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Global and Local Drift-Kinetic Simulation Models for Neoclassical Viscosities

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In this talk, we present the recent progress in the formulations of the global and local drift-kinetic simulation models and the consideration on the neoclassical viscosities obtained from these models.

Neoclassical viscosity plays the key role in the evaluation of the neoclassical radial particle and energy fluxes, bootstrap current, toroidal and poloidal torque. For helical plasmas, dependence of the neoclassical viscosity on the 3-dimensional magnetic configuration and the radial electric field E_r is the main subject of the neoclassical transport theory. In the recent years, the 3D effect on the neoclassical transport in axisymmetric tokamaks has been attracted attention in connection with the external magnetic perturbation experiments (or so called RMP) to mitigate the ELMs.

Until massive-parallel computers became a common tool, the neoclassical transport and the 3D effect had been studied with analytic formulations of the drift-kinetic equation (DKE) or local approximation codes[1-4], in which many assumptions are adopted to simplify the computation. The approximated models have been served to give the physical picture and to understand the qualitative tendency of the neoclassical transport in 3D magnetic configurations. However, it has not been fully discussed how much quantitative accuracy can be expected from the simplified drift-kinetic models.

A global delta-f DKE solver, FORTEC-3D[5], was developed to study the neoclassical transport process without relying on such approximations. It was found that the neoclassical transport predicted from the global code in helical devices can be largely different from those by the local ones[6]. The simulation has also been applied to estimate the neoclassical toroidal viscosity (NTV) in tokamaks with toroidal ripples[7]. In the benchmark of the simulation scheme, it is found that the NTV obtained from the global code in the super-banana-plateau (SBP) regime is smaller than the analytic solution and depends on the collisionality[8].

In order to clarify the mechanism of the discrepancy between the global and local neoclassical simulations, we have recently developed the radially-local reduced codes from the global FORTEC-3D. There are three levels of the local approximations[9,10]: The Zero-Orbit-Width (ZOW) model treats only the radial guiding-center drift as higher-order negligible term, while the magnetic drift tangential to the flux surface is kept. The Zero-Magnetic-Drift (ZMD) model neglects the tangential magnetic drift, too. These two models solve 4D DKE in which the change in the kinetic energy is still considered. The DKES model further adopts the mono-energy and the incompressible-$\mathrm{E}\times\mathrm{B}$ drift approximations to reduce the dimensions of the DKE from 4 to 3. The difference in the approximations is found to affect the neoclassical viscosity in two different ways in helical plasmas. If $\omega_\mathrm{E} \ll \omega_\mathrm{B}$, where ω_E and ω_B represents the poloidal precession frequency of trapped particles by the $\mathrm{E}\times\mathrm{B}$ and magnetic drift, respectively, the finite-ω_B term which is retained in the ZOW model reduces the strong resonance of the trapped particles. It results in much smaller NTV and radial flux than those from the ZMD and DKES models, especially in low-collisionality plasmas. On the other hand, if E_r is large enough, the incompressible-$\mathrm{E}\times\mathrm{B}$ approximation in the DKES model results in erroneous evaluation of neoclassical transport. The ZOW model reproduces most closely the simulation results of the 5D global model.

Benchmark of the bootstrap current calculations has also been carried out. The neoclassical parallel flow is determined by the parallel momentum balance $\mathbf{B}\cdot\nabla\cdot(\mathbf{P}_\mathrm{CGL}+\mathbf{\Pi}_2)_a = \sum_\mathrm{b} \mathrm{BF}_{\parallel,\mathrm{ab}}$, where a and b denote the particle species, $\mathrm{F}_{\parallel,\mathrm{ab}}$ is the parallel friction force, and $\mathbf{P}_\mathrm{CGL}$ and $\mathbf{\Pi}_2$ represent the diagonal and the off-diagonal pressure tensors, respectively. It is found that the expression of the $\mathbf{\Pi}_2$ tensor differs among the 3 local models. The incompressible-$\mathrm{E}\times\mathrm{B}$ approximation is found to be incorrect to evaluate the bootstrap current. The bootstrap current from the ZOW and ZMD models are almost the same in helical plasmas. However, the symmetry of the $\mathbf{\Pi}_2$ tensor in the original global model is kept only in the ZMD model, which is important to reproduce the intrinsic-ambipolarity in axisymmetric case.

The local approximation model also affects the quantitative evaluation of the NTV in tokamak with RMP. It is found that the thin resonant layer in the velocity space, which is the origin of the SBP-type NTV, is perturbed by the finite radial excursion of banana orbits around the resonant rational surface. It is also found that the toroidal precession drift in the positive magnetic shear moves the SBP resonance layer very close to the trapped-passing boundary and therefore reduces the resonance. These finite-orbit-width effects are naturally included in the global calculation and cause the difference from the local calculations.

In summary, the quantitative accuracy of the neoclassical viscosity calculation is affected by the level of approximations, magnetic configuration, and the plasma parameters. It is important to choose a proper DKE model according to the purpose of the simulations.

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