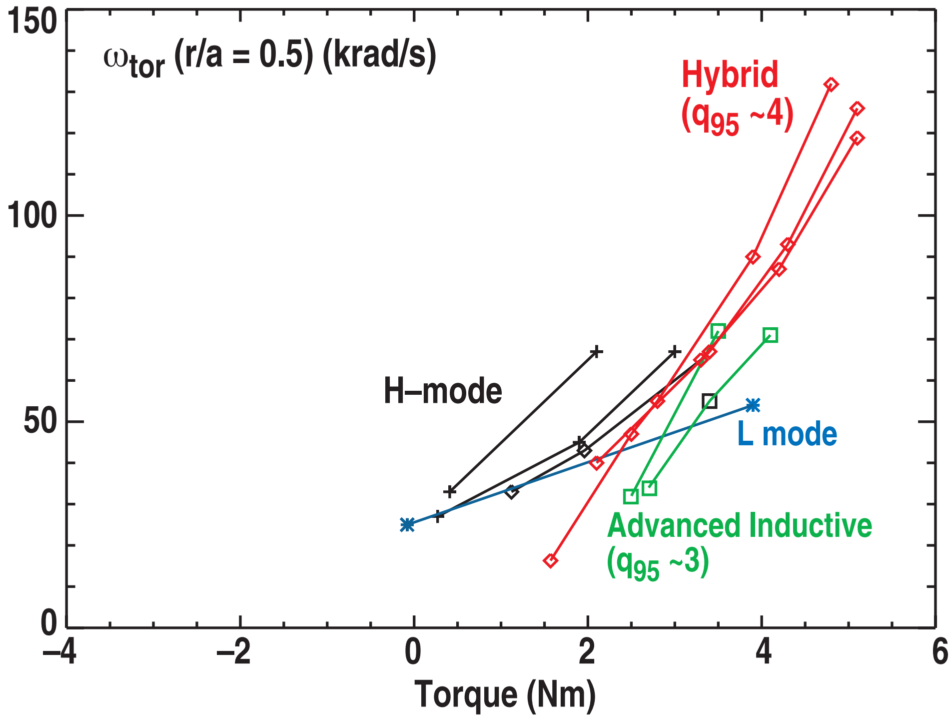
275-06/TCL/rs

Discharges With H–Mode Edge Show Significant Increase of Confinement With Increasing Torque



