25D03

Fast ion driven neoclassical parallel flows and radial fluxes in non-symmetric toroidal plasmas

非対称トーラスにおける高速イオンに駆動される磁力線方向フローと径方向輸送

Shin Nishimura[1], Hideo Sugama[1], Akinobu Matsuyama[1], Hisamichi Funaba[1], Kenji Nishioka[2] and Yuji Nakamura[2]

西村 伸[1], 洲鎌英雄[1], 松山顕之[1], 舟場久芳[1], 西岡賢二[2], 中村 祐司[2]

1 *National Institute for Fusion Science, Toki 509-5292, Japan*

2 *Graduate School of Energy Science, Kyoto University, Uji 611-0011, Japan*

1 核融合科学研究所 〒509-5292 岐阜県土岐市下石町322-6

2 京都大学大学院エネルギー科学研究科 〒611-0011 京都府宇治市五ケ庄

Parallel plasmas flows driven by tangentially injected neutral beams in non-symmetric toroidal plasmas are analyzed. The Onsager symmetric neoclassical transport matrix is now extended to include (1) Ohkawa current, (2) fast ion driven radial fluxes, and (3) parallel momentum. In contrast to symmetric systems such as tokamaks, these beam driven momentum and radial particle flux in stellarator/heliotron devices, in which the neoclassical particle diffusion is non-ambipolar, can exist without any contradictions to the experimentally observed quasi-steady-state charge neutrality.

Though many applications of a method to obtain the neoclassical transport matrix in general non-symmetric toroidal plasmas [1] have been performed especially for quantitative predictions of neoclassical parallel flows and/or currents, only the inductive parallel electric field is taken into account there as the external driving force for the parallel flows. This situation is caused by a fact that these formulations are extensions of traditional neoclassical transport theories for tokamaks. In stellarator and heliotron devices with external rotational transform, however, the inductive electric field for the toroidal current is not required. Instead of that, the momentum input by the tangentially injected heating neutral beams is more important as the driving force. One experimentally observable effect of it may be fast ion driven impurity flow velocities that can be measured by the charge exchange recombination spectroscopy [2,3], and another may be the beam driven (Ohkawa) current [4]. Although many previous theoretical and experimental studies in 1970's~1980's were motivated by a practical reason of steady-state operations of tokamaks and consequently many discussions were devoted to the current, there are also the beam driven momentum in various toroidal confinement devices [5]. Recently, an importance of the toroidal momentum is widely recognized also in a viewpoint of the MHD stability.

Besides well-known these importance, additional beam driven radial particle and heat fluxes of heated species [6] also may be important as a method of impurity control and as a formation mechanism of the ambipolar potential. The existence of these additional radial fluxes can be easily understood by an analogy of well-known Ware pinch driven by the inductive electric field. One motivation of the previous experimental studies on the effects of the external momentum input [5] was to control the radial electric fields artificially. For non-symmetric toroidal configurations where the electric field is governed by the neoclassical ambipolar condition, however, any quantitative theoretical methods for the beam driven radial fluxes had never been shown. In this viewpoint, an important aspect of this problem (fast ion driven flows) clarifying a relation between tokamak and stellarator/heliotron studies [7] is a quasi-steady-state charge neutrality. Here is an essential reason of a strange history in which the beam driven momentum cannot be theoretically discussed (at least for tokamaks) even in some neoclassical ($\mathbf{B}\bullet\nabla B \neq 0$) derivations of the beam driven current. When the external particle, momentum, and energy source term $S_{\mathrm{f}}(\mathbf{x},\mathbf{v})$ in the Landau equation of fast ions are included,

$$\sum_a \langle \mathbf{B}\bullet\nabla\bullet\boldsymbol{\pi}_a \rangle = m_{\mathrm{f}} \left\langle \mathbf{B}\bullet\int \mathbf{v} S_{\mathrm{f}}(\mathbf{x},\mathbf{v}) \mathrm{d}^3\mathbf{v} \right\rangle \neq 0 \,,$$

and thus a phenomenological damping term for the plasma rotation is required in tokamaks for explaining the experimentally observed steady-state charge neutrality [6]

$$\sum_a e_a \left\langle \mathbf{\Gamma}_a^{\mathrm{bn}} \bullet \nabla s \right\rangle = 0 \cdot$$

Here, it also should be noted that the anomalous radial particle flux caused by electrostatic and/or electromagnetic turbulences, which is intrinsically ambipolar [8], cannot solve this confliction on the charge neutrality. This is one of backgrounds of recent discussions on the momentum transport in various tokamak experiments [9]. Not only to solve this ambipolar paradox, the related "momentum transport" theories should explain also the previously observed beam driven currents. However, systematic theories are still under constructions.

In contrast to it, the flows in non-symmetric stellarator and heliotron configurations, where the parallel viscosity and the non-ambipolar particle diffusion are not directly connected to each other, can be consistently determined by the neoclassical procedure without any phenomenological damping terms. In other words, the injected momentum in non-symmetric plasmas is effectively consumed for sustaining the ambipolar potential and accompanied E_r-driven flows while that in symmetric plasmas should be removed by the radial transport. In the present study, the thermalized particles' kinetic and moment equations for general multi-ion-species plasmas [10] are extended to include the fast ion friction term, which is obtained by combining the eigenfunction method in Ref.[11] and the adjoint equation method in Ref.[12]. Then the radial particle and heat diffusions are derived by using the $[\mathbf{N}_a, \mathbf{L}_a]$ matrices defined in Ref.[1].

References

[1] H. Sugama and S. Nishimura, Phys Plasmas **9**, 4637 (2002), ibid. **15**, 042502 (2008).
[2] R.J. Fonck, D.S.Darrow, and K.P.Jaehnig, Phys. Rev. A **29**, 3288 (1984).
[3] J. Kim, et al., Phys. Rev. Lett. **72**, 2199–2202 (1994).
[4] T.Ohkawa, Nucl. Fusion **10**, 185 (1970).
[5] K.Ida, Plasma Phys. Control. Fusion **40,** 1429 (1998).
[6] S. P. Hirshman and D. J. Sigmar, Nucl. Fusion **21**, 1079 (1981), Chap.8.
[7] H.Sugama, et al., Phys.Plasmas **2**,2989 (1995), ibid. **3**, 2379 (1996)
[8] H. Sugama, T.H. Watanabe, M. Nunami and S. Nishimura, Plasma Phys. Control. Fusion **53** 024004 (2011)
[9] T.S. Hahm, P.H. Diamond, O.D. Gurcan and G. Rewoldt, Phys. Plasmas **14**, 072302 (2007).
[10] S. Nishimura, H. Sugama, H. Maaßberg, C. D. Beidler, S. Murakami, Y. Nakamura, and S. Hirooka, Phys. Plasmas **17**, 082510 (2010), ibid. **18**, 069901 (2011).
[11] C.T.Hsu, P.J.Catto, and D.J.Sigmar, Phys.Fluids B **2**, 280 (1990).
[12] M. Taguchi, Nucl. Fusion **32**, 143 (1992).