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CHARACTERIZATION OF THE EFFECTIVE TORQUE PROFILE ASSOCIATED WITH DRIVING INTRINSIC ROTATION ON DIII-D

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Recent experiments on DIII-D have focused on elucidating the drive mechanisms for intrinsic rotation in tokamak fusion plasmas. It is found that the effective torque profile associated with generating intrinsic rotation exhibits a richness of physics, with distinct mechanisms apparently active in the edge (ρ>0.8) versus the core (ρ<0.8). In particular, at the edge of DIII-D H-mode plasmas, a clear dependence of the "intrinsic torque" on the edge pressure gradient is observed, indicating the existence of a universal mechanism for intrinsic rotation drive in this region. While the "intrinsic torque" in the core tends to be comparatively small, it has been demonstrated that it can significantly alter the angular momentum profile. For example, plasmas with electron cyclotron heating (ECH) deposited near the axis are found to have a region of large counter intrinsic torque inside of the deposition radius. Similarly, typical QH-mode plasmas also tend to have large core counter intrinsic torques, which assist in producing the large rotation shear believed essential for QH-mode access. Since rotation is associated with improved confinement and stability, understanding the mechanisms leading to the self-generation of toroidal rotation is a critical step in assessing whether intrinsic rotation will be beneficial to fusion performance in next-step devices such as ITER.

Measurements at the edge of DIII-D H-mode plasmas find that the edge intrinsic torque varies linearly with the edge pressure gradient as shown in Fig. 1. In these experiments, the effective torque associated with the intrinsic rotation was measured by using the torque from neutral beam injection to null out the toroidal rotation, a technique used previously to demonstrate the existence of the intrinsic torque [1]. Theoretical work [2-4] has suggested that the *E*×*B* shear can result in a "residual stress" generated by plasma turbulence, which appears as a torque term in the angular momentum balance equation. In the plasmas studied here, with nominally zero toroidal rotation, the radial electric field arises predominantly from the pressure gradient. Therefore, the observed dependence of the edge intrinsic torque on the pressure gradient is consistent with such models relating the *E*×*B* shear as an important drive for intrinsic rotation. If the edge pressure gradient is indeed responsible for the residual stress leading to a spin up of the plasma from rest, then the H-mode pedestal may provide a ubiquitous mechanism for providing intrinsic rotation in fusion plasmas, and may help to explain the commonality of the observed H-mode intrinsic rotation across multiple machines. A good correlation is also found in these plasmas between the parameter W/I_p, where W is the plasma stored energy, and I_p the plasma current, compatible with a simple cross-machine scaling [5] linking the intrinsic rotation with various global quantities.

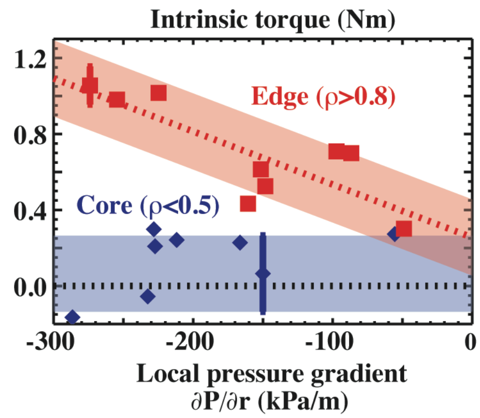

Fig 1. The intrinsic torque at the edge of the plasma shows a strong correlation with the edge pressure gradient. No obvious correlation exists in the core.

The generation of intrinsic torque in the core of H-mode plasmas appears to be much more complex, and the data indicates that there is no single physics mechanism responsible for the drive in this region. Unlike the edge, there does not appear to be any strong correlation between the core intrinsic torque and the local pressure gradients. This perhaps is not surprising in these plasmas, where the *E*×*B* shear in the core is relatively weak. The situation might be expected to be different in the case of plasmas with strong internal transport barriers.

