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the DIII-D ROTATION PHYSICS TASK FORCE

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Developments in Predictive Understanding of Plasma Rotation on DIII-D

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Abstract. Recent experiments using DIII-D's capability to vary the injected torque at constant power have focused on developing the physics basis for understanding rotation through detailed study of momentum sources, sinks and transport. Non-resonant magnetic braking due to neoclassical toroidal viscosity (NTV) has generally been considered a sink of momentum, however, recent results from DIII-D suggest that it may also act as a source. The torque applied by the field depends on the rotation relative to a non-zero "offset" rotation. Therefore, at low initial rotation, the application of non-resonant magnetic fields can actually result in a spin-up of the plasma. Direct evidence of the effect of reverse shear Alfvén Eigenmodes on plasma rotation has been observed, which has been explained through a redistribution of the fast ions and subsequent modification to the neutral beam torque profile. An anomalous momentum source 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 effectively zero. This torque profile is largest near the edge, but is still non-negligible in the core. In studies of momentum transport, the momentum confinement time τ_ϕ is found to have a strong dependence on the applied neutral beam torque, which may be favorable for improved momentum confinement and larger rotation on ITER. 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, which is qualitatively similar to theoretical predictions resulting from consideration of low-*k* turbulence.

1. Introduction

Rotation has been shown to play a beneficial role in the confinement and stability of fusion plasmas (see for example, Refs [1,2]), therefore, the performance of future burning plasma devices including ITER will depend on the attained rotation profile. Consequently, obtaining a predictive understanding of rotation, and ultimately exploiting such knowledge to generate an optimal rotation profile will result in a significant payoff for fusion. As such, a coordinated effort has been undertaken on DIII-D to develop the physics basis for understanding rotation through detailed studies of the key components that determine the rotation profile, namely the sources and sinks of angular momentum, and the associated momentum transport. Recent progress in each of these key areas will be discussed in the following sections.

2. Effect of Non-Axisymmetric Magnetic Fields on Plasma Rotation

An often overlooked aspect of determining the rotation profile is that related to sinks of angular momentum. Non-axisymmetric magnetic fields are unavoidable practically, or in some instances may be deliberately applied to the plasma for other beneficial purposes (e.g. resonant magnetic perturbations for ELM suppression [3]). Since such fields are known to affect plasma rotation, understanding precisely how they interact with the plasma rotation is of considerable importance. Generally, non-axisymmetric magnetic fields (both resonant and non-resonant) are thought of as drag terms in the balance of angular momentum. In the case of resonant magnetic fields (RMF), an electromagnetic braking torque is exerted on the plasma that can ultimately lead to a rapid collapse of the rotation once a threshold field is reached [4–6]. The torque applied by non-resonant magnetic fields (NRMF) is predicted theoretically to take the form $T_{\mathrm{NRMF}} \sim (V_\phi - V_\phi^0)$ [7], where V_ϕ is the toroidal velocity and V_ϕ^0 is the so-called neoclassical "offset" velocity, which is of the same order as the ion diamagnetic speed, but pointed in the direction counter to the plasma current, I_p. Hence, although this torque usually acts to reduce the rotation in typical experiments with large toroidal velocities resulting from uni-directional neutral beam injection, it is nonetheless the case that NRMF can actually result in a spin up of the plasma for low toroidal velocity $|V_\phi|<|V_\phi^0|$.

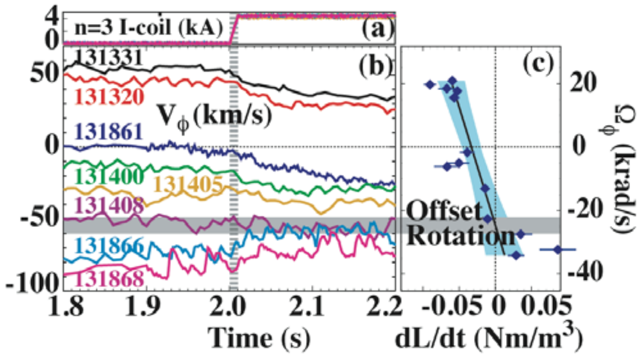

FIG. 1. (a) Waveform of applied n=3 NRMF perturbation and b) time history of toroidal velocity at ρ~0.8 for a sequence of discharges where the torque was scanned at constant β_N. (c) NRMF torque density inferred from change in angular momentum density as a function of initial rotation. The offset rotation is indicated by the gray band.

