Reduction of Sheath Potential and Dust Ion-Acoustic Wave by Negatively Charged Dust Particles

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Abstract

Formation of an electrostatic potential due to negatively charged dust particles near a target plate was studied by one-dimensional kinetic analysis. Immovable dust particles are distributed uniformly inside a system. A threshold dust density makes the electric field at the target plate zero. In case of dust density below the threshold a charge-neutral point separates into two between positions of a plasma injection and a wall. An electron sheath near the injection point changes to an ion sheath in front of the target plate through the charge-neutral point. It is clarified that the negatively charged dust particles reduce the ion-sheath potential drop from the neutral point. The stationary oscillation appears in the electrostatic potential for the dust density above the threshold. We confirmed that this oscillation is the Dust Ion-Acoustic Wave (DIAW) with a wavelength of the order of Debye length, where dust charges are effective to determine the behavior. The effective dust density to produce the oscillation is as high as $10^{13\text{-}14}$ m^{-3} for plasma density $\sim 10^{18}$ m^{-3} with plasma temperature ~ 10 eV.

1. Introduction

In recent years there has been much interest in charged dust particles in fusion plasmas as well as the space and laboratory plasmas. Dust particles were observed after a disruption of plasma current in a tokamak device [1]. In several fusion devices (TEXTOR-94, ASDEX-U, LHD), the dust particles were collected and analyzed their characteristics [2,3], where radii of dust particles widely range from 10 nm to 100 μm. These dust particles were composed mainly of carbon and constituents of stainless steel, which materials are used for most plasma-facing surfaces like the divertor plates and the vacuum vessels. With prolonged discharges in fusion-plasma experiments, the effect of dust particles on the potential formation near target plates and the impurity for a bulk plasma might be important. Despite the small amount of dust particles, the charge of a dust particle is large enough to strongly affect the potential formation and a radiation loss from the bulk plasma. Understandings of the basic phenomena between dust and plasma particles are quite important. In this study we investigate the formation of an electrostatic potential with dust particles near the target plate by using one-dimensional kinetic analysis.

2. Model

In the model for one-dimensional analysis, plasma particles with half-Maxwellian distribution functions are injected from an injection position ($x = 0$) toward a perfectly absorbing target plate ($x = x_w$) with a floating potential, where immovable dust particles are distributed uniformly. The absorption of plasma particles by dust particles and Coulomb interactions between particles are neglected because the mean-free-paths are much longer than the system length, which is assumed to be of the order of the Debye length. The negatively charged dust particles affect the potential formation through Poisson equation. In a system without particle sources and sinks, the local energy distribution function of the plasma particles $f_j(x, \varepsilon_{jx})$ [$j = i, e$], is the same as at the injection point $f_j(x = 0, \varepsilon_{jx})$. Here ε_{jx} is the total energy of a particle ($\varepsilon_{jx} = m_j v^2 + q_j \phi(x)$, m_j and q_j are the mass and electric charge of j-th particles.) in the local electrostatic potential $\phi(x)$. The local macroscopic quantities, such as plasma densities and flow velocities, are obtained as a function of a potential by using the local energy distribution function [4]. The potential at the floating wall ϕ_w is determined by the equality of particle

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fluxes of ions and electrons at the wall:

$$\phi_w = -\frac{T_{es}}{2e} \ln \left(\delta_s^2 \tau_s \frac{m_i}{m_e} \right). \tag{1}$$

Here e is the unsigned charge on an electron, δ_s and τ_s denote the density ratio and temperature ratio at the injection point: $\delta_s \equiv n_{es}^{(+)}/n_{is}^{(+)}$ and $\tau_s \equiv T_{es}/T_{is}$ respectively, where $n_{js}^{(+)}$ and T_{js} is the density of the particles with positive velocities and plasma temperature at the injection point. Note that a dust particle does not contribute to the wall potential because they are immovable.

