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

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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. i) 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 [1] (fig.1, left). 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 [4] in the core region where significant anomalous poloidal flow is observed (fig.1, middle). 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 (fig.1, middle). This result suggests that the observed collisionality scaling of anomalous poloidal flow may result from the viscous damping. Remarkably, in collisionless TEM regime, simulations of a C-MOD L-mode plasma show a fluctuation-induced torque in a direction opposite to that of ITG (fig.1, right). This is associated with the change of mode propagation direction, suggesting poloidal flow can be modified differently in CTEM regime. 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. ii) Global gyrokinetic simulations with the GTS code have been employed to investigate the bootstrap current generation in the presence of drift wave turbulence. The collisionless trapped electron mode (CTEM) is found to induce a significant, quasi-stationary parallel current due to electron flow generation by turbulent residual stress and acceleration. 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 turbulence (fig.2, left). This is consistent with earlier GTS results of CTEM turbulence simulations without neoclassical physics [5]. The total bootstrap current, however, is not a simple addition of turbulence-induced current to the neoclassical bootstrap current. Unlike the neoclassical bootstrap current which is mainly carried by passing particles the CTEM driven current is essentially carried by trapped electrons (fig.2, middle), more precisely, associated with the drift center dynamics of trapped electrons. As an example of application to realistic plasmas, a significant modification of bootstrap current is predicted for a C-MOD L-mode plasma where CTEM fluctuations are presented in the core region (fig.2, 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 than ITG mode [5] (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 (fig.3, left). Low-k fluctuations in L-modes can also produce a significant toroidal momentum flux with $\chi_\phi^{eff} \sim \chi_i$ but in a direction opposite to momentum diffusion, which consists of a significant anti-gradient residual stress along with momentum pinch and diffusion (fig.3, right). The zonal flow $\mathbf{E} \times \mathbf{B}$ shear is shown to dominate over the turbulence intensity gradient for creating $k_\parallel$ spectrum asymmetry needed for residual stress generation. 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 [6].

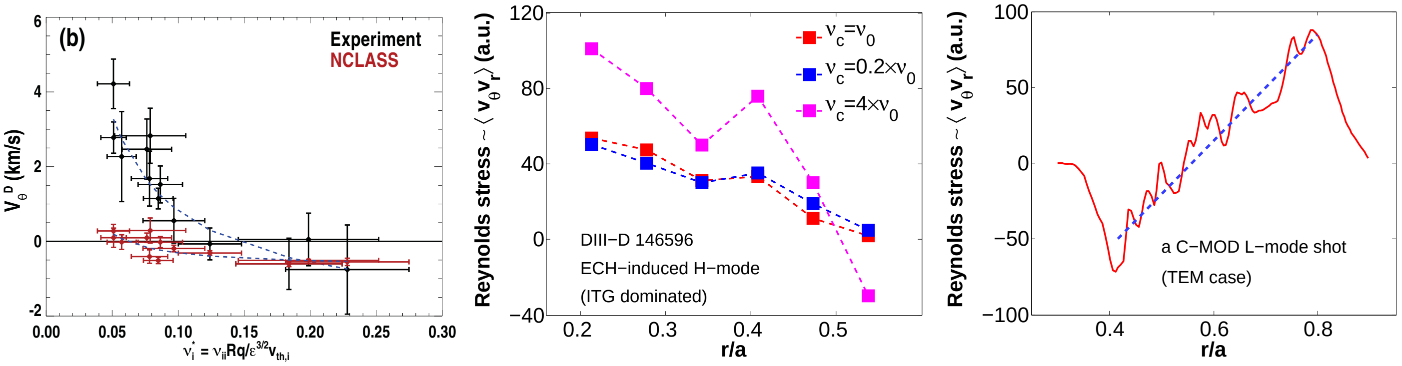

Figure 1: Poloidal flow vs. collisionality observed in DIII-D (left), simulated radial profile of Reynolds stress driven by ITG in DIII-D H-mode at different collisionality (middle), and by CTEM in C-MOD L-mode (right).

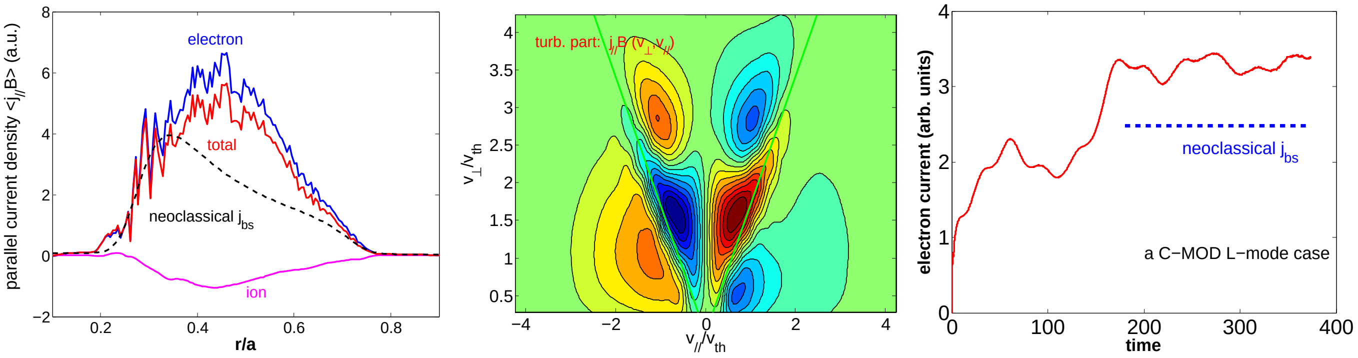

Figure 2: Simulated bootstrap current vs minor radius in the presence of CTEM in comparison with neoclassical j_{bs} (left); phase space structure of fluctuation-induced electron current (middle), showing relative contributions of trapped and passing electrons; electron j_{bs} predicted in a C-MOD L-mode core plasma with CTEM.

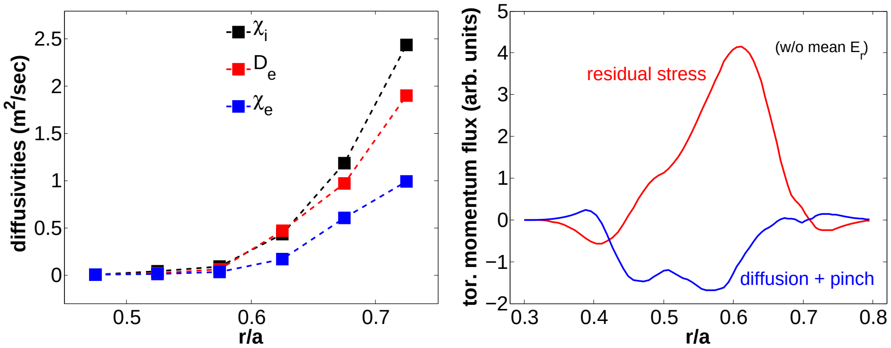

Figure 3: Diffusivity of ion heat, particle and electron heat (left) and residual stress and momentum diffusion/pinch (right) vs minor radius for a NSTX L-mode discharge.

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