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Dusty sheaths in plasmas

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Abstract

Self-consistent dusty sheaths are simulated by the PIC/MC method in both plasmas with bi-thermal electrons and low-pressure RF discharges with a secondary electron emission from electrodes. The simulations are carried out by using plasma evolution without special boundary conditions for the sheaths that allows getting a self-consistent description of the sheaths. Simulation results show that dust particles can essentially influence spatial distributions of plasma parameters in the sheaths due to the space electric charge of the dust particles and a non-equilibrium of the electron energy distribution function. In particular, the spatial distributions of a self-consistent electric potential can be non-monotonic so that charged dust particles can protect electrodes from an intensive ion sputtering by decreasing the energy of ions arriving to the electrodes.

Keywords: Plasma-wall interactions; Sheath; Dust particles; Computer simulation; PIC-MCC method

1. Introduction

Numerous works have been published concerning sheaths which can be realized in fusion plasma devices including sheaths in plasmas with bi-thermal electrons, and RF sheaths. Plasmas with two-temperature electrons can be realized in edge plasmas of fusion devices consisting of energetic (hot) electrons due to plasma heating by strong RF fields. RF sheaths separate electrodes under an RF voltage from the plasma in the cases of RF heating and plasma diagnostics. The sheaths can consist of dust particles appearing as the product of plasma-wall interaction in various technological devices including controlled fusion devices [1]. The dust particles can essentially influence the sheath parameters due to the continuous selective collection of background electrons and ions that can cause an essential change of both electron and ion energy distribution functions as well as an ion flux in sheaths [2,3].

Usually, the sheaths are investigated under an assumption about equilibrium electrons however the electron equilibrium essentially can be disturbed in collisionless sheaths [4]. Therefore the aim of this work is to investigate dusty sheaths by using a kinetic computer simulation without assumptions about equilibrium electrons.

2. Models

Sheaths are investigated theoretically very often without presheaths due to their essentially different time and space scales. Usually, relatively simple Bohm's boundary conditions formulated a long time ago [5] or their modified variants are used. The conditions consist of assumptions about equilibrium electrons, cold or warm equilibrium ions as well as the zero electric

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potential and field at the sheath edge where a drift ion velocity is equal to the ion sound speed in non-disturbed plasma. Unfortunately, the Bohm's boundary conditions are not self-consistent and therefore the sheath description obtained in the framework of the boundary conditions is also not self-consistent.

However there are several simple possibilities to consider the self-consistent dusty sheaths with presheaths as a result of plasma evolution. The possibilities include finding of asymptotic behavior of rarefaction waves created by electrodes or walls immersed into plasma [6], and a general consideration of the entire plasma with given boundary conditions on electrodes and walls [7]. The possibilities are used in this work by computer simulations of bounded dusty plasmas to get parameters of self-consistent dusty sheaths without special boundary conditions for the sheaths.

In the case of sheaths in plasmas with bi-thermal electrons, a temporal evolution is simulated of a one-dimensional slab plasma due to a collection of electrons and ions by a plane electrode initially immersed into the plasma. It is assumed that the collisionless slab quasi-neutral plasma is uniform initially and consists of two groups of electrons with densities n_{ec} and n_{eh} and temperatures T_{ec} and T_{eh}, respectively, as well as hydrogen ions with a density $n_0 = n_{ec} + n_{eh}$ and a temperature T_{i0}. Besides, motionless spherical neutral dust particles of given radius R_d are distributed close to the electrode according to a given initial distribution. The plasma starts to evolve after the initiation of a collection of background electrons and ions by the electrode and dust particles, which are charged due to the collection.

In the case of RF sheaths with the secondary electron emission, it is simulated by one-dimensional RF discharge between two plane electrodes separated by the gap of $d = 2.0$ cm which is filled with Ar at various pressures. Immobile dust particles of a given radius R_d are distributed uniformly in the interelectrode gap. The dust particles collect and scatter electrons and ions distributed in the discharge with densities n_e and n_i, respectively. The harmonic external voltage $V_e(t) = V_0 \sin(wt)$ of the frequency $f = 13.56$ MHz and the various amplitudes V_0 sustains the RF discharge. The electron-argon collision cross-sections used in the model are the same as those used in [8,9]. The secondary emission is taken into account in the framework of models [10,11] or various given constant yields γ of the effective secondary emission are used.