Recent investigations of the effect of NRMF on toroidal rotation at DIII-D have confirmed the existence of the offset rotation [8]. NRMF are produced on DIII-D using a set of 12 coils placed around the machine in two rows of 6 (above and below the midplane), which are referred to as I-coils. In Fig. 1(a), a sequence of plasma discharges were created with $\beta_N \sim 1.9\pm13\%$ and line average density $n_e \sim 4.1\times10^{19}$ m^{-3} ± 5%, with the input neutral beam torque varied from approximately -5.1 Nm to 3.6 Nm (negative values referring to counter-I_p), resulting in a thorough scan of unperturbed initial velocities V_ϕ varying from -70 km/s to 55 km/s at ρ~0.8. In these experiments, the I-coils were configured to produce n=3 NRMF. For large initial rotation in either the co- or counter-I_p directions, the application of the NRMF at t = 2.0 s results in a braking of the plasma. However, for cases where the initial rotation is relatively low (<50 km/s), the plasma is actually observed to spin up. In all cases, the rotation tends toward the offset rotation, which for these plasmas is inferred to be approximately 50 km/s or about 1% of the local Alfven frequency. In some sense, the NRMF torque may still be considered a drag, provided one appreciates that the drag is toward a finite-rotation condition. The local torque density has been computed at ρ~0.8 as the time derivative of the angular momentum density and is shown in Fig. 1(b), which shows semi-quantitative agreement (within the measurement uncertainty) with the expected theoretical torque, $T_{\mathrm{NRMF}} \sim (V_\phi - V_\phi^0)$.

In the cases where the initial plasma rotation is small, the acceleration of the plasma by the applied n=3 NRMF results in an improvement in the global energy confinement. For the discharge in Fig. 1 starting at near zero rotation (#131861), we find that β_N increases from approximately 1.6 before the NRMF, to 1.75 after about 200 ms. The H-factor, H_{89} also increases approximately 10% during this time. The rotation increases significantly at all radii. Although the measurement is based on the carbon impurity in the plasma, estimates of the main ion (deuterium) rotation, using the code NCLASS [9], show the same basic behavior.

An immediate consequence of the existence of the offset rotation is that if the plasma is initially rotating at the offset rotation, then the application of NRMF will result in no additional torque being applied and no change in the plasma rotation. This is close to the situation in discharge #131408 in Fig. 1, which shows no discernible change in the rotation following the application of the NRMF at 2000 ms. Indeed, this is true across the plasma radius, and so we may approximate the offset rotation as the actual initial rotation of this discharge. Theory predicts an offset rotation of the form $V_\phi^0 \sim (k/Z_\mathrm{i} e B_\theta)(dT_\mathrm{i}/dr)$, with k a numerical coefficient that depends on the collisionality regime [7]. In the low collisionality limit (the so-called 1/ν-regime), with the ordering $\omega_\mathrm{E} < \nu_\mathrm{i}/\varepsilon < \omega_\mathrm{ti}\sqrt{\varepsilon}$, the coefficient takes the value k~3.5, while in the so-called ν-regime, $\omega_\mathrm{E} > \nu_\mathrm{i}/\varepsilon$, k~0.9. Here, ν_i is the ion collisionality, ε the aspect ratio and $\omega_\mathrm{ti} = \sqrt{T_\mathrm{i}/m_\mathrm{i}}/R_0 q$ the ion transit frequency. The experimentally deduced offset rotation lies between these two extremes (Fig. 2). Nonetheless, since for this discharge $\omega_\mathrm{E}/(\nu_\mathrm{i}/\varepsilon) > 1$ at all radii, the connection between these two limits appears highly nonlinear, and a continuous interpolation formula applicable for all regimes is needed for a more quantitative comparison.

