§12. Electromagnetic Gyrokinetic Simulation of Turbulence in Torus Plasmas

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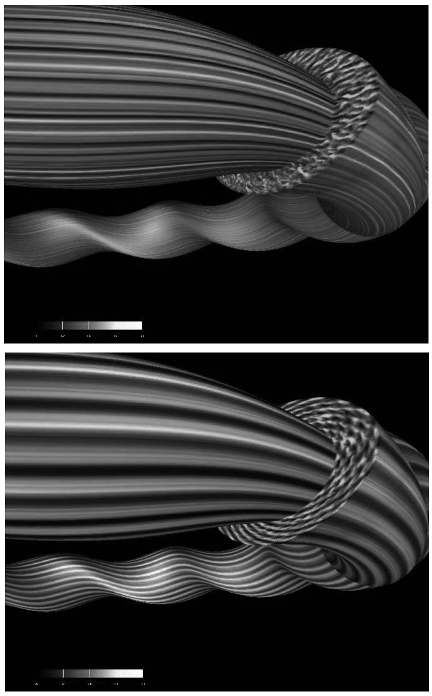
Gyrokinetic simulations of electromagnetic turbulence in magnetically confined torus plasmas including tokamak and heliotron/stellarator are reviewed [1]. Numerical simulation of turbulence in finite beta plasmas is an important task for predicting performance of fusion reactors and a great challenge in computational science due to multiple spatio-temporal scales related to electromagnetic ion and electron dynamics. The simulation becomes further challenging in non-axisymmetric plasmas. In finite beta plasmas, magnetic perturbation appears and influences some key mechanisms of turbulent transport, which include linear instability and zonal flow production. Linear analysis shows that the ion-temperature gradient (ITG) instability, which is essentially an electrostatic instability, is unstable at low beta and its growth rate is reduced by magnetic field line bending at finite beta. On the other hand, the kinetic ballooning mode (KBM), which is an electromagnetic instability, is destabilized at high beta. In addition, trapped electron modes, electron temperature gradient modes, and microtearing modes can be destabilized. These instabilities are classified into two categories: ballooning parity and tearing parity modes. These parities are mixed by nonlinear interactions, so that, for instance, the ITG mode excites tearing parity modes. In the nonlinear evolution, the zonal flow shear acts to regulate the ITG driven turbulence at low-beta. On the other hand, at finite beta, interplay between the turbulence and zonal flows becomes complicated because the production of zonal flow is influenced by the finite beta effects. When the zonal flows are too weak, turbulence continues to grow beyond a physically relevant level of saturation in finite-beta tokamaks. The finite beta turbulence is saturated by the nonlinear interactions of oppositely inclined convection cells through mutual shearing (Fig. 1), even when the zonal flow is weak. Nonlinear mode coupling to stable modes can play a role in the saturation of finite beta ITG mode and KBM. Since there is a quadratic conserved quantity, evaluating nonlinear transfer of the conserved quantity from unstable modes to stable modes is useful for understanding the saturation mechanism of turbulence.

Electromagnetic gyrokinetic simulation enables us to study turbulent transport in finite beta torus plasmas. When the plasma beta is small, the ITG and TEM/ETG modes are unstable, and the ITG turbulence is regulated by zonal flows. Magnetic perturbation with tearing parity can be produced from the ITG mode, which has ballooning parity, through nonlinear interactions, and can influence turbulent transport by violating magnetic surface.

When the beta is increased with keeping the magnetic field, density, and temperature profiles, the growth rate of ITG mode decreases, while the zonal flow amplitude is not so influenced, and thus the turbulent transport is reduced. When plasma beta exceeds a critical value, the zonal flows are weak, and then the turbulent transport becomes very large correspondingly. This unphysical large transport is observed not only for CBC but also for other DIII-D cases. The magnetic perturbation plays a central role in reducing the growth rate of ITG, and probably in weak zonal flow production. The KBM, which is an electromagnetic instability, is destabilized at high beta, and a saturation of the KBM turbulence is obtained even when the zonal flows are weak, when the electron temperature gradient is set to be small and beta value is just above the linear instability threshold. The mode structure along the magnetic field line plays a role in the saturation of turbulence, and thus the saturation level is influenced by the length of simulation domain along the magnetic field line. The spectrum of the KBM turbulence is much narrower than that of ITG turbulence and the efficiency in transport is small compared with the ITG turbulence at low beta. The condition for getting a physically relevant saturation level of ITG/TEM turbulence at finite beta and KBM turbulence at high beta has not been fully understood yet.



(a) (b)

Fig. 1: Electrostatic potential profile of (a) the ITG turbulence with very small beta and (b) the KBM turbulence with finite beta in a helical plasma. The KBM is saturated by the interactions with oppositely inclined modes, while the ITG is regulated by zonal flows.

1) A. Ishizawa, et.al., Journal of Plasma Physics, **81**, 435810203 (2015).