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Momentum transport studies in high $E \times B$ shear plasmas in NSTX

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Abstract

Experiments have been conducted on NSTX to study both steady state and perturbative momentum transport. These studies are unique in their parameter space under investigation, where the low aspect ratio of NSTX results in rapid plasma rotation with $E \times B$ shearing rates high enough to suppress low-k turbulence. In some cases, the ratio of momentum to energy confinement time is found to exceed five. Momentum pinch velocities of order 10-40 m/s are inferred from the measured angular momentum flux evolution after non-resonant magnetic perturbations are applied to brake the plasma.

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Rotation is widely acknowledged as playing a central role in the performance of fusion plasmas. It has been shown to be beneficial in the stabilization of deleterious magneto-hydrodynamic (MHD) instabilities such as resistive wall modes [1], and can improve the overall confinement of the plasma through $E \times B$ shearing suppression of low-k turbulence [2]. Despite the importance of rotation to fusion, momentum transport remains one of the least understood of the transport channels. Consequently, the ability to make predictions of rotation in next step devices is questionable. Since ITER performance projections depend on the assumed rotation profile, obtaining predictive understanding of rotation and momentum transport is of considerable importance.

Experiments have been conducted on the National Spherical Torus Experiment (NSTX) to investigate momentum transport in H-mode plasmas during relatively MHD quiescent times. NSTX is characterized by plasmas with typically high rotation speeds (Mach numbers commonly exceeding 0.5) and strong rotational shear. Coupled with the low toroidal magnetic fields $B_\phi \leq 0.55$ T on NSTX, this leads to very large values of the $E \times B$ shearing rate, in some cases approaching the MHz range. Such $E \times B$ shearing rates can exceed the growth rates of ion temperature gradient (ITG) and trapped electron mode (TEM) turbulence by up to an order of magnitude, resulting in a reduction or possible suppression of these modes in NSTX H-mode plasmas. Such characteristics place NSTX plasmas in a unique regime compared with conventional aspect ratio tokamaks, where low-k turbulence forms an integral part of the understanding of both ion thermal and momentum transport. A key question is whether the momentum transport exhibits similar properties under these different conditions as compared to conventional aspect ratio.

Previously, the energy confinement scaling at high power has been reported from NSTX, in which the B_ϕ and plasma current I_p scalings have been isolated from changes in other parameters [3]. Unlike at conventional aspect ratio, it was found that the B_ϕ scaling was strong (nearly linear), while the I_p scaling was relatively weak ($I_p^{0.4}$). In particular, the strong B_ϕ scaling seemed to be tied to the electron thermal transport, and the ion thermal transport only showed notable variation with I_p. In all cases, the ion thermal diffusivity was found to be comparable to the neoclassical predictions from the GTC-Neo code [4]. From these same scans, steady state momentum transport has also been investigated. Rotation measurements are made using charge exchange recombination spectroscopy (CHERS) [5, 6]. Although the measurement is based on impurity carbon, the neoclassically computed main ion rotation, using the NCLASS code [7], indicates only a minor difference ($\sim 5\%$) between the species. Even still, it should be noted that the difference between main ion and impurity may not always be captured adequately by NCLASS (e.g. Refs. [8, 9]). As the magnetic field was increased from 0.35 T to 0.55 T, the central rotation increased by approximately 50%, while the profile shape remained much the same. The torque deposited was roughly unchanged with B_ϕ. For the I_p scan, the rotation again showed a significant increase as the current was increased, but some of this resulted from modifications to the delivered neutral beam torque profiles. In these plasmas with strong neutral beam injection, the torque is considered to come primarily from the beams. This beam driven torque is calculated using the Monte Carlo NUBEAM package [10, 11] within TRANSP [12], and is corrected for various losses, including charge exchange and orbit losses. Angular momentum may also be contributed to the plasma from other sources, but generally these are difficult to characterize and compute. One such example is related to intrinsic rotation, which can effectively be attributed to an anomalous torque source [13]. Preliminary measurements of intrinsic rotation at the plasma edge on NSTX indicate that it may follow a similar empirical scaling as observed across multiple tokamaks. If the scaling holds to much higher β (volume-average percentage ratio of the plasma pressure to the magnetic pressure) as in these beam heated plasmas, then the intrinsic torque contribution could be a sizable fraction of the total torque. Fluctuations are also capable of inducing a torque [14], but it is unknown how large this may be in these plasmas.

