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Self-consistent Sheaths in RF Dusty Plasmas

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Abstract

Self-consistent RF sheaths are investigated using a self-consistent 1D PIC/MC simulation of a RF discharge in argon with dust particles distributed uniformly in an interelectrode gap. Spatial distributions of discharge parameters across the discharge interelectrode gap were simulated at various densities of dust particles, namely: the electron and ion densities, the electric potential and field, the time-averaged electron energy distribution function, as well as the charge of dust particles. Obtained results shown that the RF discharge with dust particles has non-stationary sheaths with a strong electric field separating the electrodes from a quasi-neutral central part. The dust particles essentially influence the spatial distributions of discharge parameters, in particular an increase of a dust particle density causes an expansion of sheaths. The dust particle charge changes non-monotonously across the interelectrode gap and has maximum close to a sheath edge, due to the spatial distribution of plasma parameters and a peculiarity of the electron energy distribution function in the quasi-neutral central part of the RF discharge.

Keywords:

dusty plasma, sheath, RF discharge, electron energy distribution function, dust charge

1. Introduction

RF sheaths separate electrodes under a RF voltage from plasma in many cases including RF heating of fusion plasmas by RF antennas, plasma diagnostics, and plasma processing in the microelectronics industry (e.g. plasma etching, plasma deposition, and plasma surface modification). The sheaths can contain dust particles, which can appear here due to an interaction of the plasma with the electrodes [1-3] or can be immersed from outside [4-7]. Dust particles can be levitated close to a RF sheath edge because the gravitational force acting on dust particles can be compensated here by a the force of the mean electric field. Besides, the conditions needed for the creation of a plasma crystal can be satisfied here. The first requirement is a strong non-ideality of the considered system, i.e. a large ratio of potential and kinetic energies of dust particles screened by background electrons and ions. Plasma crystals created by dust particles are intensively investigated now.

Dust particles can essentially influence the properties of RF sheaths due to the action of a self-consistent electric field created by charged dust particles and due

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to the collection of background electrons and ions by dust particles, like the influence on DC sheaths [8]. Both reasons indicated above depend strongly on the interaction between dust particles. Dust particles interact in dusty plasmas through a shielded Coulomb potential that is determined by both the self-consistent charge of dust particles and the characteristic shielding length. Both the charge and the shielding length have non-equilibrium values in dusty plasmas, especially in sheaths, due to the non-equilibrium distribution of background electrons and ions caused by their selective collection by dust particles [8,9] as well as due to the mutual interaction of dust particles [10].

Therefore many experiments were carried out to measure the dust charge and the dust screening length using the properties of dust oscillations or dust waves as well as shocks in RF sheaths (see for example [2,3,11-14]). However, the properties of dust oscillations or dust waves in RF sheaths depend not only on the dust charge and the dust screening length but also on the spatial distribution of the sheath parameters, especially the electric potential. Therefore, detailed investigations of RF sheaths with levitated dust particles, including computer simulations, are very actual for understanding the influence of dust particles on the sheaths. The aim of this work is 1D-computer kinetic simulations of RF discharges in argon with dust particles, which can be considered as a physical model of dusty plasmas. The kinetic simulation of dusty RF discharges was not carried out earlier.

2. Model

Electrodes or walls disturb plasmas due to the difference in the amount of electrons and ions absorbed from plasma; the disturbance penetrates far into plasma. The disturbed plasma region can be divided into a charged sheath and a quasi-neutral presheath, if these sub-regions essentially exceed a characteristic Debye length [15].

Self-consistent sheaths have to be simulated together with the corresponding presheaths in order to solve the complex problem of providing boundary conditions for sheaths [15]. Another approach is to use a self-consistent solution for a rarefaction wave in plasma [16]. However in case of sheaths created in a gas discharge plasma, the best approach is a self-consistent simulation of the entire gas discharge with corresponding boundary conditions on electrodes or walls.

