Gyrokinetic prediction of momentum transport in spherical tokamaks

W. Guttenfelder[1], S.M. Kaye[1], Y. Ren[1], W. Solomon[1], R.E. Bell[1], J. Candy[2], S.P. Gerhardt[1], B.P. LeBlanc[1], H. Yuh[3]
(email: wgutten@pppl.gov)

[1] Princeton Plasma Physics Laboratory, Princeton NJ 08543
[2] General Atomics, San Diego, CA 92186
[3] Nova Photonics Inc., Princeton, NJ 08540

Strong toroidal rotation can improve both macroscopic stability and confinement in tokamak plasmas. Therefore, it is 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 spherical tokamaks (STs) such as NSTX, many drift wave instability mechanisms are predicted to be potential contributors to the observed anomalous electron thermal transport [1], including ion temperature gradient (ITG), trapped electron mode (TEM), electron temperature gradient (ETG), microtearing (MT) and kinetic ballooning mode (KBM), each of which depend uniquely on many parameters such as beta and collisionality [2]. However, only the ion scale ($k_\theta \rho_s$<1) ballooning modes (ITG, TEM, KBM) are expected to contribute to the observed anomalous momentum transport. Previous perturbative H-mode experiments in NSTX demonstrated the existence of an inward momentum pinch [3]. 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) were measured with Prandtl numbers Pr=χ_φ/χ_i=0.3-0.6.

Local, linear gyrokinetic simulations have been run for NSTX H-modes of [3] in the region of interest (r/a=0.6-0.8). In all cases the microtearing mode is present and usually has the largest growth rate, as shown in Fig. 1a (dashed lines). Previous linear and nonlinear local simulations of microtearing turbulence [4] predict negligible transport of momentum compared to electron heat. However, in these cases there is also evidence of unstable ballooning modes at lower $k_\theta \rho_s$ (solid lines). Additional parameter scans illustrate these modes are kinetic ballooning modes (KBM), driven by the total kinetic pressure gradient, with other identifying characteristics discussed in detail in [2].

Following [5], Prandtl and Coriolis pinch numbers are calculated for KBM using the incremental change in quasilinear momentum flux as both Ω and $\nabla\Omega$ are varied, which has been successful in interpreting conventional tokamak

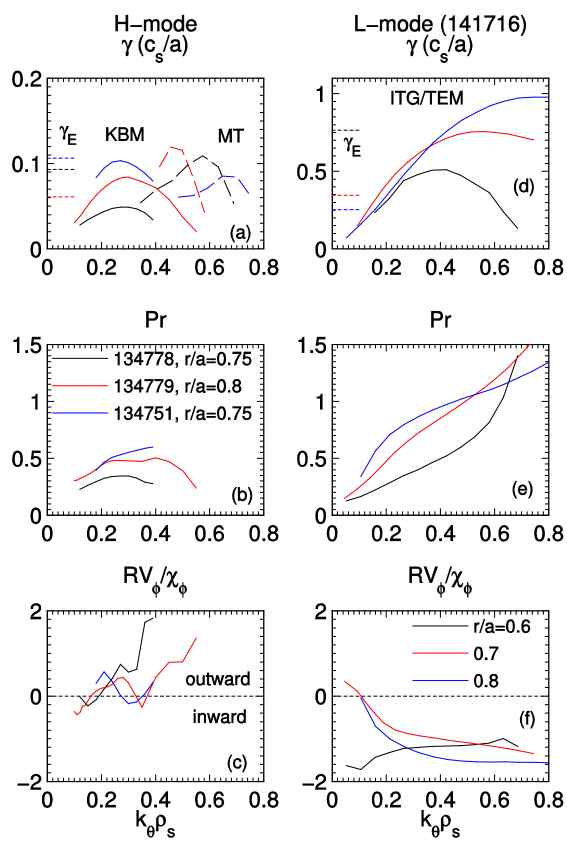

Fig. 1: (top) Linear growth rates for H-modes (left) and an L-mode (right). The H-modes are unstable to both microtearing (dashed) and KBM (solid). The L-mode is unstable to ITG/TEM. Dotted horizontal lines represent local E×B shearing rates. (middle) Corresponding quasilinear Prandtl and (bottom) pinch numbers, RV_φ/χ_φ.

