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Effect of Oblique Magnetic Field on Release Conditions of Dust Particle from Plasma-Facing Wall

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Abstract Effects of oblique magnetic field on release condition of a spherical dust particle from a plasma-facing vertical wall is studied analytically. The magnetic presheath and the Debye sheath are coupled to obtain the plasma quantities and the electric field at the wall, which are necessary to analyze the release condition. It is clarified that for the deeper potential drop inside the Debye sheath than the floating one the critical radius for release increases as the magnetic field approaches parallel to the wall. The smaller dust than the critical one can be released from the wall. On the other hand in the case of the shallower potential drop the critical radius disappears at some angle of the oblique magnetic field. From this analysis we find that the size of the released dust particle can be controllable by adjusting the plasma parameters such as plasma density and temperature as well as biasing the wall potential.

Keywords: Dust, divertor plasma, electric field, oblique magnetic field

1 Introduction

As a duration time of plasma confinement in fusion devices becomes longer, the dust particles can be important as impurities to core plasma. The handling of dust particles is one of the key issues for the development of commercial fusion reactors because of their absorption of radioactive tritium. In several fusion devices (TEXTOR-94, ASDEX-U, LHD, DIIID, JT-60U, NSTX etc.), the dust particles were collected and analyzed their characteristics [1-3], where the radii are widely ranged between few nm and few tens μm. These dusts were composed mainly of metals and hydro-carbons, which are used for most divertors and plasma-facing materials. The understanding of the characteristics of dust particles in plasma, such as charging, absorption current, and acting forces, can be important to suppress and control their behavior in plasma. We have estimated the release conditions of the spherical dust particles from the plasma-facing wall without the oblique magnetic field [4], where the threshold wall potential and the critical dust radius were discussed. In this analysis, the effects of the oblique magnetic field on the release conditions of the dust particle are discussed.

2 Model and forces

The release of a conducting spherical dust particle from a vertical conducting wall is determined by the balance between the repelling force from the wall and the pushing force toward the wall. In our case the electrostatic force repels the dust from the wall, since both dust and wall are charged negatively. Gravitational force [4] does not play a role for the present case of vertical wall. There are three forces which act to push the dust toward the wall: the ion drag force due to absorption of plasma ions by the dust, the Coulomb scattering force by plasma ions, and the electrostatic image force caused by the interaction of the dust charge with the mirror charge of itself [4]. To estimate the drag force due to absorption of plasma ions the OML (Orbit Motion Limited) model [5, 6] is applied. In our model the size of a dust is much smaller than the Debye length.

The total pressure, $F_{izw}^{total} / \pi R_d^2$, on the dust particle toward the wall has a quadratic form with respect to the dust radius R_d [4]:

$$F_{izw}^{total} / \pi R_d^2 = a_0 R_d^2 + a_1 R_d + a_2 , \quad (1)$$

where z is the normal direction to the wall and the coefficients a_j depend on the macroscopic plasma quantities at the wall such as the ion density n_{iw}, ion flow speed and velocity toward the wall V_{iw} and V_{izw} as well as the electric field at the wall E_w, which are affected by the oblique magnetic field. The three-dimensional guiding center motion of ions is applied to obtain these quantities:

$$\begin{aligned} a_0(n_{iw}, V_{iw}, E_w) &\equiv \frac{Z_i^2 e^2 \xi_d^2 \ln \Lambda n_{iw} E_w^2}{4 m_i V_{iw}^2}, \\ a_1(n_{iw}, V_{izw}, V_{iw}, E_w) &\equiv \frac{Z_i e \xi_d n_{iw} V_{izw} E_w}{2 V_{iw}}, \\ a_2(n_{iw}, V_{izw}, V_{iw}, E_w) &\equiv m_i n_{iw} V_{izw} V_{iw} E_w - \varepsilon_0 \xi_d E_w^2 (1 - \frac{\xi_d}{16}), \end{aligned} \tag{2}$$

