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

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T.C. Luce,[1] K.H. Burrell,[1] J.R. Ferron,[1] A.M. Garofalo,[2] R.J. Jayakumar,[3] D.A. Humphreys,[1] G.R. McKee,[4] M. Okabayashi,[5] C.C. Petty,[1] P.A. Politzer,[1] H. Reimerdes,[2] J.T. Scoville,[1] W.M. Solomon,[5] E.J. Strait[1]

[1]General Atomics, P.O. Box 85608, San Diego, California 92186-5608, USA
email: luce@fusion.gat.com
[2]Columbia University, New York, New York, USA
[3]Lawrence Livermore National Laboratory, Livermore, California, USA
[4]U. Wisconsin, Madison, Wisconsin, USA
[5]Princeton Plasma Physics Laboratory, Princeton, New Jersey, USA

Very recent experiments in the DIII-D tokamak have demonstrated clear effects on energy confinement and stability with variation of the applied torque from neutral beam injection (NBI) and the resulting rotation. H-mode energy confinement increases about 20% with co-rotation in both standard and high-performance "hybrid" discharges. Discharges with q_{95} = 3.3 and $G(\equiv \beta_N H_{89}/q_{95}^2)$ above the ITER Q=10 design value have been extended to >4.5 s with about a factor of 3 lower rotation than previous discharges. Even at very low rotation, hybrid discharges at q_{95}~4 sustain normalized parameters consistent with hybrid operation in ITER (Fig. 1). Discharges with elevated q_{min} (like candidate steady-state discharges for ITER) also exhibit an increase of confinement with co-rotation. L-mode discharges show much less variation with changes in applied torque. A systematic increase in the power required for transition to H mode is also observed as the applied torque in the plasma current direction increases. New experiments also show that kink-like modes remain stable above the no-wall limit down to rotation frequencies much lower than observed in previous experiments using non-axisymmetric fields to slow the rotation.

Much of the existing physics basis for burning plasma experiments such as ITER is based on tokamak discharges heated by neutral beam injection (NBI) with net external torque. The NBI is usually in the direction of the plasma current, due to the favorable shift toward the plasma axis of the ions following ionization. The DIII-D tokamak and NBI system have been modified recently to orient one of the beam lines (two sources, ~2.5 MW each at nominal voltage) for injection counter to the plasma current direction. The studies reported here are the first assessments in DIII-D of the effects of varying the applied torque without the requirement of reversing the plasma current direction.

Rotation of tokamak plasmas (or the spatial gradient of the rotation) is expected to play a

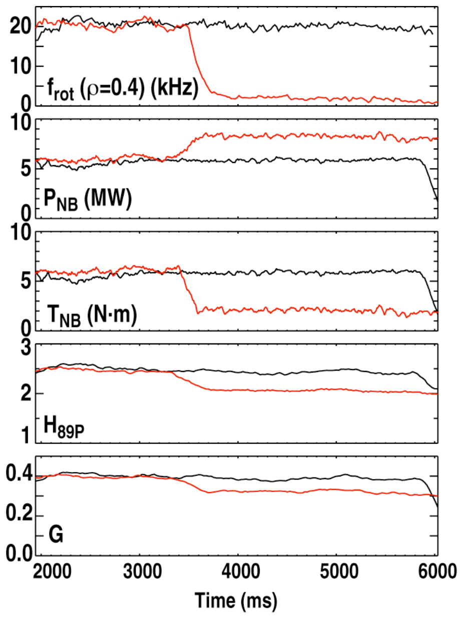

Fig. 1. Time histories of various plasma parameters for two high-performance H-mode discharges at q_{95} = 4.6 with high (black) and low (red) applied torque. (a) Rotation frequency at ρ = 0.4 (kHz), (b) NBI power (MW), (c) NBI torque (N-m), (d) ratio of the energy confinement time to the ITER-89P scaling, (e) normalized fusion gain parameter (= $\beta_N H_{89}/q_{95}^2$).

