STABLE POTENTIAL FORMATION WITH NEUTRAL AND DUST PARTICLES IN EXPANDING MAGNETIC FIELD NEAR DIVERTOR PLATE

Yukihiro Tomita
National Institute for Fusion Science, Toki, Gifu 509-5292 Japan
Yuriy I. Chutov
Taras Shevchenko Kiev University, Volodymyrs'ka 64, 252017 Kiev-17, Ukraine

The effects of neutral and dust particles for the stable or monotonically changing potential formation in an expanding magnetic field toward the divertor plate was investigated in a quasi-neutral plasma by using one-dimensional kinetic analysis. Unless there are plasma ion sources, such as ionization of neutral particles, the required ion flow velocity for injected ions to form the stable potential has to be larger than an ion sound velocity, i.e. the generalized Bohm's criterion. It was clarified that the plasma ion sources mitigate this requirement. On the other hand, since the dust particles decrease the plasma ion density due to absorption to them, the required ion flow velocity for injected ions increases. The numerical values of these effects are presented. The decreasing magnetic field in a plate direction also increases this required velocity.
PACS: 52.55Hc; 52.55Rk

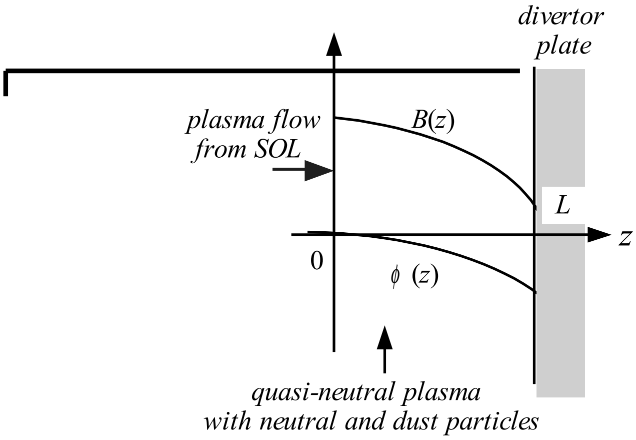
I. INTRODUCTION

The electrostatic potential can strongly influence the behavior of plasma particles near a divertor region. In fusion devices, the magnetic field is expanding in the plate direction; i.e. the magnitude of the magnetic field is decreasing to the plate. In this configuration, ions are accelerated to the plate due to the gradient of the magnetic field, so-called the mirror force. The neutral particles play an important role to remove the heat flow from the core plasma to the divertor plate. The dust particles have also same effects as neutrals. In LHD (Large Helical Device) the collection of dust particles was reported [1], where the dust particles have the size of about 10 μm with the surface mass density of around 100 mg/m^2. In this study, the effects of neutral and dust particles on formation of stable electrostatic potential in nonuniform magnetic field are discussed.

II. ION VELOCITY DISTRIBUTION AND 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 ($dB/dz < 0$) so slowly that the magnetic moment of ions μ is conserved during their motion. The neutral and dust particles are uniformly distributed in front of the divertor plate. The plasma flow from the point $z = 0$ is taken account, which corresponds the plasma flow from the SOL (Scrape-Off Layer) region to the divertor region. The electrons are assumed to satisfy the Boltzmann relation with the uniform electron temperature. In this analysis we investigate the potential formation $\phi(z)$ with the magnetic field monotonically decreasing in the divertor plate direction.

The ion velocity distribution function is expressed from Boltzmann equation in (z,ε,μ) space, where ε is the total energy of an ion $M_i v_z^2/2 + \mu B(z) + q_i\phi(z)$ which is one of the constants of motion of ions:



$$v_z(z,\varepsilon,\mu)\frac{\partial f_i(z,\varepsilon,\mu)}{\partial z} = S_i(z,\varepsilon,\mu) - S_d(z,\varepsilon,\mu)$$

Fig.1. Geometrical model for a one-dimensional analysis.

where the charge and the mass of plasma ion are denoted by q_i and M_i , respectively. The particle velocity toward the plate v_z should be expressed by the variables (z,ε,μ): $v_z^2 = 2[\varepsilon - \mu B(z) - q_i\phi(z)]/M_i$. In this study, the plasma ion source S_i due to electron impact ionization of neutral atoms and the plasma ion sink S_d due to absorption to dust particles are considered as well as the plasma flow from the SOL region.

