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Collisionality Dependence of Shielding Factor of Beam Driven Current
ビーム駆動電流における遮蔽因子の衝突率依存性

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The collisionality dependence of a shielding factor of a neutral beam driven current, which is generally neglected for most models currently used, is shown to be important especially for present-day tokamak experiments. An addition of friction coefficients involving beam ions to the Matrix Inversion method based on the moment approach readily makes it possible to estimate the collisionality-dependent shielding factor. The models proposed coincide with the collisionless model in the collisionless limit. They clearly elucidate the strong dependence of the shielding factor on collisionality, indicating that using a collisionless model always overestimates a beam driven current.

1. Introduction

There is of growing importance in accurately estimating the current driven by neutral beam injection (NBI) for obtaining a fully current-driven, steady-state plasma. Although tangential NBI typically produces circulating beam ions carrying the substantial toroidal current, electrons tend to be dragged by these ions due to parallel friction and subsequently cancel the fast-ion circulating current out effectively. Ohkawa clarified that the effective beam driven current could flow in an impure plasma [1]. Furthermore, it was found that trapped electrons could reduce the induced electron circulating current that cancels the beam-ion current, due to the neoclassical effect [2, 3]. In general, the ratio of the beam driven current, j_b, to the fast-ion circulating current, $j_{||f}$, is called a shielding factor and is often written by

$$\Gamma = j_b / j_{||f} = 1 - F(1-G), \tag{1}$$

where F stems from the impure characteristic of a plasma and usually $F = Z_b/Z_{eff}$, valid for most experiments, and G represents the neoclassically trapped electron correction. Accurately estimating the beam driven current essentially relies on accurately estimating G, i.e. Γ.

Many models for calculating G have been proposed for practical predictions. However, they all assume that the electron response is collisionless. Essentially, we believe that the models should have the collisionality dependence, because frequent collisions hinder trapped electrons from orbiting their banana motion, reducing G compared to collisionless cases.

Because the G factor purely comes from the neoclassical trapping of electrons, Kim et al. [4] and Lin-Lin and Hinton [5] independently derived the same expression of G using the neoclassical approach and the latter authors also enunciated that G is closely related to the bootstrap coefficient L_{31}. The latter model is called the Lin-Liu model hereafter, which borrows the analytical expression of L_{31} from the Hirshman's theory in the banana regime [6]. In contrast, focusing on the neoclassical properties of G, we find that the Matrix Inversion (MI) method [7], which is developed for calculating the bootstrap current and is based on the moment approach [8], is capable of accurately estimating G and thus Γ. In this paper, we elucidate the importance of the collisionality dependence of the shielding factor using the updated MI method, which has recently incorporated the Shaing's viscosity model [9], called the MI-S method.

2. Analytical derivation of the shielding factor based on the moment approach

Hirshman and Sigmar [8] showed that the G factor could be derived by the momentum balance equations for electrons. We now derive the shielding factor from the momentum balance equations with appropriate friction forces between thermal species and fast ions in a complete manner. The electron momentum equations are given by

$$\left\langle \boldsymbol{B} \cdot \nabla \cdot \overleftrightarrow{\Pi}_e \right\rangle = \left\langle BR_{ei} \right\rangle + \left\langle BR_{eb} \right\rangle, \tag{2}$$

$$\left\langle \boldsymbol{B} \cdot \nabla \cdot \overleftrightarrow{\Theta}_e \right\rangle = \left\langle BH_{ei} \right\rangle + \left\langle BH_{eb} \right\rangle, \tag{3}$$

where R and H denote the friction forces for particles and heat, respectively. Just adding the second terms on the right-hand side of both equations, frictions against fast ions, distinguishes these equations from the usual neoclassical moment equations. After some algebraic calculation, we have the shielding factor in the form:

