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DUSTY RF DISCHARGES WITH NON-UNIFORM DISTRIBUTIONS OF DUST PARTICLES

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PIC/MC computer simulations of dusty RF discharges in argon with various profiles of the dust particle density in the interelectrode gap shows a slow influence of the profiles on a dust particle charge in the quasi-neutral region of the discharges. However the profile influence spatial distributions of electrons and ions in the interelectrode gap as well as the dust particle charge in sheaths.

1. INTRODUCTION

It is well known for a long time [1-4] that dust particles can be distributed very non-uniformly in dusty RF discharges concentrating close to the sheath edge. Recent experiments [5-8] show the formation of stable dust-free regions (voids) with sharp boundaries inside a dust cloud in the dusty RF discharges. The voids are observed both in laboratory experiments [5-7] and under microgravity conditions [8]. There are several attempts [9-12] to consider physical mechanisms for non-uniform distributions of dust particles in dusty RF discharges including the void creation. The consideration includes computer simulations of an evolution of dust clouds in the dusty RF discharges [9].

However the huge difference in the time scale of the dust motion and other processes (an ionization and an excitation of neutral atoms, a collection and a scattering of electrons and ion by dust particles) in RF discharges causes a necessary to use very complex hybrid simulation schemes. The schemes consist of several linked computer models, which can be solved by time splitting and an iterative procedure. Note that the processes indicated above can cause a strong non-equilibrium of electron and ion energy distribution functions that influence strongly in turn the non-elastic processes and dust particle charging [13,14].

The complex hybrid schemes need the very large computer resources complicating their use. Besides, the simultaneous account of many processes complicates understanding physical mechanisms of the void development. Therefore it is expediently to use simple simulation schemes allowing investigations of separated elements of the mechanisms.

The aim of the work is computer simulation of dusty RF discharges in argon with given various profiles of the dust particle density to investigate an influence of the profile on dusty RF discharges and to simplify the complex hybrid schemes of their simulations.

2. MODEL

A one-dimensional RF discharge between two plane electrodes separated by the gap of $d = 0.02\ m$, filled with Ar at pressure of $0.1\ Torr$, is simulated. Immobile spherical dust particles with a radius $R_d = 1\ \mu m$ are distributed in the interelectrode gap according to a given parabolic distribution $n_d = n_{do} + a(x-x_o)^2$ where n_d and n_{do} is the dust density and a minimum density of dust particles, respectively. Note that the minimum density can be located in any point of the interelectrode gap. The distribution can be changed at the condition of a conservation of the total number N_d of dust particles in the interelectrode gap so that the ratio $\alpha = n_{dm} / n_{do}$, where n_{dm} is a maximum density of dust particles, is changed. Of course, the case $\alpha = 1$ corresponds to the uniform distribution of dust particles with the density $n_{da} = N_d / Sd$ where S is the area of an electrode. The dust particles collect and scatter electrons and ions distributed in the discharge with density n_e and n_i, respectively. A harmonic external voltage $V(t)=V_o sin(\omega t)$ with a frequency of $13{,}56\ MHz$ and various amplitudes V_o sustains the RF discharge. The right electrode at $x=d$ is grounded.

The PIC/MCC method (PDP1D3v code) described in detail in [15] for discharges without dust particles is developed for computer simulations of the RF discharge with a non-uniform distribution of dust particles. An electrode collects a "superparticle" if its center reaches an electrode surface. Each superparticle represents $4*10^7$ real electrons or ions, for the charge distribution it is a cylinder with an end area $S=0.04\ m^2$ and a hight equal to the size of the simulation cell.

The Monte Carlo technique [15] is used to describe electron and ion collisions. The collisions include elastic collisions of electrons and ions with atoms, an ionization and excitation of atoms by electrons, the charge exchange between ions and atoms, Coulomb's collisions of electrons and ions with dust particles, as well as the electron and ion collection by dust particles.