Even though the core intrinsic torque tends to be small compared with the edge, some cases have been found where it is large enough to modify the rotation profile. For example, in plasmas with ECH deposited near the axis, a significant counter intrinsic torque has been observed in the inner region of the plasma, unlike typical H-modes where the core intrinsic torque is essentially zero within error bars (Fig. 2). This counter torque associated with the ECH is consistent with previous measurements of a hollow intrinsic toroidal rotation profile in ECH H-mode plasmas [6]. This observation indicates that the intrinsic drive in the core of fusion plasmas can be directly manipulated by use of external waves, which may offer possibilities for rotation shear control in future burning plasma devices.

Large intrinsic torques have also been observed in the core of QH-mode plasmas. A new analysis technique has recently been developed to infer the contribution of the intrinsic torque to otherwise rapidly rotating plasmas with significant neutral beam torque input. This is an important advance, al–lowing intrinsic torque measurements in a range of scenarios, including QH-modes, advanced tokamak and hybrid plasmas. The basic concept is to apply a transient step in the neutral beam torque, and compare the steady state momentum confinement with the dynamic response of the rotation evolution. Any mismatch can be attributed to a missing torque responsible for driving the intrinsic rotation.

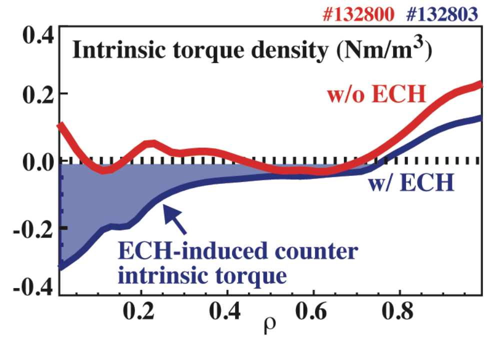

Fig 2. Comparison of intrinsic torque profiles with and without ECH. A large counter intrinsic torque is induced in the core in the case of centrally deposited ECH.

This new method has been instrumental in understanding why QH-modes with low counter neutral beam torque maintain a counter rotation, despite having edge pedestals which would suggest that a co-intrinsic torque should dominate the angular momentum balance. Indeed, these experiments show that such QH-mode plasmas follow the same H-mode scaling for the edge intrinsic torque, but surprisingly, it is found that there is a significant counter intrinsic torque across most of the core profile. The net result is an intrinsic torque which is relatively small when integrated across the entire profile, and is actually in the counter I_p direction as shown in Fig. 3. These QH-mode plasmas represent a second case where the core intrinsic torque is important in determining the toroidal rotation profile.

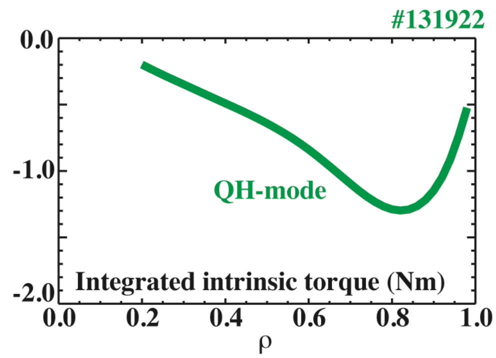

Fig. 3. Integrated intrinsic torque profiles for a DIII-D QH-mode plasma, with a net counter intrinsic torque.

Initial studies of the residual stress with the global gyrokinetic code GYRO [7], have uncovered a novel result; namely that nonlocal profile variations appear capable of driving large residual stresses and associated momentum flows. For example, small changes (of the order of 10%) in the ion temperature gradient scale length in these simulations led to the predicted momentum flows changing direction. Such extreme sensitivity of the residual stress to small profile variations makes it problematic for local transport models to treat plasmas with low levels of toroidal angular momentum. Moving forward, a better approach ultimately is to input the known heat, particle and momentum sources and self consistently calculate the set of corresponding plasma profiles.

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