In this analysis the density ratio δ_s is determined so as to satisfy the charge-neutrality condition at the injection point ($x = 0$) without the dust particles. The steady state dust charge Z_d is determined from the condition of zero net currents of plasma particles to dust particles. These currents are obtained from the local distribution function of the plasma particles and the absorption cross-section, which is adopted from the OML (Orbital Motion Limited) theory [5]. The dust charge $Z_d (> 0)$ is normalized as $\beta_d \equiv Z_d e^2 / \varepsilon_0 R_d T_{es}$, where ε_0 is the vacuum permittivity and R_d denotes the dust radius. This normalization gives the normalized charge density of dust particles as $Z_d e\, n_d / e\, n_{es}^{(+)} = n_d^* R_d^* \beta_d$, where n_d is the dust density, $n_d^* \equiv n_d \lambda_{Des}^3$ and $R_d^* \equiv R_d / \lambda_{Des}$. Here $\lambda_{Des} \equiv \sqrt{\varepsilon_0 T_{es} / e^2 n_{es}^{(+)}}$ is the electron Debye length associated with the positive-velocity electron density at the injection point.

3. Results and discussions

The spatial potential distribution is calculated from Poisson equation by using the plasma charge densities and the dust charge density according to the OML theory [5]. The spatial potential profiles for several values of the normalized dust density $n_d^* R_d^* (= n_d R_d \lambda_{Des}^2)$ are shown in Fig. 1, where the floating target is located at the position $x_w = 50\ \lambda_{Des}$, the temperature ratio at the injection point τ_s is 10, the density ratio δ_s is set as 0.501, and a hydrogen plasma is considered. Near the injection point an electron sheath is formed and the

middle region of this system a wide quasi-neutral region is formed. In front of the floating target plate an ion-sheath is formed. Note that the wall potential is not disturbed by the immovable dust particles. As the dust density increases, the potential difference between the wall and the position of charge neutrality decreases. As the ion flow velocity V_i at the charge-neutral point exceeds the sound speed $c_s (V_i/c_s \sim 2.0)$ corresponding the Bohm criterion, the potential between the charge-neutral point and the plate monotonically decreases. This potential difference corresponds to the potential drop of the Debye-sheath. As the dust density increases further, the electric field at the wall approaches zero. At the threshold dust density the electric field at the wall becomes zero, whereas the wall potential ϕ_w still remains the same value. In the case $m_i/m_e = 1836.1$, $\delta_s = 0.501$, and $\tau_s = 10$, the threshold of the normalized dust density is as high as 0.022, which corresponds to the dust density as high as $10^{13\text{-}14}$ m^{-3} for plasma density and temperature of 10^{18} m^{-3} and 10 eV, respectively.

At dust densities above the threshold, a stationary oscillation appears in the potential (Fig. 2), where the plasma parameters are the same as in Fig. 1. The higher dust density, the more the minimal potential, which is the same as the wall potential ϕ_w, is close to the injection point and the deeper potential well becomes. At the further point from the potential minimum ϕ_w, both of the particle fluxes of ions and electrons are the same, which means the floating plate can be located anywhere far from the minimal potential. The wavelength of this steady oscillation is presented as a function of the dust density by the solid line in Fig. 3, where the wavelength is the order of Debye length. At the higher dust density than the threshold, ions are accelerated enough to be a monoenergetic distribution, where the ion flow velocity is determined from the energy conservation in the electrostatic potential ϕ. As electrons are almost repelled by the highly negative dust charge, their contribution to the potential formation is neglected. The currents of plasma particles to dust particles
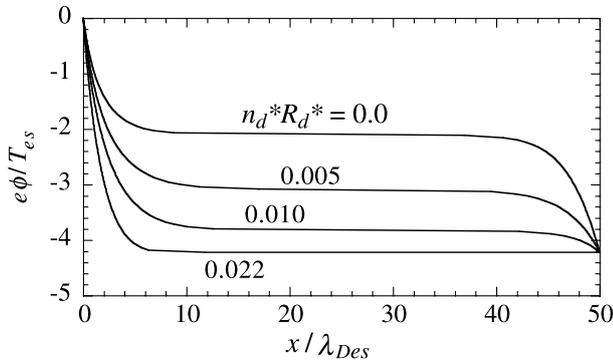