where Z_i and m_i are the atomic number and mass of plasma ion, respectively. The form factor ξ_d for charging of the conducting dust particle on the wall is introduced, which is equal to $2\pi^2/3$ in the case of a sphere in uniform electric field [7]. The coefficient a_0 comes from the Coulomb scattering force by plasma ions, where $\ln\Lambda$ is the Coulomb logarithm. The coefficient a_1 is the part of the ion absorption force. The first term of the coefficient a_2 is another part of the ion absorption force and the last term corresponds to the effects of the electrostatic repulsive force and the mirror force. The release condition ($F_{izw}^{total} < 0$) is determined by the sign of the coefficient a_2, since the coefficients a_0 and a_1 are definitely positive. In the case of the spherical dust the mirror force is smaller than the electrostatic force, i.e. $1 - \xi_d / 16 > 0$, the strong enough electric field at the wall makes the coefficient a_2 negative. This means there exists the threshold wall potential for the release of the dust.

3 Plasma and field quantities at wall

In order to estimate the forces on the dust particle, the plasma quantities, n_{iw}, V_{izw}, V_{iw}, and the field quantity, E_w at the wall are necessary. The coupling of the oblique magnetic field and the spatially changing electric field brings the polarization drift of plasma ions, which is the origin of the magnetic presheath [8, 9]. The oblique magnetic field decreases the normal component of the ion flow to the wall. On the other hand the ion polarization drift has a component directed to the dust. In this study the plasma quantities and electric field are connected at the end of magnetic presheath to the entrance of the Debye sheath, which is formed in front of the plasma-facing wall.

3.1 Magnetic presheath

The ion flow inside the magnetic presheath consists of the ion flow along the magnetic field, the ion polarization drift, and the $\vec{E}\times\vec{B}$ drift [9]:

$$\vec{V}_i = V_{i//}\frac{\vec{B}}{B} + V_{ip\perp}\frac{(\vec{B}\times\vec{z})\times\vec{B}}{B^2} + \frac{\vec{E}\times\vec{B}}{B^2}\,. \tag{3}$$

Here $V_{ip\perp}$ is the perpendicular component to the oblique magnetic field of the ion polarization drift velocity:

$$V_{ip\perp} = \frac{V_{iz}}{\omega_{ci}B}\frac{dE_\perp}{dz} = -\frac{V_{i//}\cos\beta\sin\beta}{\omega_{ci}B}\frac{d^2\phi}{dz^2}\,, \tag{4}$$

where ω_{ci}, β, and ϕ are the ion cyclotron frequency, the oblique angle of the magnetic field to the normal direction to the wall, and the electrostatic potential, respectively. At the entrance of magnetic presheath (mpe), it is assumed the ion flow is directed along the oblique magnetic field and its speed is the ion sound speed ($c_{s0} = \sqrt{Z_i T_e / m_i}$) according to the Bohm condition at the mpe, where T_e is uniform in the system. In our model the collisions between plasma particles are assumed to be negligible because of the long enough collision mean-free path as compared with the ion Larmor radius. The energy conservation of ions along the magnetic field gives us the ion flow velocity along the magnetic field at the entrance of the Debye sheath (dse), where the electrostatic potential is denoted ϕ_{dse}:

$$V_{i//}^{dse} = c_{s0}\sqrt{1-\frac{2e\phi_{dse}}{T_e}}\,. \tag{5}$$

The local ion density inside the magnetic presheath is obtained from the particle flux conservation along the z direction as a function of the local electrostatic potential ϕ:

$$n_i(\phi) = n_{i0}\left(1-\frac{\sin^2\beta}{\omega_{ci}B}\frac{d^2\phi}{dz^2}\right)^{-1} / \sqrt{1-\frac{2e\phi}{T_e}}\,. \tag{6}$$

This local ion density is coupled with the local Boltzmann electron density to obtain the local electric field by using the charge neutrality condition inside the magnetic presheath:

$$E_z^2(\phi) = \frac{2eB^2}{T_e \sin^2\beta}[\phi - \int_0^{\phi} d\phi' \exp(-e\phi'/T_e)/\sqrt{1 - \frac{2e\phi'}{T_e}}], \tag{7}$$

where the electrostatic potential and the electric field are vanishing at the mpe.

