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Effect of truncation of electron velocity distribution on release of dust particle from plasma-facing wall

Y. Tomita [a,*], R. Smirnov [b], H. Nakamura [a], S. Zhu [c], T. Takizuka [d], D. Tskhakaya [e]

[a] *National Institute for Fusion Science, Toki 509-5292, Japan*
[b] *University of California, San Diego, La Jolla, CA 92093-0417, USA*
[c] *Institute of Plasma Physics, The Chinese Academy of Sciences, Hefei 230031, China*
[d] *Japan Atomic Energy Agency, Naka Fusion Institute, Naka 311-0193, Japan*
[e] *Andronikashvili Institute of Physics, Tamarashvili Street 6, 0177 Tbilisi, Georgia*

Abstract

In modeling of release of a dust particle from a plasma-facing wall it is usually assumed that electron velocity distribution is Maxwellian. However, the absorption of fast electrons by the conducting wall can lead to truncation of fast component of reflecting electrons from the wall. In this work we study the effect of truncation of electron velocity distribution on the release condition of a conducting spherical dust particle from the plasma-facing wall. The truncation increases the electric field at the wall surface compared to that calculated in absence of the truncation. The stronger electric field makes the dust particle hard released when the gravitational force is directed from the wall and applied wall potential is shallower than the floating one.

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Keywords: Biasing; Dust; Divertor plasma; Electric field

1. Introduction

The generation of dust particles in fusion devices is of interest not only in fusion devices, but also in astrophysical, space, laboratory and semiconductor processing plasmas observed dust particles have shapes that are spherical, flake-like or irregular, with sizes from nanometers to tens of micrometers; they consist of materials from divertor plates or inner wall structures [1]. Of particular concern in fusion devices is associated with absorption of radioactive tritium [1]. After many plasma discharges, the accumulation of radioactive tritium in dust can account for a significant fraction of the tritium inventory retained inside the vacuum vessel.

In this study we theoretically investigate the effect of truncation of electron velocity distribution on

* Corresponding author. Address: 322-6 Oroshi-cho, Toki 509-5292, Japan. Fax: +81 572 58 2626.
E-mail address: tomita@nifs.ac.jp (Y. Tomita).

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release conditions of the conducting spherical dust particles attached on the plasma-facing wall, which is important to understand the behavior of the dust in the divertor plasma. This truncation is caused by absorption of the fast electrons at the wall. Previously, we have estimated the release conditions of the spherical dust particles from the plasma-facing wall for the full Maxwellian distribution [2,3], where the threshold wall potential and the critical dust radius were discussed. This study can be helpful for investigation of behavior of hydrocarbons including tritium as well as formation mechanisms of a large dust in plasmas.

2. Model and forces

The conducting spherical dust particle can be released from the conducting wall when the forces repelling the dust from the wall are stronger than the forces pushing it toward the wall. In our model, the dusts are sparse on the wall surface and the size of a dust is much smaller than the Debye length, where the deformation of electrostatic potential near the wall is negligibly small. In our case, the electrostatic repelling force $F_E = Q_d E_w$ causes the release of dust particles from a conducting wall, since both dust and wall are charged negatively. The charge Q_d on a dust particle is expressed in terms of the particle radius R_d and the electric field at the wall E_w according to the relation:

$$Q_d = -\xi_d \pi \varepsilon_0 R_d^2 E_w, \tag{1}$$

where 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 [4]. The three forces acting 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 [3]. The OML (orbit motion limited) model [5,6] for the drag force due to absorption of plasma ions is applied.

The total pressure, $F_{tw}/\pi R_d^2$, on the dust particle has a quadratic form with respect to the dust radius [3].

$$F_{tw}/\pi R_d^2 = b_0(\phi_w) R_d^2 + b_1(\phi_w) R_d + b_2(\phi_w), \tag{2}$$

where the coefficients b_j depend on the macroscopic plasma quantities such as the particle flux Γ_{iw}, ion flow velocity V_{iw} at the wall and electron temperature T_e as well as the wall potential drop ϕ_w.

