§2. Neoclassical Transport Simulation by δf Monte-Carlo Method

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To study neoclassical(NC) transport with finite-orbit-width (FOW) effect of trapped particle orbits has attracted much attention recently. There appear non-standard guiding-center orbits near the magnetic axis of tokamak called "potato" orbits[1]. Typical orbit width of potato particles is as large as $(q^2\rho^2 R_0)^{1/3}$. The standard NC transport theory constructed in the small-orbit-width (SOW) approximation is not applicable to such cases in which the orbit width is comparable to the background ground gradient scale length or in the near-axis region. We have constructed a new transport theory which can be applicable to the near-axis region of tokamak[2] by using a Lagrangian description of the drift-kinetic equation. However, in that theory the effect of radial electric field E_r has been neglected. Since the intrinsic ambipolarity of neoclassical particle fluxes breaks if the FOW effect is considered, NC transport calculation with consistent ambipolar E_r is important in tokamaks as in non-axisymmetric cases.

To study the evolution of E_r and NC transport with the FOW effect, we have developed a Monte-Carlo transport simulation code using the δf method.[3,4] In this method, the distribution function of plasma is separated into $f = f_M + \delta f$, where f_M is a local Maxwellian and δf is considered as a small perturbation from f_M. We solve the linearized drift-kinetic equation for δf as follows

$$\left(\frac{\partial}{\partial t} + (\mathbf{v}_\parallel + \mathbf{v}_d)\cdot\nabla + e\mathbf{v}_d\cdot\mathbf{E_r}\frac{\partial}{\partial\mathcal{K}} - C(,f_M)\right)\delta f = -\mathbf{v}_d\cdot\left(\nabla - \frac{e\mathbf{E_r}}{T}\right)f_M + C(f_M,\delta f), \quad (1)$$

where $\mathcal{K} = mv^2/2$. $C(\delta f, f_M) = C_{TP}$ is the test-particle collision term implemented by random kicks in the velocity space, and $C(f_M,\delta f) = \mathcal{P}f_M$ is the field-particle collision term defined so that the collision operator satisfies the conservation properties

$$\int dv^3\mathbf{v}^{\{0,1,2\}}\left(C_{TP} + \mathcal{P}f_M\right) = 0. \quad (2)$$

In eq. (1), the term $\mathbf{v}_d\cdot\nabla\delta f$ brings the FOW effect, which is neglected in standard formulation in the SOW limit. The radial electric field develops according to

$$\epsilon_0\left(1 + \frac{c^2}{v_A^2}\right)\frac{\partial E_r(r,t)}{\partial t} = -Z_i e\langle\Gamma_i(r,E_r,t)\rangle, \quad (3)$$

where Γ_i is the ion radial flux and the electron one is neglected.

In the time evolution of E_r, a rapid oscillation called geodesic acoustic mode (GAM) occurs. It is known[5] that GAM shows a rapid Landau-like damping when $q \simeq 1$. But the calculation shown in [5] uses a SOW limit model. Our δf simulation revealed [6] the global evolution of GAM as shown in Fig. 1. In a reversed-shear configuration with $q_{min} \simeq 1$ at $r = 0.5$, it can be seen that the fast GAM damping occurred at $r = 0.5$ also affects the time evolution of E_r on both sides of the resonance surface. The interference pattern of E_r at $r > 0.5$ is formed because GAM frequency $\omega_{GAM} \sim v_{th}/R0$ is different on each flux surface. These features can be found only by the global simulation.

Figure 2 shows the ion heat conductivity χ_i compared with the SOW-limit NC theory. The reduction of χ_i in the near-axis region has been predicted in our analysis[2] for a collisionless plasma. By the δf simulation, we also found that χ_i also reduces even in the plateau regime[7]. The difference of χ_i from the SOW-limit estimation becomes larger as collisionality is getting lower since the FOW effect of potato particles is significant in banana regime.

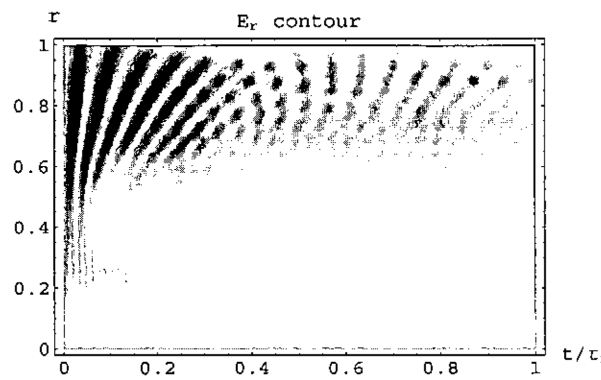

Fig. 1 : GAM oscillation in a reversed-shear configuration

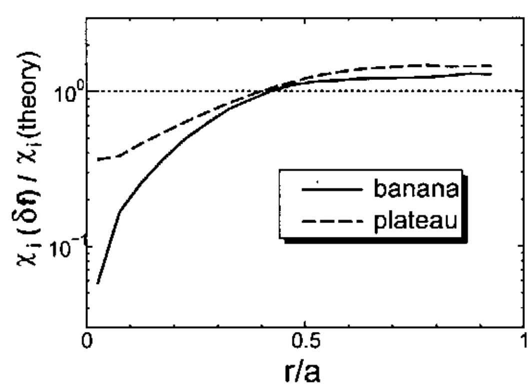

Fig. 2 : Ion heat conductivity in two collisionality regimes

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2)Satake, S. *et al.*, Phys. Plasmas **9**, 3946 (2002).
3) Wang W. X. *et al*, Plasma Phys. Control. Fusion **41**, 1091 (1999).
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6) Satake S. and Okamoto M., Bulletin of APS Vol. 48, No. 7, LP1-42 (2003).
7) Satake S. *et al*, to appear in JPFR Series **6** (accepted).