3.2 Debye sheath

The plasma and the field quantities are connected at the end of magnetic presheath to the "entrance of the Debye sheath" (dse), where the electrostatic potential is indicated by ϕ_{dse}. The energy conservation gives us the ion flow velocity toward the wall and at the wall:

$$V_{izw} = c_{s0}\sqrt{1 - \frac{2e(\phi_w - \phi_{dse})}{T_e}}, \tag{8}$$

where the ion flow velocity toward the wall at the dse is the ion sound speed c_{s0} from the Bohm criterion. The local ion density is expressed from the conservation of the ion particle flux:

$$n_i(\phi) = n_{idse}/\sqrt{1 - \frac{2e(\phi - \phi_{dse})}{T_e}}. \tag{9}$$

In order to obtain the local electric field the Poisson equation is solved using the local ion density (9) and the electron density:

$$n_e(\phi) = n_{edse} e^{e(\phi - \phi_{dse})/T_e} \frac{1 + \operatorname{erf}\sqrt{e(\phi - \phi_w)/T_e}}{1 + \operatorname{erf}\sqrt{-e(\phi_w - \phi_{dse})/T_e}}. \tag{10}$$

Here the truncation effect of the electron velocity distribution, which is caused by the absorption of electrons with higher energy than the wall potential, is indicated by the error functions [10]. The Poisson equation gives us the electric field at the wall:

$$\begin{aligned} E_w^2 = E_{dse}^2 + \frac{2n_{edse}T_e}{\varepsilon_0}\{&\frac{1}{1 + \operatorname{erf}\sqrt{-e(\phi_w - \phi_{dse})/T_e}} \\ &[e^{e(\phi_w - \phi_{dse})/T_e} - 1 - \operatorname{erf}\sqrt{-e(\phi_w - \phi_{dse})/T_e} \\ &+ \frac{2}{\sqrt{\pi}}\sqrt{\frac{-e(\phi_w - \phi_{dse})}{T_e}}] + \sqrt{1 - \frac{2e(\phi_w - \phi_{dse})}{T_e}} - 1\} \end{aligned} \tag{11}$$

The floating wall potential is obtained from the equality condition of the ion and electron currents to the wall:

$$\exp[\frac{e(\phi_w^f - \phi_{dse})}{T_e}] = \frac{1 + \mathrm{erf}\sqrt{-e(\phi_w^f - \phi_{dse}) / T_e}}{2} \sqrt{\frac{2\pi}{Z_i} \frac{m_e}{m_i}} . \qquad (12)$$

For hydrogen plasma the floating wall potential drop inside Debye sheath is $e\left|\phi_w^f - \phi_{dse}\right| / T_e = 2.85$. The Bohm condition at the dse requires the ion flow velocity toward the wall is equal or higher than the ion sound speed. Substitution of the equality (5) into the Bohm condition gives $V_{iz}^{dse} = c_{s0} \cos\beta \sqrt{1 - 2e\phi_{dse} / T_e}$, which determines the potential drop inside the magnetic presheath ϕ_{dse}:

$$e\phi_{dse} / T_e = \ln(\cos\beta) . \qquad (13)$$

The ion density, the ion flow velocity and the electric field at the wall are shown in Fig.1 as functions of the oblique angle of magnetic field for the cases of the shallower (1.8: dotted) and the deeper (5.0: dashed) potential drops than the floating potential drop (2.85: solid) inside the Debye sheath. In this case the ratio of Debye length, λ_{D0}, to Larmor radius with respect to the sound speed, $\rho_{Ls} (= c_{s0} / \omega_{ci})$, is set $\lambda_{D0} / \rho_{Ls} = \sqrt{\varepsilon_0 Z_i / m_i n_{e0}} B = 0.069$, which corresponds to the magnetic field of 3T and the electron density at mpe 10^{19} m^{-3} for the hydrogen plasma.