analysis [6]. The momentum flux includes contributions from both deuterium and carbon (Z_{eff}~3 for these plasmas) and all field perturbations (electrostatic, shear and compressional magnetic perturbations). The predicted turbulent Prandtl numbers (Pr~0.3-0.6) (Fig. 1b) are similar to experimental values, but would be smaller if neoclassical transport was included ($\chi_{tot}\approx\chi_{i,nc}>\chi_{i,turb}$ from TRANSP analysis). Furthermore, the predicted pinch number is small and directed outward ($RV_\varphi/\chi_\varphi\geq 0$, Fig. 1c), in contradiction to the measurements. The predicted pinch number is relatively insensitive to variations in normalized temperature or density gradients, beta or collisionality, almost always remaining in the outward direction. Therefore, it appears that local, quasi-linear theory for Coriolis pinch is insufficient to explain the observed momentum pinch in NSTX H-modes, if KBM is the instability responsible. Additional simulations are being run with different profile fits and equilibrium reconstructions to investigate the likelihood that KBM, as opposed to ITG/TEM, is robustly predicted to be unstable in the core of these NSTX H-modes.

For comparison to KBM, similar predictions have been done for an NSTX L-mode plasma (analyzed extensively in [7]) shown in Fig. 1(d-f). Because of much lower beta, ITG/TEM modes are unstable, instead of KBM and MT, with inward directed momentum pinch. However, the predicted pinch numbers, RV_φ/χ_φ~(-1)-(-2) are still relatively weak compared to the H-mode observations (up to -7). The momentum pinch for ITG/TEM is also relatively insensitive to parameter variations.

Other mechanisms neglected thus far are being investigated as possible solutions to the apparent discrepancy, including nonlinear effects, perpendicular E×B shear driven transport [8] and profile shearing at finite ρ_* [9]. While nonlinear simulations for the high beta H-mode remain challenging due to numerical considerations [2], they have been run for the low beta L-mode case to investigate nonlinear and E×B shear effects. When ignoring the parallel velocity gradient in the gyrokinetic equation ($u'\sim dv_\parallel/dr\rightarrow 0$, i.e. purely perpendicular E×B flow), a strong inward directed momentum flux is predicted (Fig. 2, dots), indicating it could significantly modify the quasilinear results and interpretation presented above. The dependence is non-monotonic as increasing E×B shear ($\gamma_E=-r/q\nabla\Omega$) eventually suppresses the turbulence amplitude [7]. However, if one assumes the flow is purely toroidal (parallel and perpendicular E×B flows are locked together, $u'=qR/r\cdot\gamma_E$), the momentum flux increases (outward) up to the experimental value of γ_E (circles). Repeating the toroidal shear scan including the finite toroidal flow (Mach=0.37) reduces the transport (squares), consistent with the quasilinear prediction of a weak inward pinch (RV_φ/χ_φ=-1). Simulations are ongoing in attempt to provide similar nonlinear predictions of the importance of the E×B shear on the H-mode KBM simulations.

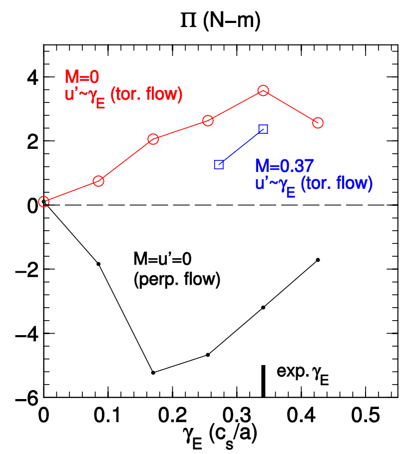

Fig. 2: Momentum flux from nonlinear L-mode ITG/TEM simulations vs. E×B shear.

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