$$b_0(\phi_w) = \frac{Z_i^2 e^2 \xi_d^2 \Gamma_{iw} \ln \Lambda E_w^2(T_e, \phi_w)}{4 m_i V_{iw}^3 (T_e, \phi_w)}, \tag{3}$$

$$b_1(\phi_w) = \frac{Z_i e \xi_d \Gamma_{iw} E_w(T_e, \phi_w)}{2 V_{iw}(T_e, \phi_w)} [1 + \delta_g(T_e, \phi_w)], \tag{4}$$

$$b_2(\phi_w) = m_i \Gamma_{iw} V_{iw}(T_e, \phi_w) + \frac{\xi_d^2 \varepsilon_0 E_w^2(T_e, \phi_w)}{16} - \xi_d \varepsilon_0 E_w^2(T_e, \phi_w), \tag{5}$$

where δ_g denotes the effect of the gravitational force, which is defined as

$$\delta_g(\phi_w) \equiv \frac{8 g \rho_d \cos\alpha V_{iw}(T_e, \phi_w)}{3 Z_i e \xi_d \Gamma_i E_w(T_e, \phi_w)} \tag{6}$$

and Z_i and m_i are the atomic number and mass of a plasma ion, respectively. The mass density of the dust is indicated by ρ_d. The direction of gravity has the angle α to the normal of the wall. Since the coefficient $b_0(\phi_w)$ is positive definite, the release condition ($F_{tw} < 0$) is determined by the signs of the coefficients $b_1(\phi_w)$ and $b_2(\phi_w)$, which depend on the wall potential drop.

3. Ion flow velocity and electric field at the wall

In order to evaluate the forces on the dust particle, the particle flux Γ_{iw}, the ion flow velocity V_{iw} and the electric field E_w at the wall are necessary. In this study the collisionless Debye sheath is considered to obtain these quantities assuming the electrostatic potential and the electric field are vanishing and the charge neutrality is satisfied at the sheath entrance. In this model the particle flux is conserved. The ion flow velocity at the wall is obtained as a function of the electrostatic potential drop at the wall ϕ_w and the electron temperature from the particle flux and energy conservations inside the collisionless Debye sheath,

$$V_{iw}(T_e, \phi_w) = V_{ise} \sqrt{1 - \frac{2 Z_i e \phi_w}{m_i V_{ise}^2}} = \sqrt{\frac{Z_i T_e}{m_i} \left(1 - \frac{2 Z_i e \phi_w}{T_e}\right)}. \tag{7}$$

Here V_{ise} is the monoenergetic ion flow velocity at the Debye sheath entrance, which is equal to the ion sound speed $c_s = \sqrt{Z_i T_e / m_i}$ from the Bohm criterion [7]. The electric field at the wall is given by integration of Poisson equation combined with the local electron and ion densities. The local ion density is expressed by the local electrostatic potential ϕ,

$$n_i(\phi) = n_{\mathrm{ise}} \Big/ \sqrt{1 - \frac{2Z_i e\phi}{m_i V_{\mathrm{ise}}^2}} = n_{\mathrm{ise}} \Big/ \sqrt{1 - \frac{2Z_i e\phi}{T_{\mathrm{e}}}}. \tag{8}$$

In this system, where there are no particle sources, sinks and collisions, the local energy distribution function of electrons, $f_{\mathrm{e}}(\varepsilon_{\mathrm{e}})$, is the same as at the sheath entrance, $f_{\mathrm{e0}}(\varepsilon_{\mathrm{e}})$. Here ε_{e} is the total particle energy $(= m_{\mathrm{e}}v^2/2 - \mathrm{e}\phi)$ in the local electrostatic potential ϕ. The local macroscopic quantities inside the system are easily calculated by using the local energy distribution function. Inside the Debye sheath there are electrons with positive and negative velocities due to the reflection by the monotonically decreasing potential.

$$n_{\mathrm{e}}(\phi) = n_{\mathrm{e}}^{(+)}(\phi) + n_{\mathrm{e}}^{(-)}(\phi) = n_{\mathrm{ese}}^{(+)} \exp(e\phi/T_{\mathrm{e}}) \times [1 + \mathrm{erf}\sqrt{e(\phi - \phi_{\mathrm{w}})/T_{\mathrm{e}}}], \tag{9}$$

where the quantity $n_{\mathrm{e}}^{(+)}$ is the local density of electrons with positive velocities, which obeys the Boltzmann relation:

$$n_{\mathrm{e}}^{(+)}(\phi) = n_{\mathrm{ese}}^{(+)} \exp(e\phi/T_{\mathrm{e}}) \tag{10}$$

and $n_{\mathrm{e}}^{(-)}$ is that with negative velocities:

$$n_{\mathrm{e}}^{(-)}(\phi) = n_{\mathrm{ese}}^{(+)} \exp(e\phi/T_{\mathrm{e}}) \mathrm{erf}\sqrt{e(\phi - \phi_{\mathrm{w}})/T_{\mathrm{e}}}. \tag{11}$$