The existence of the offset rotation and the fact that the application of NRMF can lead to a spin up may have some important consequences, especially pertaining to the use of RMF for ELM suppression. In particular, there has been significant concern for ITER, where the coils proposed to produce the RMF have significant non-resonant components. Calculations have been performed of the NRMF braking associated with these components, which estimate that the torques may exceed that from the neutral beams. Such estimates are particularly worrisome because of the increased likelihood of wall locking as the rotation is slowed. As a result, much effort has been focused on trying to minimize the non-resonant component of the applied field. To date, these calculations have not considered the role of the offset rotation, and its potential positive effect on plasma rotation and confinement. In light of this, one can also entertain an alternate possibility, whereby one maximizes the non-resonant components to force the plasma toward the offset rotation.

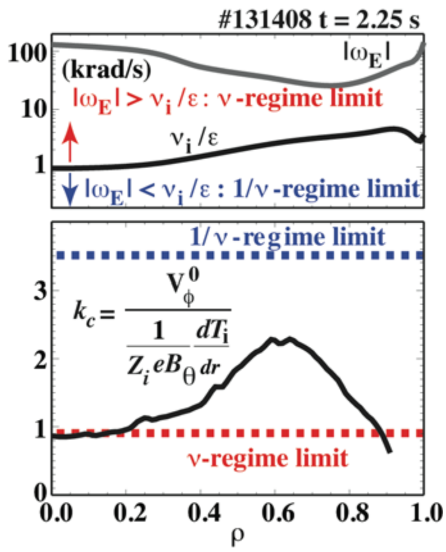

FIG. 2. (a) Radial profiles of ω_E and ν_i/ε, and (b) inferred offset rotation, normalized by $(k_i/Z_i e B_\theta)(dT_\mathrm{i}/dr)$. For comparison, the theoretical limits are over plotted.

3. Torque Delivered by Neutral Beam Injection

Neutral beams are the primary source of angular momentum to DIII-D and other large fusion plasmas. The torque profile deposited by the neutral beams is typically calculated using a code such as the NUBEAM [10,11] package within TRANSP [12], which simulates and tracks a large number of Monte Carlo beam ions as they collisionally slow down in the background plasma. Classical transport of the fast ions is included in such a computation. However, many DIII-D plasmas with even moderate neutral beam input exhibit various Alfvén eigenmode (AE) activity, which can be especially pronounced at low I_p and under reverse magnetic shear conditions. Such modes are capable of redistributing fast ions leading to non-classical fast ion transport, and generally resulting in a flattening of the fast ion pressure profile [13]. Clearly then, the presence of such modes and their associated anomalous fast ion transport may significantly alter the torque delivered by the neutral beams, making the computation of the torque profile questionable.

Experiments on DIII-D have used ECH as a tool to control the level of reverse shear Alfvén eigenmode (RSAE) activity [14]. The ECH deposition radius was scanned on a shot-to-shot basis, from near the axis, to ρ~0.4, where ρ is the normalized square root of toroidal flux. The outer locations of this scan correspond to approximately ρ_qmin, the location of the minimum of the safety factor q. The total ECH power as well as the neutral beam injection was held constant across the shots. When the ECH is deposited near ρ_qmin, the strong RSAEs observed in these plasmas are largely suppressed. In Fig. 3(a), the central toroidal rotation as a function of time is plotted for two discharges at low current during the I_p ramp phase; one with strong RSAE activity, the other with the RSAEs suppressed. In the case with reduced RSAE activity, the rotation is almost a factor of two higher. We find that the angular momentum density profile is more peaked when the RSAEs are suppressed, yet interestingly, the total integrated angular momentum in the plasma for the two cases is relatively unchanged [Fig. 3(b)]. This is suggestive of a redistribution of the fast ion profile, rather than a complete loss of fast ions per se, and is qualitatively consistent with the behavior expected from the relatively localized RSAEs.