In our case, a one-dimensional RF discharge between two plane electrodes separated by a gap of $d = 2.7$ cm filled with Ar at a pressure of 0.1 Torr is simulated. Immobile dust particles of 1 μm radius are distributed usually uniformly in the interelectrode gap with a density N_d. The uniform spatial distributions of dust particles allow us better estimate their role in various regions of the RF discharge. The dust particles collect and scatter electrons and ions distributed in the discharge with a (non-uniform) density n_e and n_i, respectively. A harmonic external voltage $V_e(t) = V_o \sin(\omega t)$ at a frequency f = 13,56 MHz with an amplitude V_o = 350 V sustains the RF discharge. The electrode at $x = d$ is grounded.

The PIC/MC method described in detail in [17] for discharges without dust particles is modified for computer simulations of the RF discharge with dust particles. The self-consistent electric field E is obtained by solving Poisson's equation using a computational grid, which is introduced by a uniform division of the interelectrode gap into 128 simulation cells. An electrode collects a "superparticle" if its center reaches the electrode surface. Each superparticle represents 8×10^7 real electrons or ions. The size of the electrodes, needed to compute the total current, is 0.04 m^2.

The Monte Carlo technique [18] is used to describe electron and ion collisions. The collisions include elastic collisions of electrons and ions with atoms, ionization and excitation of atoms by electrons, charge exchange between ions and atoms, Coulomb collisions of electrons and ions with dust particles, as well as the electron and ion collection by dust particles. The electron-argon collision cross-sections used in the model are the same as those used in [19]. The Coulomb cross-section σ for electron and ion scattering by immobile dust particles is taken from [20]. The cross-section for collection of an electron or ion by a dust particle is taken from [21].

The simulation starts with an initial uniform distribution of electrons and ions with densities equal to 10^{15} m^{-3} and is prolonged by iterations up to a moment when the change of the discharge parameters is less than 0.1 %. Simulations show that 400 cycles are enough to obtain the periodic steady state.

3. Results

Obtained spatial distributions of the electric field E across the interelectrode gap of the RF discharge are shown in Fig. 1 for various densities N_d of dust particles of 1 μm radius for various phases t/T of the sustaining external voltage where T is the RF period. The distributions show the existence of the central quasi-neutral region and non-neutral RF sheaths close to both

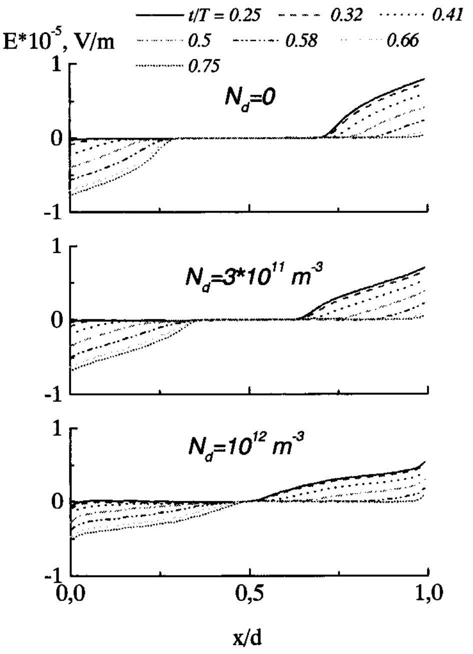

Fig. 1 Spatial distributions of the electric field E for various densities N_d of dust particles including the case without dust particles (N_d = 0), and for various phases t/T of the sustaining external voltage where T is the period of the external voltage.