Here the truncation effect makes its appearance in the error function, which does not appear in the case of the full Maxwellian distribution. It is reasonable to see that there are no electrons with negative velocities at the wall. Here $n_{\mathrm{ese}}^{(+)}$ is the density of electrons with positive velocities at the Debye sheath entrance, which is expressed by the total electron density at the Debye sheath entrance n_{ese}

$$n_{\mathrm{ese}} = n_{\mathrm{e}}(\phi = 0) = n_{\mathrm{ese}}^{(+)}(1 + \mathrm{erf}\sqrt{-e\phi_{\mathrm{w}}/T_{\mathrm{e}}}). \tag{12}$$

This gives the local electron density as a function of local potential ϕ

$$n_{\mathrm{e}}(\phi) = n_{\mathrm{ese}} \exp(e\phi/T_{\mathrm{e}}) \frac{1 + \mathrm{erf}\sqrt{e(\phi - \phi_{\mathrm{w}})/T_{\mathrm{e}}}}{1 + \mathrm{erf}\sqrt{-e\phi_{\mathrm{w}}/T_{\mathrm{e}}}}. \tag{13}$$

In the case of electron distribution without truncation, which corresponds to infinite depth of the wall potential $-\mathrm{e}\phi_{\mathrm{w}} = \infty$, the local electron density satisfies the Boltzmann relation.

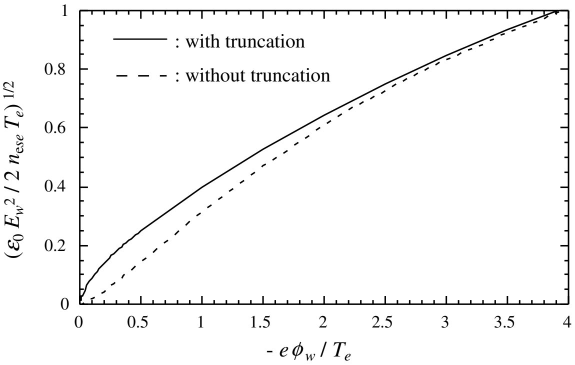

Fig. 1. Electric field at the wall as a function of normalized wall potential drop for cases with and without truncation.

The local ion density, Eq. (8), and electron density, Eq. (13), give the electric field at the wall:

$$E_{\mathrm{w}}^2(T_{\mathrm{e}}, \phi_{\mathrm{w}}) = \frac{2n_{\mathrm{se}}T_{\mathrm{e}}}{\varepsilon_0} \left\{ \frac{1}{1 + \mathrm{erf}(\sqrt{-e\phi_{\mathrm{w}}/T_{\mathrm{e}}})} \left[\mathrm{e}^{e\phi_{\mathrm{w}}/T_{\mathrm{e}}} - 1.-\mathrm{erf}(\sqrt{-e\phi_{\mathrm{w}}/T_{\mathrm{e}}}) + \frac{2}{\sqrt{\pi}} \mathrm{e}^{e\phi_{\mathrm{w}}/T_{\mathrm{e}}} \sqrt{-e\phi_{\mathrm{w}}/T_{\mathrm{e}}} \right] + \sqrt{1 - \frac{2e\phi_{\mathrm{w}}}{T_{\mathrm{e}}}} - 1 \right\}. \tag{14}$$

The first term of RHS of Eq. (14) is the effect of truncated electron distribution and the last two terms come from the ion density. These quantities are used to evaluate a balance of the forces acting on the spherical dust particle on the conducting wall. In the case of electrons with the Maxwellian velocity distribution, the electric field at the wall obtained from Poisson equation is

$$E_{\mathrm{w}}^2(T_{\mathrm{e}}, \phi_{\mathrm{w}}) = \frac{2n_{\mathrm{se}}T_{\mathrm{e}}}{\varepsilon_0} \left[\exp(e\phi_{\mathrm{w}}/T_{\mathrm{e}}) - 1 + \sqrt{1 - \frac{2e\phi_{\mathrm{w}}}{T_{\mathrm{e}}}} - 1 \right]. \tag{15}$$

In Fig. 1, the electric field at the wall is shown for both cases, where for the potential drops ~1 the electric field with the truncation effect is stronger by around 50% than that without truncation.

4. Effects of truncated electron distribution on release of dust

In this section the effects of a truncated electron velocity distribution on the release conditions of a spherical dust particle are discussed in the case of the gravitational force pointing toward or away from the conducting wall.

4.1. Gravitational force toward wall

When the gravity pushes a dust particle toward the wall with angle $0 \leqslant \alpha \leqslant \pi/2$, the coefficient b_1 in the total force, Eq. (2), becomes positive. The sign of the coefficient b_2 determines the release of the dust. It is clear the electric field at the wall is required strong enough for release of the dust from the wall. Release of a dust particle occurs only if the electric field at the wall exceeds a threshold value set by the condition $b_2(\phi_w^{th}) = 0$.

