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# §18. On the Parallel Viscosity in Heliotron-J

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As analyzed in Ref.[1], one of complicated problems caused by non-symmetries of the magnetic configurations is the integration constant for the banana regime expansion of the drift kinetic equation (DKE) determining the neoclassical parallel viscosity. Hereafter we use the word "parallel" to express the "force parallel to the magnetic field line". The viscosity is essential in determining the neoclassical parallel flows such as so-called bootstrap currents. To clarify the problem on the integration constant, it is convenient to start from the DKE defined in Ref.[2] and Ref.[1]. In this theory separating the effects of the field particle portion of the collision operator $C_a(f_{aM}, f_{b1})$ by using the friction-flow relation, the viscosity coefficient is determined by following equation with $C_a(f_{a1}, f_{bM}) \cong C_a^{PAS}$ (pitch-angle-scattering collision operator with the collision frequency of $\nu_D^a$) [2],

$$(V_{//} - C_a^{PAS}) G_{Xa} = \sigma_{Xa}\,.$$

Here $V_{//} \equiv v_{//}\mathbf{b}\bullet\nabla_{(\mu=\mathrm{const})}$ is linearized orbit propagator. It also is convenient to divide the source term $\sigma_{Xa}$ expressing the radial drifts and corresponding response perturbation $G_{Xa}$ into three components by using a method in Ref.[1], $\sigma_{Xa} = \sigma_{Xa}^{(avg)} + \sigma_{Xa}^{(sym)} + \sigma_{Xa}^{(asym)}$, $G_{Xa} = G_{Xa}^{(avg)} + G_{Xa}^{(sym)} + G_{Xa}^{(asym)}$. The difficulty in determining the integration constant appears only in $(V_{//} - C_a^{PAS}) G_{Xa}^{(asym)} = \sigma_{Xa}^{(asym)}$ since this part does not completely satisfy the solubility condition $\int (\sigma_{Xa}/v_{//}) dl = 0$ for the trapped particles in the banana regime expansion method. Even though the lowest order equation does not include the collision effects in this expansion $V_{//} G_{Xa}^{(asym)(0)} = \sigma_{Xa}^{(asym)}$ and $V_{//} G_{Xa}^{(asym)(1)} = C_a^{PAS} G_{Xa}^{(asym)(0)}$ considering $\nu_D^a$ as a expansion parameter, the actual distribution function is determined by finite collision effects. A specific method was used to derive the viscosity force only by calculating the circulating particle distribution without explicit treatments of the trapped particles [3]. It was a utilization of the particle and energy conservation of the DKE and a fact that we have to know only $\langle B\int v_{//} L_j^{(3/2)} d^3\mathbf{v}\rangle$ moments of the DKE. Explicit expressions for this circulating particle distribution $G_{Xa}^{(asym)(0)}$ are shown in Refs.[1,3], but to know them is not essential for understanding the problem. Important facts there are only that: (1) $\sigma_{Xa}^{(asym)}$ is an even function of $v_{//}$ and thus $G_{Xa}^{(asym)(0)}$ is an odd function of $v_{//}$, (2) and therefore it must be $G_{Xa}^{(asym)(0)}(v_{//}=0)=0$. Because of a relation $|v_{//}(\lambda=1)| = v\{1-B(\theta,\zeta)/B_M\}^{1/2} = v\{1-B(\theta,\zeta)/B(\theta_M,\zeta_M)\}^{1/2}$, where $\lambda \equiv \mu B_M/w \le 1$ is the normalized magnetic moment and its range of $\lambda \le 1$ corresponds to circulating particles, and $(\theta_M,\zeta_M)$ are the poloidal and toroidal angles giving the maximum value $B_M$ of the magnetic field strength $B$ on the flux surface by $B_M = B(\theta=\theta_M, \zeta=\zeta_M)$, this condition means $G_{Xa}^{(asym)(0)}(\lambda=1, \theta=\theta_M, \zeta=\zeta_M)=0$. By this determination at the trapped/circulating boundary $\lambda=1$, the lowest order solution and the parallel viscosity force derived from the resulting higher order equation include the coordinates $(\theta_M,\zeta_M)$.

When considering general non-symmetric toroidal configurations, the condition $B(\theta_M,\zeta_M)=B_M$ sometimes may correspond to a poloidally broadened "line" on the $(\theta,\zeta)$ plane. In this case, the integration constant $\cos(m\theta_M - n\zeta_M)$ is determined by a finite collision effect at the circulating/trapped boundary layer at $\lambda \cong 1$[1]. In helical heliotron devices such as LHD, this situation with the broadened $B \cong B_M$ regions on the flux surfaces may appear at the inboard side $\theta \approx \pm\pi$ in high beta plasmas. In an internal vertical (I.V.) magnetic field scan experiment in Heliotron-J (H-J) to investigate the configuration dependence of the bootstrap current, it was found that the broadened $B \cong B_M$ regions sometimes appear there [4]. In these situations, the determination of the coordinates $(\theta_M,\zeta_M)$ as the integration constant is numerically unstable if they are determined only by the magnetic field strength $B(q,z)$. Here we show a calculation example with the determination of $(\theta_M,\zeta_M)$ including the finite collision effect. Figure 1 shows the magnetic field strength on a field line in a H-J configuration with I.V.=–25, and the geometrical factor $G^{(BS)}$ expressing the parallel viscosity as the driving force for the bootstrap current. In contrast to Ref.[4] where discontinuous "jumps" in the radial distributions are caused by the numerically unstable determination of $(\theta_M,\zeta_M)$, the present calculation indicates that the "discontinuous" radial position is actually continuous. However, even in this present result, however, there is a steep radial gradient of $G^{(BS)}$. In general, this kind of radial gradients cannot exceed the upper limit determined by finite orbit width effects. Although we do not consider about this limit in the mono-energetic calculation in Fig.1 since it depends on the temperatures and particle species, it is a remaining future theme.

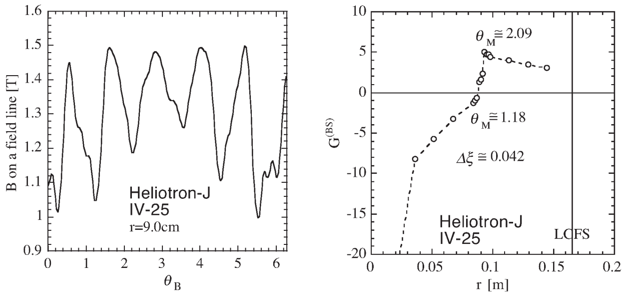


Fig.1 The magnetic field strength in the Heliotorn-J (I.V.=–25) (left), and the geometrical factor associated with the bootstrap current (right).

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