In all cases, the PIC/MC method (1D3V model) described earlier [12] in detail is developed for computer simulations of the plasma evolution with dust particles. The method is based on a kinetic description of the motion of positive and negative 'superparticles' in phase space under the influence of a self-consistent electric field E. The field is obtained by solving of the Poisson equation using a computational grid, which is introduced by uniformly dividing the simulation region. The electrode collects a 'superparticle' if its center reaches an electrode surface.

The Monte Carlo technique [12] is used to describe the interactions of electrons and ions with dust particles. The interactions include Coulomb's collisions of electrons and ions with dust particles, as well as the electron and ion collection by dust particles. The cross-sections of an electron and ion collection by dust particles are taken according to the orbit motion limited theory [13]. The Coulomb cross-section for electron and ion scattering by immobile dust particles is taken from [14].

Simulations start with an initial uniform distribution of electrons and ions and are prolonged usually up to the moment when a change of spatial distributions was not exceeding about 5% in the sheath at the moment.

3. Results

3.1. Sheaths in plasmas with two-temperature electrons

Simulation results of a one-dimensional slab plasma evolution obtained for various ratios $\alpha = n_h/n_0$ of the hot electrons density (n_h) to the total density $(n_0 = n_h + n_c)$ of all electrons and various ratios of initial temperatures $\beta = T_h/T_c$ of hot (T_h) and cold (T_c) electrons show that a disturbance of the electron and ion densities is formed close to the electrode due to the collection of electrons and ions by a plane electrode immersed into a plasma with bi-thermal electrons. The disturbance penetrates continuously in the undisturbed plasma forming a disturbance wave, which propagates in the dusty region initially and then transits into the plasma without dust particles converting into a rarefaction wave.

The propagation of the rarefaction wave in the undisturbed plasma is accompanied by a relaxation of the plasma parameters behind the wave and form a sheath in front of an electrode. The formation can be seen in Fig. 1 where the spatial distributions of the self-consistent electric potential ϕ divided by the characteristic potential $\phi_0 = kT_c/e$ of the cold electrons are shown for various times t after the start of the collection of electrons and ions at $\alpha = 0.33$, $\beta = 20$. Note that the spatial coordinate x is normalized by the initial Debye length $\lambda_d = (kT_c/4\pi n_0 e^2)^{1/2}$ of cold electrons with the total density n_0. The time t is multiplied by the initial ion plasma frequency $\omega_{pi} = (4\pi n_0 e^2/M)^{1/2}$. As can be seen in Fig. 1, the spatial distribution evolves from a monotonic distribution initially to a non-monotonic distribution.

Of course, non-monotonic spatial distributions of the self-consistent electric potential ϕ are caused by the total space electric charge Q_t. A typical spatial distribution of the charge Q_t is shown in Fig. 2 by the corresponding

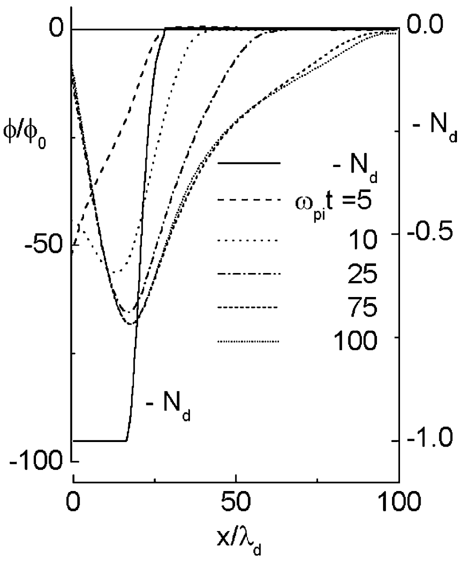

Fig. 1. Spatial distributions of the electric potential ϕ divided by the characteristic potential $\phi_0 = kT_0/e$ of cold electrons for various time t after a start fo a collection of electrons and ions at $\alpha = 0.33$, $\beta = 20$. Curve N_d is the spatial distribution of the number of dust particles in a Debye cube.

