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DUSTY SHEATHS IN NON-EQUILIBRIUM PLASMAS

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Self-consistent dusty sheaths are investigated using the kinetic PIC/MCC simulation of a temporal evolution of both dusty plasmas consisting of immersed electrodes (walls) and developing dusty discharges without special boundary conditions for the sheaths. Obtained results show an essential influence of dust particles on sheath parameters. Spatial distributions of a dust particle charge are not trivial due to a self-consistent evolution of electron and ion energy distribution functions.

1. INTRODUCTION

Electrostatic charged sheaths separate plasmas from electrodes or walls adsorbing charged particles (usually electrons and ions) from the plasmas. The sheaths are appeared due to a difference between fluxes of the adsorbed charged particles to electrodes or walls without sheaths. In the simple case of plasma without a magnetic field, the electron flux essentially exceeds the ion flux so that positively charged sheaths are created around negatively charged walls.

However the electrodes or the walls disturb the plasmas usually far from the sheaths creating here quasineutral non-uniform plasma regions with slow electric fields and slow gradients of a plasma density. The regions provide fluxes of charged particles to sheaths and are called presheaths [1]. Basic properties of the plasma-sheath transition were given in early works and considered in the detail review [2]. According to the works, a boundary between a sheath and a presheath can be determined only with a precision of several electron Debye lengths. Therefore according to the Bohm's theory [3] for sheaths in collisionless plasmas, a non-linear sheath around an electrode or a wall facing to plasmas consists of three distinct regions, namely: an ion (Child-Langmuir) sheath without electrons, a Debye sheath ranging over a few Debye lengths, and a plasma region where quasineutrality holds (presheath). In a case of equilibrium electrons and cold ions in collisionless plasmas, the sheath edge can be fixed conditionally as a point where a drift ion velocity u is equal to an ion sound speed $u_s = (kT_e/M)^{1/2}$ or an electric field E is equal to the characteristic electric field $E_o = kT_e /L_D$. The sheath edge fixed by the ion sound speed corresponds to the well known Bohm's boundary condition which used very often at a consideration of plasma sheaths.

However the electron equilibrium can be disturbed even in collisionaless sheaths (including the sheath edge) in plasmas with single electron specie. Indeed, electron energy distribution functions in collisionless plasmas are formed in any points by opposite electron fluxes, which have to be identical for equilibrium functions. Adsorbing electrodes or walls create directional electron fluxes due to a collection of tail electrons with the energy greater than the sheath potential energy so that the electrons do not return back into the plasma. As a result, the electron energy distribution function is truncated, however as was shown earlier [4], the disturbance is not essential for plasmas with a single electron species due to the smallness of such electron fraction. In case of non-equilibrium plasma electrons, the disturbance of the electron energy distribution functions can be more essential. For example, such situation can take place in plasmas with two-temperature Maxwellian electron distributions [5].

The sheaths can consist of dust particles appeared as the product of the plasma-wall interaction in various technological devices [6,7] including controlled fusion devices [8,9] or created due to coagulation of various components in chemically active plasmas with their subsequent transport into sheaths [10]. Besides, dust particles can be immersed from outside and be trapped in sheaths creating plasma crystals [11] investigated intensively now. Dust particles can essentially influence 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 [12] as well as an ion flux in sheaths.

2. MODEL

Usually sheaths are investigated without presheaths because of essential differed space and time scales of both regions. Of course at the investigations, boundary conditions have to be formulated at a sheath edge. Bohm's boundary conditions (or their later modifications) formulated for a hydrodynamic description of collisionless sheaths a long time ago [13], are used very often. The conditions consist of assumptions about equilibrium electrons, could ions as well as the zero electric potential and field at the sheath edge where a drift ion velocity is equal to the ion sound speed in non-disturbed plasma. The conditions were modified than for cases of warm ions including ions with a given energy distribution function [2], plasmas with two-temperature electrons [14,15] and are very popular also for investigations of sheaths in dusty plasmas up to last time [16,17].

