

Anomalous Bootstrap Current and Poloidal Flow Generation and Global Turbulent Transport in Tokamaks and STs

W. X. Wang, S. Ethier, B. Grierson, Y. Ren, S. Kaye, R. Nazikian, J. Chen
P. H. Diamond¹, T. S. Hahm², F.L. Hinton¹, Z. Lu¹

Princeton Plasma Physics Laboratory, New Jersey, USA; email: wwang@pppl.gov

¹University of California, San Diego, USA

²Seoul National University, Korea

Both plasma flows and self-generated non-inductive currents are key players in tokamak physics and play various critical roles in affecting confinement performance in fusion devices. The first topic of this paper will focus on the effects of microturbulence on plasma poloidal flow and bootstrap current.

Recently, significant anomalous poloidal flow has been observed for both bulk ions and impurities in DIII-D experiments [1, 2]. In ITER burning plasma experiments with little toroidal momentum input, such anomalous poloidal rotation can make a significant contribution to $\mathbf{E} \times \mathbf{B}$ flow shear, and thus strongly impact ITER confinement performance. Typically, anomalous poloidal flow is observed in low collisionality regime with large ion temperature gradients, and scales with the inverse of ion collisionality. Nonlinear gyrokinetic simulations of DIII-D experiments have been carried out to elucidate underlying mechanisms for driving anomalous poloidal flow. Simulation studies with the GTS code [3] include self-consistent neoclassical physics, allowing us to access comprehensive physics of both driver and damping in determining the poloidal flow. It is found that ITG turbulence, while producing experimentally relevant heat transport, can also drive a significant poloidal Reynolds stress in the core region where significant anomalous poloidal flow is observed. The divergence of the Reynolds stress produces a proper torque needed for driving the observed anomalous poloidal flow in the right direction. Specifically, by balancing with the magnetic-pumping-induced viscous damping, the turbulence-generated torque can drive a stationary poloidal flow consistent with the level of observed anomalous poloidal flow in ion collision time scale. Moreover, the fluctuation-induced poloidal Reynolds stress profile shows weak dependence on the ion collisionality in low collisionality regime due to time scale separation between turbulence and collisional zonal flow damping. This result suggests that the observed collisionality scaling of anomalous poloidal flow may result from the viscous damping. Finally, close coupling may exist between poloidal and toroidal flow via strong correlation between poloidal and toroidal Reynolds stress. Some possible experimental tests are suggested.

Global gyrokinetic simulations with the GTS code have been employed to investigate the bootstrap current generation in the presence of drift wave turbulence. Plasma self-generated non-inductive currents in fusion devices, e.g, the bootstrap current, have a great impact on overall plasma confinement and, specifically, on key MHD instabilities such as neoclassical tearing mode (NTM) and edge localized mode (ELM). The collisionless trapped electron mode (CTEM) is found to induce a significant, quasi-stationary parallel current. Recent nonlinear GTS simulations, which include both turbulent and neoclassical physics self-consistently and simultaneously, show that bootstrap current generation is significantly enhanced in the presence of CTEM-induced fluctuations (fig.2, left). This is consistent with earlier GTS results of CTEM turbulence simulations without neoclassical physics [4]. The total bootstrap current, however, is not a simple addition of turbulence-induced current to the neoclassical bootstrap current. The underlying dynamics is closely related to the nonlinear plasma flow generation by turbulent

fluctuations. However, unlike toroidal momentum, which is mostly carried by ions, the turbulent current is mainly carried by electrons and driven by electron residual stress with possible contribution due to turbulent acceleration. The fluctuation-induced current generation exhibits a similar characteristic dependence on plasma parameters as that of neoclassical bootstrap current, but with different physical origins. Specifically, it increases with the pressure gradient, decreases with poloidal magnetic field (and equilibrium current I_p), and increases with the radial variation of the safety factor. Interestingly, the CTEM driven current is essentially carried by trapped electrons, unlike the neoclassical bootstrap current which is mainly carried by passing particles (fig.2, middle and right).