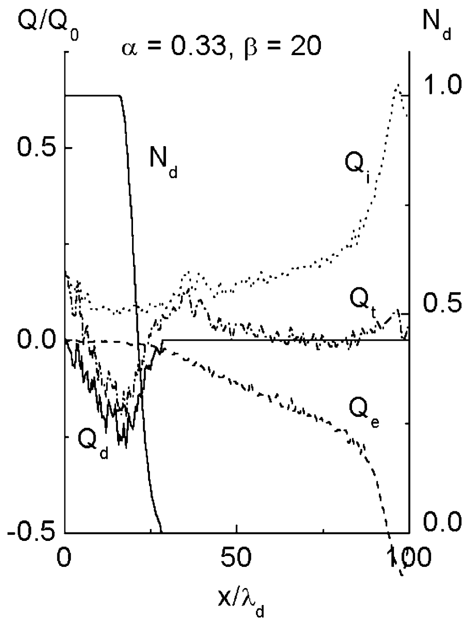

Fig. 2. Spatial distributions of the total space electric charge Q_t as well as electric charges of electrons Q_e, ions Q_i and dust particles Q_d divided by the initial ion space charge Q_0 for conditions of Fig. 1.

curve for the late evolution stage when the sheath formation is finished. As can be seen in Fig. 2, a distinctive peculiarity of the Q_t distribution is a region of negative charge, which causes the non-monotony of the electric potential. The total charge Q_t consists of electric charges of electrons Q_e, ions Q_i, and dust particles Q_d whose spatial distributions are shown also in Fig. 2 by corresponding curves. Note the electron space charge Q_e is very small compared to the ion space charge Q_i in the region of dust particles. It is caused by the usual strong decrease of the electron density in sheaths due to an action of decelerating electric fields.

Therefore the total negative space charge is caused mainly by the total negative charge Q_d of dust particles, which is shown by the corresponding curve in Fig. 2. The charge Q_d is a result of the balance between electron and ion currents into a dust particle, as usually. Our computer simulations show that the ion current density is about constant across the sheath due to rare collisions of ions with dust particles like to [2]. Therefore it is possible to propose that the ion flux into a dust particle be also about constant because the ion drift velocity exceeds essentially the ion random velocity. The electron current into a dust particle decreases continuously including the region of dust particles where the decrease is caused by the continuous collection of electrons even in the region of the reverse change of the self-consistent electric potential. As a result, the total charge Q_d of dust particles shown in Fig. 2 by the corresponding curve changes non-monotonically across the dusty region. The negative charge Q_d increases at the boundary of dust particles due to the increase of the dust particle density and then decreases due to the change of the balance of electron and ion currents into a dust particle.

The non-monotonic self-consistent electric potential in the front of the electrode with a potential minimum in the dusty region protects the electrode from the intensive ion bombardment because the ions reach the electrode with a lower energy. Therefore it is of interest to analyze the dependencies of the protection on parameters of plasmas with bi-thermal electrons. The obtained results show that the minimum negative potential is shifted and changed with a change of the spatial distributions of dust particles and plasma parameters.

As can be seen in Fig. 3, the negative minimum potential ϕ_{min} divided by the characteristic potential $\phi_0 = kT_c/e$ of cold electrons decreases nearly linearly with increasing temperature ratio $\beta = T_h/T_c$ of hot (T_h) and cold (T_c) electrons as with the probe floating potential. The potential depends also on the density ratio $\alpha = n_h/n_0$ of the of hot electrons (n_h) to the total density $n_0 = n_h + n_c$ of all electrons. The analysis shows that the dependence of the potential ϕ_{min} on α and β cannot be described by a dependence of the potential on the effective averaged temperature because a primary collection of fast electrons by electrodes and dust particles causes a quick deviation of the electron energy distribution function from an equilibrium. It is clearly seen in Fig. 3 that the negative potential is independent of the

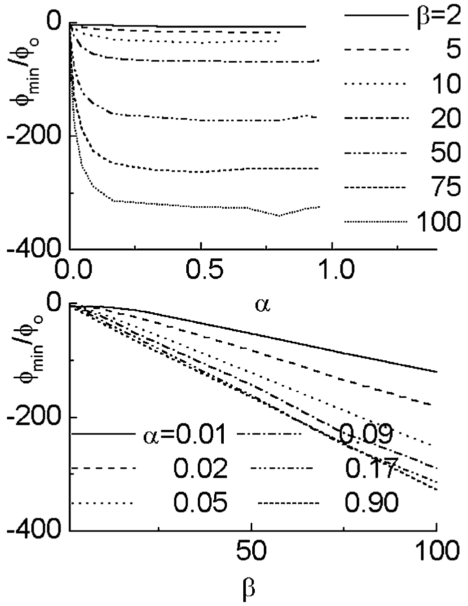

Fig. 3. Dependencies of the negative minimum potential ϕ_{min} divided by the characteristic potential $\phi_0 = kT_0/e$ of cold electrons on α and β parameters.