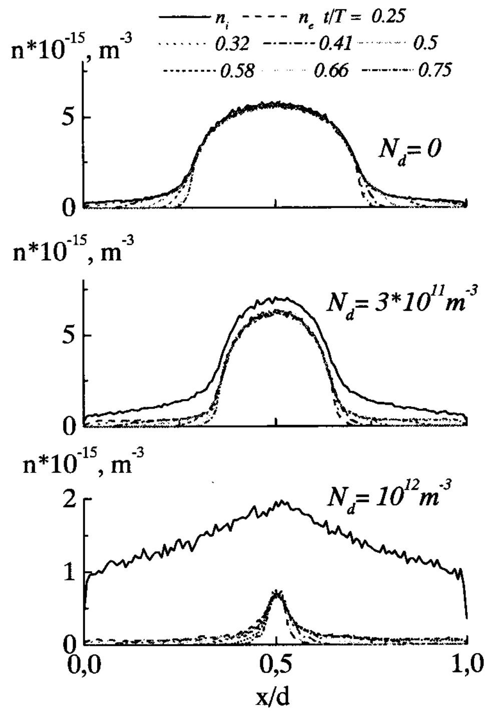

Fig. 2 Spatial distributions of the electron n_e and ion n_i densities for various densities N_d of dust particles including the case without dust particles (N_d = 0), and for various phases t/T of the sustaining harmonic external voltage where T is the period of the external voltage.

electrodes. The quasi-neutral part of the interelectrode gap corresponds here to $E = 0$ so that the sheath edge is a point between this region and the region with $E \neq 0$. The sheath edge, which corresponds to the boundary between the charged sheath and the quasi-neutral presheath [15], shifts to or from electrodes depending on the phase of the sustaining external voltage. As can be seen in the Fig. 1, the sheath edge approaches the grounded electrode and is moving away from the opposite electrode between phases $\pi/2$ and $3\pi/2$ of the sustaining external voltage. Note that the size of the central quasi-neutral part is decreased with the increase of the dust particle density N_d. This is caused by the influence of dust particles on the RF sheath size. Indeed, the sheath size is determined by a condition that an applied voltage is compensated by the total space sheath charge. As can be seen later (Fig. 3), immobile dust particles have a negative charge and therefore compensate partially the ion screening of the sustained voltage in the sheath and consequently increase the RF sheath size at the same voltage.

Spatial distributions of the electron (n_e) and ion (n_i) density across the interelectrode gap are shown in Fig. 2 for conditions of Fig.1. As can be seen in Fig.2, there are stationary spatial distributions of the ion density n_i and changed spatial distributions of the electron density n_e because the sustained voltage frequency by far exceeds the ion plasma frequency and is comparable to or less than the electron plasma frequency. Note that the electron density decreases smoothly in the RF sheath, unlike the stepwise drop in the front model [22], because the Debye length is not negligable compared to the sheath size in our case.

As can be seen in Fig. 2, dust particles essentially change the spatial distributions of the electron and ion densities. First of all, a difference between these densities appears in the central part of the RF discharge with dust particles. The difference increases with an increase of the dust particle density so that the ion density by far exceeds the electron density at large densities of dust particles. The indicated difference is caused by the negative total electric charge Q_d of dust particles of which spatial distributions are shown in the upper part of Fig. 3 for various values of N_d.

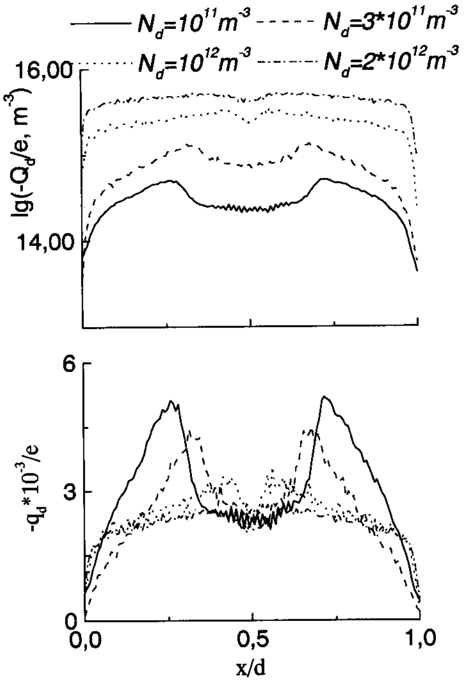

Fig. 3 Spatial distributions of the total electric charge density Q_d of dust particles and the dust particle charge q_d across the interelectrode gap for various densities N_d of dust particles.