The angular momentum balance equation is given by

$$mR\frac{\partial(nV_\phi)}{\partial t} = \eta - \frac{1}{r}\frac{\partial(r\Gamma_\phi)}{\partial r} - \frac{1}{r}\frac{\partial(mrRV_\phi\Gamma_p)}{\partial r}, \tag{1}$$

where m is the ion mass, n is the ion density, η is the local torque density, Γ_p is the (radial) ion particle flux (which gives rise to a typically small convection of momentum), Γ_ϕ is the (radial) angular momentum flux, and R and r are the major and minor radius respectively. To investigate momentum transport, the angular momentum balance equation is solved for Γ_ϕ at each time step within TRANSP, using the measured rotation and calculated torque, although unaccounted torque sources like those described above could potentially lead to systematic errors in the determination of the flux. In this framework, the angular momentum flux is treated as a purely diffusive process, that is, $\Gamma_\phi = -mnR\chi_\phi\partial V_\phi/\partial r$, where χ_ϕ is an effective momentum diffusivity, which is shown in Fig. 1 for the B_ϕ and I_p scans. The momentum diffusivity was found to be highly anomalous compared with GTC-Neo neoclassical predictions, despite the fact that the ion thermal transport was close to neoclassical in these discharges. We observed in the dedicated scans that the momentum transport varies most strongly with B_ϕ, showing very weak or no effect with I_p, which is more accordant with the observations of the electron thermal transport reported in Kaye et al. [3]. However, over a wide database of plasma conditions, this dependence is not robust, with only a weak dependence of χ_ϕ on χ_e emerging.

The lack of scaling of χ_ϕ with χ_i seen in the dedicated scaling experiments is also clear statistically in the inner half of the plasma ($\rho \lesssim 0.4$), where ρ is the square root of normalized toroidal flux. In this region, χ_i can be up to a factor of 30 greater than χ_ϕ. Farther out, at $\rho \gtrsim 0.65$, χ_ϕ is broadly seen to scale with χ_i, more consistent with results from conventional aspect ratio tokamaks [15, 16], although χ_i still tends to be about a factor of about 10 greater than χ_ϕ. The scaling, however, is not particularly tight, with approximately an order of magnitude scatter in the data.

Perturbative studies make it possible to determine whether the assumption that the momentum transport is purely diffusive is valid. On NSTX, an $n = 3$ non-resonant magnetic perturbation (NRMP) has been applied to the plasma, resulting in a braking of the plasma rotation. The maximal braking is observed near $R_{\text{maj}} \sim 1.3$ m, which shows qualitative agreement with previous calculations of the associated torque associated with the neoclassical toroidal viscosity (NTV) [17].

In these experiments, the perturbations were applied starting at 380 ms for a duration of 40 ms, of order or shorter than the energy confinement time, so that the underlying energy transport properties of the plasma (e. g. χ_ϕ and χ_i) are not significantly altered by the perturbation. The strength of the applied magnetic field perturbation was varied in a succession of shots, and at the highest levels resulted in more than a 50% reduction in the local toroidal velocity in the region of maximal NTV torque by the end of the braking period. The perturbation penetrated in to about $\rho \sim 0.25$. The overall angular momentum in the plasma was reduced by approximately 20%. The subsequent spin up of the plasma after the NRMP turned off was analyzed to characterize the momentum transport on NSTX. This period of time was chosen for the analysis since the NBI-induced torque is more readily computed quantitatively than the NRMP-driven torque. We present here the first experimental evidence of an inward pinch of angular momentum in a spherical tokamak, and show semi-quantitative agreement with theoretical predictions.

Both global and local transport quantities have been analyzed on NSTX using this technique. A simple model was used to relate the global momentum confinement time τ_ϕ to the evolution of the angular momentum, L, in the plasma, $dL/dt = T - L/\tau_\phi$, where T is the applied torque resulting from neutral beam injection. The model is readily integrable to obtain an expression for the time dependent angular momentum, $L(t) = \tau_\phi[T - (T - L_0/\tau_\phi)\exp(-t/\tau_\phi)]$, where L_0 is the initial angular momentum immediately after the NRMP is turned off. The momentum confinement time can then be determined by a non-linear least squares minimization of the the difference between the measured and modeled angular momentum evolution. From this analysis, the momentum confinement in NSTX plasmas with $I_p \sim 0.9$ MA, $B_\phi \sim 0.35$ T, injected power $P_{\rm inj} \sim 4$ MW, central electron density $n_e(0) \sim 6\times10^{19}$ m^{-3}, and ion and electron temperature $T_i(0) \sim T_e(0) \sim 0.9$ keV, was found to be surprisingly high, $\tau_\phi \sim 170$ ms, which is more than a factor of five greater than the energy confinement time $\tau_e \sim 30$ ms. This is a very different result than observed on conventional aspect tokamaks, where typically $\tau_\phi \sim \tau_e$. The momentum confinement time deduced from this perturbative analysis agrees well with the value from the steady state analysis of the discharge.

