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Nondiffusive Electron Transport in Multi-Scale Turbulence

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Introduction-- Current reactor design relies on the extrapolation of the transport level from present-day fusion experiments to much larger future devices, such as the International Thermonuclear Experimental Reactor (ITER)[1]. An important goal of predictive simulations is to replace such empirical scalings by first-principles numerical simulations.

Turbulence of the fusion plasma in a tokamak reactor is often excited by pressure-gradient-driven, electrostatic, drift-wave instabilities possessing anisotropic mode structures. In the prevailing fluid picture[2], transport is understood as arising from the eddy mixing of a random walk process with a correlation length of the eddy size and with a decorrelation time of the eddy turnover time[3,4]. The mixing length argument[5] conjectures that transport increases significantly with a larger eddy size along the radial direction of pressure gradients. The concept of turbulent transport via the eddy mixing is valid when the collisional mean-free-path of constituent particles is much shorter than the eddy correlation length so that particles and eddies move together as fluid elements. However, in high temperature fusion plasmas, the mean-free-path of charged particles along the magnetic field lines is much longer than typical eddy length in the parallel direction. In this nearly-collisionless, wave-dominated plasma turbulence, transport in the radial direction is carried by the random $E \times B$ motions of charged particles. If charged particles de-couple from turbulence eddies due to kinetic effects before eddies could execute a complete rotation, the transport process is regulated by the kinetic wave-particle decorrelation rather than by the fluid eddy mixing. The different transport processes could lead to different transport scalings.

In this study, we examine the relevance of the fluid and kinetic processes in electron heat transport from largest ever fusion simulations using the gyrokinetic toroidal code (GTC)[4]. Electron transport in fusion plasmas has not been studied as much as the ion transport, but is more important in a burning plasma ITER since the energetic fusion products (α-particles) heat electrons first. Primary candidates for driving electron heat transport in fusion plasmas are the collisionless trapped electron mode (CTEM)[6] and electron temperature gradient (ETG)[7] turbulence. Our first-principles simulations clarify device size scaling, non-diffusive, and non-local turbulent transport. A comparative study between CTEM and ETG turbulence provides important insights on the dynamics of nonlinear wave-particle interactions and the fluid eddy mixing in regulating the electron heat transport. In particular, the CTEM turbulence is characterized by the co-existence of micro- and meso-scale eddies. The electron heat transport is a fluid-like eddy mixing process even though the linear CTEM instability is driven by a kinetic resonance. In contrast, a kinetic process dominates the transport in the ETG turbulence, which is characterized by macroscopic streamers.

Numerical simulations of the electron turbulence are more challenging due to the small electron-to-ion mass ratio (thus large electron thermal velocity), which introduces smaller spatial scales and faster time scales as compared to the ion turbulence. Global GTC simulation of the multi-scale electron turbulence becomes feasible thanks to the implementation of an advanced electron model[8] based on the expansion of electron response using the mass ratio as the small parameter, an efficient global field aligned mesh[9], and a highly scalable algorithm using multi-level parallelisms[10] that enables GTC to efficiently scale up to more than 100,000 cores. The state-of-the-art GTC simulation of the CTEM turbulence used 28,000 cores for 42 hours and produced 60 TB of data. The simulation calculated the dynamics of more than 15 billions of electrons to reduce the particle noise[11].

Instability saturation and fluctuation characteristics-- The collisionless trapped electron mode (CTEM) instability with a characteristic poloidal wavelength on the order of the ion gyroradius (ρ_i) is driven by the toroidal precessional resonance between trapped electrons and driftwaves. GTC simulations[12] show that this linear CTEM instability is saturated by the shearing effects of the nonlinearly-generated zonal flows. This is further confirmed by a comprehensive analysis of kinetic and fluid time scales showing that zonal flow shearing is the dominant decorrelation mechanism. As a result, the macroscopic, linear, radial streamers are mostly broken by the zonal flows. The steady state turbulence are dominated by microscopic eddies with a scale length of $5\rho_i$, but with also a significant component of mesoscale ($5\text{-}50\rho_i$) streamers. The mesoscale eddies result from a dynamical process of zonal flow breaking of linear streamers and spontaneous merging of microscopic eddies. To quantify the perpendicular structures, we calculate the two-point correlation function $C_{r\zeta}(\Delta r, \Delta\zeta)$ averaging over toroidal ζ and radial r directions at a poloidal angle $\theta=0$. Radial correlation function $C_r(\Delta r)$ is then calculated by taking the maximal value along the ridge of $C_{r\zeta}(\Delta r, \Delta\zeta)$. The function $C_r(\Delta r)$ decays exponentially for the small radial separation but possesses a significant mesoscale tail in the range of $5\text{-}50\rho_i$. The perpendicular structure of the CTEM turbulence is thus multi-scale.

