9th Asia-Pacific Conference on Plasma Physics, 21-26 Sep, 2025 at Fukuoka

Spatial structure of ETG turbulence-driven effective diffusion and its relations with the trapped electron mode instability

Koki Yoshikawa and Tomo-Hiko Watanabe
Department of physics, Nagoya University
e-mail (speaker): yoshikawa.koki.i0@s.mail.nagoya-u.ac.jp

Turbulent transport in magnetically confinement plasma is often governed by multi-scale physics. The spatial scale of associated drift wave instabilities ranges from electron- to ion- gyroradii, separated by a factor of the square root of ion-to-electron mass ratio if their temperatures are equal. Despite the disparate scale gap between ion-scale and electron-scale turbulence, numerical simulations of plasma turbulence show that there exist cross-scale interactions between them. Since cross-scale turbulence interaction is important for understanding saturation mechanisms of turbulence and elucidating experimental results of particle and heat transport flux from the magnetic confinement device, theoretical understandings of its physical nature are required.

For analyzing electron-scale turbulence effects on ion-scale instability, a theoretical model has been derived from the electron gyrokinetic equation, inspired by a multiscale gyrokinetic simulation, where growth of the trapped electron modes (TEMs) significantly slows down under the electron temperature gradient (ETG) turbulence [1]. This formulation proposes an effective diffusion of the electron-scale turbulence $\mathcal{D}$ affecting the ion-scale fluctuation of electron distribution $\langle f_e \rangle$:

$$\mathcal{D}\langle f_e \rangle = -(\boldsymbol{k}_{\mathrm{TEM}} \cdot \mathbf{D} \cdot \boldsymbol{k}_{\mathrm{TEM}})\langle f_e \rangle,$$

$$\text{where, } \mathbf{D} = \int_0^\infty d\tau \sum_{k_{\mathrm{ETG}}} \overline{\tilde{\boldsymbol{v}}_{k_{\mathrm{ETG}}}(t)\, \tilde{\boldsymbol{v}}^*_{k_{\mathrm{ETG}}}(t-\tau)}.$$

Here, the auto-correlation of ETG flow velocity $\tilde{\boldsymbol{v}}_{k_{\mathrm{ETG}}}$ exerts an effective diffusion $\mathbf{D}$ on ion-scale dynamics.

We conducted a TEM single-scale gyrokinetic simulation with the effective diffusion model implemented so far, the result of which agreed with the multiscale simulation. Figure 1 summarizes successful reproduction of TEMs linear growth-rate reduction in presence of the ETG turbulence (blue squares), by means of the effective diffusion model (pink line).

The ETG-driven effective diffusion model introduced in the TEM simulation was assumed spatially uniform, whereas the ETG instability is driven strongly in the bad curvature region, which has the ballooning structure along the magnetic field line. Then the question arises how spatial inhomogeneity of ETG turbulence affects the effective diffusion as well as reduction of TEMs growth.

Figure 2 shows the field-aligned (θ) profile of the ETG diffusion coefficient $\mathbf{D}$, obtained from (a) the TEM-ETG multi-scale simulation and (b) the ETG single-scale simulation, where contributions of $k_y \leq 2$ are excluded. Note that the contravariant components of $\mathbf{D}$ are represented in the flux tube coordinates (x, y, z) [2]. In the result of the multi-scale simulation shown in figure 2(a), D^{xx} (blue) is driven strongly by ETG modes in the bad curvature region, while the amplitude of D^{yy} (green) increases at $|\theta| > \pi/2$ by the image modes in the ballooning representation with high k_x components [3]. Since similar trends are seen in the result from the single-scale simulation shown in figure 2(b), the influence of TEMs is supposed to be minor in the TEMs exponential growth stage, the case shown in figure 2(a). Impacts of the TEMs on the ETG turbulence will be further investigated, and the TEM single-scale gyrokinetic simulation including the effective diffusion model with this spatial inhomogeneity will be carried out soon.

References

[1] T.-H. Watanabe *et al* 2023 *Nucl. Fusion* **63** 054001
[2] M. A. Beer *et al Phys. Plasmas* 2, 2687–2700 (1995)
[3] T.-H. Watanabe *et al Phys. Plasmas* 22, 022507 (2015)

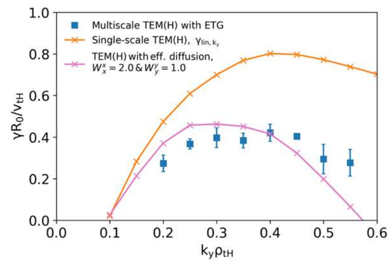

Figure 1. Linear growth rates of the trapped electron modes (TEMs) from the multi-scale simulation (blue), the single-scale simulation (orange), and the single-scale one with the effective diffusion (pink).

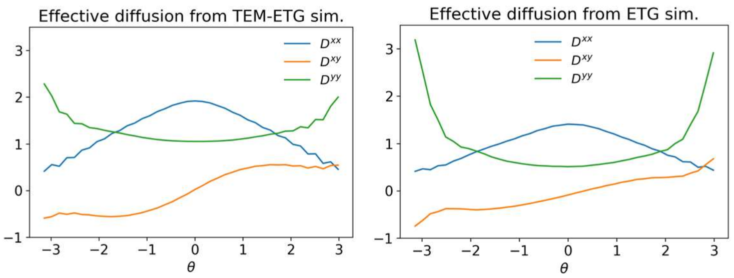

Figure 2. Field-aligned profile of ETG effective diffusion coefficient $\mathbf{D}$ from (a) the TEM-ETG multi-scale simulation and (b) the ETG single-scale simulation. D^{xx} (blue), D^{xy} (orange), and D^{yy} (green) components are plotted respectively.