In the case that the dust on the wall is immersed into the uniform electric field and the corresponding form factor ξ_d is $2\pi^2/3$, the normalized threshold wall potential drop by $-e/T_e$ becomes 1.40, which should be compared to 1.66 of that without truncation. In Fig. 2, the critical dust radii normalized by the Debye length at the sheath entrance λ_{Dese} with truncation effect are shown as a function of the wall potential drop for the case $Z_i = 1$, $\ln \Lambda = 3.0$, and $\xi_d = 2\ \pi^2/3$, where the threshold wall potential is 1.40. The gravitational parameter δ_{ga} in Fig. 2 indicates the effect of the gravitational force,

$$\delta_{ga} \equiv 0.038 \frac{\rho_d(g/cc)\cos\alpha}{n_{se,19}\sqrt{n_{se,19}T_e\ (\mathrm{eV})}}, \qquad (16)$$

where $n_{se,19}$ is the plasma density at the sheath edge in the unit of $10^{19}\ \mathrm{m}^{-3}$. Here $\delta_{ga} = 0$ corresponds to the dust particle on the vertical wall. The dusts with the radius smaller than the critical one will be released. The larger the gravitational effect becomes, the smaller the released region becomes. In the case of the carbon dust on the horizontal wall in a plasma with high density $10^{18}\ \mathrm{m}^{-3}$ and $T_e = 10$ eV, which corresponds to a divertor plasma in fusion devices, the gravitational parameter is as low as 0.78. On the other hand, the low density plasma $10^{16}\ \mathrm{m}^{-3}$ with $T_e = 30$ eV increases the gravitational parameter up to around 440, where almost dusts are pinned to the wall except for quite small dusts. In the case of electron distribution without truncation, the threshold wall potential moves to 1.66, but the critical radii at the deep wall potential are almost the same.

4.2. Gravitational force from wall

The gravitational force directing from the wall easily releases the dust particle. It changes the sign of the gravitational parameter δ_{ga} in Eq. (4), so that the particle is released even if the wall potential is shallower than the threshold. It is easy to analyse the existence of the real positive critical radii from Eq. (2). In Fig. 3, the relation of the wall potential drop ϕ_w to the gravitational parameter δ_{ga} is shown, where the solid and dashed lines indicate the cases with and without truncation effect, respectively. At the deeper wall potential than the threshold, there is one positive critical radius. On the other hand, the domain in the shallower wall potential is divided into two parts. In the region of larger magnitude of the gravitational parameter than the separation curve there are two positive critical radii. There is no positive critical radius in the region of smaller δ_{ga} than that. The truncation effect is remarkable at the shallower wall potential. The critical radii are shown in Fig. 4 for the cases of $\delta_{ga} = -5$ (a),

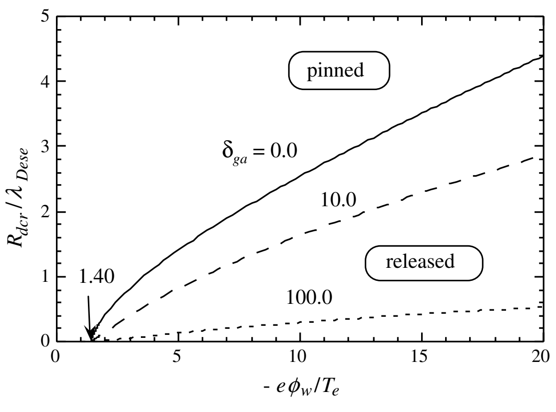

Fig. 2. Critical dust radii with truncation effect as a function of normalized wall potential drop for the cases of gravitational parameter $\delta_{ga} = 0.0$, 10.0, and 100.0 and $Z_i = 1$, $\ln \Lambda = 3.0$, and $\xi_d = 2\pi^2/3$.

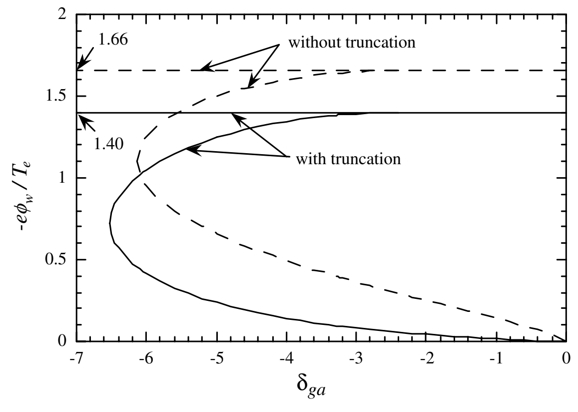

Fig. 3. Region of positive critical radii in the space of wall potential drop ϕ_w and gravitational parameter with the same parameters as in Fig. 2. The cases with and without truncation effect are shown by solid and dashed lines, respectively.