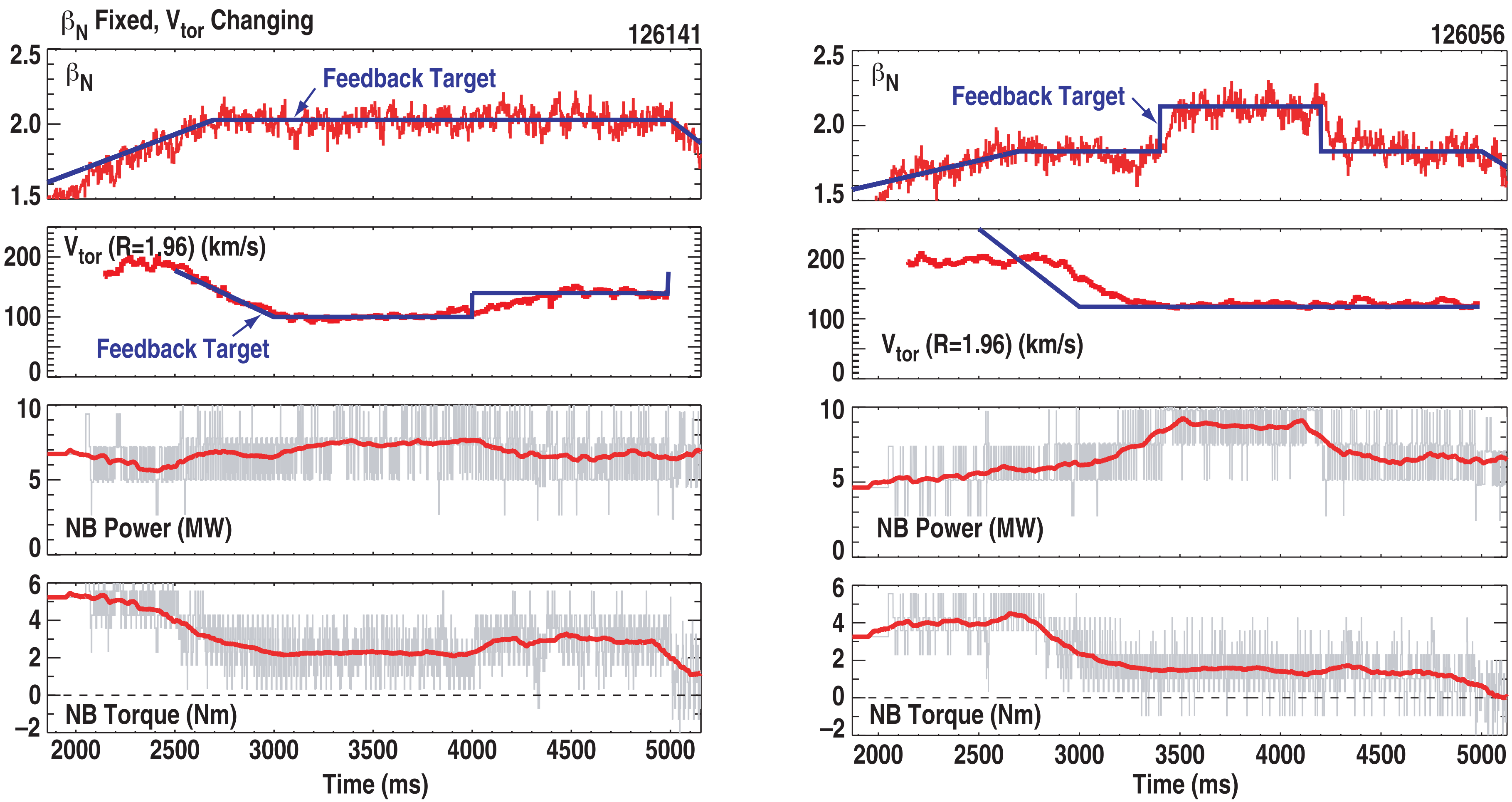
- **Points connected by lines are at constant field, current, density and pressure. Some parameters change between scans**
- **Scans in H–mode edge discharges show increases in confinement with increasing torque**
  - 50% improvement is much larger than expected prompt losses from ctr-injection
- **Adding torque in the counter current direction does not show similar improvement**
- **No variation of confinement with torque is seen in L–mode**