The momentum diffusivity χ_ϕ profile is deduced using TRANSP, from the rotation profile evolution and calculated torque profiles, assuming classical fast ion transport. The result is shown in Fig. 3(c). The effective χ_ϕ in the core, ρ<0.7, is considerably larger for the discharge with RSAE activity. One can assume that this increase in χ_ϕ is purely a consequence of additional fast ion transport induced by the RSAEs. TRANSP includes the option for *ad-hoc* anomalous transport, which was used to deduce the RSAE-induced fast ion transport by better matching the χ_ϕ profiles for the two shots. We find that the anomalous fast ion diffusion as shown in Fig. 3(d), with a value of 0.3 m^2/s in the core, and falling to zero at the edge, best modifies the inferred χ_ϕ profile for the RSAE discharge to match the shot without RSAEs.

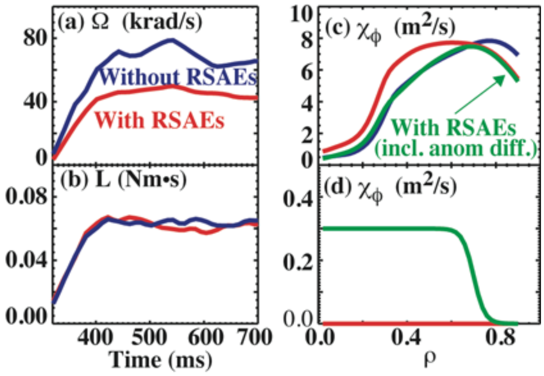

FIG. 3. (a) Central rotation frequency and (b) angular momentum content of comparison discharges with (red) and without (blue) RSAEs. Corresponding radial profile at t = 600 ms of (c) momentum diffusivity, including adjustment for RSAE-induced fast ion transport, using anomalous fast ion diffusivity in (d).

This deduced RSAE enhancement of the fast ion transport is supported by other measurements. The neutron rates for both discharges are well below the TRANSP classical prediction, but the shot with RSAE's is considerably worse (a further 25% reduction). This additional deficit can be adequately explained in TRANSP calculations using the above mentioned anomalous fast ion transport. The fast ion pressure is also significantly reduced by the deduced anomalous fast ion transport. Classically, the two discharges are expected to have similar fast ion pressures on axis (to within about 10%), The fast ion profiles from the fast ion D_α (FIDA) diagnostic [15] were measured for these two discharges and the difference between them is shown in Fig. 4. The FIDA signal is a result of a convolution of a "weight function" with the fast ion distribution function [16]. For the range of wavelengths considered in the FIDA analysis (corresponding to energies from about 30–60 keV), the weight function favors densities in the high energy region of the distribution function, and due to the near constant effective temperature of the fast ions, the FIDA signal can be considered a proxy for the fast ion pressure. In this particular analysis,

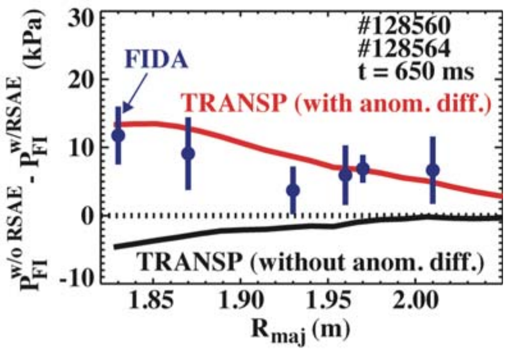

FIG. 4. Difference in fast ion pressure between discharges without RSAEs vs with RSAEs, calculated classically (black) and including the deduced RSAE induced fast ion transport (red). Comparison with FIDA measurements is shown in blue.

the relatively calibrated FIDA signals are scaled by a single constant such that the central FIDA "pressure" matches that from the discharge with no RSAE's. The FIDA measurements indicate that the shot with RSAEs has lower fast ion pressure, and the measured difference in pressure between the two discharges is in reasonable agreement with the calculated difference only when the inferred anomalous fast ion transport from Fig. 3(d) is included.

