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Developments in Predictive Understanding of Plasma Rotation on DIII-D

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Recent experiments using DIII-D's capability to vary the injected torque at constant power have focused on developing the physics basis for rotation, through detailed studies aimed at understanding momentum sources, sinks and transport. These investigations have resulted in several surprising discoveries, including empirical evidence for an effective anomalous torque source to the plasma, observation of a *spin-up* of the plasma following application of non-resonant "braking", and distinct dependences of the momentum confinement on the applied torque depending on plasma conditions. Since rotation is known to affect a broad range of fundamental issues concerning fusion plasmas, the performance of future burning plasma devices including ITER will depend on the attained rotation profile. Consequently, obtaining predictive understanding of rotation, and ultimately exploiting such knowledge to generate a desired rotation profile will result in a significant payoff for fusion.

The presence of an anomalous momentum source (Fig. 1) has been identified by varying the input torque from neutral beam injection at fixed β_N, until the plasma rotation across the entire profile is approximately zero. This experiment determined that achieving this rotation profile required approximately one net counter neutral beam source. Through simple application of the momentum balance equation, one can deduce an effective anomalous source acting on the plasma, essentially opposing the net counter neutral beam injection and resulting in zero plasma rotation, as shown in Fig. 1. This torque profile is largely peaked at the edge, but also with a significant amount of torque present in the core.

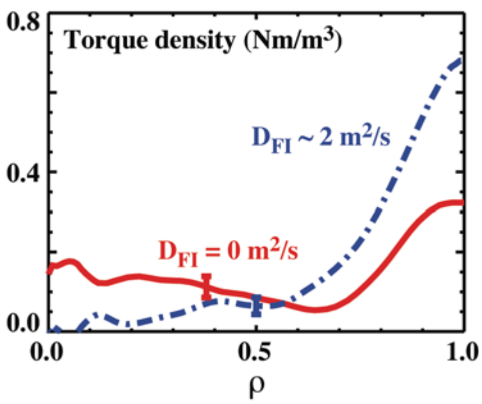

Fig. 1. Effective anomalous torque profile required to explain zero rotation profile in the presence of net counter neutral beam injection (solid). Including anomalous fast ion diffusion D_{FI} ~ 2 m^2/s (dashed) further enhances the edge torque density.

The momentum source driven by neutral beam injection can be dramatically altered in the presence of strong Alfvénic activity, resulting in reductions of the core torque density by up to a factor of three. In a series of discharges where the level of reversed shear Alfvén eigenmode (RSAE) activity was altered by means of controlled electron cyclotron heating (ECH) deposition, the central rotation frequency was found to increase by a factor of two when the RSAE activity was largely suppressed. Efforts to simultaneously reconcile the neutron rates, fast ion density profile and current drive profiles suggest that the modification to the rotation profile is a direct result of changes to the torque deposition rather than changes to the underlying momentum transport. The inference of the aforementioned anomalous torque profile is modified if one includes anomalous fast ion diffusion in the calculation of the neutral beam torque. However, including fast ion transport results in an anomalous torque profile that is larger and more localized at the edge (Fig. 1).

Non-resonant braking due to neoclassical toroidal viscosity (NTV) [1,2] has generally been considered a sink of momentum, however, recent results from DIII-D suggest that it may also act as a source. Although experimental investigations are qualitatively consistent with theoretical models, issues remain to be resolved. The effect of non-resonant braking on rotation has recently received significant attention, due to the potentially large non-resonant field components associated with the coils proposed for edge localized mode (ELM) suppression on ITER. Such fields may lead to large braking of ITER plasmas and possible locking. DIII-D experiments have shown that the strength of the braking is dependent on the unperturbed rotation (Fig. 2). Interestingly, the effect of this braking minimized at an unperturbed rotation different from zero. The existence of such an offset velocity implies that static non-resonant fields need not always result in braking of the plasma rotation; for rotation speeds less than the offset velocity, the rotation accelerates up towards it. NTV theory predicts an offset velocity with a dependence on ∇T_i [3], and the data does appear to exhibit such dependence, with data taken at lower β_N showing a lower offset velocity.

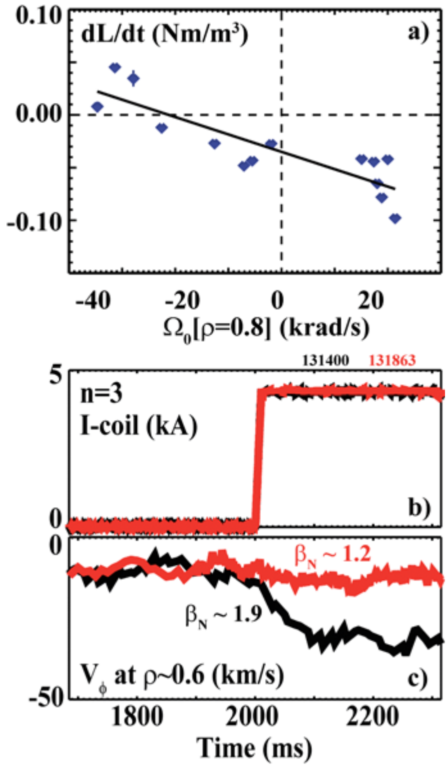

Fig. 2. (a) Change in the angular momentum (proportional to torque) as a function of the initial unperturbed rotation, Ω_0 at $\rho \sim 0.8$ for $\beta_N \sim 1.9 \pm 15\%$ and $n_e \sim 4.1 \pm 5\%$ 10^{-19} m^{-3}. Zero torque is observed for Ω_0 finite and in the counter-I_p direction. (b) Acceleration of plasma rotation with application of non-resonant fields. At high β_N, a large acceleration is observed, indicating that the offset velocity is larger than the initial rotation. At lower β_N, little or no acceleration is seen, suggesting a smaller offset rotation, close to Ω_0.

The final component required for predictive understanding of rotation, in addition to knowledge of the sources and sinks, is a description of the momentum transport. From a global perspective, it has been found that the momentum confinement time τ_ϕ can have a strong dependence on the applied neutral beam torque, which may be favorable for improved momentum confinement and larger rotation on ITER. However, somewhat surprisingly, as the torque is reduced from typical large (from all co-I_p neutral beams) to small values (using balanced beam injection), the change in momentum confinement depends on the operating regime, showing an improvement for ELMing H-mode plasmas, but a reduction for hybrid plasmas. The difference seems to be explainable at least in part due to differences in the underlying $E \times B$ shear, which leads to improved performance of hybrid plasmas at high rotation.

Although momentum transport has commonly been characterized as a purely diffusive process, perturbative studies of the rotation using combinations of co and counter neutral beams have uncovered the existence of a momentum pinch in DIII-D H-mode plasmas. The inferred inward momentum pinch velocity shows qualitative similarity to theoretical predictions resulting from consideration of low-k turbulence, in particular showing a radial dependence proportional to the momentum diffusivity.

Recent experiments on DIII-D have elucidated the importance of rotation on a variety of performance issues. Rotation scans have been conducted over a broad range of values by matching plasma conditions with normal and reverse plasma current direction, in addition to varying the mix of co and counter neutral beam injection, and strong dependences have been characterized as the rotation is systematically lowered, including a degradation of confinement, a reduction in beta limits for neoclassical tearing modes and reduction to the power threshold for the L-H transition. Hence, predictive understanding of rotation is a critical requirement for projecting these results forward to future burning plasmas such as ITER and beyond.

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