Measurement and prediction of momentum transport in spherical tokamaks

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Strong toroidal rotation can improve both macroscopic stability and confinement in tokamak plasmas. It is therefore of great interest to understand the mechanisms that determine the rotation profile in order to develop predictions for future devices such as ITER or a Fusion Nuclear Science Facility (FNSF). In addition to outward diffusion, an inward momentum convection or "pinch" has been observed in many tokamaks [1]. In many cases this pinch can be explained by the Coriolis drift mechanism [2], with relatively good quantitative agreement with predictions from local, quasi-linear gyrokinetic calculations of the ion temperature gradient (ITG) instability (e.g. [3]). Here we attempt to validate this model over a broader range of beta and aspect ratio by extending into the spherical tokamak (ST) plasma regime using data from NSTX and MAST.

Previous perturbative measurements in NSTX H-modes have indicated the existence of an inward momentum pinch with a magnitude similar to that observed in conventional aspect ratio tokamaks [4]. Assuming a momentum flux of the form $\Pi = n_i m_i \langle R^2 \rangle (-\chi_\varphi \nabla\Omega + V_\varphi \Omega)$, pinch numbers of RV_φ/χ_φ=(-1)-(-7) (directed inward) were measured. However, local, linear gyrokinetic simulations run for these cases predict the microtearing mode is the dominant micro-instability in the region of interest (ρ=0.5-0.7) due to the relatively large plasma beta (β_T=12-16%, β_N=3.5-4.6) [5]. While microtearing turbulence provides negligible momentum transport (compared to electron thermal transport), in these discharges there is also evidence of a variety of weaker yet unstable ballooning modes at lower $k_\theta\rho_s$ including ITG, compressional ballooning modes (CBM, which depend explicitly on the presence of compressional magnetic perturbations at high beta), and kinetic ballooning modes (KBM). Quasi-linear calculations were used to predict the momentum pinch from these sub-dominant ballooning modes, assuming they contribute substantially to the momentum transport. In all cases investigated the predicted pinch number is small or directed outward ($RV_\varphi/\chi_\varphi \geq 0$) for all of the ballooning modes (ITG, KBM, CBM) in contradiction to the experimental results [6]. Fig. 1 summarizes the range of measured and predicted pinch parameter for three NSTX H-modes in the region of interest ($\rho \approx$0.5-0.7). Additional scans show that the weak pinch is a consequence of how both electromagnetic effects (at relatively large beta) and low aspect ratio influence symmetry-breaking of the instabilities.

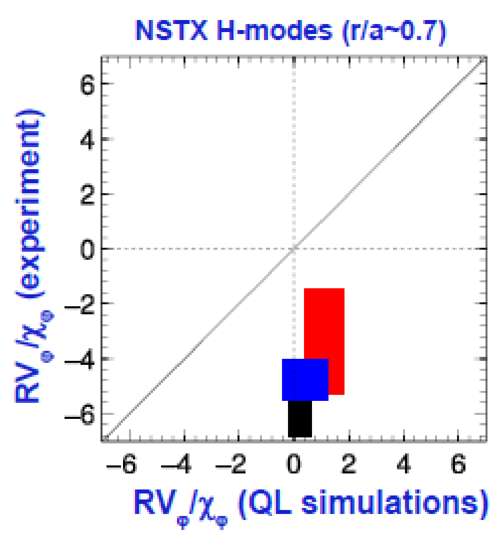

Fig. 1. Measured pinch parameter RV_φ/χ_φ vs. predictions from local, quasi-linear gyrokinetic simulations for NSTX H-modes.