Unfortunately, the Bohm's boundary conditions used in various works very often for sheaths in collisionless plasmas are not self-consistent. Indeed, it is not possible to find in the plasmas a point where the conditions are valid because an acceleration of ions to the ion sound speed from undisturbed plasma is possible only by a self-consistent electric field causing a continuous change of an electric potential. The change can be essential in the case of non-equilibrium electrons and ions indicated above.

However there are several possibilities to consider the self-consistent sheaths without special boundary conditions for the sheaths. The consideration is based on a study of a temporal evolution of systems including sheaths as a part of the systems. Examples of the consideration can be the asymptotic behavior of rarefaction waves created by electrodes or walls immersed into plasma [18] or the general consideration of entire discharge plasmas with given boundary conditions on electrodes and walls [1].

The self-consistent description of dusty sheaths has to consist of a self-consistent behavior of dust particles including their charge depending strongly on electron and ion energy distribution functions. The kinetic simulation of the self-consistent dusty sheaths was developed in [19-22] using the PIC/MCC method (1D3V model) described in detail earlier [23-24] for computer simulations of the plasma without dust particles. The method is based on a kinetic description of the motion of positive and negative "superparticles" in phase space under an influence of a self-consistent electric field E. The field E is obtained by solving of the Poisson equation using a computational grid, which is introduced by dividing the simulation region. The Monte Carlo technique is used here to describe various elementary processes in plasmas.

The method was developed in [19-22] for dusty plasmas using the self-consistent charging of dust particles according to the Orbit Motion Limited (OML) theory [25]. The Monte Carlo technique [23,24] is used in developed method to describe 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 from [25]. The Coulomb cross-section for electron and ion scattering by immobile dust particles is taken from [26]. The simulation region size is chosen to be equal to several hundreds of the Debye length so that the region exceeds essentially a sheath size. Electrodes or walls collect a "superparticle" if its center reaches an electrode (wall) surface.

In addition to a usual PIC/MCC scheme, the weighting procedure is used in the developed method for the determination of a superparticle charge, which is interacting with a dust particle. In all cases of sheath simulations, one boundary of the simulation region is bounded by an electrode or a wall in front whose the sheath is created. The second boundary can be located in a plasma with given parameters where presheath is developed during the plasma evolution. The continuous exchange by superparticles takes place on the second boundary that has to be taking into account at the computer simulation. In this work, the original model of the exchange was developed with the self-consistent change of the electric potential as well as electron and ion energy distribution functions on the boundary.

3. RESULTS

Obtained results show essential influence of dust particles on sheath properties. The influence is caused by a selective collection of electrons and ions by dust particles with self-consistent electric charge and depends on the ratio between an ion transit time through a sheath and characteristic times of ion collection and scattering [19]. Dust particles can strongly change an ion flux so that the flux is not constant in the sheath. That causes a change of both the well known Bohm's criterion on the sheath boundary and the distributions of other sheath parameters.

