Dynamics of multi-sized dust grains in the electrostatic sheaths in presence of magnetic field

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Abstract

In this work, we have investigated the dynamics of the multi-sized dust grains in the electrostatic sheaths in presence of magnetic field. For this, we have established a tri-dimensional, stationary and magnetized plasma sheath model. The electrons are considered in thermodynamic equilibrium; however the ions and the dust grains are described by fluid equations, where the dust size is modelled by Gaussian law. To describe the dust charge, we have used the orbit motion limited model. The numerical results show that the presence of magnetic field reduces the sheath thickness. Moreover, the contribution of the neutral drag force in the total force acting on the dust grains is negligible. However, the contribution of the gravity force is significant only for micrometer dust grains. The trapping of dust grains is possible only for a small micrometer dust radius interval.

I. Introduction

The study of the dynamics of multi-sized charged dust grains in the electrostatic sheath region[1] of plasma discharges above a negative electrode has a great deal interest to understand many physical phenomena such as levitation or crystallization of nano-particles[2-4]. These particles, ranging from nanometers to micrometers[5-6], can appear as the product of the plasma-wall interaction in various technological devices. They can also be created due to coagulation of various components in chemically active plasmas with their subsequent transport into sheaths. Furthermore, dust particles can be immersed from outside and be trapped in sheaths creating plasma crystals.

In this work, we have investigated the dynamics of dust particles with different sizes by computed the electrostatic sheath parameters in the first time. Thereafter in order to study the dynamics of dust grains, we have computed both their total energy and the corresponding potential energy.

II. Theoretical model

We consider a tri-dimensional and stationary plasma consisting of electrons (e), singly charged ions (i) and spherical dust grains (d) with different sizes. We assume that the electrode (plane solid surface) is situated at the position $z = L$. The sheath region lies between $z = 0$ and the electrode (the pre-sheath region is neglected), where z is the position along the vertical axis, which is in the same direction as gravity. Thus, $z < 0$ is the plasma region and $z > 0$ is the sheath region. At the edge $(z = 0)$, we assume the electrostatic potential ϕ, and the number density of specie l $(l = e, i, d)$ is n_{l0}. The subscript "0" denotes the equilibrium $(\phi = 0)$ quantities.

The electrons are assumed to be in thermal equilibrium; thus, their number density is

$$n_e = n_{e0} \exp(e\phi / T_e) . \tag{1}$$

The ions are considered adiabatic[7] and they are described by the continuity and momentum equations,

$$\frac{d(n_i \mathrm{v}_i)}{dz} = k_i n_i n_e , \tag{2}$$

$$\mathrm{v}_{iz} \frac{d\mathrm{v}_{ix}}{dz} = -n_n \sigma_{in} \lambda_{Di} \mathrm{v}_i \mathrm{v}_{ix} + \frac{eB}{m_i} \mathrm{v}_{iy} \cos\theta , \tag{3}$$

$$\mathrm{v}_{iz} \frac{d\mathrm{v}_{iy}}{dz} = -n_n \sigma_{in} \lambda_{Di} \mathrm{v}_i \mathrm{v}_{iy} + \frac{eB}{m_i}\left(-\mathrm{v}_{ix} \cos\theta + \mathrm{v}_{iz} \sin\theta\right) , \tag{4}$$

$$\mathrm{v}_{iz} \frac{d\mathrm{v}_{iz}}{dz} = -\frac{e}{m_i}\frac{d\varphi}{dz} - n_n \sigma_{in} \lambda_{Di} \mathrm{v}_i \mathrm{v}_{iz} - \frac{eB}{m_i} \mathrm{v}_{iy} \sin\theta - \frac{5T_i}{3m_i n_{i0}^{2/3} n_i^{1/3}} \frac{dn_i}{dz} , \tag{5}$$

where B is the magnetic field making an angle θ with the vertical axis Oz, σ_{in} is the ion-neutral diffusion cross section, k_i is the electronic impact ionization rate, n_n is the neutral gas density, λ_{Di} is the ionic Debye length, and the other parameters have their usual names.