Momentum Transport Presents Puzzling Questions



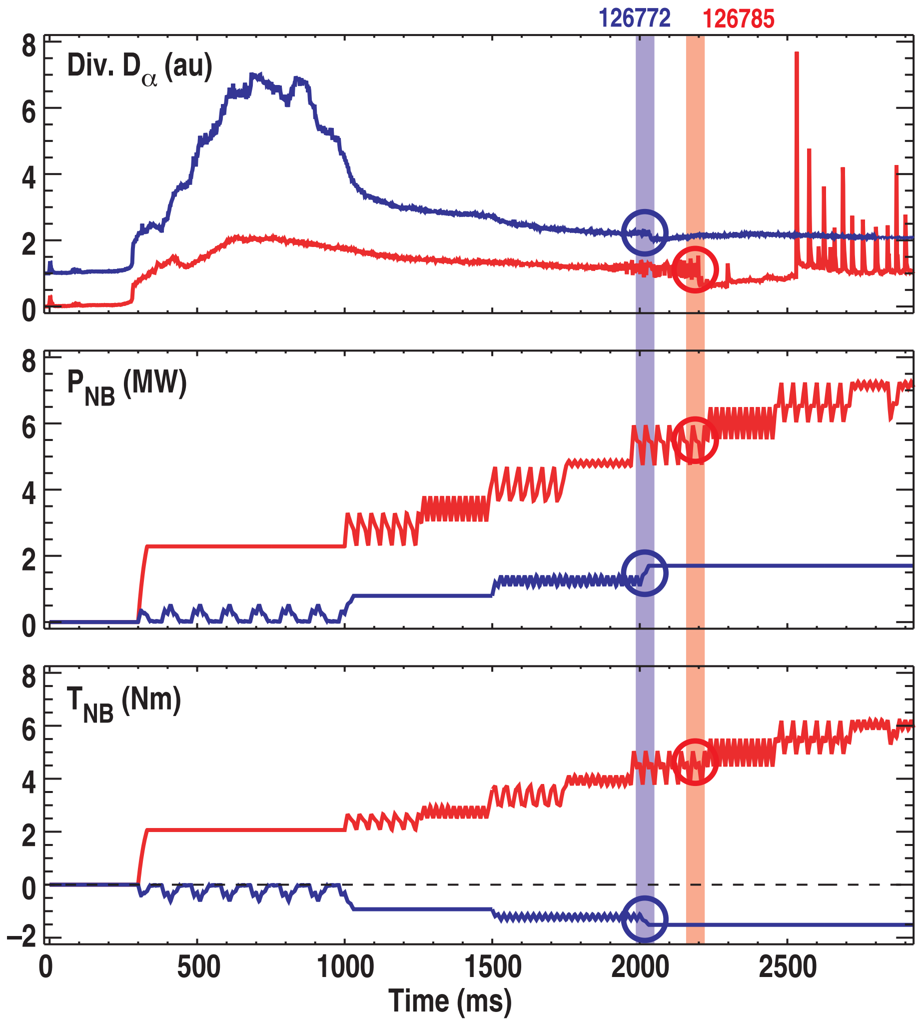
- Same dataset as previous graph on τ_{th}
- The different confinement regimes have variations in τ_{th} up to 4x at equal torque, while ω_{tor} varies by typically 2x
- There is intrinsic rotation without torque input that is not described by a simple momentum conservation equation
- The hybrid data show a non-linear response of ω_{tor} to torque, possibly due to interaction of tearing modes with the wall or due to skin depth reduction of non-axisymmetric magnetic fields

New NBI Configuration and Real-Time Analysis of Toroidal Rotation Allows Simultaneous Control of Stored Energy and Rotation