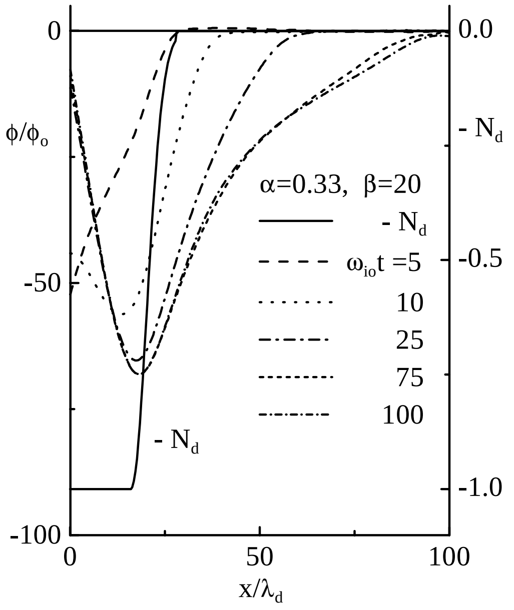

Fig.1. Spatial distributions of of the self-consistent electric potential ϕ

In the case of dusty sheaths in non-equilibrium plasmas with two-temperature electrons [27,28], non-monotonic distributions of the self-consistent electric potential caused by spatial distributions of total charge of dust particles take place in sheaths. Examples of spatial distributions of the self-consistent electric potential ϕ divided by the characteristic potential $\phi_o = kT_c/e$ of cold electrons are shown in Fig.1 for various times t after the start of the collection of electrons and ions by the electrode and dust particles for conditions of Fig.1. Parameters of Fig.1 are the given population ratio $\alpha = n_h / n_o$ of the hot electrons density (n_h) to the total density ($n_o = n_h + n_c$) of all electrons and the given ratio of initial temperatures $\beta = T_h / T_c$ of hot (T_h) and cold (T_c) electrons for the case $T_{io} << T_c$.

The solid line shows here the spatial distribution of the dust particle number N_d in a Debye cube in order to mark out the dusty region and to make clearer understanding the spatial distributions of other parameters.

Note that the spatial coordinate x is divided here by the initial Debye length $\lambda_d = (kT_c/4\pi n_o e^2)^{1/2}$ of cold electrons with the total density n_o, and the time t is multiplied by the initial ion plasma frequency $\omega_{io} = (4\pi n_o e^2/M)^{1/2}$, where M is the ion mass.

As can be seen in Fig.1, the distributions evolve from monotonic distributions to non-monotonic distributions with a potential minimum in the dusty region. It is important that the distributions are almost constant close to the electrode (wall) after some time allowing one to assert that a sheath is formed. Simulations show that the characteristic time of sheath formation is about equal to the transit time of an ion sound wave through the sheath.

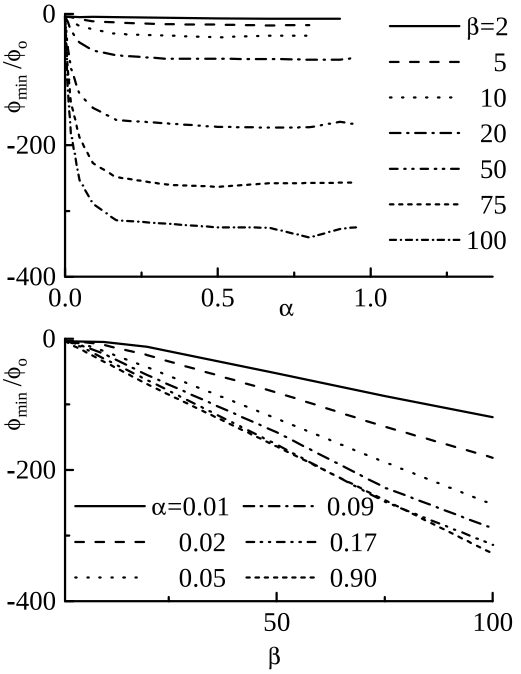

Fig.2. Dependencies of the negative minimum potential ϕ_{min} divided by the characteristic potential $\phi_o = kT_c/e$ of cold electrons on α and β parameters

The non-monotonic self-consistent electric potential in the front of electrodes and walls with a potential minimum in dusty plasma causes a protection of the electrodes and walls from the intensive ion bombardment because the ions reach the electrodes and walls with a lower energy corresponding to the electrode and walls potentials. The protection is depending plasma parameters including the temperature and density ratios of hot and cold electrons.

As can be seen in Fig.2, the negative minimum potential ϕ_{min} decreases about linearly with increasing the temperature ratio $\beta = T_h / T_c$ of hot (T_h) and cold (T_c) electrons like to the probe floating potential. The potential ϕ_{min} depends also on the density ratio $\alpha = n_h / n_o$ of the of hot electrons (n_h) to the total density $n_o = n_h + n_c$ of all electrons.

A simple analysis shows that the dependence of the potential ϕ_{min} on α and β can not be described by any dependence of the potential ϕ_{min} on the effective electron temperature T_o because various minimum potentials obtained from various combination of α and β correspond to the same effective electron temperature. A possible reason is an evolution of the electron energy distribution. function in the dusty region due to the primary collection of fast electrons by dust particles. This suggestion is confirmed also by the fact that the negative potential is independent of the number of hot electrons at $\alpha > 0.3$, as can be seen in Fig.2.