In light of the impact of non-classical fast ion transport on the deposited torque profile, it is clear that more careful validation of the computed neutral beam torque profiles from codes like TRANSP is required as part of the effort to gain predictive knowledge of plasma rotation in future devices.

4. Anomalous Torque and Intrinsic Rotation

A current mystery pertaining to rotation studies relates to the existence of the so-called "intrinsic" rotation [17–19], where the plasma is found to rotate at significant levels, in the absence of any auxiliary torque input. Therefore, in addition to readily identifiable sources of angular momentum to the plasma such as neutral beams, rotation studies have now recently had to confront the existence of additional effective source(s) of rotation. While the existence of intrinsic rotation has been demonstrated in several tokamaks, the role of intrinsic rotation in the presence of strong neutral beam injection has not been investigated as thoroughly.

Torque scans at constant β_N have been conducted in ELMing H-mode with $\beta_N \sim 1.7\% \pm 10\%$ and elevated q_{min} to investigate intrinsic rotation and momentum transport [20]. Across the entire profile, we find a residual co-rotation in the plasma, even when the neutral beams are nominally balanced. This rotation at zero net torque is related to the intrinsic rotation, although it is somewhat more complicated to interpret due to the details of the individual neutral beam torque profiles (specifically, due to the different deposition profiles for co and counter beams, net "balanced" torque invariably implies regions of both co and counter torque densities at different ρ). Perhaps more definitive evidence of the intrinsic rotation comes then from the fact that the rotation profile remains peaked and in the co-I_p direction even when the total torque is negative (meaning in the counter I_p direction), and the torque deposition profile is essentially zero from $0 < \rho < 0.7$ and negative beyond that. Although the rotation data comes from impurity carbon measurements, the neoclassical corrections for the main ion deuterium tend to further *increase* the amount of co-rotation.

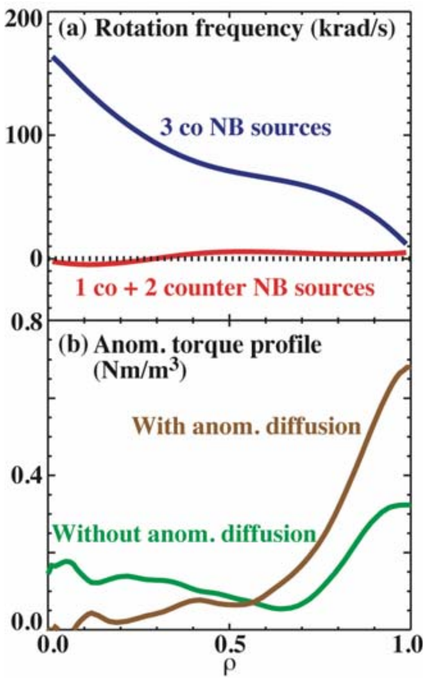

FIG. 5. (a) Change in rotation frequency profile going from 3 co-sources (blue) to 1 co plus 2 counter (red). (b) Inferred anomalous torque associated with intrinsic rotation (green), and considering possible role of anomalous fast ion diffusion (brown).

In an impressive display of the role of the intrinsic rotation even in the presence of neutral beam input, we see in Fig. 5(a), the toroidal rotation frequency profile at two times during a discharge in which the beam balance went from 3 co-neutral beams to 1 net counter beam (produced from 2 counter + 1 co beam). In the later time, the rotation profile is effective zero everywhere and steady for several hundred milliseconds, *despite the fact that there is one net counter source*. From a simple momentum balance equation,

$$mnR\partial V_\phi / \partial t = \eta + \nabla \cdot \Gamma_\phi \quad , \tag{1}$$

where

$$\Gamma_\phi = -mnR\left(\chi_\phi \partial V_\phi / \partial r - V_\phi V_{\text{pinch}}\right) \qquad (2)$$

