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Dynamics of Dust Particles Coming off a Wall in Sheath and Presheath

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Abstract

Dynamics of a single dust particle in near wall plasma is studied in wide range of dust radii and masses. Dust motion and charging equations are solved simultaneously in the stationary plasma parameters distributions that are simulated for sheath and ionizing presheath using one-dimensional particle model. It was found that the balance of electric and ion drag forces acting on the dust particle provides two critical dust radii differentiating motion of dust started at the wall between pinned against the wall, short and long-range oscillating. Delayed charging causes the mass dependence of the second critical radius until transition from short to long-range oscillations becomes undistinguishable for dust particles lighter than the critical mass.

Keywords:

Debye sheath, ionizing presheath, dust particle, dynamics, delayed charging, oscillations

1. Introduction

A dust particle as any immersed into plasma body obtains usually negative electric charge that is self-consistent with surrounding plasma parameters and can be as large as $10^{4\text{-}5}e$. Thanks to both the big size and charge dust particles can be considerably accelerated by electric field and particle fluxes in plasma and strike the wall surface damaging processed materials or fly far from the wall contributing in impurity transport in fusion devices.

As known, the largest fields and plasma particles fluxes usually concentrated in near wall plasma where a sheath region exists. Due to this circumstance, the most of laboratory plasma-dust experiments concerned with dust particles levitating in the sheaths. Recently a number of theoretical and numerical studies devoted to investigation of the dust particles charging and levitating in sheaths as well as altering of the sheaths potential distributions by dust [1–6]. Usually these studies consider self-consistently charged immovable dust particles or their stationary states [1–5]. In many works, simple fluid plasma models for sheaths are considered with boundary conditions that satisfy the Bohm criterion [5,6]. That does not allow to analyze dust particles motion in extent quasineutral but nonuniform transition region or presheath where ions are accelerated up to the sound speed and for formation of which some presheath mechanism (ion-neutral momentum loss collisions, ionization or oblique magnetic field) is necessary [7].

In the present work, we analyze motion of a single dust particle that started from the wall including charging dynamics on wide range of dust radii and masses in both sheath and presheath, which were simulated with particle model of plasma.

2. Model

Simulation of one-dimensional plane model of plasma is carried out using one-dimensional in real space and three-dimensional in velocity space (1D3V) particle-in-cell code. The plasma includes protons, electrons, and neutral hydrogen atoms with constant density n_a and temperature T_a. The simulated system of the length L is bounded at one side by isolated perfectly absorbing wall and at another side by the bulk hydrogen plasma with fixed electron and ion densities $n_e = n_i = n_b$ and the corresponding temperatures T_{eb}, T_{ib}. Electrons and ions with positive velocities are injected through the bulk plasma boundary into the system. That provides the bulk plasma boundary condition in the form of half-Maxwellian incoming fluxes of electrons and ions. Ionization of hydrogen atoms by electron impact is accounted in the system using Monte-Carlo technique [8] to provide the ionizing presheath.

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Boundary conditions constitute zero potential at the bulk plasma boundary, $\varphi(-L) = 0$, and the electric field at the wall $E_w = -\sigma_w / \varepsilon_0$, which corresponds to the wall's accumulated surface charge density $\sigma_w < 0$, where ε_0 is the dielectric constant. The parameters of the bulk plasma were chosen $T_{eb} = T_{ib} = 10$ eV and $n_b = 10^{12}$ cm^{-3} that close to parameters of divertor plasmas of present fusion devices. The system length is $L = 100\lambda_D$, where $\lambda_D = (\varepsilon_0 T_{eb}/n_b e^2)^{1/2}$ is the electron Debye length in the bulk plasma, that is much longer than the expected sheath width. Therefore, it is possible to simulate the presheath, which length is order of ionization mean free path using the effective density of neutral hydrogen gas $n_a = 10^{15}$ cm^{-3} with the temperature $T_a = 0.025$ eV.

The motion of a spherical dust particle with a R_d in the simulated system is described by momentum and charging equations

$$m_d \frac{\mathrm{d}^2 x}{\mathrm{d}t^2} = F(x,t), \qquad \frac{\mathrm{d}Q_d(x,t)}{\mathrm{d}t} = I(x,t), \tag{1}$$

where m_d is the mass of dust particle and Q_d is its charge. We consider motion of the dust particle that initially placed at the wall as probable formation position with zero velocity and the charge that corresponds to the wall surface charge density $Q_d\ (t = 0) = -4\pi\varepsilon E_w R_d^2$.