The ion source S_i is introduced as [2,3]:

$$S_i(z,\varepsilon,\mu) = \frac{M_i^2}{4\pi T_s^2} n_e(z) n_s \langle\sigma v\rangle_i \left|v_z(z,\varepsilon,\mu)\right| \times \exp[-M_i v^2(z,\varepsilon,\mu)/2T_s]$$

where n_s is the uniform density of the neutral atoms, $\langle\sigma v\rangle_i$ is the ionization rate by electron impact and T_s is the temperature of source ions, which is assumed spatially uniform. In this distribution function, the ion velocity v

and υ_z should be expressed by the function of (z, ε, μ). Taking into account the turn of generated ions with negative velocity in z-direction ($\upsilon_z < 0$) in the decreasing potential and magnetic field, the density of the generated source ions is obtained in case of a weak nonuniformity of magnetic field and potential as following:

$$n_{is}(z) = \sqrt{\frac{\pi M_i}{2T_s}}\, n_s n_{e0} <\sigma\upsilon>_i \exp[-q_i\phi(z)/T_s] \times \int_0^L dz' \exp[(q_i/T_s + e/T_e)\phi(z')]$$

where n_{e0} is the electron density at the position of $\phi = 0$.

The injected plasma ion distribution function from the SOL region is determined by the absorption to dust particles. Since the dust particles is at rest due to their heavy masses, the plasma ion absorption rate is expressed by

$$S_d(z,\varepsilon,\mu) = n_d\sigma_d(\upsilon)\upsilon f_i(z,\varepsilon,\mu)$$

From this expression the injected ion density is obtained as follows.

$$n_{in}(z) = \frac{2\pi B(z)}{M_i^2}\int_0^\infty d\mu \int_{\mu B(0)}^\infty d\varepsilon \frac{f_{i0}(\varepsilon,\mu)}{|\upsilon_z(z,\varepsilon,\mu)|} \times \exp\{-\int_0^z dz' n_d\sigma_d[\upsilon(z',\varepsilon,\mu)]\upsilon(z',\varepsilon,\mu)/|\upsilon_z(z',\varepsilon,\mu)|\}$$

These expressions of plasma ion densities are used to study the stable electrostatic potential formation.

III. POTENTIAL FORMATION

The potential formation in the quasi-neutral plasma immersed in the expanding magnetic field is investigated by using the charge neutrality condition with negatively charged (Z_d) dust particle density n_d: $n_e + Z_d n_d = Z_i n_{is} + Z_i n_{in}$ and the equality of the density gradients for uniformly distributed dust particles:

$$\frac{dn_e}{dz} = Z_i\left(\frac{dn_{is}}{dz} + \frac{dn_{in}}{dz}\right)$$

The density gradient of electron is obtained from its Boltzmann distribution:

$$\frac{dn_e}{dz} = \frac{e}{T_e}\frac{d\phi}{dz}n_e(z)$$

The density gradient of plasma ion source generated by the electron impact ionization is expressed from Eq.(3).

$$\frac{dn_{is}}{dz} = -\frac{q_i}{T_s}\frac{d\phi}{dz}n_{is}(z)$$

From considering the spatial dependence of the injected ion density Eq.(5), we can easily obtain its density gradient.

$$\frac{dn_{in}}{dz} = [\frac{d\ln B}{dz} + \frac{1}{2}<\upsilon_\perp^2/\upsilon_z^2>_z\frac{d\ln B}{dz} + \frac{q_i}{M_i}<\upsilon_z^{-2}>_z\frac{d\phi}{dz} - <n_d\sigma_d\upsilon/|\upsilon_z|>_z]n_d$$

where the quantity $<\cdots>_z$ denotes the average over the velocity distribution function of the injected ions. The equality condition (6) of the quasi-neutral plasma gives the relation between spatial dependences of the potential, the magnetic field and the ion velocity.