Fig. 1 Spatial distributions of the normalized electrostatic potential for several values of dust density below the threshold, where the temperature, the density ratio at the injection point, and the mass ratio are $\tau_s = 10$, $\delta_s = 0.501$, and $m_i/m_e = 1836.1$. The normalized threshold dust density is 0.022 in these plasma parameters.
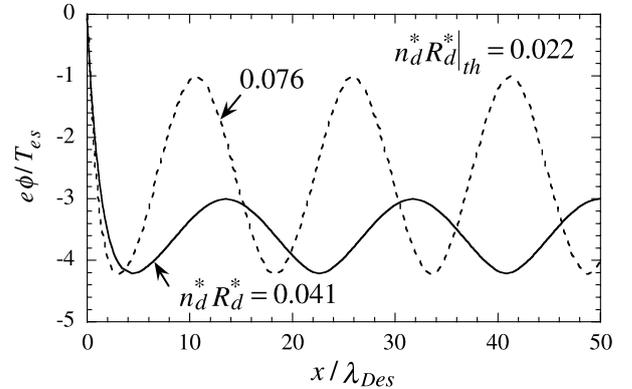

Fig. 2 Spatial distributions of the normalized electrostatic potential for the dust density above the threshold, which is 0.022 in the plasma parameters, which are the same as in Fig. 1. The minimal potential is equal to the wall potential ϕ_w in case of dust density below the threshold.
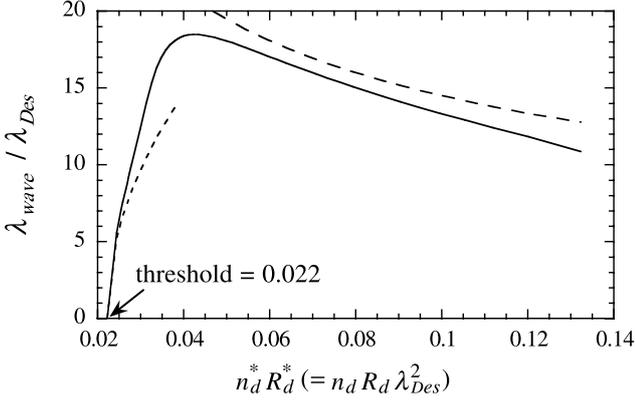
Fig. 3   The wavelength as a function of normalized dust density: solid line. The approximated wavelengths, eqs. (3) and (4), are presented by the dashed and the dotted lines, respectively. The parameters of the plasma are the same as in Fig. 1.

are almost the same in the highly negative potential. This result gives us the dust charge is nearly proportional to the square of the ion flow velocity according to the charging cross-section. From these conditions, the wave number k is obtained by Poisson equation with respect to fluctuations of potential $\tilde{\phi}$:

$$\frac{\varepsilon_0 k^2}{e} \tilde{\phi} \cong Z_i \tilde{n}_i - \tilde{Z}_d n_d = \left(\frac{Z_i n_{iw}}{-2\phi_w} + \frac{Z_{dw} n_d}{-\phi_w} \right) \tilde{\phi} , \qquad (2)$$

where the ion atomic number is denoted by Z_i. The corresponding wavelength is expressed by the normalized quantities at the wall/minimal potential ϕ_w:

$$\lambda_{wave} / \lambda_{Des} = \frac{2\pi \sqrt{-e\phi_w / T_{es}}}{\sqrt{Z_i \overline{n}_{iw}/2 + \beta_{dw} n_d^* R_d^*}} , \qquad (3)$$

where the particle density is normalized by $n_{es}^{(+)}$, which is the electron density with positive velocities at the injection point. The dashed line in Fig. 3 shows the obtained wavelength, where the difference from the real value comes from the assumption of the proportionality of Z_d to V_i^2. The conventional DIAW is assumed the fluctuation of the charging effect of dust particles is neglected and the fluctuation of electrons determined the dispersion relation [6]. On the other hand in our case the fluctuation of the electron density is neglected and the effect of the dust charging is dominant to determine the wavelength.