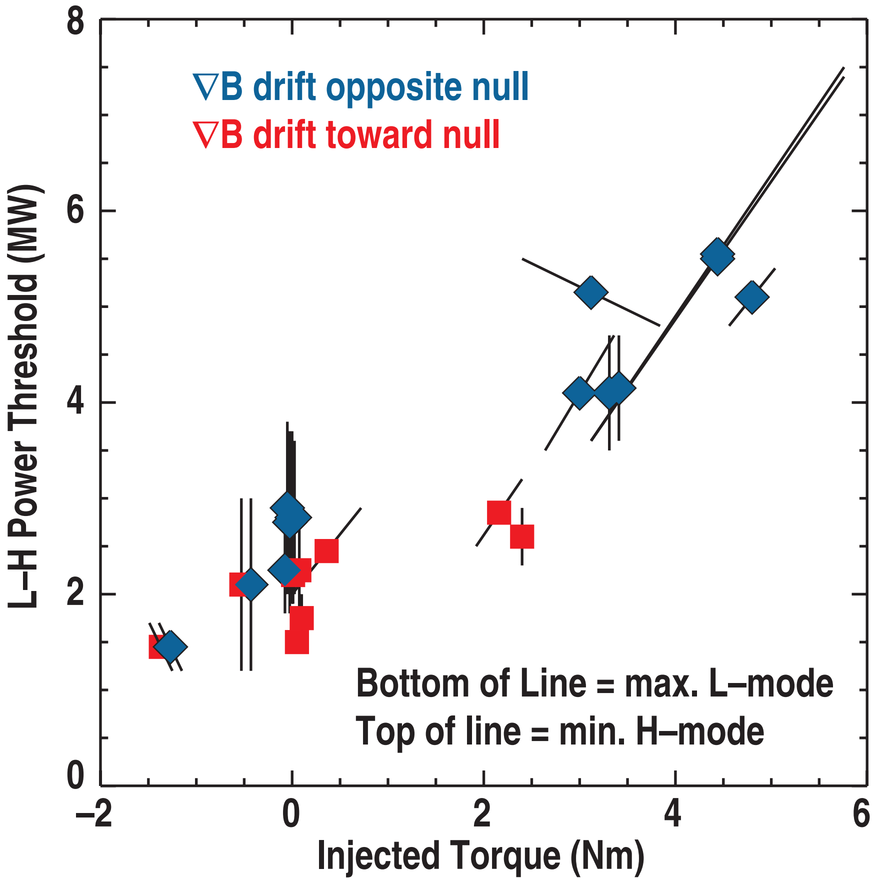
- **Uses proportional-integral controller with gains determined prior to the experiment through modeling**

L–H Power Threshold Varies Strongly with the Torque Injected by the Neutral Beams



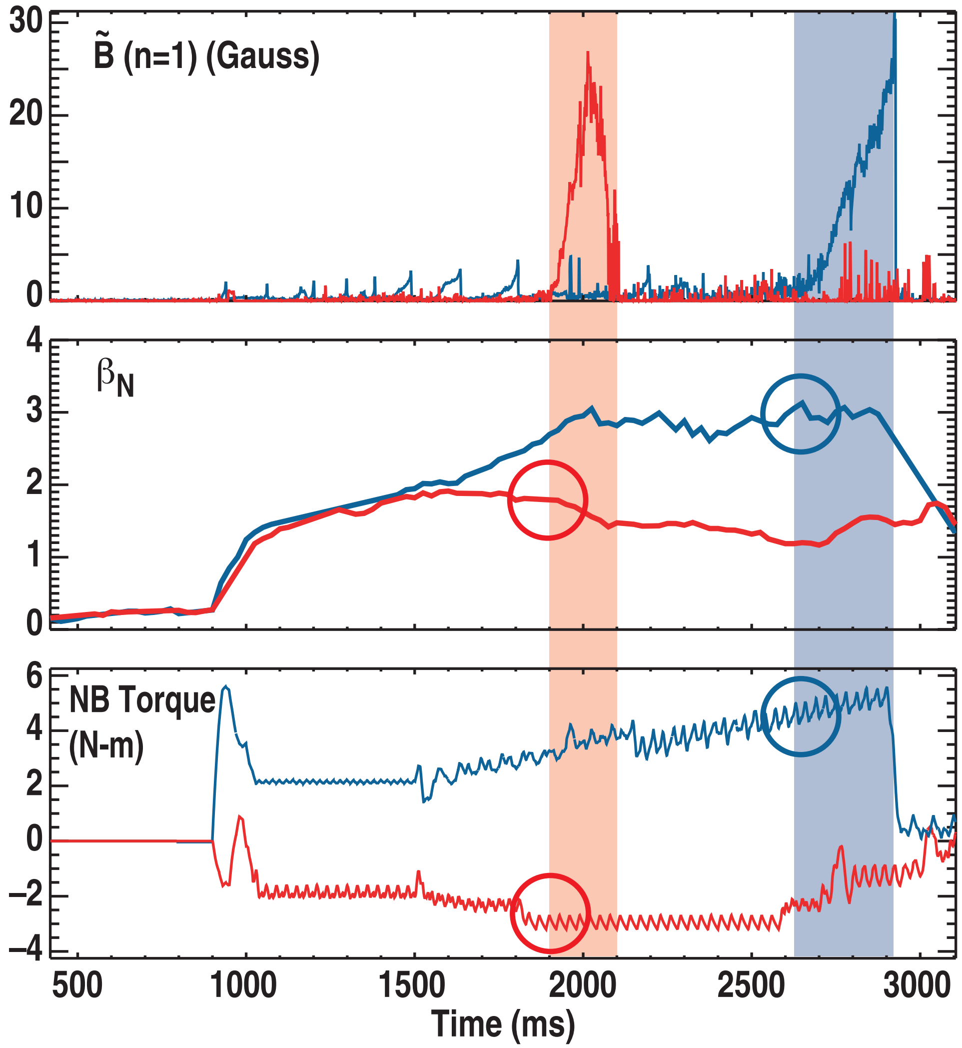
- **Neutral beam power is varied in < 1 MW increments by modulation**
- **Torque is varied by the mixture of co-injection and counter-injection of the neutral beams**
- **More than a factor of 3 difference in L–H power threshold is seen from full co-injection to full counter-injection**