$$\frac{e}{T_e}\frac{d\phi}{dz} = -\frac{Z_i n_{is}}{n_e}\frac{q_i}{T_s}\frac{d\phi}{dz} + \frac{Z_i n_{in}}{n_e}[(1+\frac{1}{2}<\upsilon_\perp^2/\upsilon_z^2>_z)\frac{d\ln B}{dz} + \frac{q_i}{M_i}<\upsilon_z^{-2}>_z\frac{d\phi}{dz} - <n_d\sigma_d\upsilon/|\upsilon_z|>_z]$$

First we investigate the effects of neutral particles without dust particles ($n_d = 0$) on stable potential formation. The spatial variation of potential and magnetic field is expressed from Eq.(10) and $n_d = 0$.

$$\frac{T_e}{e}(1+\frac{1}{2}<\upsilon_\perp^2/\upsilon_z^2>_z)\frac{d\ln B}{d\phi} = -\frac{Z_iT_e}{M_i}<\upsilon_z^{-2}>_z + (1+\frac{Z_iT_e}{T_s}\delta_{is})/(1-\delta_{is})$$

Here δ_{is} is defined by the ratio of the density of the generated ions to the electron density : $\delta_{is} \equiv Z_i n_{is}/n_e$. In our case of decreasing potential and magnetic field, LHS of Eq. (11) is positive. Hence in order to be formed the monotonically decreasing potential in the decreasing magnetic field in the plate direction, the ion flow velocity have to be satisfied the following condition:

$$<\upsilon_z^{-2}>_z^{-1}/c_s^2 \geq (1-\delta_{is})/(1+\frac{Z_iT_e}{T_s}\delta_{is})$$

where $c_s (= \sqrt{Z_iT_e/M_i})$ is the ion sound speed. Without plasma source inside quasi-neutral plasma ($\delta_{is} = 0$), this relation leads the generalized Bohm's criterion [4,5]:

$$<\upsilon_z^{-2}>_z^{-1} \geq 1$$

The effect of ion source is shown in Fig. 2 for the case of $Z_i = 1$, $T_e = 10$ eV , and $T_s = 0.03$ eV , which corresponds to the room temperature of 20 $^\circ C$. This result shows ion source in a divertor region mitigates the generalized Bohm's criterion (for example: the 1 % of source ions decreases this limit to 0.48).

It is clearly understand the existence of dust particles increases the limit of ion flow velocity because they decrease the density of plasma ions due to absorption. The requirement for the ion flow velocity is obtained from Eq.(10).

$$\langle v_z^{-2}\rangle_z^{-1}/c_s^2 \ge \frac{1-\delta_{is}+Z_d n_d/n_e}{1+\frac{Z_i T_e}{T_s}\delta_{is}+\langle n_d\sigma_d v/|v_z|\rangle_z \frac{T_e}{e\,d\phi/dz}}$$

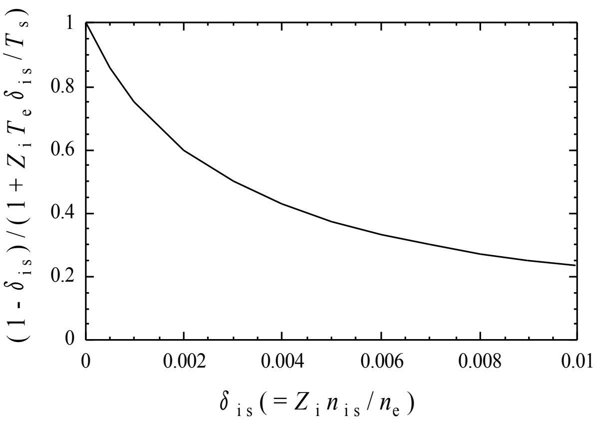


Fig. 2 Limit value of $\langle v_z^{-2}\rangle_z^{-1}/c_s^2$ as a function of concentration of plasma ion generated by ionization, where $Z_i = 1$, $T_e = 10\,\mathrm{eV}$ and $T_s = 0.03\,\mathrm{eV}$.