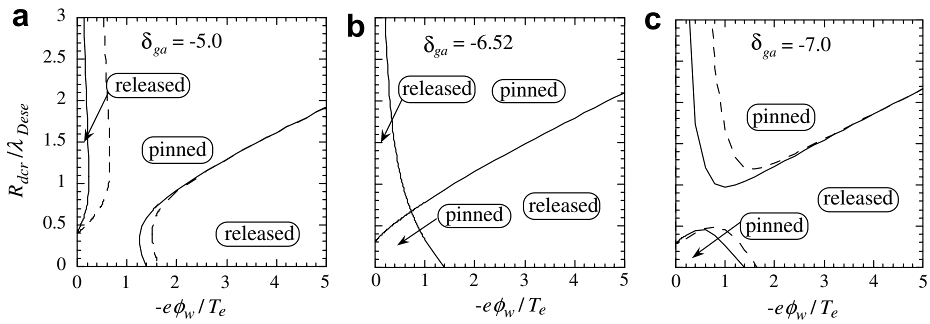

Fig. 4. Critical radius as a function of wall potential drop with the same parameters as in Fig. 2 for $\delta_{ga} = -5.0$ (a), -6.52 (b), and -7.0 (c). The solid and dashed lines indicate the case with and without truncation effect, respectively.

-6.52 (b), and -7 (c), where the solid and dashed lines indicate the cases with and without truncation effect, respectively. At the small magnitude of δ_{ga}, Fig. 4(a), there are two separated regions of the released dust, where the released region at the shallower wall potential than threshold does not appear in the case of the positive gravitational parameter. On the other hand, for the larger magnitude of δ_{ga}, Fig. 4(c), these two released regions are overlapped. The gravitational parameter $\delta_{ga} = -6.52$, Fig. 4(b) is the marginal one for the case with truncation, where the two released regions are merged. At the released dust region in the shallower wall potential, where the repulsive electrostatic force is not so strong, the gravitational force makes the dust particle released. One can see the truncation effect is significant at the shallower potential drop. A dominant force divides the region in Fig. 4 into four parts. In the shallower potential and the larger dust region, the gravitational force is dominant. The strong electrostatic force releases the dust from the wall in the region of deeper potential drop and the smaller dust particle. In the pinned dust region with the deeper wall potential and the larger dust particle, the Coulomb scattering force pushes the dust toward the wall. On the other hand, in the shallower potential with the smaller dust, the ion drag force due to absorption of ions by the dust is dominant compared to the other forces. It is clear that these results show adjusting the plasma parameters such as plasma density and temperature as well as biasing the wall potential control the size of the released dust particle.

5. Summary

We analyzed the effect of truncation of the electron distribution on release conditions of the spherical dust particle on the plasma-facing wall. The truncation effect of electron velocity distribution enlarges the electric field at the wall compared to the Maxwell distribution at the shallower potential drop: for the potential drops $-e\phi_w/T_e \sim 1$ it is stronger by around 50%. There is a threshold wall potential drop for the release of the dust, which is as low as $-e\phi_w^{th}/T_e \sim 1$. In the case of the gravity directed toward the wall, there exist the released dusts even if the wall potential is shallower than the threshold, where the truncation effect of electron distribution becomes important. These results clarify that one can control the size of the released dust particle by adjusting the plasma quantities such as plasma density and temperature as well as the wall potential. When we apply the shallower biasing to the wall, the truncation effect is important. In the case of large dust compared to the Debye length, the multi dimensional effect like potential formation near the dust surface is important, where the study by using the computer simulation is necessary to analyze the release conditions of the dust particle [8]. The investigation of a dust with irregular shapes like flakes is one of the future issues, where the formation process and the attachment condition are different from the considered dust in this study. One of the major compositions of dust particles is hydrocarbon, which seems to dielectrics. The charging of dielectrics is different from that of metals, and the corresponding study probably requires a numerical simulation. The drag force from neutrals should be included in the detached plasma. The dynamic phenomena like disruptions and ELM events also should be considered as one of the future issues. These researches are helpful to investigate the dynamic phenomena of the dust particle in the divertor and SOL plasmas as well as the boundary plasma in fusion devices [9].

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