is the angular momentum flux, χ_ϕ is the local momentum diffusivity and V_{pinch} is the convective momentum pinch, and η is the local torque density (from all sources) it is evident that for the case where the rotation is zero everywhere across the profile and not evolving, the effective torque profile must also be zero (an alternative interpretation is that we are not accounting for all the momentum fluxes, but as a matter of practicality, any terms that are not proportional either to the velocity or the gradient of the velocity cannot be readily distinguished from a torque source). In other words, there must be an anomalous torque profile acting on the plasma opposing the neutral beam torque, and to a first approximation, it must simply be the negative of the net neutral beam torque profile. Accordingly, the anomalous torque source must integrate to approximately one co-source, and the plasma rotates as if there was an additional co-neutral beam source being injected into the plasma. The deduced anomalous torque in these plasmas is shown in Fig. 5. The neutral beam torque profile is calculated assuming classical fast ion transport, although as highlighted in the previous section, such assumptions are likely too simple. Indeed, these discharges show a variety of AEs, and the classically predicted neutron rate is 25%–30% above the measured quantity. Allowing flat anomalous fast ion diffusion profiles to account for this discrepancy in the neutrons modifies the inferred anomalous torque profile as shown in Fig. 5, which becomes notably more peaked at the edge, qualitatively consistent with a model of anomalous torque due to thermal ion orbit loss [21] and may be a direct observation of the so-called “residual stress” [22-23].

5. Momentum Confinement and Transport

Finally, we turn to the role of momentum transport in the determination of the rotation profile. Momentum transport is generally found to be largely anomalous relative to neoclassical predictions, even in cases where the ion thermal transport has been reduced to neoclassical levels due to strong $E\times B$ stabilization of long wavelength turbulence. Therefore, in some ways, momentum transport remains the least well understood of all the transport channels, and the characterization of momentum transport leading to some fundamental understanding of the anomalous transport mechanism is sorely needed. Nonlinear gyrokinetic codes such as GYRO [24] and GTS [25] are only now reaching a level of completeness to properly start to address momentum transport. In this respect, experimental observations of momentum transport are valuable in guiding theoretical and modeling studies.

Global momentum confinement studies have been conducted in a range of DIII-D plasmas. In particular, investigations have been made into confinement as a function of the applied torque. One important point to realize in such studies is the importance of the intrinsic rotation at low neutral beam torque input. Typically, in steady state, the momentum confinement time is defined simply as $\tau_\phi = L/T$ where L is the total angular momentum in the plasma, and T is the total torque (which is typically taken to be just the neutral beam torque). It is apparent that such a definition fails if there is finite angular momentum in the plasma as the neutral beam torque goes to zero as described in Sec. 2. Clearly the proper treatment of the intrinsic rotation is crucial in order to make meaningful assessments of momentum transport, by including the associated torque in the total torque. In the ELMing H-mode plasmas described in Sec. 2, we find that the momentum confinement time, corrected for the intrinsic rotation, improves as we go to lower torque and rotation (Fig. 6). The same behavior is also found by considering the dynamic behavior of the rotation following a step in torque from one state to another. However, the exact opposite trend is found for hybrid scenario plasmas, which are characterized by stationary conditions and small benign MHD (typically in the form of a m/n=3/2 mode). For hybrid mode plasmas, there is a significant degradation in both thermal and momentum confinement as the torque is reduced. The difference seems to be explainable at least in part due to differences in the underlying $E\times B$ shear, which leads to much improved performance of hybrid plasmas at high rotation. GLF23 [26] modeling has been undertaken to try to understand these two different responses. It was found that the hybrid plasmas benefit much more significantly from $E\times B$ shear at high rotation than do the H-mode plasmas discussed here. Therefore, it is speculated that the trend observed in the H-mode plasmas may be an underlying effect, which is obscured in the case of the hybrids where $E\times B$ shear strongly affects the turbulence. If so, then momentum confinement and rotation may be somewhat higher than previously predicted for next-step devices, which are expected to operate with lower torque input than today's machines.

