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閉じ込め時間スケールのfull-fジャイロ運動論シミュレーション
Full-f gyrokinetic simulation over a confinement time

井戸村　泰宏
Yasuhiro IDOMURA

原子力機構
JAEA

In recent years, new generation of gyrokinetic simulations based on the so-called full-f approaches are emerging. In full-f gyrokinetic simulations, both turbulent transport and profile formations are computed under fixed power, momentum, and particle inputs as in the experiment. This approach, in principle, has the capability of dictating plasma profiles, provided that the simulation is performed over a confinement time. In fact, recent Peta-scale supercomputers made such long time scale simulations feasible. However, before proceeding to such a huge computation, one needs to examine the accuracy of physical and numerical models. In particular, recent work [Parra, POP2011] pointed out a serious concern about the accuracy of momentum transport calculations using standard 1st order gyrokinetics.

In order to resolve this critical issue, we have implemented 3rd order gyrokinetics [Mishchenko, POP2011] to the Gyrokinetic Toroidal 5D Eulerian code GT5D [Idomura, CPC2008, NF2009], and the quantitative convergence of turbulent momentum transport is examined in the ion temperature gradient driven (ITG) turbulence [Idomura, CSD2012]. The result shows that both heat and momentum fluxes are well converged even with 1st order gyrokinetics. It is found that in the ITG turbulence with $k_\perp \rho_i < 1$, higher order corrections to the ion polarization density are negligibly small, and that non-diffusive momentum transport due to residual stress and related intrinsic rotation are an order of magnitude larger than those assumed in the so-called low flow ordering. These corrections to the conventional ordering arguments lead to the convergence of momentum transport.

After verifying the accuracy issue, long time ITG turbulence simulations are performed for a normal shear tokamak with $\rho^{*-1} \sim 100$, P_{in}=4MW, and no momentum input. In the simulation, the quantitative convergence of steady temperature and (intrinsic) rotation profiles is confirmed after an energy confinement time, while profiles after a collision time are rather close to them. It is shown that the profile relaxation can be significantly accelerated when the simulation is initialized with linearly unstable temperature profiles. In the steady state, the temperature profile and the ion heat diffusivity are self-consistently determined by the power balance condition, while without momentum input, the intrinsic rotation profile is sustained by complicated momentum transport processes. The steady turbulent momentum transport is characterized by bursty non-diffusive fluxes, and the resulting turbulent residual stress is consistent with the profile shear stress theory [Camenen, NF2011], in which the residual stress depends not only on the profile shear and the radial electric field shear but also on the radial electric field itself. Based on the toroidal angular momentum conservation, it is found that in the steady null momentum transport state, the turbulent residual stress is cancelled by the neoclassical counterpart, which is greatly enhanced in the presence of turbulent fluctuations.

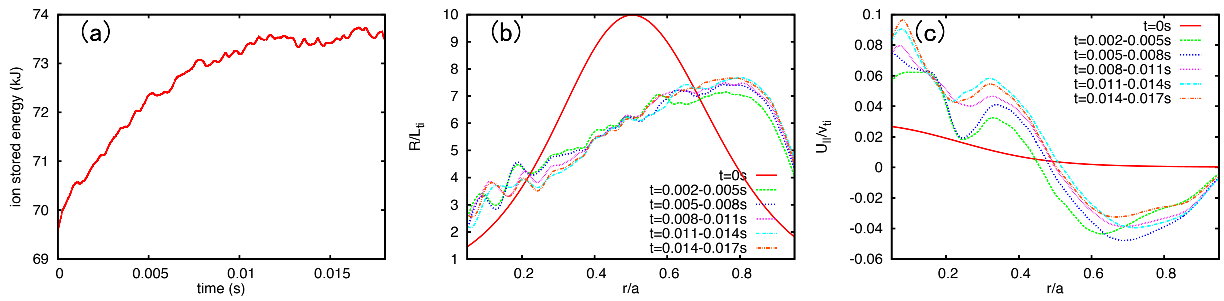

Fig.1: Long time ITG turbulence simulation. Time evolutions of (a) plasma stored energy, (b) temperature gradient profiles, and (c) parallel flow profiles. Profiles after a collision time (~3ms) are qualitatively similar to converged ones.