$$\Gamma = 1 - Z_{\mathrm{b}}/Z_{\mathrm{eff}}\,(1 - L_{31}),$$
$$= 1 - \frac{Z_{\mathrm{b}}}{Z_{\mathrm{eff}}}\left[1 - \frac{(\hat{\mu}_3^{\mathrm{e}} - \ell_{22}^{\mathrm{ee}})\hat{\mu}_1^{\mathrm{e}} - (\hat{\mu}_2^{\mathrm{e}} + \ell_{12}^{\mathrm{ee}})\hat{\mu}_2^{\mathrm{e}}}{(\hat{\mu}_3^{\mathrm{e}} - \ell_{22}^{\mathrm{ee}})(\hat{\mu}_1^{\mathrm{e}} - \ell_{11}^{\mathrm{ee}}) - (\hat{\mu}_2^{\mathrm{e}} + \ell_{12}^{\mathrm{ee}})^2}\right], \quad (4)$$

where $\hat{\mu}$ and ℓ represent viscosity and friction coefficients, respectively. This expression, called the MI-S analytic model, is essentially identical to the Lin-Liu model that has been derived from the Fokker-Planck equation if the viscosities in the banana regime [6] are substituted. In this sense, using eq. (4) with the collisionality dependent viscosities that can be calculated by the MI-S method yields the collisionality dependent Γ. Of course, the MI-S method alternatively can estimate Γ in a more fundamental way, expressed by

$$\Gamma = \frac{\langle B j_{\mathrm{b}} \rangle}{\langle B j_{\parallel \mathrm{f}} \rangle} = \frac{\sum_{k=\mathrm{e},j,\mathrm{b}} Z_k n_k [(\overleftrightarrow{M} - \overleftrightarrow{L})^{-1}]_{k\mathrm{b}}}{Z_{\mathrm{b}} n_{\mathrm{b}} [(\overleftrightarrow{M} - \overleftrightarrow{L})^{-1}]_{\mathrm{bb}}}. \quad (5)$$

Here, the matrices are computed by the MI-S method.

3. Numerical results

The following calculations have been done using a concentric circular equilibrium calculated by an equilibrium code. Figure 1 shows the comparison of the MI-S model in eq. (4) and the MI-S analytic model in eq. (5) against the Start and Cordey model [10], which consists of tabulated numerical values based on the collisionless Fokker-Planck calculations.

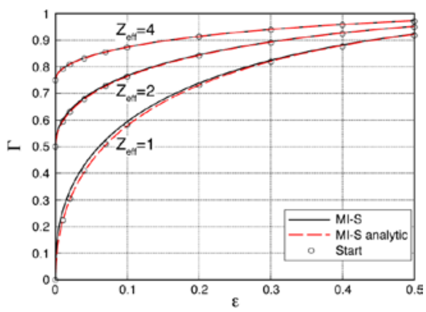

Fig.1. Γ profiles in the collisionless regime.

Clearly, for this collisionless case, very good agreement has been obtained among them for any Z_{eff}. As shown in Fig. 2, Γ rapidly decreases as the effective collisionality $\nu_{*\mathrm{e}}$ increases, once collisionality is taken into account. This clear degradation of Γ in the high collisionality regime implies that collisionality has a significant impact on Γ and this tendency would be effective in the edge region and/or in present-day tokamak experiments, as shown in Fig.3 for example.

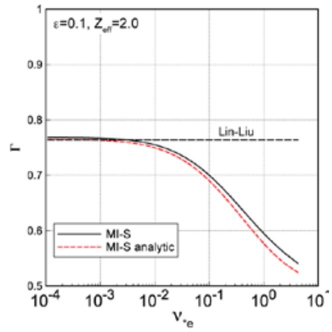

Fig.2. Collisionality dependence of Γ at ε=0.1 for Z_{eff}=2.0.

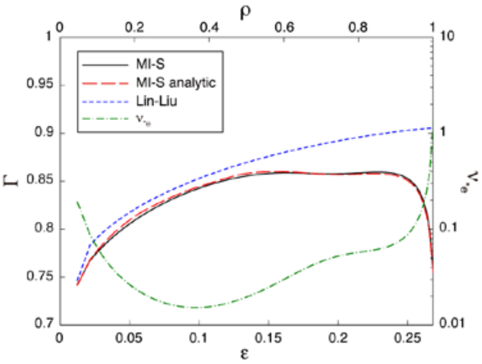

Fig.3. Profiles of Γ and $\nu_{*\mathrm{e}}$ for JT-60U #48822 at *t*=12.7 s.

Acknowledgments

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