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Effects of electron-scale turbulence on ion-scale turbulence in Tokamak plasmas

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Plasma turbulence is inherently multi-scale physics including various spatio-temporal scales. Most of turbulence studies assume scale separation between fast and small electron-scale physics and slow and large ion-scale physics, whose spatial scales are characterized by their gyroradii. However, thanks to recent development of supercomputer and high-performance computing algorithms, gyrokinetic simulations are now applicable for direct numerical simulations of multi-scale plasma turbulence covering both of electron and ion scales. The latest simulation studies reported the existence of cross-scale interactions between electron/ion-temperature-gradient (ETG/ITG) driven turbulence [1]. Such a cross-scale interactions seemed to be observed in some experimental studies, e.g., Alcator C-Mod [2], DIII-D and JET. It was also stressed that cross-scale coupling between electron and ion scales was considerable in ITER-baseline parameters [3].

To extend our knowledge on multi-scale plasma turbulence, we have newly analyzed the cross-scale interactions between micro-tearing modes (MTM) and ETG. MTM is regarded as a kinetic extension of the MHD tearing modes driven by electron temperature gradient. The linear mode structure of MTM has poloidal wave lengths of the order of ion gyroradius and, at the same time, a radially-localized current sheet much thinner than ion gyroradius, which can be affected by electron-scale turbulence. For the analysis of the cross-scale coupling, we have to evaluate nonlinear interaction between modes of fluctuations in two disparate scales. To pick up the collective behavior of the nonlinear coupling between ion-scale MTM and electron-scale ETG, we have defined the subspace transfer function by [4],

$$J_{\Omega_k}^{\Omega_p,\Omega_q} = \sum_{\boldsymbol{k}\in\Omega_k} \sum_{\boldsymbol{p}\in\Omega_p} \sum_{\boldsymbol{q}\in\Omega_q} J_{\boldsymbol{k}}^{\boldsymbol{p},\boldsymbol{q}},$$

where $J_{\boldsymbol{k}}^{\boldsymbol{p},\boldsymbol{q}}$ is the triad entropy transfer function, and $\Sigma_{\boldsymbol{k}\in\Omega_k}$ means the summation over the subspace of the wavenumber space Ω_k. The subspace transfer function physically describes the nonlinear excitation ($J_{\Omega_k}^{\Omega_p,\Omega_q} > 0$) or damping ($J_{\Omega_k}^{\Omega_p,\Omega_q} > 0$) of the modes in the subspace Ω_k via the coupling with the modes in Ω_p and Ω_q. It retain the symmetry $J_{\Omega_k}^{\Omega_p,\Omega_q} = J_{\Omega_k}^{\Omega_q,\Omega_p}$ and the detailed balance $J_{\Omega_k}^{\Omega_p,\Omega_q} + J_{\Omega_q}^{\Omega_k,\Omega_p} + J_{\Omega_p}^{\Omega_q,\Omega_k} = 0$.

Gyrokinetic turbulence simulations of cross-scale interactions between ETG and MTM clearly show that MTM can be suppressed in the presence of ETG turbulence. We have applied the subspace transfer analysis technique to examine the nonlinear cross-scale coupling during MTM suppression by ETG. Figure 1 plotted the resultant entropy transfer as a function of the poloidal wave number k_y (summed over k_x). The figure represents that electron-scale contribution $J_{\boldsymbol{k}}^{\Omega_e,\Omega_e}$ has significant negative values at the ion scale $\Omega_\mathrm{i} = \{\boldsymbol{k}|k_y\rho_\mathrm{ti} < 2.1\}$. Additionally, considering the detailed balance among subspace $\sum_{\boldsymbol{k}\in\Omega_\mathrm{i}} J_{\boldsymbol{k}}^{\Omega_e,\Omega_e} + 2\sum_{\boldsymbol{k}\in\Omega_\mathrm{e}} J_{\boldsymbol{k}}^{\Omega_i,\Omega_e} = 0$ the above ion-scale entropy is transferred to electron-scales $\Omega_\mathrm{e} = \{\boldsymbol{k}|k_y\rho_\mathrm{ti} > 2.1\}$. It is clearly shown in Fig. 1 as $2J_{\boldsymbol{k}}^{\Omega_i,\Omega_e} > 0$ for $k_y\rho_{ti}$>6, whose spectral peak is consistent with the linearly most unstable ETG modes around $k_y\rho_{ti}$~12. This means that MTM is destroyed in the presence of ETG turbulence, and breaks up into smaller electron scales. More detailed analysis of 2D spectra of subspace transfer reveals that low-k_y but high-k_x component of MTM is strongly coupled with ETG turbulence, since radially localized current sheet structures of MTM were strongly distorted by ETG turbulence. Consequently, electron-scale turbulence dominates electron heat transport [5].

This result suggests that cross-scale interactions are important not only for tokamak-core ETG/ITG turbulence, but also for transport in a spherical tokamak or in an H-mode pedestal, where MTM and ETG may coexist. Comparing results in this work and in the previous ITG/ETG turbulence, we emphasize the importance of sub-ion-scale structures, i.e., intermediate structures between ion and electron scales, for cross-scale coupling.

References

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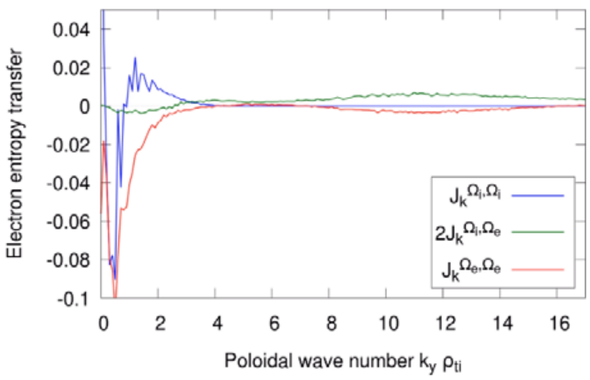

Figure 1. Nonlinear entropy transfer [a.u.] during MTM suppression by ETG. Contributions by the low-k_y, low-k_y coupling, $J_{\boldsymbol{k}}^{\Omega_i,\Omega_i}$, by low-$k_y$, high-$k_y$ coupling $2J_{\boldsymbol{k}}^{\Omega_i,\Omega_e}$, and by high-$k_y$, high-$k_y$ coupling, $J_{\boldsymbol{k}}^{\Omega_e,\Omega_e}$, are plotted by blue, green, and red lines, respectively.