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

by

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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

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 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

- $\beta_N = 2.7$ (feedback controlled), $q_{95} = 3.3$
- Transition to low rotation occurs at the initiation of the high $\beta_N$ phase
- High performance at low rotation maintained for $t > 4 \tau_R$
- Extrapolates to Q > 10 in ITER at 15 MA for several common scalings:
  - ITER89-P: $Q = 10.3$
  - IPB98y2: $Q = 10.2$
  - DS03: $Q = \infty$ (even with 7% lower $H_{DS03}$)
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 $\tau_{th}$
- The different confinement regimes have variations in $\tau_{th}$ up to 4x at equal torque, while $\omega_{tor}$ 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 $\omega_{tor}$ 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 $\beta_N$ than the plasma with **co-injection**
- Caveat: effect of current profile change on $\Delta'$ 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 $\Delta^\prime$ 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 $\beta_N$ and torque applied
- 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 and Theoretical Predictions

- Lower thresholds have been observed for torque input cases, even at pressures closer to the ideal wall limits.
- Present experimental results agree with theoretical predictions.
- Low rotation thresholds for stabilization in cases with axisymmetric magnetic fields is encouraging for access to high $\beta_N$ in ITER.
Changes in rotation lead to significant variations in many plasma phenomena that impact ITER performance:

- Advanced inductive scenario performance still projects to $Q > 10$ in ITER with no rotation, but the margin is reduced compared to cases with rotation.

- Going from no rotation to large co-rotation leads to:
  - increased energy confinement (over 50% in some cases)
  - increased L-H power threshold (> 2x)
  - increased pressure limits to $m=2/n=1$ tearing modes (~1.5x)

- Rotational stabilization of RWMs appears to have a much lower rotation requirement than previous data using magnetic breaking indicated.

- Accurate prediction of momentum transport, especially accounting for MHD modes and non-axisymmetric magnetic fields, will be challenging.