For comparison, the instability saturation and fluctuation characteristics of the electron temperature gradient (ETG) turbulence are quite different. The ETG instability with a much shorter characteristic poloidal wavelength on the order of the electron gyroradius (ρ_e) is driven by electron parallel resonance. The nonlinear saturation of the ETG instability is primarily due to a nonlinear toroidal mode coupling[13]. In this process, the spectral energy successively flows toward longer wavelengths, eventually down to damped modes. The effects of zonal flows in the ETG turbulence are very weak. Therefore, the ETG turbulence after saturation is dominated by macroscopic radial streamers. The perpendicular structure of the ETG turbulence is thus strongly anisotropic. In the steady state, the ETG turbulence is also mediated by a radial spreading[14] where small scale turbulence eddies are generated in the unstable region and flow along the nonlinearly generated radial streamers to the stable region.

Transport processes-- To study the transport mechanism, we examine the correlation between heat conductivity to the local turbulence intensity and compare various characteristic time and spatial scales. In the CTEM turbulence[11], the time and flux-surface-averaged ion heat flux Q_i, electron heat flux Q_e, and radial ExB drift intensity I during the nonlinear stage is shown in the lower right panel of Fig. 1. The radial profile of the fluctuation intensity I contains a global envelope plus an oscillating part with a spatial period of $\sim 10\rho_i$. The correlation between the radial profiles of the fluctuation intensity I and the ion heat flux Q_i suggests that the ion heat transport is driven by the local $E \times B$ drift intensity I. On the other hand, the radial profile of the electron heat flux Q_e is much smoother and lacks the small scale oscillations. Nonetheless, the global profile is quite similar to the global envelope of the fluctuation intensity I. This suggests that the electron heat transport is close to diffusive on the global scale, but not on the microscopic and meso-scale. The remarkable similarity between the ion heat flux Q_i (top left panel) and the fluctuation intensity I (top right panel) in both radial structure and time evolution further confirms that the ion heat transport is driven by the local fluctuation intensity. However, the electron transport demonstrates a ballistic propagation in the radial direction (lower left panel).

To understand the transport processes, we calculate all relevant kinetic and fluid time scales. Because of the fast bounce motion, which averages out the parallel electric field, the trapped electrons cannot decorrelate from the wave in the parallel direction. In the spectral range of interest, the CTEM frequency is proportional to the toroidal mode number (i.e., non-dispersive). Thus the resonant electrons cannot decorrelate from the wave in the toroidal direction. On the other hand, the resonant electrons can decorrelate from the wave in the radial direction due to the radial dependence of the precessional frequency. However, this dependence is very weak (on the device size scale). Therefore, the radial de-tuning time is also very long. Trapped electrons thus remain resonant with the wave until they are diffused nonlinearly across the turbulence eddies. This nonlinear kinetic time scale is the resonance broadening time τ_{rb}, which is calculated as $\tau_{rb} = 5.1 L_{ne}/v_i$. For fluid time scales, the Lagrangian time correlation function $C_t(\Delta t)$ decays exponentially with an autocorrelation time $\tau_{auto} = 11 L_{ne}/v_i$. The eddy turnover time τ_{eddy}, which describes how fast the eddy rotates due to the E X B drift without the zonal flow shearing, is $\tau_{eddy} = L_r/\langle\delta v_r\rangle = 1.6 L_{ne}/v_i$ for microscopic eddies. Another fluid time scale that relates to the dynamics of the turbulence eddies is the zonal flow shearing time, $\tau_s = 0.66 L_{ne}/v_i$. Therefore, all kinetic time scales are much longer than the fluid time scales, i.e., CTEM transport is a fluid-like process.