The momentum flux, including a radial momentum pinch term, $V^{\rm pinch}$ can be written

$$\Gamma_\phi = -mnR\chi_\phi \frac{\partial V_\phi}{\partial r} + mnRV^{\rm pinch}V_\phi. \quad (2)$$

In the present work, we have investigated the role of diffusive versus convective momentum transport, again during the relaxation period, by doing the complete 0-D analysis, with η driven by the beams. Although the torque associated with intrinsic rotation is neglected, β remains relatively constant during and following the perturbative pulse. Therefore, based on the present ideas about the scaling of intrinsic rotation, this intrinsic torque is not expected to change during the relaxation period, and therefore should not lead to unexpected rotation changes.

The viscous angular momentum flux is inferred from momentum balance in TRANSP during the relaxation of the rotation following the NRMP. This experimentally determined flux is modeled according to Eq. (2), and using a non linear least squares fit we obtained time constant profiles for χ_ϕ and $V^{\rm pinch}$.

The results for the inferred momentum diffusivity and momentum pinch velocity are shown in Fig. for one such NSTX discharge after the NRMP perturbation was turned off. Although the TRANSP analysis is on a uniform ρ grid, the analysis is only shown at points that are statistically significant. In particular, if either the reduced χ^2 value is larger with the additional degree of freedom offered by including V^{pinch}, or the local χ_ϕ is poorly determined (resulting from collinearity of the local rotation and its gradient), then the analysis at that radius is excluded. The region of highest confidence in the determination of χ_ϕ and V^{pinch} is in the region where the $n = 3$ perturbative torque is believed to be highest.

A large inward pinch up to 40 m/s is observed between $0.6 < \rho < 0.8$. A similar inward pinch profile was observed on a sequence of NSTX discharges, with the applied current increased from approximately 700 A to 1400 A, resulting in a change of applied field from approximately 1.4 mT to 2.8 mT at the plasma edge. The analysis is also performed imposing $V^{\mathrm{pinch}} = 0$. The inferred effective momentum diffusivity (χ'_ϕ) in this case closely matches the time average of the TRANSP determined χ'_ϕ over the time period (which also serves as a consistency check). Including the inward pinch increases the inferred momentum diffusivity, more than a factor of two in the region of maximum pinch.

There has been theoretical consideration of a momentum pinch drive resulting from low-k turbulence drive [18, 19]. Both theories find that the momentum pinch should scale with the momentum diffusivity, $V^{\mathrm{pinch}} \sim \chi_\phi/R$, although Peeters et al. [19] claim an additional term (proportional to the inverse gradient scale length L_n) related to the Coriolis force. Experimentally, we observe a scaling of the inferred momentum pinch velocity with the diffusivity. Fig. 3 plots the theoretical prediction versus the experimental measurement for the two theories at discrete radial locations. Although this limited data set is not able to discriminate between the two theories, further studies with larger variations in L_n should permit this. The fact that the experimentally determined momentum pinch velocity is consistent with theory derived from low-k turbulence considerations suggests that the low-k turbulence is not completely suppressed, but rather reduced in magnitude due to $E\times B$ shear. Nonetheless, this reduction appears sufficient to completely alter the dependences of the momentum transport compared with conventional aspect ratio tokamaks. Additionally, this may suggest a role for trapped electron mode (TEM) turbulence, which might directly relate to the observed coupling of the momentum diffusivity to the electron thermal diffusivity in some cases.

The presence of a momentum pinch further complicates simple comparisons of χ_ϕ and

χ_i. In particular, the absolute value of the χ_ϕ's presented in Fig. 1 are almost certainly underestimated. While it is not possible to extract an experimental $V^{\rm pinch}$ from the steady state conditions of the discharges used in those data, we can make estimates based on the above theoretical expectations. By doing so, the ratio of χ_ϕ to χ_i will decrease closer to unity, especially in the outer region of the plasma.