Strong Variation with Injected Torque May Lead to Better Understanding and Prediction of the L–H Power Threshold



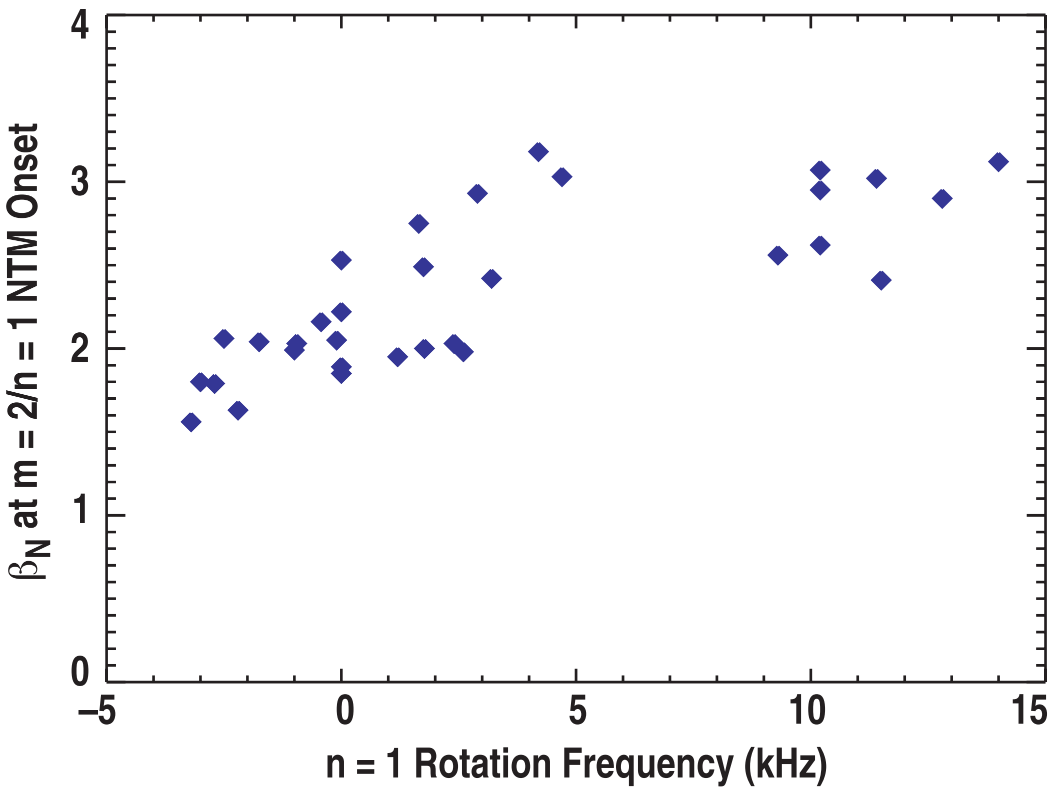
- All data from single operational day to minimize systematic effects from changing wall conditions
- Little difference seen between upper and lower single null with low or counter rotation
- Detailed analysis of prompt orbit losses, radial electric field and fluctuation data in progress

