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Global full-*f* kinetic simulation of neoclassical transport in stellarator/heliotron plasmas

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Recently, full-*f* gyrokinetic simulations, in which the total particle distribution is evolved based on the first principle, are regarded as powerful tools to explore the plasma transport and profile formations. Although rich physics has been revealed by the global full-f gyrokinetic simulations for axisymmetric tokamak plasmas, there have been no applications to three-dimensional non-axisymmetric plasmas such as stellarator/heliotron plasmas. 3D physics is also important even in tokamaks since non-axisymmetric 3D perturbations always exist due to error fields caused by coil imperfection. Also, 3D perturbations are externally imposed to control the tokamak plasma.

In this work, a global full-*f* gyrokinetic simulation code, GT5D [1], has been extended to incorporate general 3D magnetic equilibria provided by a widely-used equilibrium code, VMEC [2]. The numerical conservation of the particle and energy is essential for the full-f gyrokinetic simulations of GT5D. Also, treating the magnetic coordinates by the finite difference scheme leads to a pole singularity at the magnetic axis. To remove the numerical difficulties in general curvilinear coordinates, we introduce the new magnetic coordinates, in which the poloidal angle is defined so as to have the poloidal symmetry with respect to the magnetic axis. Based on the new coordinates, we extend Morinishi's conservative non-dissipative finite difference operator for Cylindrical coordinates [3] to non-orthogonal systems, in which the phase space conservation of the Hamiltonian flow is numerically satisfied. Equilibrium data provided by VMEC is successfully transformed to the new coordinates through a newly developed preprocessing interface code for GT5D.

In 3D plasmas, the neoclassical transport can be as large as the turbulent transport and thus, it is rather an important ingredient in transport studies. As the numerical verification for the 3D extension of GT5D, the neoclassical transport physics in a perturbed tokamak and a typical LHD equilibrium is examined in detail.

First, the neoclassical toroidal viscosity (NTV) in a perturbed tokamak is benchmarked against a global neoclassical transport code, FORTEC-3D [4], which is based on the δf Monte Carlo method. A quantitatively good agreement is confirmed. The NTV of both simulations shows quite similar collisionality dependency despite many differences in their numerical approaches, while a standard local neoclassical theory based on the superbanana-plateau resonance [5] predicts the constant NTV. In order to clarify the cause of the discrepancy, the velocity space structure and the particle orbit are explored. It is demonstrated that the superbanana-plateau resonance observed in the small banana width limit disappears when the banana width becomes large. It is also identified that the finite banana width effect causes the phase mixing along the bounce motion. The bounce phase mixing generates the fine scale structures in the velocity space as the collisionality decreases, leading to the collisionality dependency of the NTV in the global simulations.

Next, to verify GT5D simulations in a fully three-dimensional plasma, GT5D is applied to a LHD plasma for the first time: collisionless zonal flow damping tests and the neoclassical transport simulations including the ambipolar radial electric field are carried out, respectively. The wave-number dependency of the residual zonal flow level is compared to a standard local analytical theory of Sugama-Watanabe [6], showing a reasonable agreement. Then, the neoclassical transport and the ambipolar radial electric field are again benchmarked against FORTEC-3D. It is demonstrated that GT5D well reproduces the neoclassical radial particle/heat fluxes and the ambipolar radial electric field of FORTEC-3D.

As the numerical verification of the neoclassical transport in GT5D are successfully completed, GT5D is used to explore the temporal transition of the radial electric field, which is often observed in stellarator and heliotron plasmas. In the presentation, effects of the electron transport, which plays a key role in determining the ambipolar radial electric field, on the transition will be discussed. Finally, GT5D is now extended to multi-species plasmas. The recent upgrade of GT5D will be presented.

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