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Potential formation and ion distribution function in expanding magnetic field to divertor region

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Abstract

The stable electrostatic potential formation in quasi-neutral plasma with an expanding magnetic field to a divertor plate was studied by a one-dimensional analysis. The requirement for flow velocity of ions at an injection point is obtained. In case of no ion source in the quasi-neutral plasma region, the flow velocity of injected ions should be greater than the ion sound velocity, i.e. Bohm's criteria. The ion source inside the quasi-neutral plasma, such as electron impact ionization, considerably mitigates this requirement.

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1. Introduction

Formation of the stable electrostatic potential in a divertor plasma immersed in a non-uniform magnetic field is important for plasma–surface interactions. The magnetic field expands in the direction of the plate, i.e. the magnitude of magnetic field decreases towards the plate in the magnetically confined fusion plasma. The plasma–wall interaction in a uniform and oblique magnetic field to the plate has been studied by means of 1D-PIC numerical simulation [1]. This analysis shows the formation of a quasi-neutral magnetic presheath preceding the electrostatic Debye sheath, which scales to the ion gyroradius at the sound speed and to the incidence angle of the magnetic field. With the use of a two dimensional kinetic analysis, Sato [2] clarified the ion polarization drift causes this magnetic presheath formation. The potential formation of a presheath in an open magnetic field was studied analytically and numerically [3].

2. Ion velocity distribution and its density

The model geometry for a one-dimensional analysis is shown in Fig. 1, where the divertor plate is located at the position of $z = L$. The magnitude of magnetic field $B(z)$, which is directed toward the z direction, decreases to the plate so slowly that the magnetic moment of ions is conserved. The ion distribution $f_i(z, v_z, v_\perp)$ is obtained from Boltzmann equation:

$$v_z \frac{\partial f_i(z, v_z, v_\perp)}{\partial z} + \frac{dv_z}{dt}\frac{\partial f_i(z, v_z, v_\perp)}{\partial v_z} + \frac{dv_\perp}{dt}\frac{\partial f_i(z, v_z, v_\perp)}{\partial v_\perp} = S_i(z, v_z, v_\perp). \quad (1)$$

The kinetic equations of an ion are

$$\frac{dv_z}{dt} = -\frac{q}{M}\frac{d\phi}{dz} - \frac{\mu}{M}\frac{dB}{dz} \quad \text{and} \quad (2)$$

$$\frac{dv_\perp}{dt} = \frac{\mu}{Mv_\perp}\frac{dB}{dt} = \frac{\mu v_z}{Mv_\perp}\frac{dB}{dz}, \quad (3)$$

where the charge and mass are denoted by q and M, respectively. The magnetic moment of an ion μ is one of the constants of motions because of the slow change of the magnetic field. In the case of an expanding magnetic

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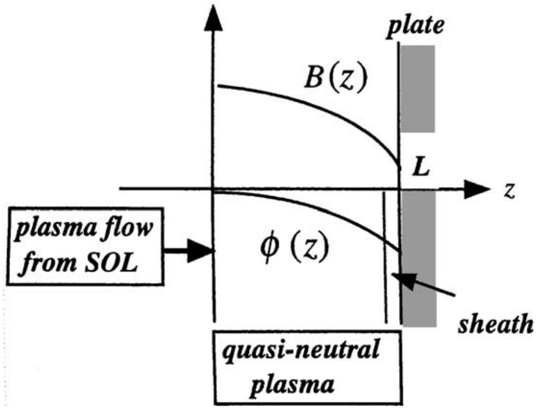

Fig. 1. Model geometry for a one dimensional analysis.

field ($dB/dz < 0$), the second term of RHS in Eq. (3) plays a role of a mirror acceleration for ions. The Boltzmann equation changes by the transformation of variables from $(z, \upsilon_z, \upsilon_\perp)$ to (z, ε, μ) to the simple one in (z, ε, μ) space:

$$\upsilon_z(z,\varepsilon,\mu)\frac{\partial f_i(z,\varepsilon,\mu)}{\partial z} = S_i(z,\varepsilon,\mu), \quad (4)$$

where ε is the total energy of an ion $M\upsilon_z^2/2 + \mu B(z) + q\phi(z)$ and the υ_z is the particle velocity towards the plate, which should be expressed by the new variables (z, ε, μ). In this study the ion source due to electron impact ionization of neutral atoms is considered as well as the plasma flow from the SOL region. In a divertor region ionization by electron impact is effective because of the electron temperature of 10–100 eV. The model distribution function of the ion source is introduced [4,5]:

$$S_i(z,\varepsilon,\mu) = \frac{M^2}{4\pi T_s^2} n_e(z) n_a \langle\sigma\upsilon\rangle_{io} \times |\upsilon_z(z,\varepsilon,\mu)| \exp[-M\upsilon^2(z,\varepsilon,\mu)/2T_s], \quad (5)$$