In the case of sheaths in oblique magnetic fields [20], dust particles change also boundary conditions and spatial distributions of sheath parameters causing a double structure of sheaths shown in Fig.3. The change is caused by an effective collection of ions by dust particles in sheaths.

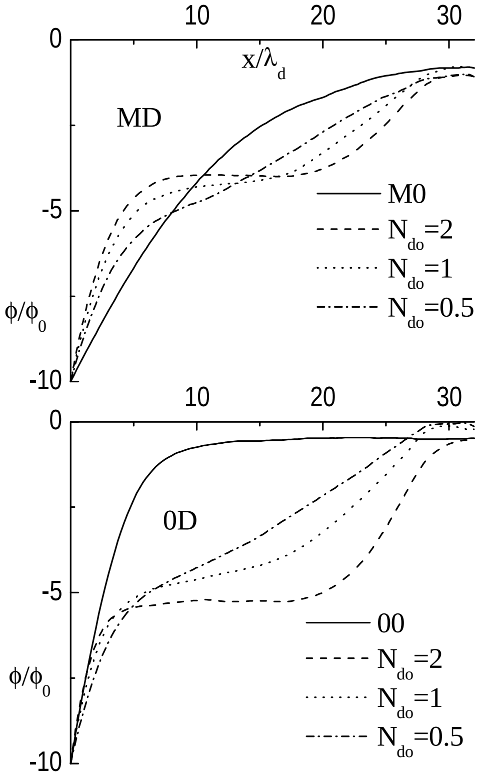

Fig.3. Spatial distributions of the electric potential ϕ in sheaths with a variable number of dust particles

In both cases indicated above, the dust particle charge is non-trivial due to peculiarities of spatial distributions of electrons and ions in dusty sheaths and

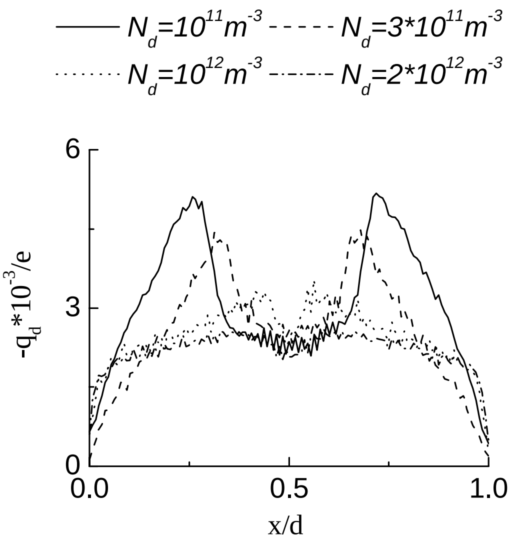

Fig. 4. Spatial distributions of across the interelectrode gap for various densities N_d of dust particles

can even change the sign.

Dust particles influence parameters of non-stationary dusty RF sheaths [21,22] separating the electrodes from a quasi-neutral central part of RF discharges. Spatial distributions of the dust particle charge q_d divided by the negative electron charge e are shown in Fig.4 for for various densities N_d of dust particles.

As can be seen in Fig.4, the dust particle charge changes non-monotonously across the interelectrode gap and has maximum close to a sheath edge. The non-monotony of the distributions are caused by a peculiarity of the electron energy distribution function in the quasi- neutral central part of the RF discharge and the spatial distribution of plasma parameters. The secondary electron emission from electrodes and walls can strongly influence on RF discharge parameters however dust charge spatial distributions are invariability [29] due to the conservation of the ratio of the electron and ion currents into a dust particle.

4. CONCLUSION

Self-consistent dusty sheaths are investigated using the kinetic PIC/MCC simulation of a temporal evolution of both dusty plasmas consisting of immersed electrodes (walls) and developing dusty discharges without special boundary conditions for the sheaths. Obtained results show an essential influence of dust particles on sheath parameters. Spatial distributions of a dust particle charge are not trivial due to a self-consistent evolution of electron and ion energy distribution functions.

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