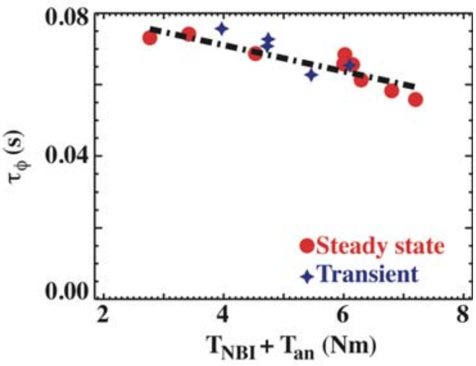

FIG. 6. Momentum confinement time versus total torque in the plasma for ELMing H-mode, including the inferred anomalous torque source in the plasma, from both steady state and dynamic response of the plasma angular momentum.

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 revealed the existence of a momentum pinch in DIII-D H-mode plasmas. In particular, a train of neutral beam "blips" is fired into the plasma at constant power. Each blip is 50 ms long, which is short compared with the confinement time, but long enough to have a measurable affect on the rotation. The plasma is then given 200 ms between blips to recover.

The viscous angular momentum flux is inferred from angular momentum balance [Eq. (1)] in TRANSP during the rotation relaxation following the NB blip perturbations. One must appreciate that the inferred flux is intimately related to accurately characterizing the sources and sinks as discussed in the previous sections, and given the relatively large unknowns in these terms, momentum transport studies are consequently somewhat uncertain. To some extent, we alleviate these problems with perturbative studies; for example, at constant β_N we should expect that the anomalous torque associated with the intrinsic rotation is not significantly changed based on the present ideas about the scaling of intrinsic rotation. Likewise, if we have error fields dragging on the plasma, then these too should be relatively unchanged by our perturbations, and the torque should be relatively constant.

The evolution of the viscous flux is modeled according to Eq. (2) following the NB blip perturbations, using a nonlinear least squares fit to obtain time-invariant profiles for χ_ϕ and V_{pinch}. For this analysis to succeed, the rotation perturbation must result in the velocity changing independent of its radial gradient, so that as we model the momentum flux evolution, we have a decoupling of the two terms in Eq. (2). In these experiments, plots of V_ϕ vs $\partial V_\phi / \partial r$ result in elliptical trajectories, suitable for such decomposition. The inferred inward momentum pinch velocity from this analysis shows qualitative similarity to theoretical predictions resulting from consideration of low-k turbulence, in particular showing a radial dependence proportional to the momentum diffusivity. A comparison of the inferred pinch velocity and comparison with a theoretical prediction for the momentum pinch [27] is shown in Fig. 7. Relatively good agreement is observed across the profile, although the notable discrepancy outside of ρ~0.8 still needs to be understood. Similar results have also been obtained on NSTX [28]. In the presence of an inward pinch of momentum, the inferred χ_ϕ is generally larger than from an analysis that treats the transport purely in terms of an effective diffusivity. It is therefore unlikely that an effective χ_ϕ will be satisfactory for prediction of the rotation profile.

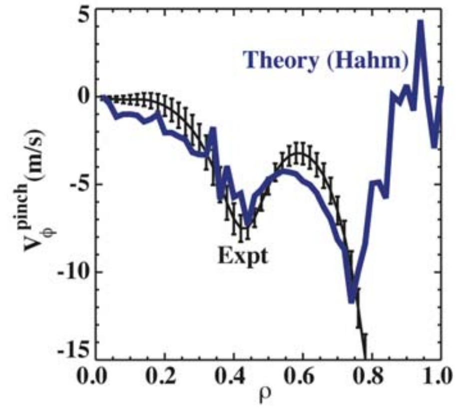

FIG. 7. Experimentally determined pinch velocity from perturbation experiment (black) compared with theory of Hahm [22] (blue).

