§5. The Resonant Viscosity Effect in N-ITB Plasmas

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In previous plasma rotation measurements in CHS and neoclassical transport calculations for interpreting their results, it was obvious that the impurity ions such as C^{6+} reach so-called resonant condition (well-known poloidal mach number becomes order unity M_p~1). In both of tokamak and stellarator studies, this resonant effect has been considered to be important in the edge transport barrier physics [1]. Also in CHS, a phenomenon suggesting its role in the spontaneous transition in the edge transport barrier (ETB) formation is observed [2]. However, various implicit assumptions in quantitative and predictive theories such as neoclassical transport theory are violated at the edge region, and thus the discussion was only qualitative. On the hand, an analysis of the neoclassical internal transport barrier (N-ITB) in CHS [3] clarified that the impurity ions reach the resonant condition in the core regions. This is caused by a fact that the N-ITB is formed by an artificial generation of the strong positive radial electric field of E_r~10kV/m (so-called electron root) by the ECH in the low ion temperature plasmas with $T_i(r=0)$~400eV [4]. Even when $cE_r/B \ll v_{Ta}$, which is required for the consistency with the stellarator MHD equilibrium $n_a m_a \mathbf{u}_a \cdot \nabla \mathbf{u}_a \ll \nabla p_a \Leftrightarrow u_a \ll v_{Ta}$, is satisfied, the first toroidal resonant condition $cE_r/B \sim v_{Ta}(\iota/2\pi)\langle r\rangle/\langle R\rangle$ for the Fourier mode $(m,n)=(1,0)$ often occurs for impurity ions in inner regions in heliotron configurations $(\iota/2\pi)\langle r\rangle/\langle R\rangle \ll 1$. Figure 1 shows this situation occurred in the N-ITB operation in CHS [3].

Here we show a systematic and faster calculation method for the resonant viscosity. The drift kinetic equation for the plateau and Pfirsch-Schlüter (P-S) regimes can be solved by Fourier expansions and the anisotropy relaxation Krook collision term $-\nu_T^a f_{a1}$ [1]. For practical applications, a direct Fourier expansion in the Boozer coordinates [5] is better than that in the Hamada coordinates used in Ref.[1]. The result for each Fourier modes $\sin(m\theta - n\zeta)$ in the viscosity coefficients includes following pitch-angle integral.

$$F(a,\,b) \equiv a\int_{-1}^{1} \frac{(\xi^2 - 1/3)^2}{(\xi - b)^2 + a^2}\,\mathrm{d}\xi$$

$$= -2a^3 - \frac{2}{3}a + 6ab^2 - 2ab\left(a^2 + \frac{1}{3} - b^2\right)\ln\frac{(1-b)^2 + a^2}{(1+b)^2 + a^2}$$

$$+\left\{a^4 - a^2\left(6b^2 - \frac{2}{3}\right) + \left(6b^2 - \frac{1}{3}\right)^2\right\}\times$$

$$\left\{\tan^{-1}\frac{1-b}{a} + \tan^{-1}\frac{1+b}{a}\right\}$$

Here, $a_{mn} \equiv (\nu_T^a/v)(V'/4\pi^2)\left\langle B^2\right\rangle^{1/2}/\left|\chi' m - \psi' n\right|$ and $b_{mn} \equiv (cE_s/v)\left\langle B^2\right\rangle^{-1/2}(B_\zeta m + B_\theta n)/(\chi' m - \psi' n)$, respectively. Though this approximated solution with $E_s/v=0$ in collisionless and collisional limits of $\nu/v \to 0,\infty$ reproduces the exact plateau and P-S asymptotic values, as a result of a break of collisional particle and energy conservation, the approximation becomes worth at the transition condition $\nu_T^a/v \simeq (8/5\pi)(4\pi^2/V')\left|\chi' m - \psi' n\right|/\left\langle B^2\right\rangle^{1/2}$ of each Fourier modes (m,n). Use of it should be limited to the large E_s/v range of $|b_{mn}| > 3.0\times10^{-2}$. Therefore the mono-energetic viscosity coefficients in the plateau and P-S energy ranges are given by connecting the function

$$\left\{\left(\frac{8}{\pi}\left|\chi' m - \psi' n\right|\right)^{3/2} + \left(5\frac{\nu_T^a}{v}\left\langle B^2\right\rangle^{1/2}\frac{V'}{4\pi^2}\right)^{3/2}\right\}^{-2/3}$$

in Ref.[5] for $|b_{mn}| < 3.0\times10^{-2}$ to the function $(9/8)\left|\chi' m - \psi' n\right|^{-1} F(a_{mn},\, b_{mn})$ expressing the resonance effect at $|b_{mn}| = 3.0\times10^{-2}$ in the E_s/v space. This technique is recently adopted for the neoclassical viscosity coefficients of Ne^{10+} in a calculation using a LHD configuration (R_{ax}=3.6m, B=2.45T, r/a=0.5) [6].

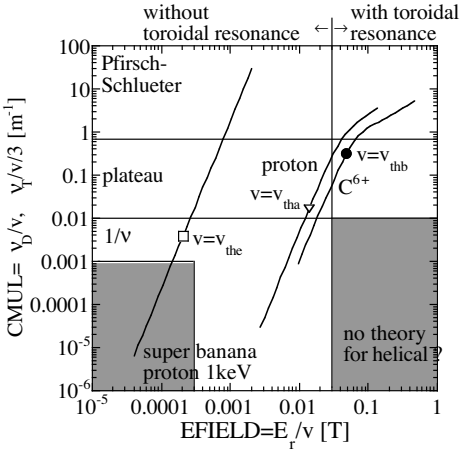

Fig.1 mono-energetic collisionality (ν/v) and E×B parameter (E_r/v) for electron, proton, and fully ionized carbon calculated with the measured parameters at r/a=0.5 in an experimental condition in Ref.[4]

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