Also reported are extended simulation studies which attempt to directly access these effects in ITER experiments with focus on electron-transport-dominated regimes.

Low aspect ratio and strongly shaped ST plasmas possess highly distinct features compared to conventional tokamaks, for which using global gyrokinetic simulations are crucial for addressing turbulence and transport physics. Global GTS simulations have been applied to both H- and L-mode plasmas of NSTX for various transport issues. Large toroidal rotation generally characterizing in ST experiments, on one hand, is found to drive shear flow instability in L-mode plasmas. For the first time, the shear flow mode characterized by finite k_{\parallel} and broader k_{θ} [4] than ITG mode (also presented in L-mode) is found relevant to realistic fusion plasmas. On the other hand, the strong rotation gradient creates a strong $\mathbf{E} \times \mathbf{B}$ shear which is shown to largely suppress low-k fluctuations and associated transport both linearly and nonlinearly. The remaining finite low-k fluctuations, while contributing weakly to the observed highly anomalous electron thermal transport, can produce a significant ion thermal transport relevant to experimental level in the outer core region where the so-called transport shortfall is seen in the similar DIII-D L-mode discharges. Low-k fluctuations can also produce a significant toroidal momentum flux with $\chi_{\phi}^{eff} \sim \chi_i$ but in a direction opposite to momentum diffusion, suggesting the presence of a significant anti-gradient momentum pinch. On the other hand, low-k electrostatic turbulence is shown to play little role in NSTX H-mode plasmas due to strong-shaping-induced increase in gradient threshold for instabilities, although significant momentum pinch is observed in experiments [5].

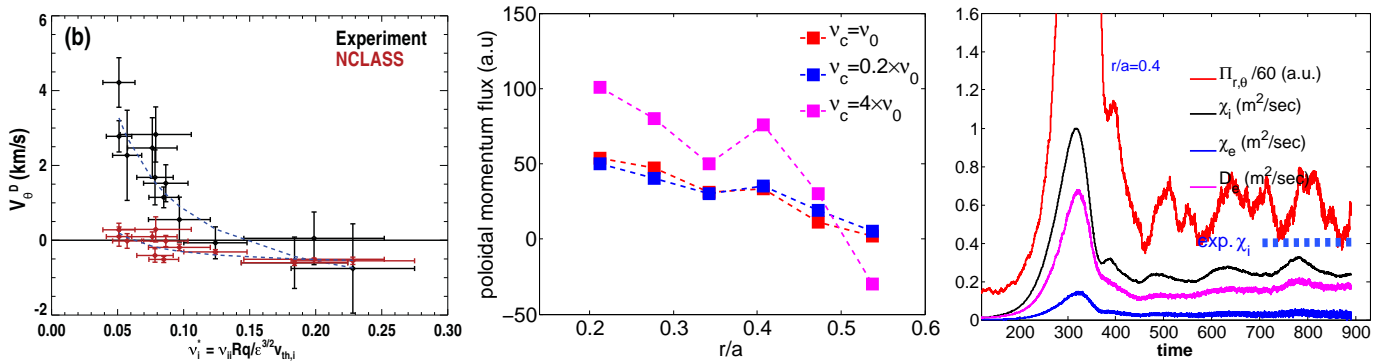


Figure 1: Poloidal flow vs. collisionality observed in DIII-D (left); simulated radial profile of ITG fluctuation-induced poloidal Reynolds stress at different collisionality (middle); and time history of simulated ion and electron heat, particle and poloidal momentum fluxes (right). the current generation increased with dq/dr .

This work was supported by U.S. DOE Contract DE-AC02-09CH11466.

[1] B. A. Grierson *et al.*, Nucl. Fusion 53, 063010 (2013).

[2] C. Chrystal, "Testing neoclassical and turbulent effects on poloidal rotation in the core of DIII-D", invited talk, 55th Annual Meeting of the APS Division of Plasma Physics Nov. 11-15, 2013, Denver, Colorado.