where n_a is the uniform density of the neutral atoms, $\langle\sigma\upsilon\rangle_{io}$ is the rate coefficient of ionization by electron impact and T_s is the temperature of source ions, which is assumed spatially uniform. In this distribution function, the ion velocity υ_z and υ should be expressed by the function of (z, ε, μ). Taking into account the turn of source ions with negative velocity to z-direction ($\upsilon_z < 0$) in decreasing potential and magnetic field, the density of the source ions is obtained in case of a weak non-uniformity of magnetic field and potential,

$$n_{is}(z) = \sqrt{\frac{\pi M}{2T_s}} n_a n_{e0} \langle\sigma\upsilon\rangle_{io} \exp[-q\phi(z)/T_s] \times \int_0^L dz' \exp[(q/T_s + e/T_e)\phi(z')], \quad (6)$$

where n_{e0} is the electron density at the position of $\phi = 0$. For the ions injected from the SOL region, the ion density is obtained by the equation without ion source of Eq. (1). The local density gradient of these ions is easily obtained,

$$\frac{dn_i}{dz} = n_{in}(z)\left[\frac{q}{M}\langle\upsilon_z^{-2}\rangle_{in}\frac{d\phi}{dz} + \left(1 + \frac{1}{2}\langle\upsilon_\perp^2/\upsilon_z^2\rangle_{in}\right)\frac{d\ln B}{dz}\right] - n_{is}(z)\frac{q}{T_s}\frac{d\phi}{dz}, \quad (7)$$

where n_{in} and n_{is} are the injected ion and source ion density, respectively, and $\langle\cdots\rangle_{in}$ denotes the average over the ion velocity distribution function at the plasma injection boundary ($z = 0$). Electron density, which is assumed to satisfy the Boltzmann relation, and the charge neutrality condition in this region give the relation between the ion flow velocity and the gradients of electrostatic potential and the magnetic field:

$$\frac{ZT_e}{M}\langle\upsilon_z^{-2}\rangle_{in} = \frac{1}{1-\delta_s}\left[1 + \delta_s\frac{ZT_e}{T_s} - (1-\delta_s)\frac{T_e}{e} \times \left(1 + \frac{1}{2}\langle\upsilon_\perp^2/\upsilon_z^2\rangle_{in}\right)\frac{d\ln B}{d\phi}\right], \quad (8)$$

where δ_s is defined by the ratio of the density of the source ions to the electron density: $\delta_s \equiv Zn_{is}/n_e$. The temperatures of electrons T_e and source ions T_s are assumed spatially uniform inside the quasi-neutral plasma region.

In case of the monoenergetic ion distribution of the injected ions,

$$f_{in} = n_{in0}\delta(\upsilon_\perp)\delta(\upsilon_z - \upsilon_{z0})/2\pi\upsilon_\perp, \quad (9)$$

the relation between potential and magnetic field is obtained:

$$\frac{-T_e}{e}\frac{d\ln B}{d\phi} = \frac{(1-\delta_s)\frac{ZT_e}{M}\upsilon_{z0}^{-2} - 1 - \delta_s\frac{ZT_e}{T_s}}{1-\delta_s}, \quad (10)$$

which should be negative for the decreasing potential and magnetic field to the divertor plate, i.e.:

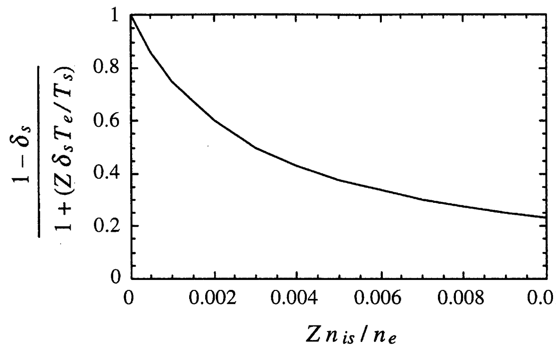

Fig. 2. Limit of $\upsilon_{z0}^2/(ZT_e/M)$ in case of $Z = 1$, $T_e = 10$ eV, and $T_s = 0.03$ eV.

$$v_{z0}^2 \Big/ \left(\frac{ZT_e}{M}\right) > \frac{1-\delta_s}{1+(Z\delta_s T_e/T_s)}. \tag{11}$$

Without plasma source inside quasi-neutral plasma ($\delta_s = 0$), this relation leads the generalized Bohm's criterion:

$$v_{z0}^2 \Big/ \left(\frac{ZT_e}{M}\right) > 1. \tag{12}$$

The effect of ion source is obtained in Fig. 2 for the case of $Z = 1$, $T_e = 10$ eV, and $T_s = 0.03$ eV, which corresponds of room temperature of 20 °C. This result shows ion source in a divertor region mitigates the generalized Bohm's criterion.

3. Concluding remarks

The effect of the ion source inside the quasi-neutral plasma, such as ionization of neutral particles due to electron impact, is studied. The ion source considerably reduces the requirement of ion flow velocity, where the required ion flow velocity becomes lower than the ion sound speed. The expansion of this analysis to the spatially two or three-dimensional to satisfy the divergence-free magnetic field is one of the important issues. The effect of spatial distribution of neutral atoms and electron temperature as well as the velocity distribution of injected ions, such as loss-cone distribution, are left for the near future issues. The computer simulation studies with particle model as well as the theoretical approach may be carried out.

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