§16. Development of Neoclassical Viscosity Simulation Method

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Control of the toroidal rotation is an important issue in tokamaks in order to improve the stability of the confined plasmas. Recent studies have shown that the non-axisymmetry as small as $\delta B/B_0 \sim 10^{-4}$ can induce significant damping in toroidal rotation by the neoclassical toroidal viscosity (NTV). To give a precise prediction of the toroidal rotation damping by small perturbation, a new simulation to evaluate NTV is developed using the δf Monte Carlo method.[1)] It is the first application of the δf simulation to NTV calculation. The advantage of this method is that we can calculate NTV without relying on the conventional approximations used in analytic theories such as zero-orbit-width limit, mono-energy treatment with pitch-angle scattering operator, etc.

We utilize FORTEC-3D neoclassical transport code[2)] to this purpose. It solves the drift-kinetic equation for δf in 5-dimensional phase space, where δf is the deviation of plasma distribution function from local Maxwellian. One can directly evaluate NTV $\langle \mathbf{e}_\zeta \cdot \nabla \cdot \mathbf{P} \rangle$ from δf as followings;

$$\langle \mathbf{e}_\zeta \cdot \nabla \cdot \mathbf{P} \rangle = B_0 \sum_{m,n\neq 0} n\delta_{m,n} \left\langle \frac{\delta P}{B} \sin(m\theta - n\zeta) \right\rangle, \quad (1)$$

where $\delta P = M \int d^3v \delta f (v_\perp^2/2 + v_\parallel^2)$ measures the pressure anisotropy, M is ion mass, and $\delta_{m,n}$ are Fourier components of magnetic field in Boozer coordinates, $B(r,\theta,\zeta) = B_0 \left[1 + \sum_{m,n} \delta_{m,n}(r) \cos(m\theta - n\zeta) \right]$.

Since it is the first application of the δf simulation for NTV calculation in weakly-perturbed tokamaks, we have carried out detailed benchmark tests in $\mathbf{E} \times \mathbf{B} \to 0$ case with analytic formulae,[5)] which are derived from bounce-averaged drift kinetic equation. The one is Shaing's asymptotic limit formula for the $1/\nu$ and Superbanana-plateau regimes,[3)] and the other is Park's combined analytic formula which is applicable wide range of collisionality regimes.[4)] Figure 1 shows the dependence of NTV on the normalized collisionality ν_* in a tokamak with (a): $(m,n) = (7,3)$ single-helicity and (b): $(m = 13, 14, 15,\ n = 3)$ multi-helicity perturbation cases, respectively. The perturbation amplitude each case is $d_{m,n} \sim 10^{-3}$, and the resonant flux surface on which the rotational transform q equals to m/n is located at $r = 0.49a$ (Fig. 1(a)) and $r = 0.70a$ (Fig. 1(b)), respectively. In each case, we found good agreement between FORTEC-3D simulation and Park's combined analytic formula. On the other hand, the asymptotic limit formulae is found to fail the dependence of NTV on collision frequency as ν_* becomes lower. The benchmark result proved that proper model that takes account of ν_*-dependence of NTV is important to quantitative evaluation of NTV in low-collisionality plasmas.

Neoclassical viscosity is also important in transport studies on helical plasmas. FORTEC-3D is also applicable to neoclassical poloidal and toroidal viscosity calculations in LHD. We have shown that the neoclassical radial flux evaluated from linear combination of toroidal and poloidal viscosities exactly equals to that calculated from the radial drift velocity, $\Gamma = \left\langle \int d^3v \mathbf{v}_d \cdot \nabla \hat{r} \delta f \right\rangle$, which demonstrates the accuracy of the viscosity calculation in helical configurations[1)]. It is planned to study the dependence of the neoclassical viscosity on radial electric field, magnetic axis position, collision frequency. etc.

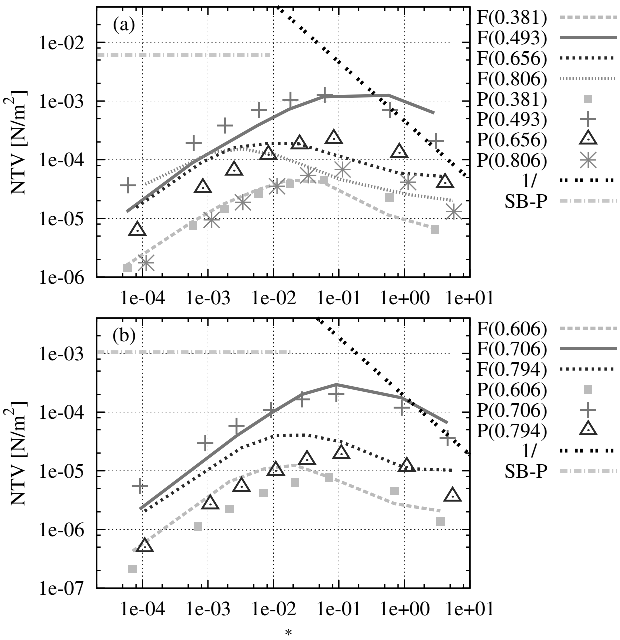

Fig. 1: NTV dependence on ν_* in tokamak with (a):single-helicity and (b):multi-helicity magnetic perturbation. The numerals on the legend describe the radial position r/a. The "F" curves are results from FORTEC-3D, "P" symbols are Park's formula, and straight lines are asymptotic limit formulae, respectively.

1) Satake, S. *et al.*, Plasma Phys. Control. Fusion **53** (2011) 054018.

2) Satake, S. *et al.*, Plasma and Fusion Res. **3** (2008) S1062.

3) Shaing, K. C. *et al.*., Nucl. Fusion **50** (2010) 025022.

4) Park, J.-K. *et al.*., Phys. Rev. Lett **102** (2009) 065002.

5) Satake, S. *et al.*., *"Neoclassical Toroidal Viscosity Calculations in Tokamaks using a δf Monte Carlo Simulation and Their Verifications"*, accepted to publish in Phys. Rev. Lett.