The third terms of the fraction of RHS indicate the effects of dust particles, where note that the potential gradient is negative ($d\phi/dz < 0$). The effect of dust particles on stable potential formation is shown in Fig. 3, where $Z_i = 1$, $T_e = 10\,\mathrm{eV}$, $T_s = 0.03\,\mathrm{eV}$, $\delta_{is} = 0.01$, $Z_d = 10^3$ and the parameter ν_d is defined by the ratio of the characteristic length of potential decrease to the mean-free path of the absorption to dust particles:
$\nu_d \equiv n_e \langle \sigma_d v/|v_z|\rangle_z T_e/e|d\phi/dz|$.

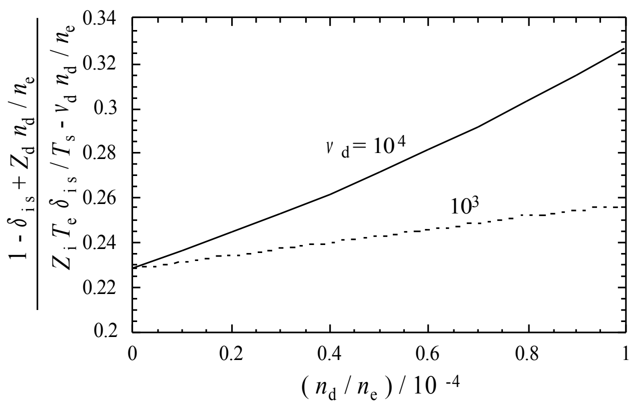


Fig. 3. Effects of dust particles ($Z_d = 10^3$) on the limit value of $\langle v_z^{-2}\rangle_z^{-1}/c_s^2$ for the same parameters as Fig. 2 and $\nu_d \equiv n_e \langle \sigma_d v/|v_z|\rangle_z T_e/e|d\phi/dz|$.

In this case the limiting factor for injected ion flow velocity becomes 0.58, which is compared to the value of 0.48 without dust particles.

IV. CONCLUDING REMARKS

The effects of neutral and dust particles on monotonically changing electrostatic potential were investigated in quasi-neutral plasma with nonuniform magnetic field by using of one-dimensional kinetic analysis. It is clarified that plasma ion source, such as ionization of neutrals, mitigates the condition for the input flow velocity. For example, in case of $Z_i = 1$, $T_e = 10$ eV , and $T_s = 0.03$ eV and the density ratio of the generated ions to the electron density of 0.01 without dust particles, the injected ion flow velocity have to be larger than 0.48 c_s. Please note that without neutrals this factor is 1.0, i.e. generalized Bohm's criterion. Plasma ion sink, such as absorption to dust particles, increases this required ion flow velocity. In the same values of above plasma parameters and the density of dust particles with $Z_d = 10^3$ to the electron density of 10^{-4}, this limit factor increases from 0.48 to 0.58. The expanding magnetic field in the direction of the plate increases the required flow velocity.

There are few future issues left: 1) Two-dimensional kinetic analysis has to be carried out in order to take into account of ion motion in divergence free magnetic field. 2) Other processes, such as Coulomb collisions, charge exchange collisions, should be included in this analysis.

ACKNOWLEDGMENT

This collaborated research was supported by the Heiwa-Nakajima Foundation.

REFERENCES

[1] A. Sagara, S. Masuzaki, et al., 15th International Conference on Plasma Surface Interactions in Controlled Fusion Devices, May 27 - 31, 2002, Gifu, Japan, Program and Book of Abstracts.- p. R-01 and P. Sharpe et al., ibid. p. P3-46.

[2] G.A. Emmert, R.M. Wieland, A.T. Mense, and J.N. Davidson, Phys. Fluids, **23** (1980) 803.

[3] R.C. Bissell and C. Johnson, and P.C. Stangeby, Phys. Fluids, **B1** (1989) 1133.

[4] D. Bohm, *The Characteristics of Electrical Discharges in Magnetic Fields*, edited by A. Guthrie and R.K. Wakerling (McGraw-Hill, New York, 1949), Chap.4, p.77.

[5] E.R. Harrison and W.B. Thompson, Proc. Phys. Soc. London, **74** (1959) 145.