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

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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 $G(=\beta_nH_{99}/q_{95}^2)$ 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

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig1.png}
\caption{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 $\rho = 0.4$ (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 ($=\beta_nH_{99}/q_{95}^2$).}
\end{figure}
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 of 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 \( \beta \)
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 \( q_{\text{min}} \), compatible with steady-state operation. The energy
confinement time increases by about 20% in both the hybrid and elevated \( q_{\text{min}} \) 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 \( (\pi \omega_{\text{tor}} R/c_s, \text{where } c_s \text{ is the ion sound speed}) \) in
the range (0–0.5). Density and temperature profiles were matched without varying current or
magnetic field, yielding fixed dimensionless parameters \( (\rho^*, \beta, v^*, q) \). 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 \( \omega_{\text{tor}} \) and \( \beta \).
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
counter- 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 \( \omega_{\text{tor}} \) at the \( q=2 \) surface >0.6% of the local Alfven speed. In the recent
experiments, stable DIII-D discharges have been observed with \( \beta \) exceeding the no-wall
stability limit by more than 30% and \( \omega_{\text{tor}} < 0.3% \) of the Alfven speed at the \( q=2 \) surface.
Observations on the effect of rotation on tearing mode amplitude and error field penetration
will also be discussed.