The resonant trapped electrons can be convected by the E X B drift across the large number of mesoscale eddies. This mesoscale ballistic process then drives a non-diffusive component in the electron heat transport and smooths small radial scale structure of the turbulence intensity. The mesoscale ballistic electron heat flux, together with the turbulence spreading, leads to the deviation from the gyroBohm transport scaling for the small devices. The electron heat transport thus exhibits a device size scaling characterized by a gradual transition from Bohm to gyroBohm scaling.

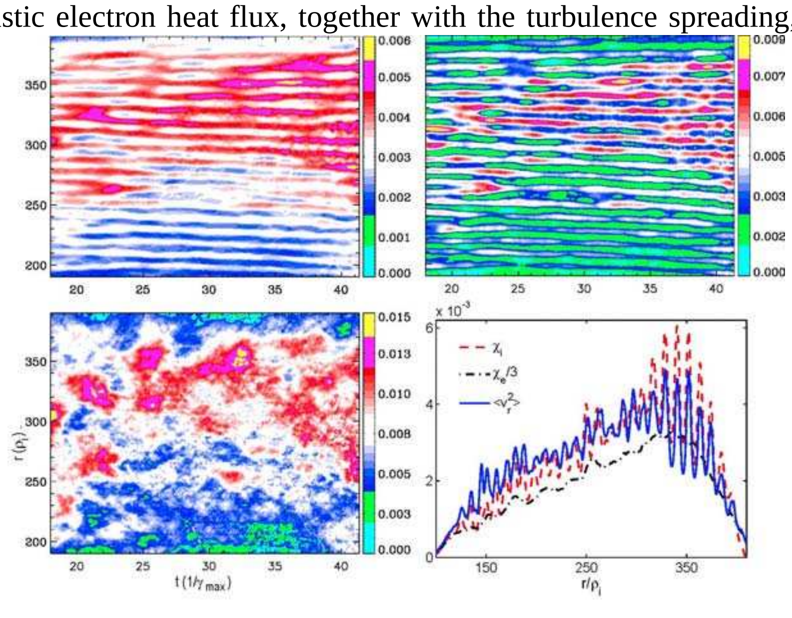

Fig. 1. *Time-radial contour plot for CTEM turbulence intensity (I, top right), ion heat flux (Q_i, top left), electron heat flux (Q_e, lower left), and the radial profiles of the time-averaged I, Q_i,, and Q_e (Lower right panel).*

In contrast, we find that stochastic wave-particle decorrelation[15] is the dominant mechanism responsible for the electron heat transport driven by the ETG turbulence with extended radial streamers. The phase-space island overlap due to the interactions of many toroidal modes leads to a diffusive transport process with a time scale comparable to the wave-particle decorrelation time, determined by the parallel spectral width. This kinetic time scale of the wave-particle decorrelation is much shorter than the fluid time scales of the eddy mixing. Consistently, the transport is proportional to the local fluctuation intensity, and quasilinear calculation of the electron heat conductivity using measured spectra agrees well with the simulation value.

Our results have important implications on the extrapolation of transport properties from present-day tokamaks to future large reactors and on the choice of time scales in transport models. The transition from Bohm to gyroBohm scaling of the electron heat transport in the CTEM turbulence is favourable for the large fusion reactor ITER. The nonlocal transport properties require a global simulation (instead of a local, flux-tube simulation). The non-diffusive transport in the CTEM turbulence cannot be accurately described by the quasilinear theory underlying most of the existing transport models. The kinetic picture of wave-particle decorrelation for ETG transport is inconsistent with the prevailing picture of fluid eddy mixing. Since the ratio of fluid-to-kinetic time scales increases with the device size, the extrapolation of the transport level from present-day experiments to future larger reactors could be overly pessimistic, if the simplistic mixing length argument with the streamer length as the spatial step size and the fluid time scale as the time step size is invoked.

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