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Release conditions of dust particle from plasma-facing wall in oblique magnetic field

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ABSTRACT

Release conditions of a spherical dust particle from a plasma-facing vertical wall immersed in an oblique magnetic field are studied analytically. The Poisson's equation is solved in the magnetic pre-sheath and electrostatic Debye sheath to obtain the electric field at the wall, which repels the dust particle from the wall. The electric field decreases as the direction of the magnetic field approaches parallel to the wall. On the other hand the ion flow velocity becomes larger at moderate oblique angle than that without magnetic field. It is clarified that in the case of the strong magnetic field or the low plasma density the critical dust radius for the release of the dust increases as magnetic field becomes more acute. In the case of the weak magnetic field or the high plasma density, the critical radius disappears at the moderate angles of the oblique magnetic field. The surface roughness widely changes the angle between the magnetic field lines and the surface normal.

1. Introduction

The generation and accumulation of dust particles in fusion devices is one of the crucial topics in development of commercial fusion reactors. One of the particular attentions in fusion devices is associated with absorption of radioactive tritium [1]. After operation of plasma discharges, the treatment of the radioactive dusts is one of key issues from the viewpoint of the safety and preservation of environment. In this study we theoretically investigate the effect of the oblique magnetic field to the plasma-facing vertical wall on release conditions of the spherical dust particle attached on the wall, which is important to understand the behavior of the dust in the divertor plasma. In order to estimate the release condition of the dust particle from the wall, the plasma quantities and the electric field at the wall are necessary. In the previous study we obtained these quantities in the magnetic pre-sheath (MP) and the Debye sheath (DS) separately applying the boundary condition between them [2]. In this study the electric field is obtained by solving the Poisson's equation in the whole region of the MP and the DS. The effect of the surface roughness on the oblique angle of magnetic field to the surface normal is discussed.

2. Model and forces

The conducting spherical dust particle can be released from the vertical conducting wall when the repelling forces are stronger than the pushing forces on the dust. In our case the electrostatic repelling force $F_E\,(=Q_d\cdot E_w)$ is to release the dust from the conducting wall. Gravitational force [3] does not play a role for the present case of the vertical flat wall. There are three kinds of pushing forces: the ion drag force due to absorption of plasma ions by the dust, the ion drag force due to Coulomb scattering of plasma ions, and the electrostatic image force caused by the interaction of the dust charge with the mirror charge of itself. The OML (Orbit Motion Limited) model [4,5] for the drag force due to absorption of plasma ions is applied.

3. Ion flow velocity and electric field at the wall

In order to investigate the forces on the dust particle, the plasma quantities and the electric field, E_w, at the wall are necessary. The spatially changing electric field in the oblique magnetic field create the polarization drift of the plasma ions to the perpendicular direction of the magnetic field, which is the cause of the magnetic pre-sheath [6,7]. The oblique magnetic field decreases the normal component of the ion flow to the wall. In this study the electric field is obtained by solving the Poisson's equation in the whole region of the MP and the DS.

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The ion flow inside the magnetic pre-sheath consists of the ion flow along the magnetic field, the ion polarization drift, and the $\vec{E}\times\vec{B}$ drift [7], where the ion Larmor radius is much smaller than the characteristic length of spatial change of the electric field:

$$\vec{V}_i = V_{i\parallel}\frac{\vec{B}}{B} + V_{ip}\frac{(\vec{B}\times\vec{z})\times\vec{B}}{B^2} + \frac{\vec{E}\times\vec{B}}{B^2}. \quad (1)$$