6. Conclusions

A considerable amount of progress required to obtain predictive knowledge of rotation has been made on the important aspects sources, sinks and transport. Many of the predictions of the theory relevant to the effect of non-resonant magnetic fields on rotation have been confirmed experimentally, including the existence of an offset rotation, toward which such fields "drag" the plasma rotation. The fact that this offset rotation is non-zero opens up the possibility of using non-resonant magnetic fields as a means of driving toroidal rotation in fusion plasmas. New measurements have been made to characterize the modification to neutral beam torque profiles in the presence of Alfvén eigenmode activity, and the profile of the anomalous torque responsible for intrinsic rotation has also been directly measured. Studies of momentum transport have indicated a dependence of the global momentum confinement time on the applied torque. However, the relative importance of $E\times B$ shear can completely change whether the confinement improves at low torque.

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References

[1] BURRELL, K.H., Phys. Plasmas **4**, 1499 (1997).
[2] STRAIT, E.J., *et al.*, Phys. Rev. Lett. **74**, 2483 (1995).
[3] EVANS, T.E., *et al.*, Phys. Rev. Lett. **92**, 235003 (2004).
[4] JENSEN, T.H., Phys. Fluids B **5** 1239 (1993).
[5] FITZPATRICK, R., Phys. Plasmas **5** 3325 (1998).
[6] GAROFALO, A.M., *et al.,* Nucl. Fusion **47**, 1121 (2007).
[7] COLE, A.J., *et al.,* Phys. Rev. Lett. **99**, 065001 (2007).
[8] GAROFALO, A.M., *et al.,* accepted for publication in Phys. Rev. Lett. (2008).
[9] HOULBERG, W.A., *et al.,* Phys. Plasmas **4**, 3230 (1997).
[10] GOLDSTON, R.J., *et al.,* Comput. Phys. Commun. **43**, 61 (1981).
[11] PANKIN, A., *et al.*, Comput. Phys. Commun. **159**, 157 (2004).
[12] HAWRYLUK, R., *Phys. Plasmas Close to Thermonuclear Conditions,* B. Coppi, *et al.*, Editor (CEC, Brussels, 1980) Vol. 1, pp. 19–46.
[13] HEIDBRINK, W.W., *et al.*, Phys. Rev. Lett. **99**, 245002 (2007); HEIDBRINK, W.W., *et al.*, Nucl Fusion **48**, 084001 (2008).
[14] VAN ZEELAND, M.A., *et al.*, Plasma Phys. Control. Fusion **50**, 035009 (2008).
[15] LUO, Y., *et al.*, Rev. Sci. Instrum. **75**, 3468 (2004).
[16] HEIDBRINK, W.W., *et al.*, Plasma Phys. Control. Fusion **49**, 1457 (2007).
[17] ERIKSSON, L.G., *et al.,* Plasma Phys. Control. Fusion **39**, 27 (1997).
[18] RICE, J.E., *et al.,* Nucl. Fusion **38**, 75 (1998).
[19] deGRASSIE, J.S., *et al.,* Phys. Plasmas **11**, 4323 (2004).
[20] SOLOMON, W.M., *et al.,* Plasma Phys. Control. Fusion **49**, B313 (2007).
[21] deGRASSIE, J.S., *et al.,* this conference, EX/P5-2.
[22] GÜRCAN, Ö.D., *et al.*, Phys. Plasmas **14**, 042306 (2007).
[23] DOMINGUEZ, R.R and STAEBLER, G.M., Phys. Fluids B **5**, 3876 (1993).
[24] CANDY, J., *et al.,* J. Comput. Phys. **186**, 545 (2003).
[25] WANG, W.X., *et al.,* Phys. Plasmas **13**, 092505 (2006).
[26] WALTZ, R.E., *et al.,* Phys. Plasmas **4**, 2482 (1997).
[27] HAHM, T.S., *et al.,* Phys. Plasmas **14**, 072302 (2007).
[28] SOLOMON, W.M., *et al.,* Phys. Rev. Lett. **101**, 065004 (2008).