§17. On Neoclassical Flows in Drift-optimized Helical Configurations

Nishimura, S.,
Nakamura,Y. (Kyoto Univ.)

For the equilibrium and stability analysis including the "self-consistent" bootstrap current under the self-consistent ambipolar radial electric field E_r [1], we had derived an analytical expression for the boundary layer correction for the neoclassical parallel viscosity [2]. In the $1/\nu$ regime ($E_r/v\approx 0$) without the collisionless detrapping/entrapping by the E×B drift suppressing the so-called ripple diffusion, this effect is caused by the large perturbation in the ripple-trapped pitch-angle range coupled with a collisional detrapping/entrapping at the ripple-trapped/untrapped boundary layer in the pitch-angle space [3]. The parallel viscosity force as the driving force for the neoclassical parallel flows such as the bootstrap current differs from a prediction by Shaing, et al.[4] in this $1/\nu$ regime since their theory was derived neglecting the ripple diffusion. It was confirmed by our previous benchmark tests that we have to interpret this previous theory as expressions for the collisionless detrapping ν regime ($E_r/v\neq 0$) where the E×B drift suppresses the perturbation in the ripple-trapped pitch-angle range. By adding our formula for the boundary layer correction $N^*_{(boundary)}$ to the viscosity coefficient given by their theory $N^{*(sym)}+N^{*(asym)}$, correct $1/\nu$ regime values are obtained [2]. Therefore there is a dependence of the total viscosity coefficient $N^* = N^{*(sym)}+N^{*(asym)}+N^*_{(boundary)}$. This is another new mechanism to cause dependences of the bootstrap current on the radial electric field.

One of interesting predictions given by our formula is that the sign of this correction depends on the ripple spectra. A previously reported benchmarking example [2] was that in a case with single helical ripple mode. In this case the boundary layer correction $N^*_{(boundary)}$ enhanced the total driving force for the flows. However our theory predicts that the boundary layer correction sometimes may cancel the viscosity force or reverse the direction of the force. Recent devices without quasi-symmetry often apply an idea of so-called σ-optimization [5] to improve collisionless drift orbits and the $1/\nu$ ripple diffusion. There are side-band helical and/or bumpy ripple spectra. This kind of side-band ripple gives significant change of the viscosity coefficient in the $1/\nu$ regime ($E_r/v\approx 0$). Here we show another benchmarking example in which the boundary layer correction reverses the direction of the bootstrap current in the $1/\nu$ regime. Figure 1 shows the magnetic field strength in a configuration with

$$B = B_0[1-0.1\cos\theta_B + 0.2\cos(\theta_B-5\zeta_B) - 0.1\cos(5\zeta_B) - 0.1\cos(2\theta_B-5\zeta_B)]$$

in the Boozer coordinates (θ_B, ζ_B), and B_0=1T, χ'=0.15T·m, ψ'=0.4T·m, B_θ=0, B_ζ =4T·m. The Fourier modes of (m,n)=(0,5) and (2,5) correspond to the side-band spectra. Figure 2 shows a comparison of the analytical formulas for the $1/\nu$ and ν regimes with the numerical results given by the DKES (Drift Kinetic Equation Solver) code in this configuration. Following Ref.[2], we show here the geometrical factor $G^{(BS)} \equiv -\langle B^2\rangle N^*/M^*$ instead of the total mono-energetic viscosity coefficient N^* itself. Although the $G^{(BS)}$ in the ν regime ($E_r/v\neq 0$) has a positive value indicating a bootstrap current to the co-direction, it has a negative value corresponding to the current in the counter direction in the $1/\nu$ regime ($E_r/v\approx 0$). In viewpoint of practical applications, the strong radial electric field limit $N^*=N^{*(sym)} + N^{*(asym)}$ given by the previous analytical theory [4] may be appropriate for ions although, the boundary layer correction $N^*_{(boundary)}$ should be added for electrons with a large thermal velocity ($E_r/v\approx 0$). In the future integrated simulation for LHD [1], this dependence of the electron viscosity coefficients on the radial electric field will be important in inward shifted configurations with improved collisionless drift orbits.

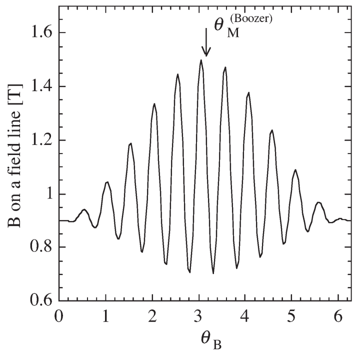

Fig.1 The model magnetic field used here

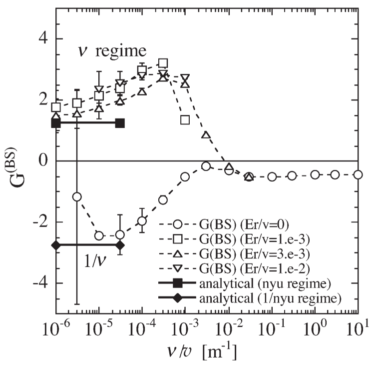

Fig.2 The geometrical factor expressing the parallel viscosity as the driving force for the neoclassical flows. The numerical results given by the DKES (open symbols) and the analytical formulas (solid lines) are compared.

Reference

[1] Nakamura,Y., et al., Fusion Sci.Technol. **50**, 457 (2006)
[2] Nishimura,S., Sugama,H., and Nakamura,Y., Fusion Sci.Technol. **51**,61(2007)
[3] Shaing,K.C.,and Callen,J.D., Phys.Fluids **25**,1012 (1982)
[4] Shiang,K.C., et al., Phys.Fluids **29**,2548(1986), B**1**,148(1989), B**1**,1663(1989)
[5] Mynick,H.E., Phys.Fluids **26**, 1008 (1983)