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significant role in both energy transport and macroscopic stability. For transport, a significant reduction in the transport due to drift-wave turbulence is expected in radial locations where the shear length of the equilibrium ExB velocity profile approaches the local correlation length of the turbulence. In the case of stability, a resistive wall appears perfectly conducting to modes moving with the plasma at frequencies such that the skin depth in the resistive wall is shorter than the wall thickness. Conversely, rotating plasmas are expected to be insensitive to non-axisymmetric magnetic fields if the resonant rational surfaces are farther than a skin depth into the plasma.

Long-duration, high-performance H-mode discharges have been demonstrated with ITER-relevant Mach number ($M \approx 0.04$), while maintaining performance suitable for hybrid operation in ITER (Fig. 1). The continued absence of sawteeth for many resistive times independent of the mixture o co- and ctr-NBI also indicates that current profile evolution in these discharges is not sensitive to the details of the NB current drive. Feedback control of β and density is maintained as the applied torque is changed. The n_e, T_e, and T_i profiles do not change significantly, but the required heating power decreases with increasing torque. As the Mach number increases, the electron and ion thermal diffusivities decrease, and the momentum diffusivity also decreases. Theoretical modeling is underway to try to separate the effects of the changes in the rotational and magnetic shear. Torque scans were also performed in experiments with elevated $q_{\min}$, compatible with steady-state operation. The energy confinement time increases by about 20% in both the hybrid and elevated $q_{\min}$ as the applied torque is increased from nearly 0 to 4N-m. The global momentum confinement drops by 50% as the torque increases from 1 to 4 N-m in these discharges, which is the opposite trend than observed for the energy confinement.

Experiments were also performed in L mode and standard H mode. Energy confinement in L mode shows little change with rotation, while H-mode plasmas exhibit about a 20% increase in energy confinement as rotation increases. The higher sensitivity of the recently upgraded beam emission spectroscopy system was used to assess the dependence of turbulence characteristics on the Mach number ($\equiv\omega_{tor} R/c_s$, where c_s is the ion sound speed) in the range (0–0.5). Density and temperature profiles were matched without varying current or magnetic field, yielding fixed dimensionless parameters (ρ^*, β, ν^*, q). Clear changes in the density fluctuation spectra were observed in L mode between high and low rotation plasmas. The Doppler-shift of the spectrum and the poloidal fluctuation velocity, related to local radial electric field, varied by a factor of 2. Slight increases in the radial and poloidal correlation lengths were seen in the lower Mach number plasmas. Density fluctuation amplitudes showed a modest increase at lower Mach number. H-mode plasmas at lower rotation exhibited strong eddy asymmetry with increased radial correlation lengths, but the poloidal correlation lengths were smaller than observed in L-mode turbulence. Plasmas with some counter-NBI have a lower power threshold for access to H mode than those with co-NBI only.

The new capability of the DIII-D plasma control system to analyze charge exchange spectroscopy data in real-time has allowed simultaneous feedback control of both v_{tor} and β. Torque input changes (to control the velocity) can be made independent of the input power (used to control the stored energy) by adjusting the difference between the power injected by co- and counter-injection neutral beams. The feedback control is implemented using a proportional/integral controller using gains determined from a model-based controller design.

Recent stability experiments show that the plasma rotation threshold for stable operation above the no-wall beta limit is more than a factor of two lower than previously reported. Slow plasma rotation is achieved by reducing the neutral beam torque, in place of the magnetic braking used in the previous experiments. Previous experiments indicated that stability required v_{tor} at the q=2 surface >0.6% of the local Alfvén speed. In the recent experiments, stable DIII-D discharges have been observed with β exceeding the no-wall stability limit by more than 30% and $v_{tor} < 0.3\%$ of the Alfvén speed at the q=2 surface. Observations on the effect of rotation on tearing mode amplitude and error field penetration will also be discussed.