§12. Neoclassical Transport of Impurity in General Non-symmetric Toroidal Plasmas

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A previous formulation of the neoclassical transport in helical/stellarator devices based on the moment equation approach [1] is extended to allow the poloidal and toroidal variation of the densities and temperatures of $\delta n_a/n_a$, $\delta T_a/T_a < \delta B/B$. Since the transport of impurities with high collisionalities (so-called Pfirsch-Schlüter diffusions which are separated in our previous works) is determined by the local parallel force balance before the flux-surface averaging including these variations δn_a, δT_a, an important purpose of this extension is to study radial profiles of the impurity density under the self-consistent ambipolar radial electric field E_r in plasmas containing electrons and main ions corresponding to the collisionless ($1/\nu$, ν, or banana) regimes or the plateau regime, and impurity ions in the Pfirsch-Schlüter regime. The Legendre-Laguerre expansion with orders of l=0,1 and j=0,1,2 is used for this local momentum balance to include the collisionless detrapping/retrapping effect, which is peculiar to the non-symmetric configurations, and the energy scattering collisions [2].

By solving the particle, momentum and energy balance equations, following Pfirsch-Schlüter (P-S) diffusion coefficients $(L^{\rm PS})^{ab}_{i\,j}$ are obtained.

$$\begin{bmatrix} \Gamma^{\rm PS}_a \\ q^{\rm PS}_a/T_a \end{bmatrix} = -\frac{c}{e_a}\begin{bmatrix} \langle \tilde{U} F_{\| a1}\rangle \\ \langle \tilde{U} F_{\| a2}\rangle \end{bmatrix} \equiv \sum_b \begin{bmatrix} (L^{\rm PS})^{ab}_{11} & (L^{\rm PS})^{ab}_{12} \\ (L^{\rm PS})^{ab}_{21} & (L^{\rm PS})^{ab}_{22} \end{bmatrix}\begin{bmatrix} X_{b1} \\ X_{b2} \end{bmatrix}$$

$$X_{a1} \equiv -\frac{1}{\langle n_a\rangle}\frac{\partial\langle p_a\rangle}{\partial s} - e_a\frac{\partial\langle \Phi\rangle}{\partial s},\quad X_{a2} \equiv -\frac{\partial\langle T_a\rangle}{\partial s}$$

Since this transport matrix fully includes non-diagonal coupling between all particle species, and between particle and heat diffusion, which are important in determining the impurity density profiles, all coefficients cannot be shown here even in 2 ion species cases. Although total entropy production rate given by total diffusion fluxes will determine the steady-state ion density profiles, we shall consider here only the particle diffusion coefficients of ions. When the ions (a,b,…≠e) have a common flux-surface-averaged temperature $\langle T_a\rangle = \langle T_b\rangle = \ldots = \langle T_{\rm i}\rangle$, the particle diffusion fluxes of them are given by

$$\Gamma^{\rm PS}_a = -(L^{\rm PS})^{ae}_{11}\langle T_{\rm e}\rangle\frac{\partial \ln\langle n_{\rm e}\rangle}{\partial s} + \left\{(L^{\rm PS})^{ae}_{11} + (L^{\rm PS})^{ae}_{12}\right\}\frac{\partial\langle T_{\rm e}\rangle}{\partial s}$$
$$-\sum_{b\neq {\rm e}}(L^{\rm PS})^{ab}_{11}\langle T_{\rm i}\rangle\frac{\partial \ln\langle n_b\rangle}{\partial s} - \sum_{b\neq {\rm e}}\left\{(L^{\rm PS})^{ab}_{11} + (L^{\rm PS})^{ab}_{12}\right\}\frac{\partial\langle T_{\rm i}\rangle}{\partial s}$$

Note that this diffusion flux $\Gamma^{\rm PS}_a$ is intrinsically ambipolar and thus $e_a\partial\langle\Phi\rangle/\partial s$ in X_{a1} vanish in this summation of all forces, and that $(L^{\rm PS})^{ab}_{11} = (L^{\rm PS})^{ba}_{11}$ (Onsager symmetry).

Figure 1 shows an example of the results. In this example, following Refs.[1], the magnetic field assumed there is that with $B/B_0 = 1 - \varepsilon_{\rm t}\cos\theta_{\rm B} + \varepsilon_{\rm h}\cos(L\theta_{\rm B} - N\zeta_{\rm B})$, L=2, N=10, B_0=1T, χ'=0.15T·m, ψ'=0.4T·m, B_θ=0, and B_ζ=4T·m. The contained ion assumed here is a mixture of protons (H^+) and fully ionized neon (Ne^{10+}), which is used for the charge exchange spectroscopic measurements and the impurity transport studies in the Large Helical Device (LHD) [3-4], with an ion density ratio corresponding to $Z_{\rm eff}$=5.74, and the assumed temperatures are $T_{\rm e}$=$T_{\rm i}$=1keV. With these assumptions, a dependence of the diffusion coefficients on the density in a range of $n_{\rm e} \le 5\times10^{20}{\rm cm}^{-3}$ (up to the "SDC" [4] density regime) is investigated here. The mean free path of electron-electron collision is $v_{\rm Te}\tau_{\rm ee}$=28.3m corresponding to the plateau regime even at $n_{\rm e}=5\times10^{20}{\rm cm}^{-3}$.

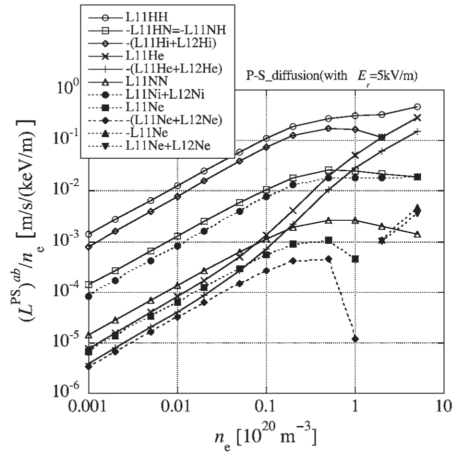

Fig.1 The P-S particle diffusion coefficients $(L^{\rm PS})^{ab}_{11}$, $(L^{\rm PS})^{a{\rm i}}_{11} + (L^{\rm PS})^{a{\rm i}}_{12} \equiv \sum_{b\neq{\rm e}}\left\{(L^{\rm PS})^{ab}_{11} + (L^{\rm PS})^{ab}_{12}\right\}$, $(L^{\rm PS})^{a{\rm e}}_{11} + (L^{\rm PS})^{a{\rm e}}_{12}$.

In high density regime of $n_{\rm e} > 10^{19}{\rm m}^{-3}$, deviations from simple $\propto n_{\rm e}$ scaling are caused by the collisionless detrapping/retrapping effects due to the finite radial electric field strength of E_r =5kV/m, whose value is typical as the ambipolar electric field, and by the energy scattering collisions. We can see that non-diagonal coupling between electron and ions dominates over the contributions of ion temperature gradient $\partial\langle T_{\rm i}\rangle/\partial s$ and thus controls of the electron density and temperature profiles will be important in the high density operations.

1) H.Sugama and S.Nishimura, Phys.Plasmas **9**,4637(2002), ibid. **15**,042502(2008).
2) S.Nishimura, H.Sugama, and Y.Nakamura, in proc.of ITC17/ISHW16 (Oct.15-19, 2007, Toki, Japan) P2-018
3) Y.Nakamura, Y.Takeiri, R.Kumazawa, et al, Nucl.Fusion **43**, 219 (2003)
4) N.Ohyabu, T.Marisaki, S.Masuzaki, et al., Phys.Rev.Lett.**97**, 055002 (2006)