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Theoretical and numerical studies on multi-scale turbulence interactions causing effective diffusion

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Drift wave turbulence in magnetized plasma has been intensively investigated by theory, simulations, and experiments as it should play a key role in the anomalous transport of particles and heat in fusion and space plasmas. The typical space and time scales of the drift wave is characterized by the gyroradius and the drift velocity of charged particles. It is quite natural to focus on the characteristic scales in studies of the drift wave turbulence. In contrast, recent gyrokinetic simulations with high spatial resolution covering from the ion to electron gyroradius scales have revealed interactions of the drift wave turbulence beyond the scale gap.

Influence of the electron temperature gradient (ETG) turbulence on the ion temperature gradient (ITG) driven transport was pointed out by several gyrokinetic simulations, showing enhancement of the ITG turbulent transport in the case with the ETG turbulence [1, 2]. In contrast, stabilization of ion gyroradius scale fluctuations by the ETG turbulence has been found in the micro-tearing mode (MTM) instability [3] and the trapped electron mode (TEM) in a multi-species plasma [4]. A comprehensive understanding on the variety of multi-scale turbulence interactions is, thus, desired for more quantitative modeling and prediction of the anomalous transport.

A detailed numerical analysis on the TEM instability growth in the case with the ETG turbulence has demonstrated that the growth rate reduction of TEMs can be modeled by means of the effective diffusion coefficient δ_{eff} caused by the ETG turbulence such that

$$\gamma_{\mathrm{TEM}} - \gamma_{\mathrm{lin}} = -\delta_{\mathrm{eff}} k_y^2$$

where k_y is the poloidal wavenumber of TEM, and γ_{TEM} and γ_{lin} denote the TEM growth rate for the multi-scale and single-scale cases, respectively [5]. We have also derived a theoretical model of the effective diffusion,

$$D_{k_\perp}\tilde{f} = -\tau_{ac}\boldsymbol{k}_\perp \cdot \sum_{\boldsymbol{k}'_\perp} \overline{\boldsymbol{v}_{\boldsymbol{E}k'_\perp}\boldsymbol{v}^*_{\boldsymbol{E}k'_\perp}} \cdot \boldsymbol{k}_\perp \tilde{f} \ ,$$

where $\tilde{f}$ means the perturbed gyrocenter distribution function of electrons, τ_{ac} and $\boldsymbol{v}_{\boldsymbol{E}k_\perp}$ are the auto-correlation time and the $E \times B$ flow velocity of the ETG turbulence with the perpendicular wavenumber $\boldsymbol{k}_\perp$. From the multi-scale gyrokinetic simulation results of TEM/ETG turbulence, we have directly evaluated the auto-correlation function of the ETG turbulence fluctuations as shown in Fig. 1 which is responsible for the effective diffusion in consistent with the growth rate reduction of TEMs.

The effective diffusion model of the ETG turbulence may lead a variety of multi-scale turbulence interactions. One of the examples is enhancement of the isotope effect of the TEM turbulent transport [6]. While the linear TEM instability growth rate γ_{lin} decreases with the ion mass through the electron collision, the effective diffusion δ_{eff} with quite weak ion-to-electron mass ratio plays a more important role in the case with heavier ion mass. Also, the effective diffusion model elucidates reduction of the ITG instability growth rate by the ETG turbulence [7] through the electron response change. In addition, anisotropy in the effective diffusion may give rise to damping of zonal flows with a sub-ion-gyroradius scale which was considered as a main cause of the transport enhancement in the ITG/ETG turbulence [2] as well as suppression of the micro-tearing model with a thin electron current sheet [3].

The rich physics in multi-scale turbulence is now being revealed by the gyrokinetic theory and simulation, and waiting more intensive experimental validations.

References

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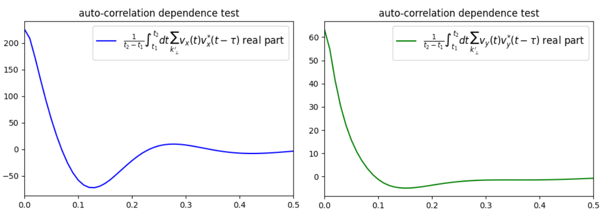

Figure 1: Auto-correlation functions of the electron temperature gradient turbulence for the radial (left) and poloidal (right) components of the $E \times B$ flow velocity fluctuations.