§20. Effects of $1/\nu$ Ripple Diffusions on the Parallel Viscosity and Bootstrap Current

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In recent studies for advanced helical devices, neoclassical plasma flows such as bootstrap currents due to the viscosity effects are attracting much attention as a new measure for configuration optimization. In many applications of the theory of the flows, a "$1/\nu$ regime" formula derived by Shaing, Carreras, et al.[1,2] in the Boozer coordinates has been often used. This representation was an extension of a previous theory developed in the Hamada coordinates [3]. As stated in Ref.[3], these existing formulas were obtained neglecting effects of $1/\nu$ component of the perturbation at the ripple trapped pitch-angle range and the trapped/untrapped boundary layer in the phase space. In this sense, we may have to interpret the formulas derived by them rather as the expressions for the collisionless-detrapping ν regime [4]. Although this problem was already suggested in Ref.[3], the discussion was only qualitative. After our work in Ref.[5] to solve a problem on collisional momentum conservation, it was quantitatively confirmed that the analytical formulas express the viscosity in the collisionless limits of the ν regime ($E_s/v\neq 0$) [6]. Even if the mono-energetic viscosity coefficients N^* in the $1/\nu$ regime can be obtained by using a direct numerical calculation of the linearized drift kinetic equation [5], this kind of numerical calculations cannot be incorporated in large scaled codes utilizing iterative processes. A MHD equilibrium calculation including the "self-consistent" bootstrap currents is an example of the iterative calculation. For this kind of application, a derivation of an analytical expression for the $1/\nu$ regime ($E_s/v\cong 0$) including the boundary layer effect is now the next theme. By combining our formulation and previous analytical theories for the boundary layer [8] and the ripple diffusions[9], we obtained the boundary layer correction $N^*_{\rm (boundary)}$ in the $1/\nu$ regime [6],

$$N^*_{\rm (boundary)} = -\frac{12}{\pi^3}\frac{\nu_D^a}{v}\frac{\langle B^2\rangle}{\chi'\psi' f_c}\frac{V'}{4\pi^2}\times$$

$$\int_0^{\pi} d\theta_B\,(2\delta_{\rm eff})^{1/2}(\pi-2\sin^{-1}\alpha^*)\,\theta_B\left(\frac{\partial\varepsilon_T}{\partial\theta_B}-\frac{2}{3}\sqrt{1-\alpha^{*2}}\,\frac{\partial\varepsilon_H}{\partial\theta_B}\right).$$

Here, we basically adopt the notations in Refs.[5,6], except that $\delta_{\rm eff}$ and α^* are the effective ripple well depth and the effective ripple well length correction, respectively[7], and magnetic field strength is assumed to be $B=B_0[1+\varepsilon_T(\theta)+\varepsilon_H(\theta)\cos\{L\theta-N\zeta+\gamma(\theta)\}]$ [8]. Figure 1 shows the analytical results given by an inter-regime connection between the n regime ($N^*=N^{*(\nu)}$) and the $1/\nu$ regime ($N^*=N^{*(\nu)}+N^*_{\rm (boundary)}$), where $N^{*(\nu)}$ is given by Refs.[1-3]. Following Refs.[5,6], the magnetic fields assumed here is $B=B_0[1-\varepsilon_t\cos\theta_B+\varepsilon_h\cos(L\theta_B-N\zeta_B)]$ with L=2, N=10, B_0=1T, χ'=0.15T·m, ψ'=0.4T·m, B_θ=0, B_ζ=4T·m, ε_t=0.1 and ε_h=0.05, respectively. The radial electric field strength is changed in the range of 1×10^{-6}T$\leq E_s/v\leq 3\times10^{-3}$T, and the N^* becomes smaller with increasing the radial electric field strength. In viewpoint of practical applications, this strong radial electric field limit $N^*=N^{*(\nu)}$ given by the previous analytical theory[1-3] may be appropriate for ions although, the boundary layer correction should be added for electrons with a large thermal velocity ($E_s/v\approx 0$).

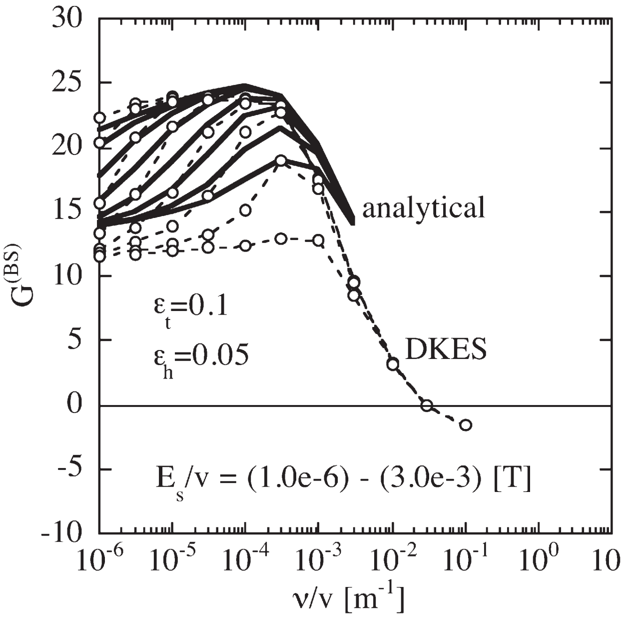

Figure 1 geometrical factor $G^{\rm (BS)}\equiv -\langle B^2\rangle N^*/M^*$ defined in Refs.[5,6] as a function of the collisionality parameter ν/v and the electric field parameter E_s/v. Both of the analytical (solid curve) and the numerical results using the DKES code (open circles) are shown.

References

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