4 Release condition of dust from wall

According to the results in section 2, the threshold potential drop inside the Debye sheath is obtained as shown in Fig.2, where for the shallower potential drop than the threshold one all dusts are pinned to the wall. In the case of the deeper potential drop than 1.95 / (T_e / e), there is a critical dust radius for any oblique angle β. The critical dust radius for release is shown in Fig.3 as a function of the angle β of the oblique magnetic field, where the parameters are the same as in Fig.1. The dust with the smaller radius than the critical one can be released. On the other hand the bigger dust can be pinned to the wall because of the large pushing Coulomb scattering force. In the case of the shallower potential drop there is no critical radius between 73.0° < β < 85.0°, where the potential drop is lower than the threshold one. The oblique magnetic field decreases the normal

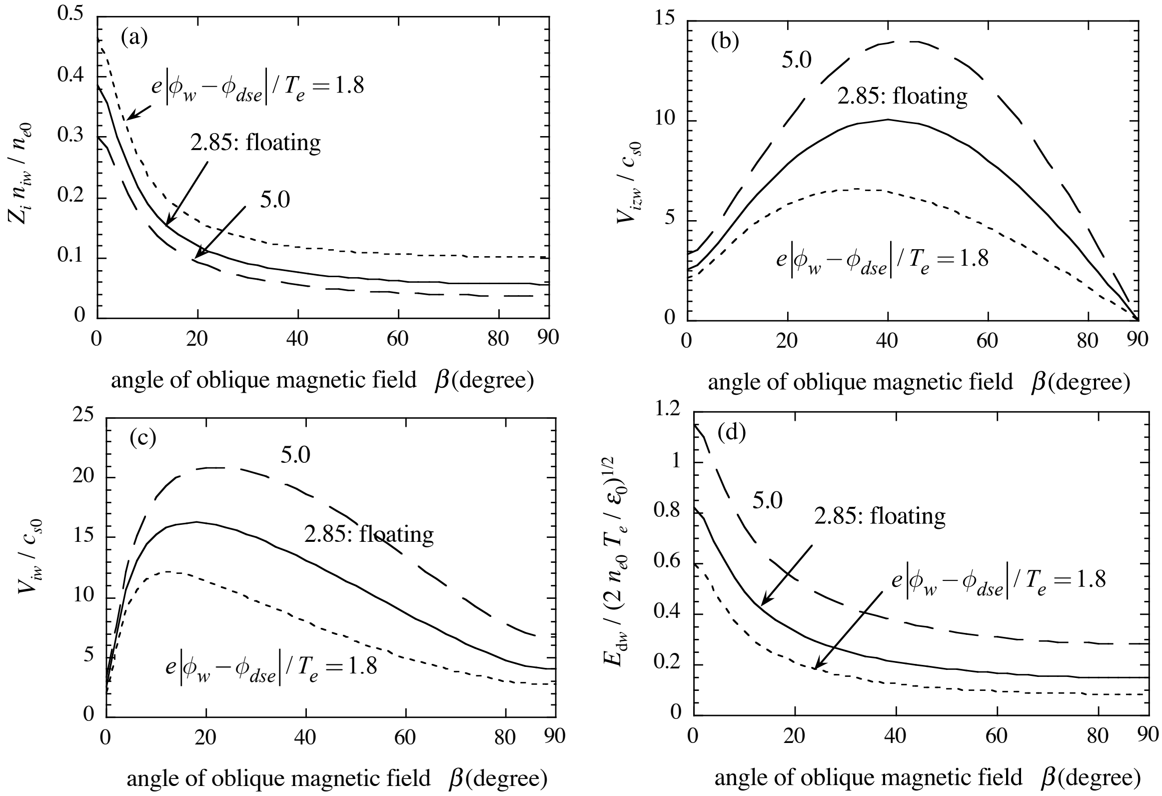

Fig. 1 The plasma quantities, ion density (a), ion flow velocity toward wall (b), ion speed (c) and the electric field (d) at the wall as functions of the oblique angle $\beta$of magnetic field for the cases of the shallower (1.8: dotted) and the deeper (5.0: dashed) potential drops than the floating potential drop (2.85: solid) inside the Debye sheath.

component of the ion flow to the wall. On the other hand the ion polarization drift has a component directed to the dust, which however vanishes for the parallel magnetic field to the wall. The corresponding ion drift flow pushes the dust to the wall modifying the critical radius. The oblique magnetic field of 45° for the floating case increases the critical radius from 0.77 λ_{De0} to 0.93 λ_{De0}. The more