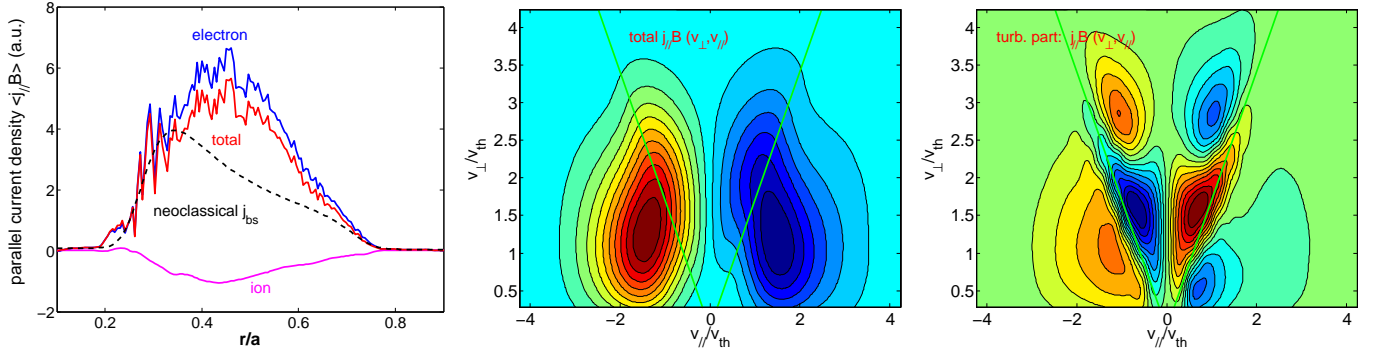


Figure 2: Radial profile of total bootstrap current in the presence of CTEM turbulence in comparison with neoclassical bootstrap current (left); phase space structure of total (middle) and fluctuation-induced (right) electron current, showing relative contributions of trapped and passing electrons.

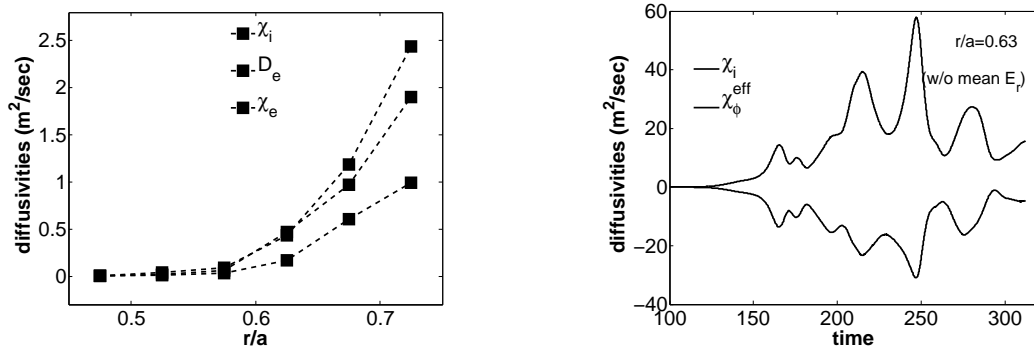


Figure 3: Diffusivity of ion heat, particle and electron heat vs minor radius (left) and time history of simulated ion heat and effective momentum diffusivity (right) for a NSTX L-mode discharge.

- [3] W. X. Wang *et al.*, Phys. Plasmas **17**, 072511 (2010).
- [4] W. X. Wang *et al.*, "Turbulence Generated Non-inductive Current and Flow Shear Driven Turbulent Transport in Tokamaks", Proc. of the 24th IAEA Fusion Energy Conference, San Diego, USA (IAEA, Vienna, 2012) (IAEA Report No. IAEA-FEC/TH/P7-14, 2012).
- [5] S. M. Kaye *et al.*, Nucl. Fusion **49**, 045010 (2009).