Plasma Rotation Affects the Pressure Limit to m=2/n=1 Tearing Modes



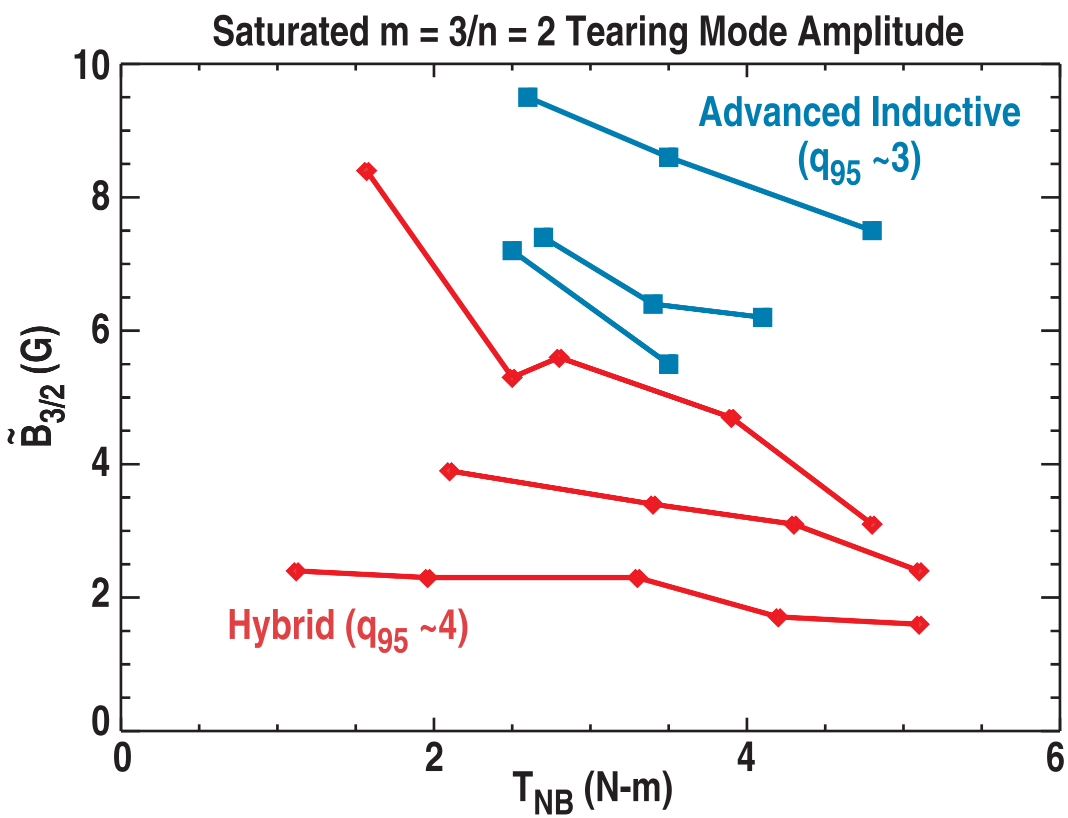
- Conventional H-mode discharges at q_{95} = 4.5 with sawteeth
- Plasma with counter-injection is unstable at much lower value of β_N than the plasma with co-injection
- Caveat: effect of current profile change on Δ' is not yet quantified

Pressure Limit to m=2/n=1 Tearing Modes Varies Significantly with Injected Torque



