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Toward a systematic understanding of multi-scale interactions between ion and electron-scale turbulence

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Recent direct numerical simulation (DNS) studies revealed the existence of cross-scale interactions between electron and ion-scale turbulence in magnetized plasma.[1,2] The cross-scale interactions can be regarded as bi-directional interactions, i.e., effects from large to small (or from small to large) scales, as depicted in Fig. 1. From the gyrokinetic simulation studies of electron/ion temperature mode (ETG/ITG) driven turbulence, various interactions have been reported. For the large-to-small effects, the large ITGs tend to suppress small-scale ETGs,[3] where short-wavelength ITG eddies mainly distort ETGs.[1] If ITG is weak, ETG can cause significant electron heat transport.[4,5] Although a possibility of destabilization of ETG by ion-scale profile corrugation was discussed theoretically,[6] it has not yet been reported in gyrokinetic simulations. For the small-to-large effects, while it was expected to be small previously,[6] enhancement of near-marginal ITG in the presence of ETGs was found.[1,5] By applying nonlinear triad wave interaction analysis, the damping of short-wavelength zonal flows by ETG is pointed out to be a physical mechanism.[1] Additionally, another type of small-to-large scale interactions has been reported in micro-tearing-mode (MTM) turbulence, where ETG destroys current sheets of MTM, and then, small-scale ETG dominates rather than MTM.[2] There are two important phenomenological notions. The first is the importance of sub-ion-scale structures like ITG-driven short-wavelength eddies/zonal flows, and radially-localized current sheet of MTM. Secondly, different scale turbulence seems to be mutually exclusive. Namely, ITG eddies suppress ETGs, ETG damps short-wavelength ITG-driven zonal flows (which eventually enhances ITG fluctuations because of reduction of zonal flow shearing rate), and ETG destroys current sheet of MTM. These may suggest the existence of some generic features of cross-scale interactions.

While the gyrokinetic turbulence simulation is a powerful tool to explore the physics of cross-scale interactions, the number of studies of DNS based on gyrokinetic theory is still limited because of high computational costs. Toward a systematic understanding, theoretical approaches are indispensable.

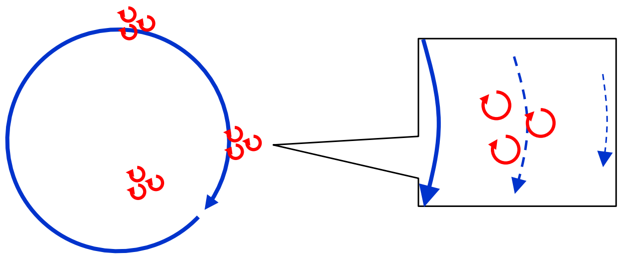

Fig. 1: Schematic picture of cross-scale interactions between large ion-scale and small electron-scale eddies.

From the viewpoint of large-to-small effects, Hardman et al. discussed a scale-separated theory which is valid in the infinite ion-to-electron mass ratio limit.[7] They find that electron-scale turbulence is affected by large ion-scale shear flows, which has shear not in perpendicular but in parallel to the magnetic field line. Although the formulation is rigorous, the present theory has some limitations: gyro-Bohm scaling of ion- and electron-scale transport and no small-to-large scale effects, both of which originate from the assumption of electron scale k_radial ~ k_poloidal~ρ_e.

On the other hand, from viewpoints of small-to-large effects, Maeyama and Watanabe discussed the generalized Langevin form of small-scale effects on large-scale turbulence.[8] Their formulation based on the application of Mori-Zwanzig projection operator method allows numerical analysis of small-scale effects from DNS data. Applying this statistical data analysis to the Kuramoto-Sivashinsky spatio-temporal chaos and Hasegawa-Wakatani 2D plasma turbulence demonstrates the proof of concept.

Promoting theoretical approaches of bi-directional views of cross-scale interactions, with discussing pros and cons via comparing the results of gyrokinetic DNS, is a promising way toward a systematic understanding of multi-scale interactions between ion and electron-scale turbulence.

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