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Sheaths with Dust Particles in the Oblique Magnetic Field

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Abstract

It is simulated the non-linear one-dimensional sheaths with dust particles of the given size, density and profile in an oblique magnetic field, using the modified PIC method with self-consistent dust particle charge. The Coulomb scattering and the collection of electrons and ions by dust particles are simulated by the Monte-Carlo method with 3D velocity distribution functions for electrons and ions.

It is shown that an influence of dust particles on sheaths is depending on the ratio between characteristic times and lengths of the considered problem. Dust particles change boundary conditions and spatial distributions of sheath parameters causing a double structure of sheaths at an effective collection of ions by dust particles in sheaths.

Keywords:

sheath, dust particle, oblique magnetic field, edge plasma, fusion device

1. Introduction

It is well known [1] that electrostatic sheaths separate plasma from electrodes or walls adsorbing charged particles (usually electrons and ions) from the plasma. 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 a magnetic field can strongly modifies the situation so that the ion flux can exceed the electron flux and sheaths will be negatively charged around positively charged walls [2-5].

Usually the electrodes or walls disturb plasmas far from sheaths creating quasineutral non-uniform plasma regions with slow electric fields and slow gradients of the plasma density which are called preasheaths [6,7]. The presheaths provide boundary conditions for the sheaths and therefore the sheaths have to be considered together with the self-consistent presheaths. In the case of electron-ion collisionless plasma without a magnetic field, the presheath provides the well known Bohm criterion according to which ions have to be accelerated in a presheath to the velocity more or equal to the ion sound speed.

Dust particles can strongly influence on sheaths without a magnetic field [8-11] due to the selective adsorption of background electrons and ions (penetrating through sheaths) by dust particles. In the result, dust particles create the space electric charge influencing on the sheath structure. Note that the selective adsorption of electrons and ions can cause a deviation of electrons and ions from their equilibrium in the non-disturbed plasma including their energy distribution functions [12]. However sheaths with dust particles are considered usually [9-11] under the assumption of the electron and ion equilibrium except [8] where a self-consistent treatment is developed of background electrons and ions in the sheaths with dust particles.

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Sheaths in oblique magnetic fields exist at the material walls of fusion devices (divertors, limiters, etc) and determine particle and energy fluxes to the wall [13,14]. Investigations of the sheaths are started in [3] and are prolonged intensively now [15-18]. However, it was established recently [19] that dust particles can be created due to the plasma-wall interaction in fusion devices and therefore can influence on sheaths like their influence on sheaths without magnetic fields, indicated above. Therefore, investigations of sheaths with dust particles in an oblique magnetic field are very actual.

The purpose of the present work is to simulate non-linear one-dimensional sheaths with dust particles of the given size, density and profile in an oblique magnetic field with self-consistent electrons and ions. After the finish of our investigations, it was published the work [17] considering the sheaths with dust particles distributed uniformly in an oblique magnetic field under the assumption of equilibrium ions that differs the paper [17] from our work.

2. Model

It is considered first an one-dimensional slab plasma consisting of equilibrium electrons and ions with densities $n_{en} = n_{io} = n_o$ and temperatures T_{eo} and T_{io} which is separated by an equilibrium sheath from an electrode to which a large negative potential V is applied. According to Bohm's sheath criterion [1], the ion drift velocity u_o has to satisfy the boundary condition $u_o \geq (kT_e/M)^{1/2}$ close to the sheath boundary where M is the ion mass.

Then at some initial time, an oblique magnetic field and/or dust particles of the given size, density and profile appear in this sheath and both collection and scattering of electrons and ions by these dust particles starts here. These processes cause an evolution of the sheath to a new steady state with self-consistent boundary conditions.

It is assumed that these boundary conditions correspond to a collisionless quasineutral presheath providing the continuous change of plasma parameters on the sheath boundary due to the self-consistent change of the electric potential, the ion drift velocity, and the plasma density at this boundary.

The PIC method is used for computer simulation of sheaths, taking into account the dynamics of the dust particle charge in plasmas with self-consistent energy distribution functions of electrons and ions which can vary due to the select collection of electrons and ions by dust particles like [12]. The Coulomb scattering and the collection of electrons and ions by dust particles is taken into account in the framework of the Monte-Carlo method with 3D velocity distribution functions for electrons and ions. Effective cross-sections of collection and scattering of electrons and ions are taken from [20].