acute magnetic field enlarges the released radius, because at the right angle (β = 90°) all pushing forces are vanishing in our model. For example the angle of 80° for the floating case enlarges the released radius to 2.0 λ_{De0}. Here λ_{De0} is the Debye length at the entrance of magnetic presheath.

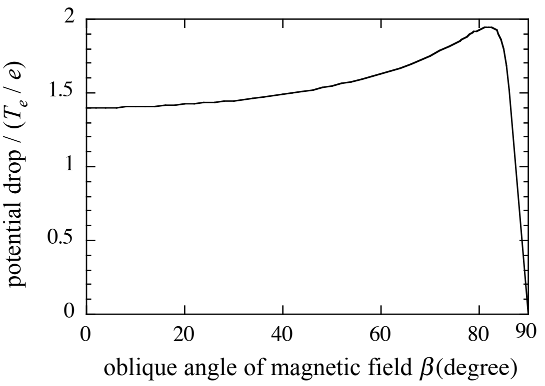

Fig. 2 The threshold potential drop inside Debye sheath as a function of oblique angle of magnetic field. parameters are the same as in Fig.1.

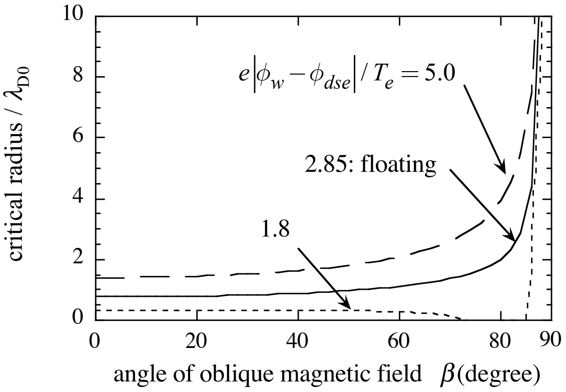

Fig.3 The critical dust radius for the cases of the shallower (1.8: dotted) and the deeeper deeper (5.0: dashed) potential drops than the floating potential drop (2.85: solid) inside the Debye sheath.

5 Summary

We analyzed the effect of the oblique magnetic field on release conditions of the spherical dust particle on the vertical plasma-facing wall. The non-linear dependence on the oblique angle of the forces acting on the dust changes the release conditions. For the case of deeper potential drop the critical radius of dusts increases as the acute oblique angle. On the other hand, for the shallower potential drop there is a region of oblique angle where there is no critical radius. To analyze the release of dusts for the case of larger dust radius than the Debye length or the very acute angle $\beta \sim 90°$, the three-dimensional particle simulation study is necessary, where the ion gyromotion is taken into account. The results can show us how to suppress and control the release of the dust particle from the wall. These studies are helpful to investigate the dynamic phenomena of dust particles near the divertor plate in fusion devices.

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