§8. Simulation Studies of the Finite-orbit-width Effect on Neoclassical Transport in LHD Plasmas

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Neolclassical transport analysis and determination of the ambipolar radial electric field are one of the key issue to study the plasma confinement property of LHD plasmas. It is known that LHD plasma has a wide flexibility for optimizing the neoclassical transport level by shifting the magnetic axis position and by changing the ambipolar condition. The radial electric field, which autonomously develops so that the $E \times B$ rotation suppresses the ion and electron radial fluxes to match the ambipolar condition $\Gamma_i = \Gamma_e$, is important to understand the neoclassical transport level in experiments. It is also recognized these days that the neoclassical transport and the ambipolar electric field will affect the suppression mechanism of the micro-turbulence by the zonal-flow, which has been studied with gyrokinetics.

Since detailed and accurate treatment to solve the drift-kinetic equation (DKE) is difficult in helical plasmas, many assumptions and approximations has been used in the analytic formula or numerical solvers of neoclassical transport in 3-D geometry. Among them, the finite-orbit-width (FOW) effect will be an important factor to calculate neoclassical transport as the core plasma temperature becomes higher. Though conventional neoclassical theory neglects the radial drift width of charged particles, ripple-trapped ions shows large excursion across the flux surfaces in high-T_i plasmas. In recent LHD experiments, high-T_i and low-collisionality plasmas ($T_i > 5keV,\ n_e \sim 10^{19}m^{-3}$) are achieved, and the zero-orbit-width (ZOW) limit approximation is no longer valid. To study the transport property in such plasmas, non-local nature of transport by the FOW effect should be properly included in the analysis.

To address the problem, we have been developing a neoclassical transport code FORTEC-3D[1], which solves the DKE and the time evolution of radial electric field in helical plasmas by the δf Monte-Carlo method. It can properly treats the FOW effect of ions, and the global time evolution of the radial electric field is simultaneously and self-consistently solved. It has also been applied to study the magnetic-field configuration dependency of GAM oscillation and damping in LHD[2]. It is found that the ambipolar electric field in LHD obtained from the precise calculation by FORTEC-3D is factor $2 \sim 3$ different from that is predicted from the conventional theory[1], and the reason is partly explained by the FOW effect. However, it was found that FORTEC-3D had a difficulty when the ambipolar condition has a multiple roots. It was also found that numerical noise level was quite larger in 3-D simulation than that was seen in axisymmetric tokamak cases.

To overcome the problems, we improved the numerical schemes in FORTEC-3D[3]. We ascertained the cause of these problems were from inaccuracy in the way of solving the radial electric field and evaluating the flux, and from the emergence of huge-weight markers as some trapped particles drift away from the initial position. Both points should be carefully treated in transport simulations where non-local nature in neoclassical transport is important. The improvements adopted are as follows:

1. A staggered-mesh scheme for evaluating electric field and particle flux, which is high-order accuracy and has a numerical stabilizing effect.
2. Filtering scheme for huge-weight markers, which reduces numerical noise without changing transport value and transition speed of radial electric field.
3. Improvement of the conservation property of the Landau collision operator in the existence of huge-weight markers.

With these improvements, it becomes possible to simulate time evolution of electric field in a LHD plasma with bifurcation, as shown in Figs. 1 and 2. The radial electric field shows continuous transition from negative to positive root, and the numerical noise in Γ_i is successively suppressed without changing the time-averaged value. This progress enables us to push forward the research of the FOW effect in high-T_i LHD plasmas.

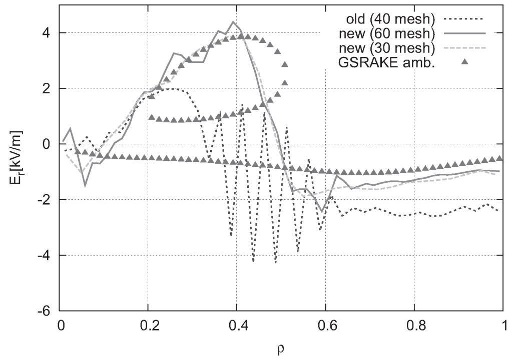

Fig.1: Comparison of the transiting radial electric field profiled solved by the old and improved FORTEC-3D.

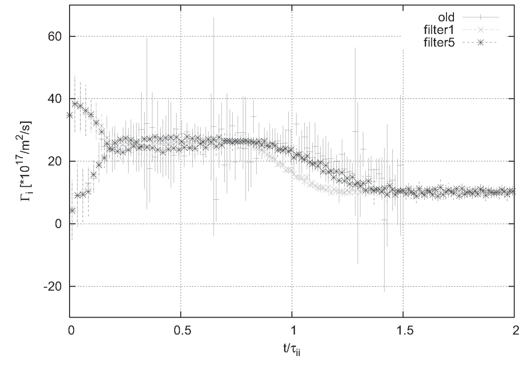

Fig.2: Comparison time evolution of the ion flux Γ_i on $\rho = 0.45$ surface among old and new simulations.

1) Satake, S. *et al.*, Plasma Fusion Res. **1**, 002 (2006).
2) Satake, S. *et al.*, Nucl. Fusion **47**, 1258 (2007).
3) Satake, S. *et al.*, to be appeared in Plasma Fusion Res. **3** (2008).