Here V_{ip} is the ion polarization drift velocity:

$$V_{ip} = \frac{V_{iz}}{\omega_{ci}B}\frac{dE_\perp}{dz} = -\frac{V_{i\parallel}\cos\beta\sin\beta}{\omega_{ci}B}\frac{d^2\phi}{dz^2}, \quad (2)$$

where ω_{ci}, β, and ϕ are the ion cyclotron frequency, the oblique angle of the magnetic field to the wall normal, and the electrostatic potential, respectively. At the entrance of the MP, it is assumed the ion flow is directed along the oblique magnetic field and its speed is the ion sound speed ($c_s = \sqrt{Z_iT_e/m_i}$) according to the Bohm condition, where T_e is the uniform electron temperature. The approximate energy conservation of the ions along the magnetic field gives the local parallel ion flow to the magnetic field:

$$V_{i\parallel}(\phi) = c_s\sqrt{1-\frac{2e\phi}{T_e}}. \quad (3)$$

Here we assume relatively cold ions. The local electrostatic potential is obtained from the Poisson's equation:

$$\begin{aligned}\varepsilon_0\frac{d^2\phi}{dz^2} &= e[n_e(\phi) - Z_in_i(\phi)\\ &= en_{e0}\left\{\exp(e\phi/T_e)\frac{1+\mathrm{erf}\sqrt{e(\phi-\phi_w)/T_e}}{1+\mathrm{erf}\sqrt{-e\phi_w/T_e}}\right.\\ &\left.\quad -\frac{1}{\sqrt{1-\frac{2e\phi}{T_e}(1-\frac{\sin^2\beta}{\omega_{ci}B}\frac{d^2\phi}{dz^2})}}]\right\},\end{aligned} \quad (4)$$

where the charge neutrality condition at the MP entrance, $Z_i\cdot n_{i0} = n_{e0}$, is used. This equation gives the quadratic equation with respect to the second order derivative of the potential:

$$b_0\left(\frac{d^2\phi}{dz^2}\right)^2 + b_1(\phi)\frac{d^2\phi}{dz^2} + b_2(\phi) = 0, \quad (5)$$

where

$$b_0 = \frac{\varepsilon_0\sin^2\beta}{en_{e0}}, \quad (6)$$

$$b_1(\phi) = -\left[e^{e\phi/T_e}\frac{1+\mathrm{erf}\sqrt{e(\phi-\phi_w)/T_e}}{1+\mathrm{erf}\sqrt{-e\phi_w/T_e}}\sin^2\beta + \frac{\varepsilon_0\omega_{ci}B}{en_{e0}}\right], \quad (7)$$

and

$$b_2(\phi) = \omega_{ci}B\left[e^{e\phi/T_e}\frac{1+\mathrm{erf}\sqrt{e(\phi-\phi_w)/T_e}}{1+\mathrm{erf}\sqrt{-e\phi_w/T_e}} - \frac{1}{\sqrt{1-2e\phi/T_e}}\right]. \quad (8)$$

The local electric field is expressed by using the one of the solutions of Eq. (5):

$$\begin{aligned}E_z^2(\phi) &= 2\int_0^\phi\frac{d^2\phi}{dz^2}d\phi\\ &= -\frac{1}{b_0}\int_0^\phi\left[b_1(\phi)+\sqrt{b_1^2(\phi)-4b_0b_2(\phi)}\right]d\phi.\end{aligned} \quad (9)$$

Another solution of Eq. (5) makes the value of E_z^2 negative.

The floating wall potential ϕ_{wf} is obtained from the equality condition of the ion and electron particle fluxes to the wall:

$$\exp\left(\frac{e\phi_{wf}}{T_e}\right) = \frac{1+\mathrm{erf}\sqrt{-e\phi_{wf}/T_e}}{2}\sqrt{\frac{2\pi}{Z_i}\frac{m_e}{m_i}}. \quad (10)$$

