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

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

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 $N^*_{(\text{boundary})}$ in the $1/\nu$ regime [6],

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

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

Here, we basically adopt the notations in Refs.[5,6], except that δ_{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 ($N^* = N^{*(\nu)} + N^*_{(\text{boundary})}$), 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≤ E_s/v ≤3×10^{-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 ($E_s/v\approx 0$).

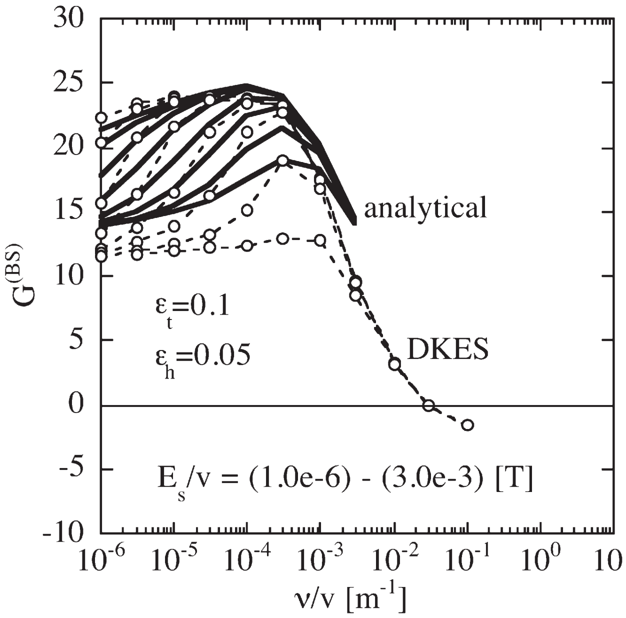

Figure 1 geometrical factor $G^{(BS)}\equiv-\langle B^2\rangle N^*/M^*$ defined in Refs.[5,6] as a function of the collisionality parameter ν/v and the electric field parameter E_s/v. Both of the analytical (solid curve) and the numerical results using the DKES code (open circles) are shown.

References

[1] Shaing,K.C., Carreras,B.A., et al., Phys.Fluids B**1**, 1663 (1989)
[2] Nishimura,S., et al., Ann.Pep of NIFS 2005 p.327, p.328
[3] Shaing,K.C, et al., Phys.Fluids **29**, 2548 (1986); B**1**, 148 (1989)
[4] Crume,Jr.,E.C., et al, Phys.Fluids **31**, 11 (1988)
[5] Sugama,H. and Nishimura,S.,Phys.Plasmas **9**,4637(2002)
[6] Nishimura,S., et al., to be published in Fusion Science & Technol.
[7] Shaing,K.C. and Callen,J.D., Phys.Fluids **25**,1012(1982)
[8] Shaing,K.C. and Hokin,S.A., Phys.Fluids **26**,2136(1983)