To minimize electromagnetic effects, experiments were performed in MAST L-mode plasmas at relatively low beta (β_N=2). These experiments were conducted during the final MAST campaign (2013) using applied n=3 fields to perturb the plasma rotation. Similar to the NSTX analysis [4], the time-dependent response of the rotation after the n=3 field is removed is used to infer both momentum diffusivity and pinch, where the momentum flux Π is determined from TRANSP. Fig. 2 shows the inferred momentum and ion thermal diffusivities, Prandtl number and pinch parameter. Fits to both χ_φ and V_φ are only shown where Ω and $\nabla\Omega$ are sufficiently decorrelated to provide a unique solution (symbols). In these cases, the quality of fit is improved compared to fitting only a diffusive component (V_φ=0, red lines). From Fig. 2a it is seen that the ion thermal transport has a significant neoclassical component even for this L-mode plasma. As a result, the purely turbulent Prandtl number (subtracting the neoclassical ion thermal transport), $Pr=\chi_\varphi/(\chi_i-\chi_{i,NC})$, reaches values much larger than unity near the mid-radius (Fig. 2b, open symbols). The inferred pinch values (Fig 2c), RV_φ/χ_φ=(-2)-(-11), are similar to those found in conventional tokamaks and to those in the NSTX H-modes. Initial linear, local gyrokinetic simulations indicate that even for the low beta L-modes, the predicted momentum pinch is relatively small and cannot reproduce the large experimentally inferred pinch. A similar L-mode experiment is planned for NSTX-U in the upcoming run campaign (spring, 2016) to provide additional experimental measurement of momentum pinch in low beta spherical tokamak plasmas.

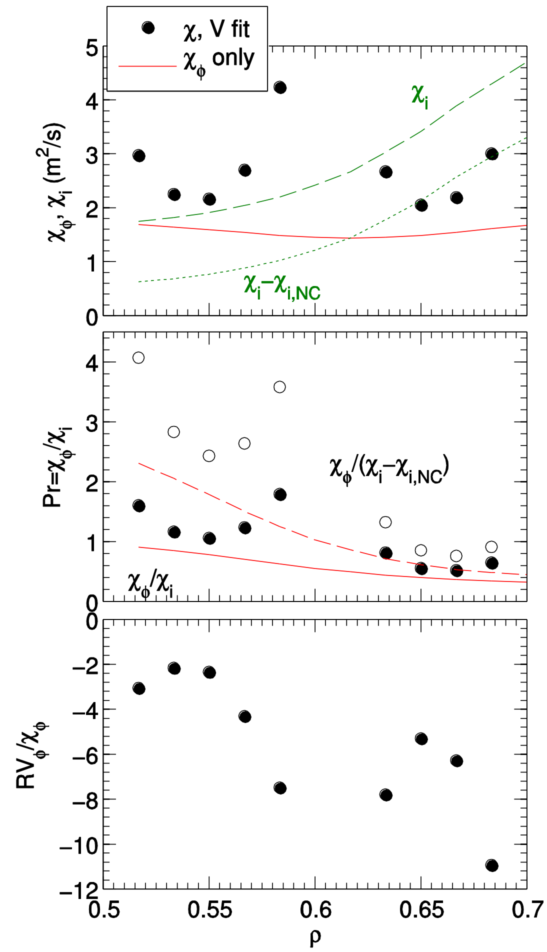

Fig. 2. (a) Momentum and ion diffusivities (without and with $\chi_{i,NC}$ subtraction) from a MAST L-mode discharge. Fit assuming V_φ=0 is shown by red line. (b) Prandtl number without $\chi_{i,NC}$ subtraction (solid lines, closed symbols) and with (dashed lines, open symbols). (c) Pinch parameter RV_φ/χ_φ.

Based on the above observations and simulations, the Coriolis pinch mechanism predicted from local, linear gyrokinetic theory does not appear to explain perturbative momentum transport at low aspect ratio. Other mechanisms neglected thus far are being investigated as possible solutions to the apparent discrepancy, including nonlinear effects, perpendicular E×B shear driven transport [7], centrifugal effects [8] and profile shearing [9]. In particular, profile shearing is of great interest as it should become more significant compared to the Coriolis pinch for the larger values of $\rho_*=\rho_i/R$ found in spherical tokamaks. Non-local (global) simulations are underway in an attempt to simulate the importance of this effect.

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