Electron-electron collisions are not taken into account due to the low argon ionization degree $\beta = n_e/n_a$ where n_e and n_a is electron and atom density, respectively. The degree is equal about to 10^{-6} for our conditions (see below Fig. 2). Indeed, electron-electron collisions are essential with respect to electron-atom collisions if the electron-electron energy exchange is essential in comparison with the electron-atom energy exchange. The boundary condition corresponding to the energy exchanges is $\gamma_{ee}q_{ee}n_e^2v_e \sim \gamma_{ea}q_{ea}n_en_av_e$ where γ and

q are the energy accommodation coefficient, and the effective cross-section, respectively for electron-electron (ee) and electron-atom (ea) collisions, v_e is the electron velocity. Simple estimations show that an argon ionization degree $\beta = n_e/n_a$ corresponding to the last condition exceeds the value of 10^{-6} at least for fast electrons determining the excitation and the ionization of atoms as well as the dust particle charge.

The cross-sections of electron collection by immobile dust particles is taken according to the Orbit Motion Limited (OML) theory [16]. The Coulomb cross-section for electron and ion scattering by immobile dust particles is taken from [17].

The simulation starts with an initial uniform distribution of electrons and ions with densities equal to 10^{15} m^{-3} and is prolonged in time using a leap-frog scheme up to the moment when the change of the discharge parameters during 10 periods of the applied voltage is less *0.1 %*. The simulations show that no more than 500 cycles are needed to obtain the periodic steady state of RF discharges. Note that the simulation time can be strongly different from relaxation times of various collisions due to an initial electron density.

3. RESULTS

Spatial distributions of the dust particle density n_d used in the simulations are shown in Fig. 1 for various ratios $\alpha = n_{dm} / n_{do}$ of a maximum n_{dm} and minimum n_{do} density of dust particles, as well as for various positions x_o of the minimum density of dust particles. Curves in Fig. 1 are chosen at a conservation of the total number N_d of dust particles in the interelectrode gap of the RF discharge. The case of $\alpha = 1$ corresponds to uniform distributions of dust particles with $n_d = 1*10^{12}$ m^{-3}.

Spatial distributions of the electron n_e (straight lines) and ion n_i (dashed lines) density across the interelectrode gap are shown in Fig. 2 (cases *a, b, c*) for

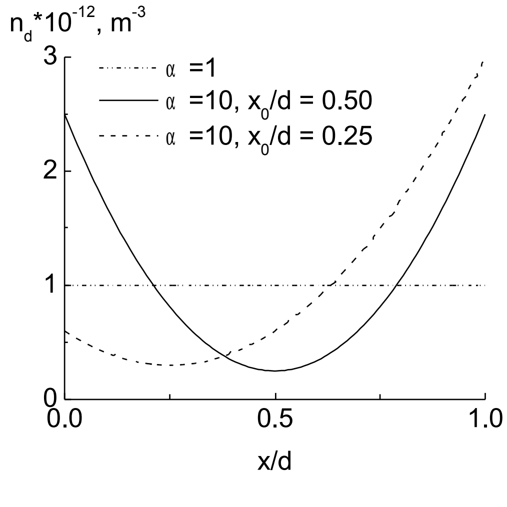

Fig. 1. Spatial distributions of the dust particle density N_d

the cases of Fig. 1 at V_o = *300 V* and *p= 0.1 Torr*. In addition, the distributions are shown also in Fig. 2 (case *d*) for the RF discharge without dust particles. The distributions are obtained for the phase $\varphi = \omega t = 0$ of the harmonic external voltage *V (t)*. As simulation results show [14], spatial distributions of the ion density n_i does not change during the period of the sustaining external harmonic voltage but the electron density n_e changes in oscillating non-neutral RF sheaths close to both electrodes according to a phase $\varphi = \omega t$ of the sustaining voltage.

As can be seen in Fig. 2, there is the central quasi-neutral region where the electron density n_e is about equal to n_i and does not change like to the ion density n_i. It means a space charge of dust particles is small with respect to n_i and n_e, so that dust particles do not influence essentially a total space electric charge in