Poisson's equation for the self-consistent electric potential takes into account the space charge of electrons, ions, and dust particles with the boundary potential given at the electrode.

Boundary conditions at the quasineutral edge of the simulation region of $L = 32\lambda_D$, where $\lambda_d = (kT_e/4\pi n_o e^2)$ is the electron Debye length in undisturbed plasma, consist of the Maxwellian distribution function for electrons and ions. The ion distribution function is shifted by the drift velocity, which corresponds to the electric potential at this point. Self-consistent boundary conditions are simulated under the assumption about the collisionless infinite presheath by iterations starting from the boundary conditions for the sheath without dust particles and the magnetic field. Simulations are prolonged up to time when changing of sheaths parameters including boundary conditions became less 0.1 %.

3. Results

Typical results of computer simulations are shown in Figs. 1–3 for various parameters, where N_{do}, R_d , and ϕ are the number of dust particles in a Debye cube close to the electrode, the normalised radius of a dust particle, and the normalised potential, respectively. The spatial coordinate x and the radius R_d are divided here by the initial electron Debye length λ_d, the time t is multiplied by the ion plasma frequency $\omega_{pi}=(4\pi n_o e^2/M)$ in the undisturbed plasma, the potential ϕ is divided by the characteristic value $\phi_o=kT_e/e$. The causes labelled by MD and 0D in these figures correspond to sheaths with dust particles but with the magnetic field and without one, respectively. Curves labelled by M0 and 00 are obtained for sheaths without dust particles but with the magnetic field and without one, respectively. The figures are obtained for the plasma with $T_e/T_i = 0.5$ immersed in the uniform magnetic field with oblique angle of 8° and provided the ion gyroradius of $R_i = 10\lambda_d$. Dust particles with radius $R_d = 10^{-2}\lambda_d$ are distributed according to the Gaussian $N_d = N_{do}\exp(-x^2/x_o^2)$ with $x_o = 16\lambda_d$ and the sharp breakdown at $x = 28\lambda_d$.

Obtained results show that an influence of dust particles on sheaths depends on relations between some characteristic times, namely: the time τ_p of an ion penetration through a sheath, the ion collection time τ_p,

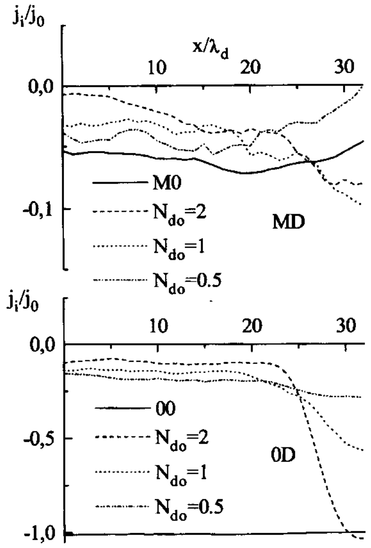

Fig. 1 Spatial distributions of the ion current j_i in sheaths with variable number of dust particles.

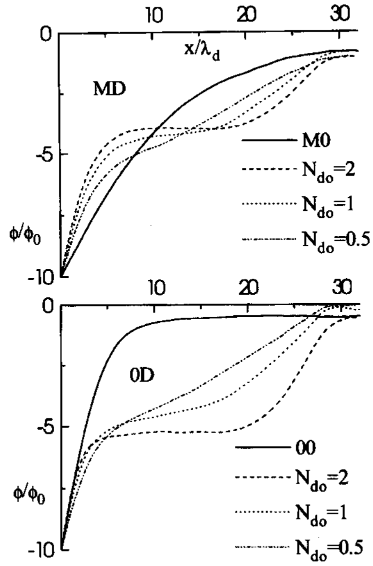

Fig. 2 Spatial distributions of the electric potential ϕ in sheaths with a variable number of dust particles.