Total force acting on the dust particle $F(x,t) = F_E(x,t) + F_d(x,t)$ includes the electrostatic force $F_E(x,t) = Q_d(x,t)E(x)$ and the ion drag force due to the absorption of ions $F_d(x,t)$, here $E(x)$ is the local electric field. We have not included gravitational force, because in dense plasma it can be neglected in comparison with the ion drag force and in general its direction in respect to the wall is not defined, for example, in the divertor of helical fusion devices. The charging current on the dust particle $I(x,t) = I_e(x,t) + I_i(x,t)$ consists of two components: electron current $I_e(x,t)$ and ion current $I_i(x,t)$.

Local values of the total force $F(x,t)$ acting on the dust particle and the charging current $I(x,t)$ are obtained using simulated distributions of plasma parameters in the system and the approximated electron and ion distribution functions. The real electron velocity distribution function is formed at any point by decelerating and reflecting of injected electrons in the decreasing potential, absorption by the wall and electron-neutral collisions. Here we approximate electrons by Maxwellian distribution function, which temperature corresponds to the simulated local effective temperature $T_e(x) = m_e(\langle v_e^2\rangle - \langle v_e\rangle^2)_x$, where m_e is mass of electron, v_e is local velocity of an electron. The ions are approximated as monoenergetic with the simulated local ion flow velocity $V_i(x)$. According to this approach and the Orbital Motion Limited (OML) theory [9] the ion drag force can be expressed as

$$F_d(x,t) = \pi R_d^2 m_i n_i(x) V_i^2(x)\left(1 - \frac{Q_d(x,t)e}{2\pi\varepsilon_0 R_d m_i V_i^2(x)}\right), \tag{2}$$

and the electron and ion currents to the dust particle are

$$I_e(x,t) = -\pi R_d^2 e n_e(x)\sqrt{\frac{8T_e(x)}{\pi m_e}}\exp\left[\frac{Q_d(x,t)e}{4\pi\varepsilon_0 R_d T_e(x)}\right], \tag{3}$$

$$I_i(x,t) = \pi R_d^2 e n_i(x) V_i(x)\left(1 - \frac{Q_d(x,t)e}{2\pi\varepsilon_0 R_d m_i V_i^2(x)}\right), \tag{4}$$

where m_i is ion mass, $n_i(x)$ and $n_e(x)$ are the local ion and electron densities, respectively. It should be noted that in relative ion and electron to dust motion we neglected the dust particle velocity because of large dust mass.

3. Results

The computer simulations of plasma in the system were carried out in [10] and the spatial distributions of electric potential, electron and ion charge densities, flow velocities and effective temperatures were obtained. The typical picture of plasma profiles in sheaths was observed. The simulated electrostatic potential monotonically decreased toward the wall. The largest potential drop accompanied with steep acceleration of ions and decreasing of electron and ion densities occurred at the positively charged Debye sheath in front of the wall. The quasineutral presheath with small plasma density gradient and electric field provided smooth transition of perturbed by the wall plasma to the parameters of bulk plasma. We had set the imaginary sheath boundary at the point where the Bohm criterion is satisfied [7,11]. The obtained sheath width was order of a few Debye lengths that is much shorter comparatively with the presheath scale. Therefore, the dust particles motion started at the wall is considered here in the continuous sheath-presheath system extended far from the wall.

As was shown in previous works [3–6], usually there is equilibrium position for a dust particle with fixed radius around which it can oscillate. We have shown [10] that the first critical dust radius R_{c1} exists, so that bigger dust particles cannot leave the wall due to large ion drag force. The dependencies of the farthest positions that a dust particle

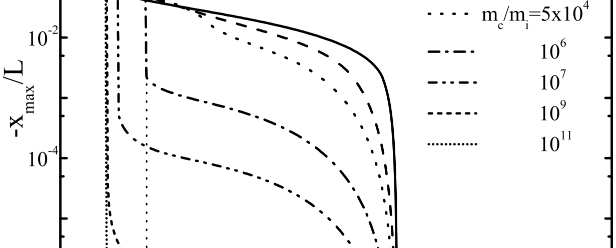

Fig. 1 Dependencies of the farthest position that dust particles reach moving off the wall on their radii for various masses of the dust particles.