For hydrogen plasma the floating wall potential drop inside Debye sheath is $e|\phi_{wf}|/T_e = 2.847$. In the case of the deeper wall potential drop, $-e\phi_w = \alpha$, the conventional expression for the wall potential drop is obtained. In Fig. 1 (a) the ion flow speed and velocity toward the wall, (b) the ion density, and (c) the electric field at the wall are shown as functions of the angle of the oblique magnetic field β from the wall normal for the case of the smaller magnetic field or the higher density ($\delta_B = 5.0\times10^{-3}$ solid lines) and the larger magnetic field or the lower plasma density ($\delta_B = 5.0\times10^{-2}$dashed lines), where the parameter δ_B characterizes of the effect of the magnetic field;

$$\delta_B = \frac{\varepsilon_0Z_iB^2}{m_in_{e0}} = \frac{\lambda_{D0}^2}{\rho_{Ls}^2}, \quad (11)$$

where λ_{D0} is the Debye length at the MP entrance and ρ_{Ls} is the ion Larmor radius with respect to the ion sound speed. The value of $\delta_B = 5.0\times10^{-3}$ corresponds to the magnetic field of 3 T and the electron density of $10^{19}\ \mathrm{m}^{-3}$. In Fig. 1 the wall potential drop is set as the floating one, $-e\phi_w/T_e = 2.847$. In the case of the lower magnetic field or the higher density, i.e., smaller δ_B, the plasma flow velocity and speed become much larger than in the case without magnetic field ($\beta = 0$) except the region where the magnetic field is near parallel to the wall ($\beta \simeq 90^\circ$). On the other hand the electric field, which repels the dust particle from the wall, becomes much weaker than in the case without magnetic field. In the case of the higher magnetic field or the lower density, i.e., larger δ_B, the increase of the flow velocity and the decrease of the electric field compared to those without magnetic field are moderate.

4. Release condition of dust from wall

The critical radius for the release of the dust particle from the vertical flat wall is shown in Fig. 2, where the parameters are the same as in Fig. 1. The larger dust particle than the critical one is pinned to the wall by the ion drag forces. In the middle region of the oblique angle ($11^\circ \leqslant \beta \leqslant 74^\circ$) for the weaker magnetic field or the higher ion density ($\delta_B = 5.0\times10^{-3}$ solid line) there is no dust release region, because the ion drag force due to the ion absorption becomes larger than the repelling electrostatic force.

In the case of the stronger magnetic field or the lower plasma density ($\delta_B = 5.0\times10^{-2}$ dashed line), there exists the critical radius. The oblique magnetic field of 45° for the floating case increases the critical radius from 0.77 λ_{De0} to 0.97 λ_{De0}. The more acute magnetic field enlarges the released dust radius, because at the right angle ($\beta = 90°$) all pushing forces are vanishing in our model. For example the angle of 80° enlarges the released radius to 3.5 λ_{De0}.

5. Discussion

In order to investigate effect of the surface roughness on dust release conditions it is modeled as a sinusoidal form with amplitude a_s and a wavelength λ_s, which are assumed to be much larger than the dust radius. The angle β between the oblique magnetic field and the surface normal changes as a function of position at the wall and depends on the amplitude a_s and the wavelength λ_s:

(a) $2\pi a_s/\lambda_s \leqslant 1$ or $0 \leqslant \theta_{sm} \leqslant \pi/4$

$$\begin{array}{ll}\frac{\pi}{2}-(\theta_B+\theta_{sm}) \leqslant \beta \leqslant \frac{\pi}{2}: & 0 \leqslant \theta_B \leqslant \theta_{sm}\\ \frac{\pi}{2}-(\theta_B+\theta_{sm}) \leqslant \beta \leqslant \frac{\pi}{2}-(\theta_B-\theta_{sm}): & \theta_{sm} < \theta_B \leqslant \frac{\pi}{2}-\theta_{sm}\\ 0 \leqslant \beta \leqslant \frac{\pi}{2}-(\theta_B-\theta_{sm}): & \frac{\pi}{2}-\theta_{sm} < \theta_B \leqslant \frac{\pi}{2}\end{array} \quad (12)$$