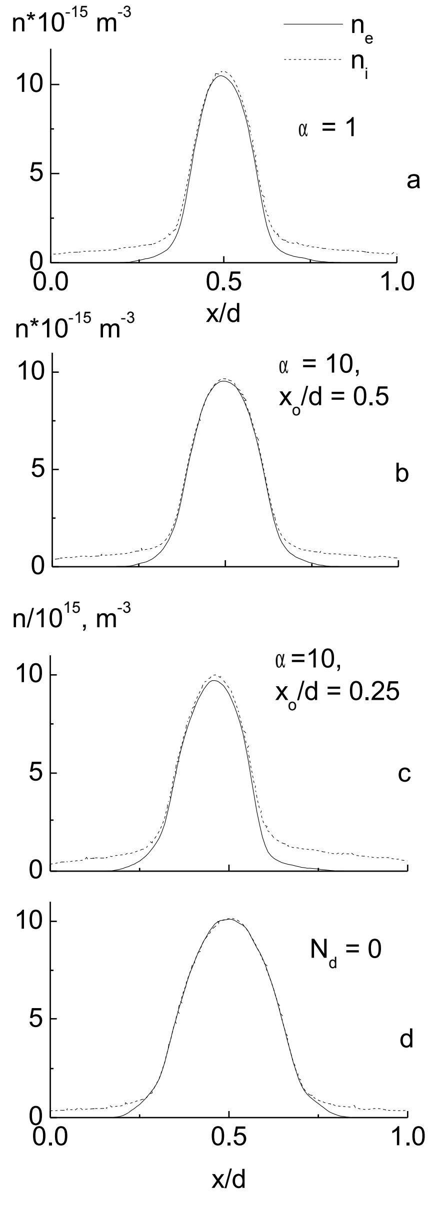

Fig. 2. Spatial distributions of the electron n_e and ion n_i density

simulated regimes.

As can be seen comparing various regimes in Fig. 2, a change of the dust density profile causes a change of the spatial distributions of the electron and ion density. First of all, dust particles expand RF sheaths (cases *a,b,c* in Fig. 2) with respect to the RF discharge without dust particles (case *d* in Fig. 2) and consequently constrict the central quasi-neutral region of the discharge. The indicated influence of dust particles is caused by an additional space negative electric charge of dust particles in the sheaths discussed earlier in [14]. Besides, as can be seen comparing Fig. 1 (straight and dashed lines) and Fig. 2 (cases *b* and *c*), the maximum of the electron and ion densities shifts towards the minimum of the dust density in a case of non-symmetric spatial distributions of dust particles. The effect can be essential for mechanisms of a void creation in dusty RF

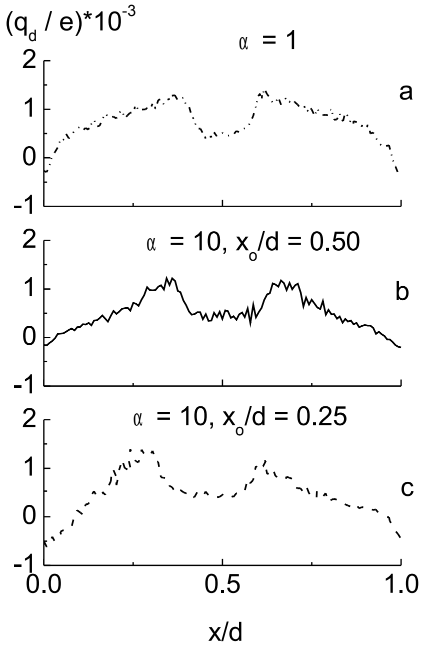

Fig. 3. Spatial distributions of the dust particle charge q_d

discharges.

Spatial distributions of the dust particle charge q_d divided by the negative electron charge *e* are shown in Fig. 3 for the cases of Fig. 1. As can be seen in Fig. 3, the negative charge q_d is practically constant in the quasi-neutral central part of the RF discharge. The charge is equal about to $7.5*10^2 e$ that correspond to the surface potential $V_s \sim 1.5\ eV$. The dust particle charge q_d does not change practically in the quasi-neutral region of the RF discharge at a change of a dust density profiles. Therefore it is possible to use the charge q_d, obtained for the quasi-neutral region in the case of uniform distribution of dust particles, at a simulation of a dust cloud evolution in RF discharges including a void creation.

As can be seen in Fig. 4, in which spatial distributions of the total space electric charge ρ are shown for cases of Fig. 2, the charge ρ is not changing also in the quasi-neutral region of the interelectrode gap.

However, the dust particle charge q_d is strongly changing in sheaths and even can change the sign. As can be seen in Fig. 3, the charge is positive close to the electrodes of the RF discharge and depends on the profile of dust particle density. The positive charge of dust particles is caused by a strong decrease of an electron density in sheaths close to the electrodes (see Fig. 2).

