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Kinetic ion dynamics in the electron-scale turbulent transport: a key ingredient of multi-scale interactions in turbulence

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The present gyrokinetic simulation study reveals roles of kinetic ion dynamics on the electron temperature gradient (ETG) turbulence and transport in magnetic fusion plasma, and provides new insights into a fundamental process in cross-scale interactions in plasma turbulence. The polarization effect due to finite ion gyroradius ρ_i turns out to play essential roles not only in enhancement of the linear instabilities of the slab and toroidal ETG modes but also in the nonlinear saturation of the ETG turbulent transport.

The anomalous electron heat transport has long been a key issue in physics of burning plasma confinement. Recent large-scale gyrokinetic simulations have also demonstrated contributions of electron-scale turbulence to the total heat transport through cross-scale interactions of turbulence (REf. 1). Historically, importance of kinetic ion dynamics on the ETG turbulence was pointed out by gyrokinetic simulations (Ref. 2), while the physical mechanism leading to a lower transport level has long been an open issue. We have clarified the ion polarization effects on destabilizing and stabilizing the ETG turbulence by means of comprehensive gyrokinetic simulations for slab (Ref. 3) and toroidal configurations.

In the slab ETG turbulence, which is supposed to drive the electron heat transport near the q-minimum surface, we found dominance of the long wave length fluctuations after the initial saturation of the instability growth in case with "kinetic"ions and in the electrostatic (ES) limit. The observed heat transport was quite strong and an order of magnitude higher than that of the "adiabatic"ions (where the ion density perturbation is approximated in proportion to the ES potential fluctuation) or the electromagnetic (EM) cases (Fig. 1). Detailed analysis of the linear stability has revealed enhancement of the ETG growth rate γ in a long wavelength regime ($k_\perp \rho_i \sim 1$) by the ion polarization effect which was absent in the "adiabatic"ion model. In spite of the tiny enhancement of γ, the high saturation amplitude of the low $k_\perp$ mode brings a great impact on the transport. Interestingly, the long wavelength modes can be almost stabilized by the magnetic flutter in the EM turbulence, and lead to less impact on the transport in a finite β_e (EM) regime of $\beta_e > (m_e/m_i)^{1/2}$.

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Role of the ion dynamics on the toroidal ETG turbulence is, however, more puzzling. It is known that the linear growth rate $\beta_e = 0$ of the toroidal ETG modes are increased in case with "kinetic"ions with respect to the "adiabatic"ion case, which turns out to be explained by the ion polarization effect (Ref. 3). However, it is widely known that the ETG turbulence is saturated at lower amplitudes (an order of magnitude smaller in some cases) in case with "kinetic"ions even with no ion scale turbulence (Ref. 2). The present gyrokinetic simulation confirms the physical saturation of the "adiabatic"ion case even with the moderate magnetic shear (γ) as well as the lower transport level of the toroidal ETG turbulence in case with "kinetic"ions (Fig. 2 (green)). It also shows that an ion response modeled with the polarization effect (Fig. 2 (cyan)) results in the lower saturation level. The clear difference in nonlinear behaviors of the ETG turbulence with and without the ion polarization effect is attributed to enhancement of the nonlinear Kelvin- Helmholtz type instability of ETG streamers (Ref. 4). Contours of potential fluctuations (Figs. 3 and 4) confirms strong deformation of the ETG streamers in case with "kinetic"ions (Fig. 4) by growth of vortices in scale of $\hat{s} = 0.8$, showing an impact of cross-scale interaction on ETG turbulence.

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