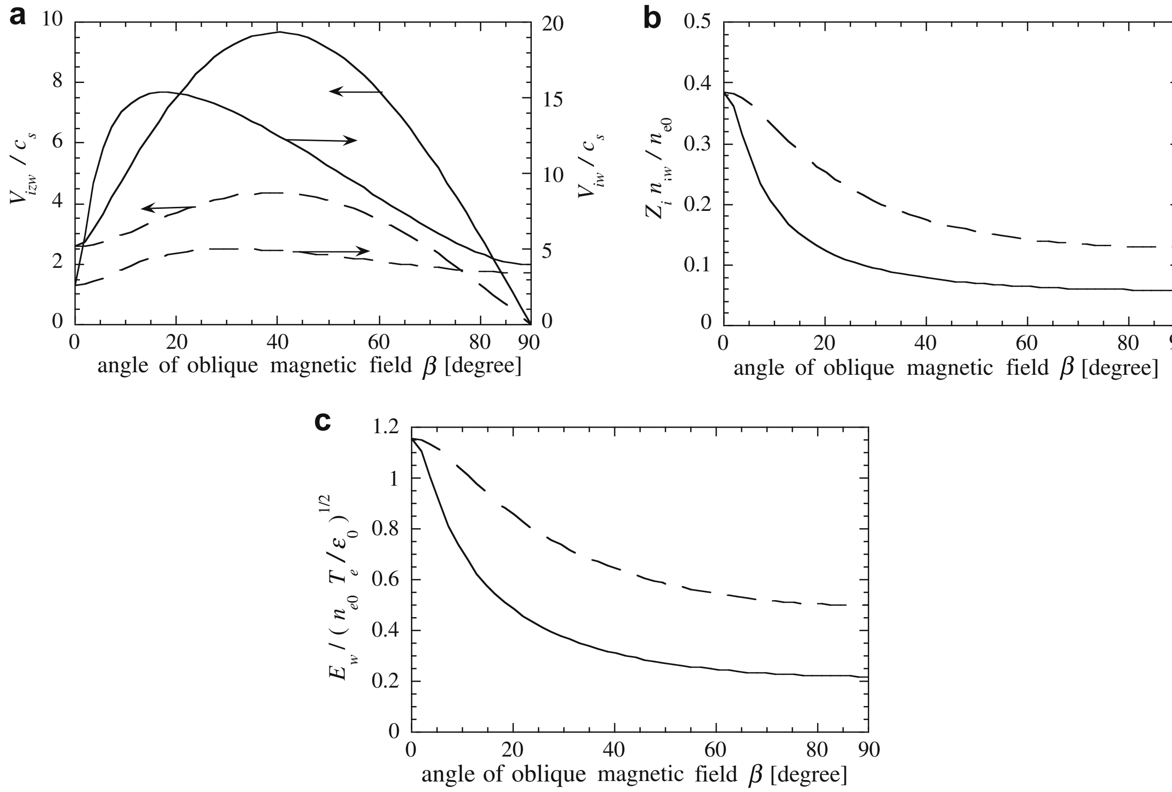

Fig. 1. The ion flow velocity toward the wall V_{izw} and ion speed V_{iw} (a), ion charge density $Z_i n_{iw}$ normalized by the electron density at the MP entrance (b) and electric field E_w at the wall as functions of the angle of oblique magnetic field from the wall normal for the case of $\delta_B = 5.0 \times 10^{-3}$ (solid lines) and 5.0×10^{-2} (dashed lines).

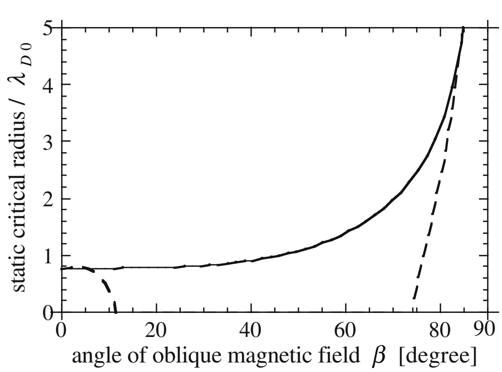

Fig. 2. The critical radius for the release of the dust particle normalized by the electron Debye length defined at the entrance of the MP as a function of the angle of oblique magnetic field. The parameters are the same as in Fig. 1.