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Figures

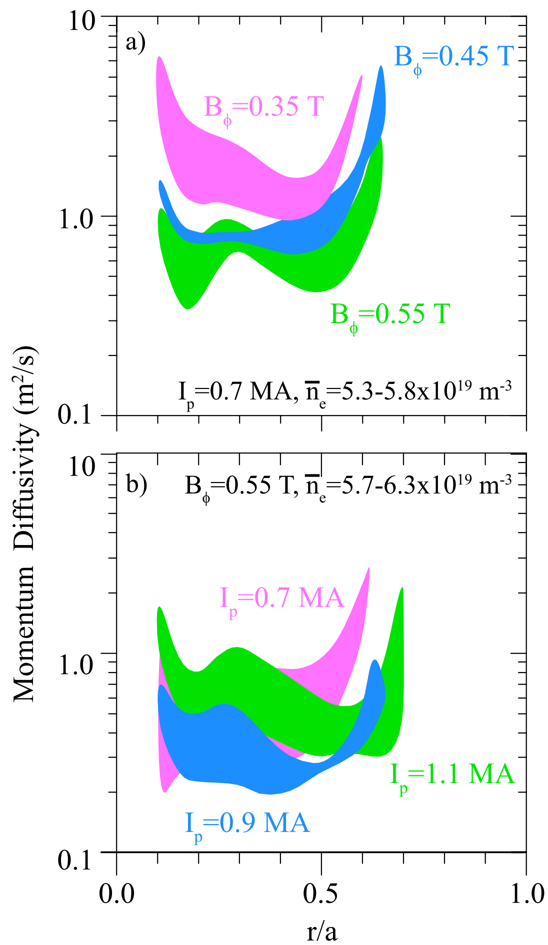

FIG. 1: Momentum diffusivity from (a) the B_ϕ scan at $I_p = 0.7$ MA, and (b) the I_p scan at $B_\phi = 0.55$ T. The momentum diffusivity is found to depend much more strongly on B_ϕ than I_p, which is more consistent with the electron thermal transport than the ion thermal transport.

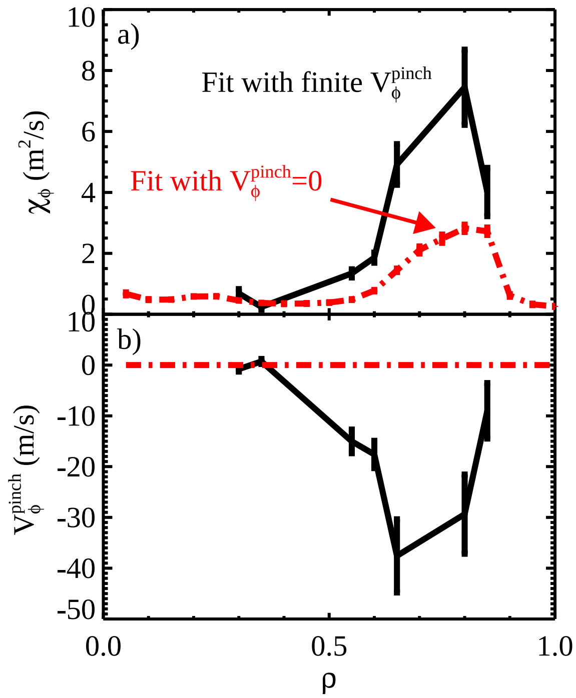

FIG. 2: (a) Momentum diffusivity and (b) momentum pinch velocity inferred using n=3 non-resonant magnetic perturbations to the plasma. For comparison, the inferred diffusivity neglecting any momentum pinch is also shown (dashed).

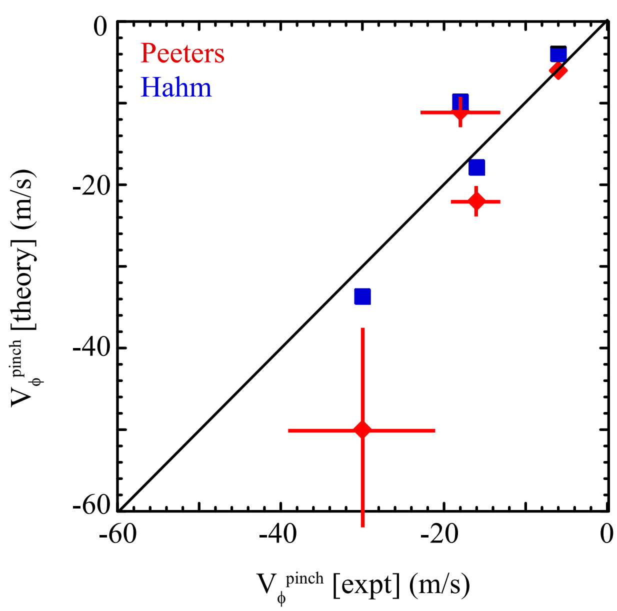

FIG. 3: Comparison of the theoretically predicted momentum pinch velocities from Hahm et al. [18] (■) and to Peeters et al. [19] (♦) the experimentally determined quantity.

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