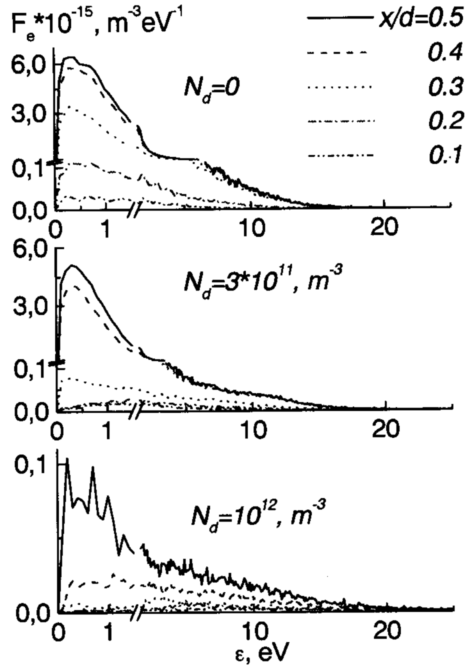

Fig. 4 Averaged electron energy distribution functions F_e in various points x/d of the interelectrode gap for various densities N_d of dust particles including the case without dust particles (N_d = 0).

Note the non-monotonic spatial distributions of the dust particle charge q_d shown in the bottom part of Fig. 3. As can be seen here, the charge q_d in the quasi-neutral central part of the RF discharge is equal to about 2.5×10^3 e, corresponding to a surface potential of 3.6 eV. The charge q_d increases towards the sheaths and then decreases in the sheaths. As a result, the charge q_d has a maximum close to the sheath edge. This maximum shifts together with the sheath edge when the dust particle density N_d changes.

The complex spatial distribution of the dust particle charge is caused by the balance of the electron and ion charging currents onto a dust particle, as usually [7]. In our case of a non-uniform plasma with negatively charged dust particles, the ion charging current is proportional to the ion density and therefore has to decrease monotonically from the center of the interelectrode gap towards the electrodes due to the monotonic decrease of the ion density shown in Fig. 2. The electron charging current depends on the surface potential of the dust particles and the time-averaged energy distribution function F_e shown in Fig. 4 for the cases of Fig. 1. Note that the distribution functions F_e practically coincide in the energy region $\varepsilon > 3$ eV in the quasi-neutral central region of the interelectrode gap, due to a free mixing of fast electrons in this almost equipotential region. Therefore, the electron charging current onto a dust particle is almost the same for various points in the central region. The constant electron charging current and the decrease of the ion charging current cause the increase of the dust particle charge $|q_d|$, when moving outward from the centre (Fig. 4).

Another situation prevails in the sheaths where a free mixing of electrons is not possible due to the strong voltage drop in sheaths (Fig. 1). Therefore the number of fast electrons is not constant in various sheath points (Fig. 4) decreasing towards electrodes so that the electron charging current decreases also. Obtained results show that the ratio of the time-averaged electron density $\langle n_e \rangle$ to the constant ion density n_i decreases in the sheaths towards electrodes. This results in a decreasing dust particle charge q_d towards the electrodes, creating a maximum close to the sheath edge (Fig. 4).

4. Conclusion

Self-consistent 1D PIC/MC simulations of a RF discharge in argon with dust particles distributed uniformly in the interelectrode gap show that the dust particles essentially influence the spatial distribution of the discharge parameters. An increase of the dust particle density causes an expansion of sheaths.

The dust particle charge varies non-monotonously across the interelectrode gap and has maximum close to a sheath edge, due to the spatial distribution of the plasma parameters and free maxing of the energetic electrons in the quasi-neutral central part of the RF discharge.

Acknowledgments

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