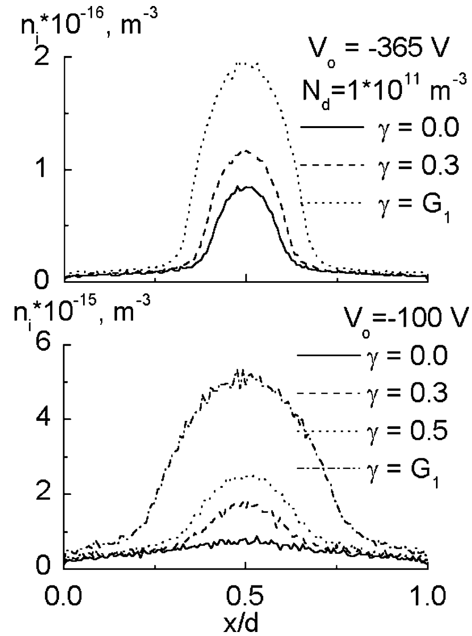

Fig. 4. Spatial distributions of the ion n_i density for various γ and V_0.

number of hot electrons for approximately at $\alpha > 0.3$ due to the primary collection of fast electrons.

3.2. RF sheaths with secondary electron emission

The influence of the secondary emission on the dusty RF discharge can be seen in Fig. 4 where spatial distributions of the ion n_i density across the interelectrode gap are plotted for various both effective secondary-emission yields γ and amplitudes V_0 of the harmonic external voltage. It is seen that the increase of the constant yields γ causes an essential increase of the ion n_i density in the central part of the discharge at $V_0 =$ constant whereas the ion density is maintained practically in the RF sheaths. The density increase is caused by an additional ionization in the central discharge part by secondary electrons. As the obtained results show, the remarkable influence of the secondary emission on the discharge parameters takes place only at $\gamma > 0.2$. Note, the discharge parameters obtained in the framework of the secondary emission model [11] ($\gamma = G_2$) do not differ from the parameters in the discharge without the secondary emission ($\gamma = 0$) because the effective secondary emission yields γ in the model are less than $\gamma = 0.2$. The model [10] provides a very strong increase of the ion density in the central discharge part because the model gives the effective secondary emission yield γ, which can amount to high values.

Spatial distributions of the dust particle charge q_d are shown in Fig. 5 for the conditions of Fig. 4. As can be seen in Fig. 5, the charge q_d is very weakly dependent on the yield γ at $V_0 = 365$ V unlike the ion n_i density shown in Fig. 4. It is a typical result for intensive RF discharges

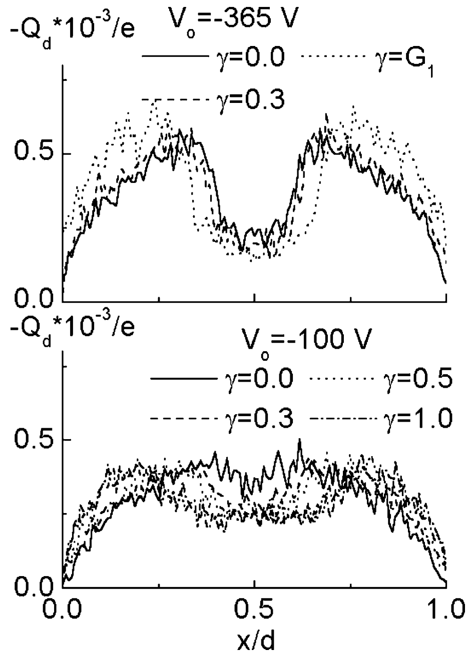

Fig. 5. Spatial distributions of the dust particle charge q_d for various γ and V_0.

and is caused by the dust particle charging in low-pressure RF discharges considered earlier in [7]. It was shown here that non-monotonic profiles of the dust particle charge in RF discharges are caused by the change of the ion current into a dust particle in a non-uniform quasi-neutral plasma with common fast electrons due to their fast mixing in slow electric fields. The simulations of RF discharges with the secondary emission show that the ratio of the electron and ion currents into a dust particle is nearly conserved when the effective secondary emission yields γ change in the intensive RF discharges that causes the invariability of the dust charge distributions.

Typical examples of spatial distributions of the dust particle charge q_d for slow RF discharges are shown in Fig. 5 in the case of $V_0 = 100$ V. As can be seen in this case, the secondary emission changes a few the negative charge of a dust particle in the quasi-neutral central part of the discharge due to the more intensive RF discharge. However the change of the yield γ does not result in the change of the spatial distributions as in the intensive RF discharges.

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