(b) $2\pi a_s/\lambda_s > 1$ or $\pi/4 < \theta_{sm} \leqslant \pi/2$

$$\begin{array}{ll} \frac{\pi}{2} - (\theta_B + \theta_{sm}) \leqslant \beta \leqslant \frac{\pi}{2}: & 0 \leqslant \theta_B \leqslant \frac{\pi}{2} - \theta_{sm} \\ 0 \leqslant \beta \leqslant \frac{\pi}{2}: & \frac{\pi}{2} - \theta_{sm} < \theta_B \leqslant \theta_{sm} \\ 0 \leqslant \beta \leqslant \frac{\pi}{2} - (\theta_B - \theta_{sm}): & \theta_{sm} < \theta_B \leqslant \frac{\pi}{2} \end{array} \tag{13}$$

where θ_B is the angle between the oblique magnetic field and the vertical plane, and $\theta_{sm}(= \tan^{-1} 2\pi a_s/\lambda_s)$ is the maximum angle between the wavy surface and the vertical plane. Along the wavy surface the angle β widely spreads. For example, at the acute angle of oblique magnetic field θ_B (= 5°), the angle β changes from the minimum angle β_m to the right angle (β = 90°). The value of β_m changes from 21.6°, 40.0° and 58.4° for the case a_s/λ_s = 2.0, 1.0, 0.5, respectively. The high amplitude of the roughness leads to large variation of the angle β. On the other hand, at the obtuse angle of oblique magnetic field θ_B (= 85°), the angle β changes from 0° to the maximum angles, which are 68.4°, 50.0° and 31.6° for the case of case a_s/λ_s = 2.0, 1.0, 0.5, respectively. In this case when the wavelength of the surface roughness becomes longer, the angle β spreads widely. The large variation of the angle β along the surface can strongly affect the critical dust radius, when magnetic field is strong. In order to analyze the release condition of the dust on the rough surface more precisely, the effect of the gravity should be taken in to account.

6. Summary

We analyzed the effect of the oblique magnetic field on release conditions of the spherical dust particle from the vertical plasma-facing wall. The non-linear dependence on the oblique angle of the forces acting on the dust changes the release conditions. In this study we solved the Poisson's equation in the whole region of the MP and the DS to obtain the electric field. In the case of the weaker magnetic field or the higher ion density, the critical radius for the release of the dust can vanish in the middle range of angles of the oblique magnetic field from the wall normal, where the dust particle is pinned by the ion drag forces. On the other hand in the case of the stronger magnetic field or the lower plasma density, the critical radius increases as the acute angle of the oblique magnetic field increases. The surface roughness widely changes the angle between the magnetic field lines and the surface normal, where the release condition from the wavy surface is left as one of the future issues. To analyze the release of dusts for the case of the 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 dynamics is taken into account. These studies are helpful to investigate the dynamic phenomena of dust particles near the divertor plate in fusion devices [8].

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References

[1] J. Winter, Plasma Phys. Control. Fus. 46 (2004) B583.
[2] Y. Tomita, R.D. Smirnov, T. Takizuka, D. Tskhakaya, Contribution Plasma Phys. 48 (2008) 285.
[3] Y. Tomita, R.D. Smirnov, T. Takizuka, D. Tskhakaya, Contribution Plasma Phys. 46 (2006) 617.
[4] H. Mott-Smith, I. Langmuir, Phys. Rev. 28 (1926) 727.
[5] J.E. Allen, Phys. Scr. 45 (1992) 497.
[6] R. Chodura, Phys. Fluids 25 (1982) 1628.
[7] K. Sato et al., Contribution Plasma Phys. 34 (1994) 13.
[8] S. Krasheninnikov, Y. Tomita, R. Smirnov, R. Janev, Phys. Plasma 11 (2004) 3141.