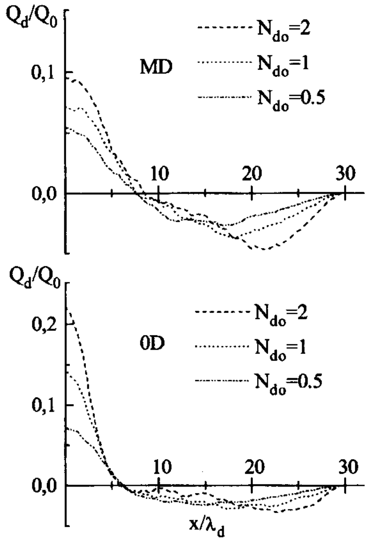

Fig. 3 Spatial distributions of the total charge Q_d of dust particle in sheaths with a variable number of dust particles.

and the ion scattering time τ_s. In particular, the influence is differed in the cases $\tau_p \ll \tau_a + \tau_s$ and $\tau_p \sim \tau_a + \tau_s$ when electrons and ions can reach the electrode but their collection and scattering are small and effective, respectively.

The influence of dust particles is especially clear seen from spatial distributions of the ion drift flux j_i shown at an effective collection of ions by dust particles in Fig. 1 where j_i is divided by the Bohm's flux j_o. As can be seen, the flux j_i is practically uniform in a sheath without dust particles and the magnetic field (the solid curve labelled by 00) because it corresponds to the case of a usual steady-state electrostatic sheath [1]. However, dust particles decrease this flux and cause its essential heterogeneity in sheaths with the magnetic field and without one at their relative high density of dust particles (dashed and dotted curves in Fig.1) due to an intensive ion collection by dust particles in a sheath. In the case of a small collection (dashed-dotted curves for $N_{do} = 0.5$), the flux j_i is like to curves without dust particles but essentially slower than corresponding fluxes without dust particles. It is caused by an influence of dust particles charged during time, which essentially exceeds the time τ_p of an ion penetration through a sheath.

The self-consistent boundary fluxes obtained at the iterations in the simulations are correspond to their values close to $x = 32\lambda_d$ in Fig. 1. Note that the fluxes are differed from the Bohm's flux in all cases with dust particles (including the case of the oblique magnetic field) and depended on the density and the size of dust particles. This difference is strongler for sheaths without the magnetic field and slower for sheaths in the oblique magnetic field. It means that the usual Bohm's boundary condition can not use always for sheaths with dust particles.

Sheath structures are shown in Figs. 2 and 3 where self-consistent spatial distributions of the electric potential ϕ, and the average densities of the total space charge Q_d of dust particles are plotted, respectively. The charge Q_d, and the electric potential ϕ are divided by the density of the total space ion charge Q_o in the non-disturbed plasma, and the characteristic potential $\phi_o = KT_e/e$, respectively.

As can be seen in Fig. 2, there are two differed regions of strong variations of the potential ϕ in sheaths, namely: the region close to the electrode and the region close to the edge of spatial distributions of dust particles at $x = 28\lambda_d$, where a sharp breakdown of the dust particle density takes place. These two regions provide the screening of the electric potential ϕ applied to the electrode.

Dust particles have a differed charge in the indicated regions. As can be seen in Fig. 3, dust particles are charged positively close to the electrode and negatively close to $x = 28\lambda_d$ that is caused by spatial distributions of electrons and ions in the self-consistent potential shown in Fig. 2. Indeed, electron and ion densities are about equal close to the sheath edge and therefore dust particles have a negative charge here, as usually. However, electrons can not reach practically the electrode because $e\phi \gg kT_e$ and therefore dust particles are charged here only by ions. As a result, the charge of dust particles changes the sign about at $x \sim 7\lambda_d$.

Obtained results show that the positive space charge Q_d of dust particles gives an essential contribution to the total space electric charge close to the electrode. It means that the positive charged dust particles provide here a main screening of the negative potential ϕ applied to the electrode. Therefore this region can be called as a sheath of dust particles.

In the second region close to $x = 28\lambda_d$, the positive charge Q_t is created only by ions which compensate the negative charge of electrons and dust particles as well as screen the potential ϕ. This region is a usual ion sheath with dust particles. Note that the ion drift current j (Fig. 1) damps essentially here due to a collection of electrons and ions by dust particles.

4. Conclusion

Computer simulations of the non-linear one-dimensional sheaths with dust particles in an oblique magnetic field and without one show that an influence of dust particles on sheaths is depending on the ratio between characteristic times and lengths of the considered problem. Dust particles change boundary conditions and spatial distributions of sheath parameters causing a double structure of sheaths at an effective collection of ions by dust particles in sheaths.

Acknowledgements

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