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Multi-scale interactions between electron- and ion-scale turbulence and their effects on turbulent transports

電子／イオン系乱流のマルチスケール相互作用とその乱流輸送への影響

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Multi-scale plasma turbulence including ion temperature gradient, trapped electron, and electron temperature gradient modes is investigated by means of the electromagnetic gyrokinetic simulations in the flux-tube model. We find two important impacts of multi-scale interactions on the turbulent transport: suppression of electron-scale transport and enhancement of ion-scale transport. Gyrokinetic triad transfer analyses reveal that the former is due to the stabilization of electron-scale streamers by ion-scale turbulent eddies, and that the latter is due to the damping effects of electron-scale turbulence on zonal flows.

1. Introduction

One of the critical issues in ITER is electron heat transport, because alpha particles mainly heat electrons rather than ions. The difficulties of the electron heat transport analysis come from its multi-scale nature. For over a decade, electron temperature gradient modes (ETGs) have been regarded as a candidate of the electron heat transport, where the radially elongated eddies streamers cause large heat transport [1]. Although such an analysis is based on the single scale simulations resolving only electron scales, multi-scale simulations resolving both of ion and electron scales were carried out in 2007 and 2008 [2-4]. They show that ETGs cause small transport levels if there are ion-scale instabilities such as ion temperature gradient modes (ITGs) and trapped electron modes (TEMs). Their works, however, were limited to the reduced ion-to-electron mass ratio (m_i/m_e=400,900) and the electrostatic approximation (β=0). The scales of electron- and ion-scale turbulence are separated by a factor of the square root of mass ratio, and the finite β effects introduce electromagnetic fluctuations which stabilize ITGs but not ETGs. Since the real mass ratio and β value change the balance of ion- and electron-scale turbulence, the following points are not yet clarified: (1) Are there multi-scale interactions even with the real mass ratio and β value? (2) If there are multi-scale interactions, how do they occur? To answer these two questions, we have carried out direct numerical simulations of multi-scale turbulence resolving electron- and ion-scale turbulence simultaneously, which is realized by using the massively parallelized spectral/finite difference gyrokinetic code GKV [5,6].

2. Simulation model

The GKV code solves perturbed distributions of ions and electrons associated with the potential fluctuations based on electromagnetic gyrokinetics. The employed simulation model is the conventional one-poloidal-turn flux-tube model in the circular tokamak configuration. While the turbulence dynamics perpendicular to the equilibrium magnetic field line is calculated by the spectral method, the others are solved by using finite difference methods. Plasma parameters are set to be the so-called Cyclone base case parameter sets [7], and we employ the real hydrogen-to-electron mass ratio m_i/m_e=1836 and the experimental β value, β=2%.

3. Simulation results

First of all, linear dispersion is examined by using the GKV code as an initial value solver of linear gyrokinetic equations. The analysis shows that scales of ITGs of ETGs are separated by the square root of mass ratio $(m_i/m_e)^{1/2}$~43. The linear growth rates of ETGs agree with those in adiabatic ion approximation. Although ITGs are destabilized by the trapped electron effects, the finite-β electromagnetic effects strongly stabilize ITGs by one fourth of the electrostatic limit. Therefore, the real mass ratio and β value change the balance of linear instabilities from the reduced mass ratio and electrostatic approximations.

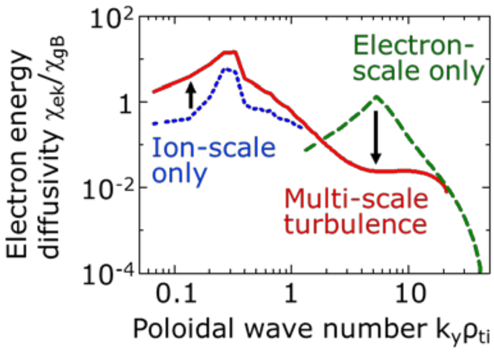

Fig. 1 Electron thermal diffusion coefficients as functions of poloidal wave number in gyrokinetic simulations with three-types of resolutions.

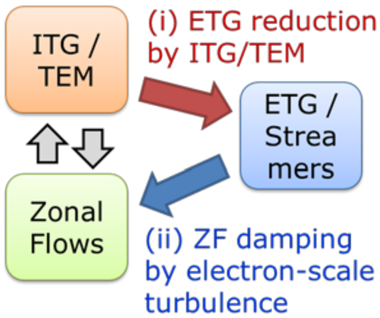

Fig. 2 Schematic picture of the multi-scale interactions between ion-scale turbulence (ITG/TEM and zonal flows) and electron-scale turbulence (ETG/Streamers).

We perform nonlinear multi-scale turbulence simulations covering ITGs, TEMs, and ETGs. For references, the single-scale simulations resolving only ion scales or electron scales are also carried out. The obtained spectra of the electron thermal diffusion coefficients are plotted in Fig. 1. This shows that the multi-scale spectrum is not a simple sum of the single-scale ones. There are two clear differences between the multi-scale spectrum and single-scale one. First, the peak at $k_y\rho_{ti}$~5 in the electron-scale simulation, which is the poloidal wave number of the streamers, is suppressed in multi-scale simulations. Second, the transport levels at $k_y\rho_{ti}<1$ are enhanced in the multi-scale simulation, compared to that in the ion-scale simulation. While the former have already reported in the previous works [2-4], the latter is newly found in this work.

Since such multi-scale interactions should occur through nonlinear wave interactions, we further analyze the nonlinear interaction dynamics. We use the gyrokinetic triad transfer analysis [8]. This describes the nonlinear transfer of gyrokinetic perturbed entropy among three waves satisfying the resonant condition $\boldsymbol{k}+\boldsymbol{p}+\boldsymbol{q}=\boldsymbol{0}$, where $\boldsymbol{k}$, $\boldsymbol{p}$, and $\boldsymbol{q}$ are their wave numbers. Using this technique, we investigate the dynamics of the above multi-scale interactions. It is revealed that the suppression of electron-scale transport is due to the stabilization of electron-scale streamers, which is sheared by the ion-scale turbulent eddies. It is also indicated that the electron-scale turbulence has damping effects on the zonal flows. Then, the reduction of the shearing rate of zonal flows leads to the enhancement of the ion-scale turbulence and transport. Hence, the observed differences of the transport spectra are explained by these multi-scale interactions, which are schematically summarized in Fig. 2.

4. Summary

Multi-scale ITG/TEM/ETG turbulence simulations reveals the existence of multi-scale interactions between electron- and ion-scale turbulence. One of the interactions is the suppression of the electron-scale turbulence due to the shearing of the ion-scale turbulent eddies. Another interaction is the enhancement of the ion-scale turbulence due to the reduction of the zonal flow shearing, which is caused by the damping effects of the electron-scale turbulence. These results indicate that the importance of the appropriate treatment of multi-scale interactions for evaluating and modeling turbulent transport.

Acknowledgments

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