In the vicinity of the threshold density the contribution of electrons to a wavy potential cannot be neglected. After troublesome algebra one can obtain the wavelength with respect to the lowest order of the difference of the dust density from the threshold, $n_d^* R_d^* - n_d^* R_d^*\big|_{th}$:

$$\lambda_{wave} / \lambda_{Des} \cong c_{lw} \sqrt{n_d^* R_d^* - n_d^* R_d^*\big|_{th}} , \qquad (4)$$

where the coefficient c_{lw} is expressed by the physical quantities at the wall/minimal potential:

$$c_{lw} = 3\sqrt{2\pi \beta_{dw}} / \left(\alpha_{lw} n_d^* R_d^*\big|_{th} - \overline{n}_{ew} \right), \qquad (5)$$

$$\alpha_{lw} \equiv \frac{2\pi^{3/2}(Z_i e\phi_w / T_{es} - 1/2\,\tau_s - \beta_{dw}/4\pi)}{1 - Z_i e\phi_w / T_{es} + 1/2\,\tau_s + \beta_{dw}/4\pi}$$

$$\left[\sqrt{\beta_{dw}/4\pi} + \sqrt{\pi}(1/2 - \beta_{dw}/4\pi)\exp(\beta_{dw}/4\pi)\mathrm{erfc}\left(\sqrt{\beta_{dw}/4\pi}\right) \right], \quad (6)$$

where erfc is the complementary error function. The wavelength near threshold is presented by the dotted line in Fig. 3.

In this analysis the absorption of plasma particles by a dust particle is not taken into account. In case of the larger dust radius than 1 μm in $T_{es} = 10$ eV and $n_{es}^{(+)} = 10^{18}$ m^{-3}, the absorption length to the wavelength is not ignorable where the dumping of the oscillation may be appreciable.

4. Summary

The effects of dust particles have been investigated on the potential formation in the near-target region. The local charge of the dust particles is calculated according to the absorption cross-section from OML theory [5]. We found that the uniformly distributed immovable dust particles in front of the target plate reduce the potential drop in the sheath effectively, so that the bombardment of the plate by ions with high energies is avoided. Above the threshold dust density, where the electric field at the plate becomes zero, the stationary oscillation in a potential distribution appears. This oscillation is confirmed to be a dust ion-acoustic wave, where the dust charge determines the wavelength and electrons do not contribute to the oscillation except for the vicinity of the threshold. This comes from that electrons are repelled by the highly negative dust charge. The effective dust density ($\sim 10^{13\text{-}14}$ m^{-3}) is so high compared to the observed and expected dust density in fusion devices, which means the collective effect of dust particles in fusion plasma may be neglected. In this simple analytical study there are several issues left for the understanding the dust-particle effect in a realistic divertor plasma. The presheath such as the geometric, collisional, ionizing, or magnetic presheath is important to determine the spatial distribution of dust particles. The magnetic field obliquely penetrating the divertor plate affects the potential formation in the existence of dust particles. The Coulomb coupling might be important to investigate dynamics of dust particles in this high dust density. From the results the absorption effect of plasma particles by the dust particles with large radii (> 1 μm) may not be ignored. For a dust particle with a radius smaller (< 100 nm) the OML theory is not applicable, because of a short Debye shielding length of a dust particle. These effects are needed to incorporate to the model.

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