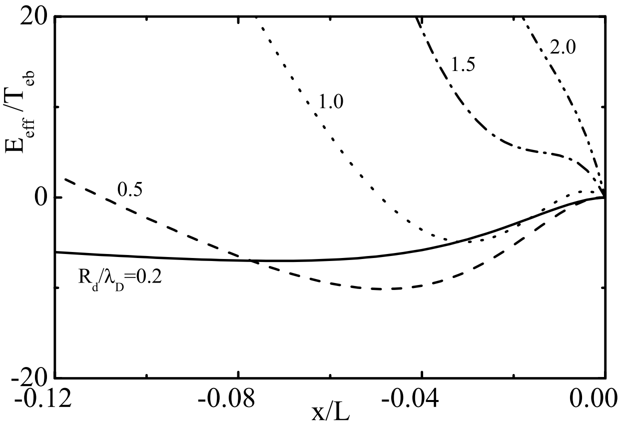

Fig. 2 Spatial profiles of effective potential energy for heavy dust particles with different radii.

reaches moving off the wall in the simulated system on its radius are shown in Fig. 1 for various masses of the dust particle. In Fig. 1 one can see that there is no motion of dust particles of any masses, which size is bigger than the first critical radius R_{c1}. Otherwise the dust particle can leave the wall penetrating into the plasma on maximal distance x_{max}.

There are two types of motion of the heavy dust particles sharply discriminated by the second critical radius R_{c2} between the short and long-range trajectories. Existence of such trajectories for very heavy dust particles, which oscillation frequencies are much smaller than charging frequencies, can be described with effective potential energy $E_{eff}(x) = \int_0^x F(x')\mathrm{d}x'$, Fig. 2. Dust particles smaller that the critical radius R_{c2} have positive gradient of the effective energy near the wall and potential minimum around which they oscillate reaching far from the wall positions. Dust particles bigger that R_{c2} have no minimum of potential energy or separated from it with potential barrier that does not allow them to move far off the wall. Note, that such dust particles will be reattached to the wall, where they are recharged and detach from the wall again if theirs radii smaller than R_{c1}.

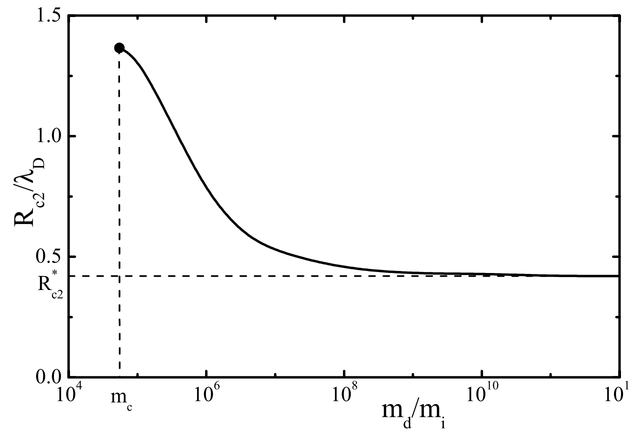

Fig. 3 Dependence of the second critical radius on mass of dust particle.

As can be seen in Fig. 1, radii of dust particles lighter than a critical mass m_c cannot be strictly differentiated in respect to dust particles trajectories. Thus, there is no second critical radius for them. The mass dependence of R_{c2} is shown in Fig. 3. The asymptotic value R^*_{c2} corresponds to the appearance of effective potential barrier in the above description of trajectories of very heavy dust particles. Lighter particles have no time to obtain equilibrium charge [10] at any position during motion, and strictly speaking, we cannot describe their motion with some effective potential energy. This delayed charging effect leads to increasing of the second critical radius with decreasing of the dust mass due to gradual relaxation during motion of the large initial dust charge, which corresponds to the wall potential. For very light dust particles with $m_d < m_c$ this effect is so strong that the electric field in sheath region propelled them against the ion flux for any dust radius that smaller that the first critical one.

4. Conclusions

Dynamics of a dust particle coming off the floating wall in sheath and presheath was analyzed in wide range of the dust radii and masses. The forces acting on the dust particle and the charging currents were calculated using spatial distributions of plasma parameters obtained with computer simulations. It was shown that in addition to the mass independent first critical radius of dust particles, which yields the bigger dust to stick on the wall, the second critical radius exists for heavy dust particles, $m_d > m_c$, which separates short and long-range trajectories. Dynamics of dust particle charging during motion causes dependence of the second critical radius on the dust mass and finally leads to its vanishing for $m_d < m_c$. Therefore, the behavior of dust particles in sheaths also critically depends on their mass rather than just size. That can be important for dynamics of porous or empty shell particles in future applications.

In the present work in order to estimate the currents and forces on the dust particle, we used the analytical OML approach, which is strictly valid only for particular spherically symmetrical potential distributions around the dust particle, where are no trapped ions. In order to obtain the precise plasma current to dust, a multidimensional particle simulation is necessary.

It should be noted that here we neglected an influence of single dust particle on plasma parameters in the sheath. It may not be the case for a large dust particle, which radius comprisable with the sheath width in very proximity to the wall, where mirror force can be important. These issues will be addressed in our future researches.

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