§16. Simulation Studies on Neoclassical Viscosity in Torus Plasmas

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We have developed a simulation method to evaluate neoclassical poloidal and toroidal viscosity (NPV, NTV) in torus plasmas based on the δf drift-kinetic equation solver FORTEC-3D[1]. Using the simulation code, in 2012 we investigated the NPV in LHD and NTV in tokamak with small magnetic perturbation (resonant magnetic perturbation, RMP), especially the dependence of them on $\mathbf{E}\times\mathbf{B}$ rotation speed.

NPV in LHD bias experiment In bias experiments where large poloidal $\mathbf{E}\times\mathbf{B}$ rotation is driven, it is observed that the bias voltage-current relation shows a transition as the bias voltage is increased. This transition has been phenomenologically explained by the non-linear dependence of NPV on $\mathbf{E}\times\mathbf{B}$ rotation speed, or poloidal Mach number M_p. When the $\mathbf{J}\times\mathbf{B}$ torque of electrode current exceeds the local maximum value of NPV at the critical M_p, the transition occurs. We analyzed a LHD biasing experiment (shot #109521) by FORTEC-3D using observed data as input parameters. Figure 1 shows the dependence of NPV on M_p near the electrode, which was inserted to $r \simeq 0.8a$. The simulation predicts the transition happens at $M_p \simeq 0.8$, or $V_E \sim 300$V, and the peak NPV is about 0.05 N/m^2. Though there are ambiguities in potential and temperature, this prediction is close to the observation of bias voltage $V_E \sim 200$ and the peak value of $\mathbf{J}\times\mathbf{B}$ torque 0.07 N/m^2 at transition point, respectively. Thus it has been demonstrated that the δf simulation can give qualitative prediction of the transition in biasing experiment.

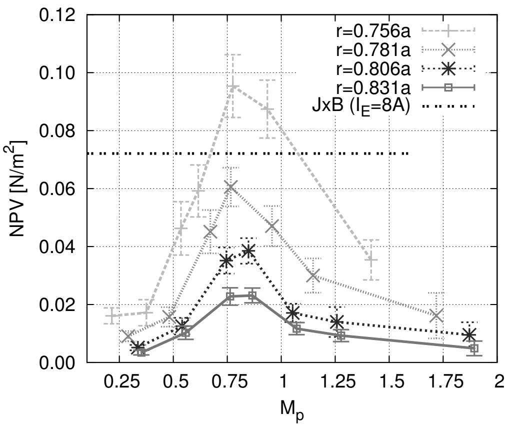

Fig. 1: Dependence of NPV in LHD on several flux surfaces near the biasing electrode[2]. Peak value of $J\times B$ torque in a biasing experiment is also plotted.

NTV in RMP tokamak External magnetic perturbation is applied to mitigate edge-localized modes (ELMs) in tokamak experiments. A related issue is NTV, which was found to damp toroidal rotation in many tokamak RMP experiments. Simulation study has been carried to study NTV in finite-$\mathbf{E}\times\mathbf{B}$ cases. A new phenomenon was found from the δf simulation when ω_E is finite, where ω_E is $\mathbf{E}\times\mathbf{B}$ rotation frequency. A double-peak of NTV radial profile emerges on the both sides of the $q = m/n$ resonant rational flux surface as ω_E increases, and the distance between two peaks depends linearly on ω_E. We observed the contribution to NTV in velocity space at the peak radial position as shown in Figure 2, where $dQ_{m,n}$ represents the integrand inside the equation to evaluate NTV,

$$\mathrm{NTV} \propto \int d^3v dQ_{m,n} \sim \int d^3v(v_\perp^2 + v_\parallel^2/2)\delta f.$$

It is found that passing particles $v_\parallel \sim v_{th}$ resonate with RMP on the two peak positions. We proved that the passing-resonant condition can be expressed as $q(nq-m)\omega_{tr} = m\omega_E$, where $\omega_{tr} = v_\parallel/qR$ is transit frequency[3]. In the existence of q-shear, the factor $nq-m$ is a small quantity near the $q = m/n$ resonant surface, and the resonant condition is satisfied on the both sides of $q = m/n$ surface with finite ω_E value, which results in the double-peak structure in NTV radial profile. This new finding of the mechanism to create double-peak NTV reveals the important fact that both trapped and passing particles should be taken into account when NTV is evaluated in RMP tokamaks.

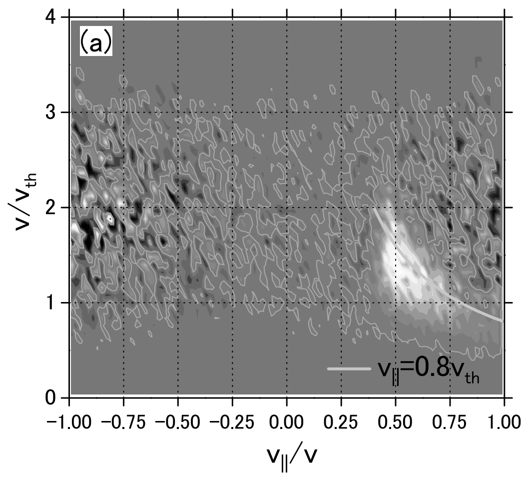

Fig. 2: Contour plot of δQ_{mn} in the velocity space when the double-peak appears in radial profile of NTV. The curve represents the resonant passing particles.

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

2) Kitajima, S. *et al.*, accepted to publish in Nuclear Fusion.

3) Satake, S. *et al.*, submitted to Nuclear Fusion.