Comparing curves in Fig. 3, it can be seen that the charge q_d has a maximum close to the sheath edge, the maximum shifts together with the sheath edge at changing a dust particle density profile. The charge maximum is equal about to $1.3*10^3 e$ and the maximum is practically not depending on the profile of the dust particle density. Therefore the maximum charge obtained for corresponding uniform distributions of dust particles can be used also for simulations of a dust cloud

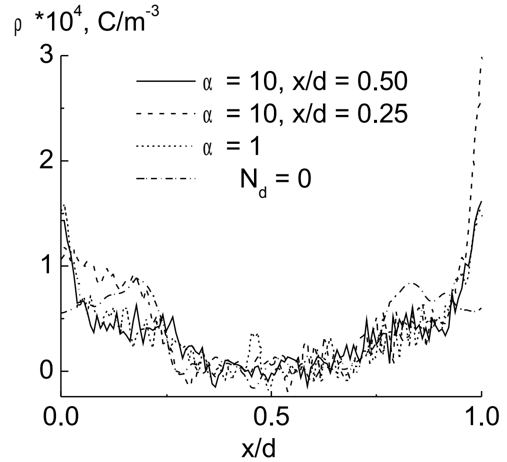

Fig. 4. Spatial distributions of the total electric space charge ρ

evolution in RF discharges including a void creation.

In the case of a non-symmetric distribution of dust particles (case *c* in Fig. 3), the spatial distribution of the dust particle charge q_d is also non-symmetric in sheaths. Comparing fig. 1 (dashed line) and Fig. 3 (case *c*), it can be seen that the dust particle charge is a few lower in the right region of the interelectrode gap, where the density of dust particles is higher. The decrease is caused by the higher ion density in the region (case *c* in Fig. 2).

The non-monotonic distributions of the dust particle charge q_d shown in Fig. 3, are caused by the peculiarities of dust particle charging in RF discharges. It is well known that the dust particle charge q_d is determined by a balance of electron and ion charging currents into a dust particle [18]. In the case of equilibrium uniform plasma without any emission from dust particles, a negative charge of an isolated dust particle depends strongly only on the electron temperature and the size of a dust particle. Furthermore, the negative dust particle charge can be diminished in plasmas with non-neutral dust particles due to a difference between electron and ion densities.

In our case of non-uniform plasma with negative charged dust particles, the ion charging current is proportional to the ion density and therefore has to decrease monotonically at a removal from the maximum of the ion density due to the monotonic decrease of the ion density shown in Fig. 1. The electron charging current is depending on the surface potential of dust particles and the averaged electron energy distribution function F_e.

As simulation results show [14], the distribution functions F_e coincide practically in the energy region ε >2eV in the quasi-neutral center region of the interelectrode gap, due to a free mixing of fast electrons in the almost equipotential center region. Therefore, the electron charging current into a dust particle is the same for various points in the center region. The constancy of the electron charging current and the decrease of the ion charging current in the center region of the interelectrode gap towards the sheath edge, cause the change of the dust particle charge q_d shown in Fig. 3.

Other situation takes place in sheaths where a free mixing of electrons is not possible due to a strong voltage drop in sheaths. Therefore the number of fast electrons is not constant in various sheath points decreasing towards electrodes so that the electron charging current decreases also in sheaths at a removal from the sheath edge towards electrodes. Besides, the mean electron density $<n_e>$ is less than the approximately constant ion density n_i in positive charged sheaths. As can be seen from simulation results, the density ratio $<n_e>/ n_i$ decreases here towards electrodes. As a result, the dust particles charge q_d decreases towards electrodes creating a maximum close to the sheath edge (Fig. 3).

4. CONCLUSION

The PIC/MCC computer simulation of dusty RF discharges in argon with various profiles of the dust particle density in the interelectrode gap shows a slow influence of the profiles on a dust particle charge in the quasi-neutral region of the discharges at low densities of dust particles. Therefore computer simulations of an evolution of dust clouds can be carried out using the dust particle charge in the quasi-neutral region of RF discharges (including the maximum value of the charge) obtained for a uniform distribution of dust particles in RF discharges. The change of the profile influence spatial distributions of electrons and ions in the interelectrode gap as well as the dust particle charge in sheaths.

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