Gyrokinetic simulation of fusion and space plasmas

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Abstract

The gyrokinetics provides a theoretical basis for analytical and numerical studies on low-frequency drift waves and turbulence, or magnetohydrodynamic (MHD) phenomena, in fusion and space plasmas with a mean magnetic field. After development of the nonlinear gyrokinetic formulation in 1980's, computer simulations based on the gyrokinetic theory have largely been advanced in fusion plasma research. In this lecture, after introduction of the basic concept of the gyrokinetics, we discuss numerical simulation models and their applications to fusion and space plasmas.

The gyrokinetic equations consist of the kinetic and field equations. The Vlasov equation is averaged over the gyro-motion of charged particles so that high-frequency fluctuations are eliminated by construction. Electromagnetic fields are given by the quasi-neutrality condition and the Ampere's law. In the derivation of the gyrokinetic equation, one needs to assume the gyrokinetic ordering, where a smallness parameter ε is introduced, such that

$$\varepsilon \sim \omega/\Omega \sim \rho/L \sim k_{\parallel}/k_{\perp} \sim \delta f/f_0 \sim e\phi/T$$

where Ω, ρ and L mean the gyrofrequency, thermal gyroradius, and an equilibrium scale-length. Frequency, ω, and the parallel and perpendicular wavenumbers, $k_{\parallel}$ and $k_{\perp}$, are defined for fluctuations. Distribution functions of equilibrium and perturbed parts are denoted by f_0 and δf, respectively. Potential energy of fluctuations normalized by the background temperature, $e\phi/T$, also obeys the ordering. Since the gyrokinetic ordering is consistent to nature of drift waves and the shear Alfven law, applications to the drift wave turbulence, the shear Alfven wave turbulence, and the ballooning-type instabilities are quite straightforward. By using the gyrokinetic equations, the theoretical and numerical analysis can be free from the closure problem of fluid equations as well as the high-frequency plasma oscillations and cyclotron motions, while keeping effects of the finite gyroradius and the drift orbits.

The gyrokinetic simulation model is designed to resolve the low amplitude of fluctuations, $e\phi/T \sim \varepsilon$, where the conventional particle-in-cell method is inefficient. Thus, the Vlasov (continuum) simulation approach and/or the δf-formulation are widely employed. The distribution function is discretized on the five-dimensional phase space in the former. Only the perturbed part of the distribution function, δf, is handled in the latter. High phase-space resolution achieved in the δf-Vlasov simulation is successfully applied to magnetized plasma turbulence, where transfer processes of entropy fluctuations on the phase space is clearly identified, extending a frontier of plasma turbulence theory.

Applications of the gyrokinetic simulation to the anomalous transport in fusion plasma have extensively been promoted in the last two decades. Discovery of turbulence regulation by zonal flows is a significant outcome of the gyrokinetic simulations which have also been applied to analysis of the fusion plasma experiments. State of the art of the gyrokinetic simulations of plasma turbulence reveals cross-scale interactions of ion- and electron-scale turbulence, where the peta-scale computing plays a key role in simultaneously resolving the electron and ion dynamics.