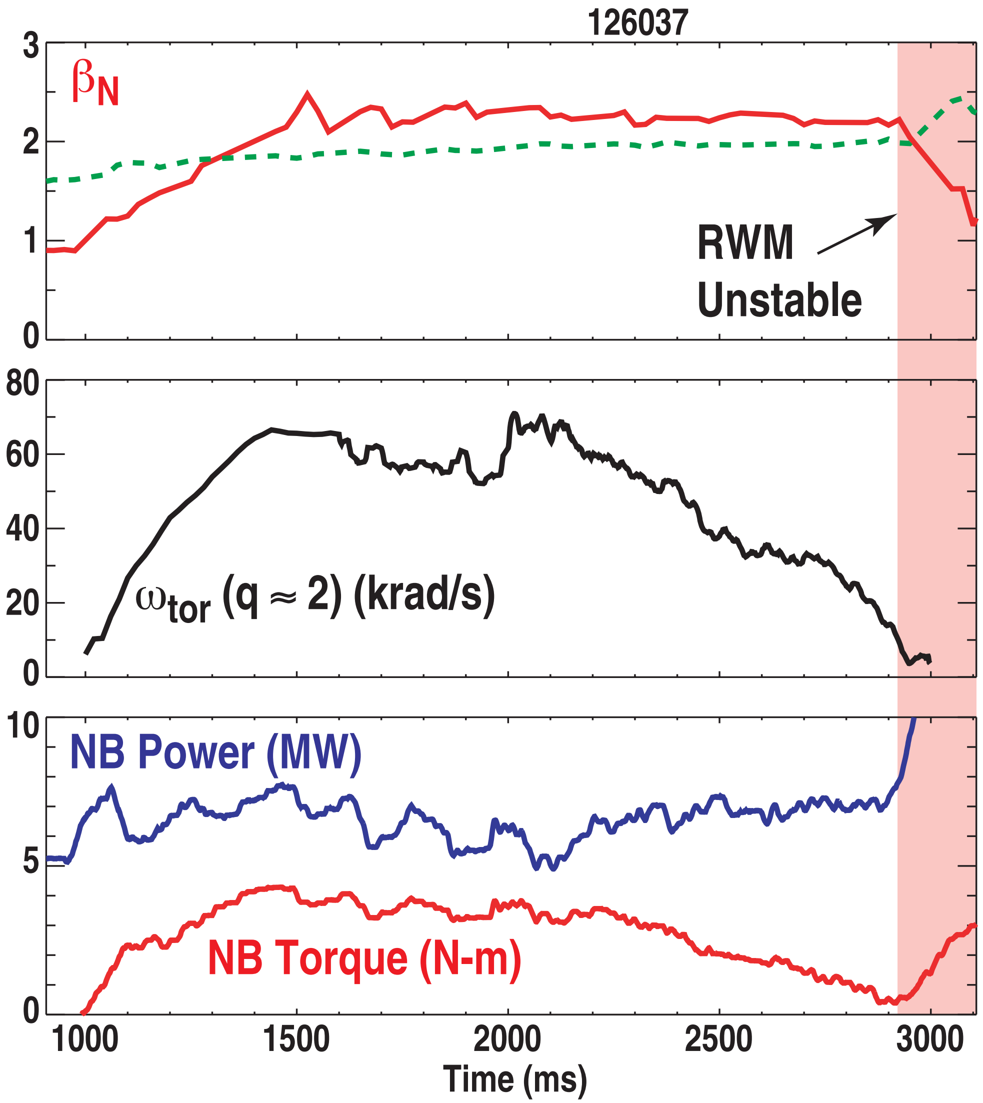
- Onset determined by NB power ramps with different ratios of co-injection and ctr-injection
- Effect of additional n=1 error fields small compared to the variation with injected torque

Saturated m=3/n=2 Tearing Mode Amplitude Decreases With Increasing Torque



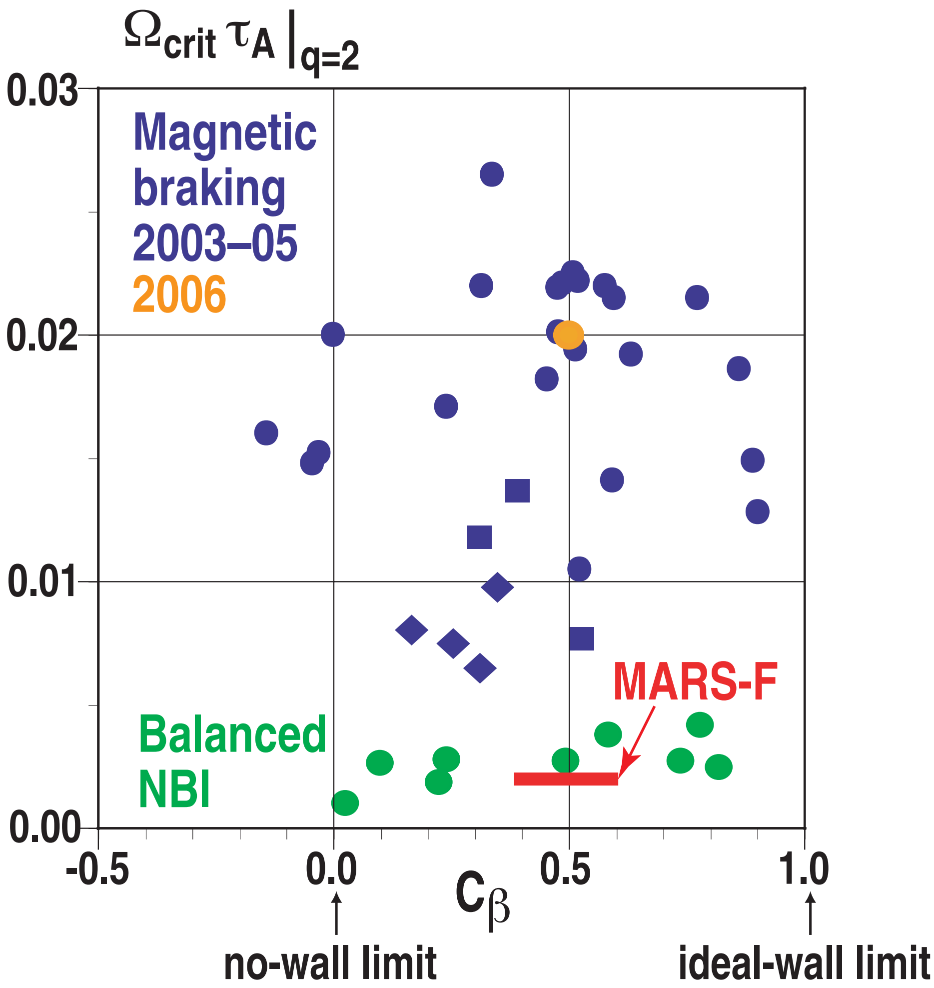
- **Both classes of discharges demonstrate high performance in the presence of m=3/n=2 tearing modes**
- **Magnitude of change in current profile with ctr-NBI and the effect on Δ´ has not been evaluated**

Threshold for Rotational Stabilization of RWMs Found With Balanced NBI is Low



- **Correction of n = 1 error fields optimized by direct feedback**
- **Simultaneous feedback control of β_N and torque apllied**
- **Plasma remains stable until toroidal velocity is < 0.3 % of the Alfvén velocity at the q = 2 surface**

Observed Threshold for Rotational Stabilization is Lower Than Previous Results with Magnetic Braking



- Lower thresholds have been observed for torque input cases, independent of the proximity to the ideal wall limit
- Present experimental results agree with theoretical predictions
- Low rotation thresholds for stabilization in cases with axisymmetric magnetic fields is encouraging for access to high β_N in ITER