The dust grains are also considered as a cold fluid with different sizes, and then they are described by the continuity and momentum equations. For the kth dust grain, we have

$$\frac{d(n_{dk} \mathrm{v}_{dk})}{dz} = 0, \tag{6}$$

$$\mathrm{v}_{dkz} \frac{d\mathrm{v}_{dkx}}{dz} = \frac{q_{dk}}{m_{dk}} \mathrm{v}_{dky} B\cos\theta + \frac{f_{idkx}}{m_{dk}} + \frac{f_{inkx}}{m_{dk}} , \tag{7}$$

$$\mathrm{v}_{dkz} \frac{d\mathrm{v}_{dky}}{dz} = \frac{q_{kd}}{m_{kd}}\left(\mathrm{v}_{dkz} \,\mathrm{B}\sin\theta - \mathrm{v}_{dkx} B\cos\theta\right) + \frac{f_{idky}}{m_{dk}} + \frac{f_{inky}}{m_{dk}} , \tag{8}$$

$$v_{dkz}\frac{dv_{dkz}}{dz}=-\frac{q_{dk}}{m_{dk}}\frac{d\phi}{dz}-\frac{q_{dk}}{m_{dk}}v_{dky}\ B\sin\theta\ +g+\frac{f_{idkz}}{m_{dk}}+\frac{f_{ndkz}}{m_{dk}}, \quad (9)$$

where $\vec{f}_{idk}$ and $\vec{f}_{ndk}$ are the ion drag force[8]and neutral drag force[9], respectively. Their expressions are given by:

$$\vec{f}_{idk}=\pi\, m_{ik}\, n_{ik}\, r_{dk}^2 v_{sk}\, \vec{v}_{ik}\left(1-2b_{\pi/2k}^2/r_{dk}+4\Gamma_k\, b_{\pi/2k}^2/r_{dk}^2\right), \quad (10)$$

$$\vec{f}_{ink}=-\frac{8}{3}\sqrt{2\pi}\, r_d^2\, m_n\, T_n\left(\vec{v}_d-\vec{v}_n\right)/v_{tn}, \quad (11)$$

where $b_{\pi/2k}=e\,q_{dk}/m_{ik}\,v_{sk}^2$ is the orbital impact parameter, Γ_k is the de Coulomb logarithm and

$v_{sk}=\left(v_{ik}^2+8T_i/\pi m_i\right)^{1/2}$ is the total ion velocity.

The formulation is completed with the Poisson's equation,

$$\frac{d^2\phi}{dz^2}=-\frac{1}{\varepsilon_0}\left(n_i e-n_e e+\sum_k n_{dk}\, q_{dk}\right). \quad (12)$$

By using the orbital motion limited model (OML)[10-11], the dust charge is given by

$$v_{dk}\frac{dq_{dk}}{dz}=a_{ek}q_e n_e+a_{ik}q_i n_i, \quad (13)$$

where a_e and a_i are the electrons and ions attachment rates by the dust grains respectively.

Finally, the dust size distribution is described by a Gaussian law[12],

$$f(r_d)=D\exp\left(-\mu\left(r_d-r_{dm}\right)^2\right), \quad \text{for} \quad r_{d\min}\le r_d\le r_{d\max}, \quad (14)$$

otherwise the distribution function has zero value, where r_{dm} is the average dust radius, D is the normalization constant and the constant μ is given by

$$f(r_{d\min})=f(r_{d\max})=0.01f(r_{dm}). \quad (15)$$

III. Numerical results and discussion

In order to investigate the dust grains dynamics, we have computed the total force acting on them $F_T(z)$ and the corresponding potential energy $E_p(z)=-\int_0^z F_T(z')dz'$. We implement the present model by considering an argon gas with the following parameters: $T_e=2\,eV$, $T_i=T_n=0.01\,eV$, $n_{i0}=10^9\,cm^{-3}$, $P_n=10\,mTorr$, $\sigma_{in}=5\times10^{-15}\,cm^2$, $\theta=20^\circ C$, $r_{d\min}=0.01\,\mu m$, $r_{d\max}=6\,\mu m$, $\rho_d=2\,g/cm^3$, $\delta_d=10^{-4}$, $u_{i0}=1.5$[13], and $u_{d0}=2.5$.

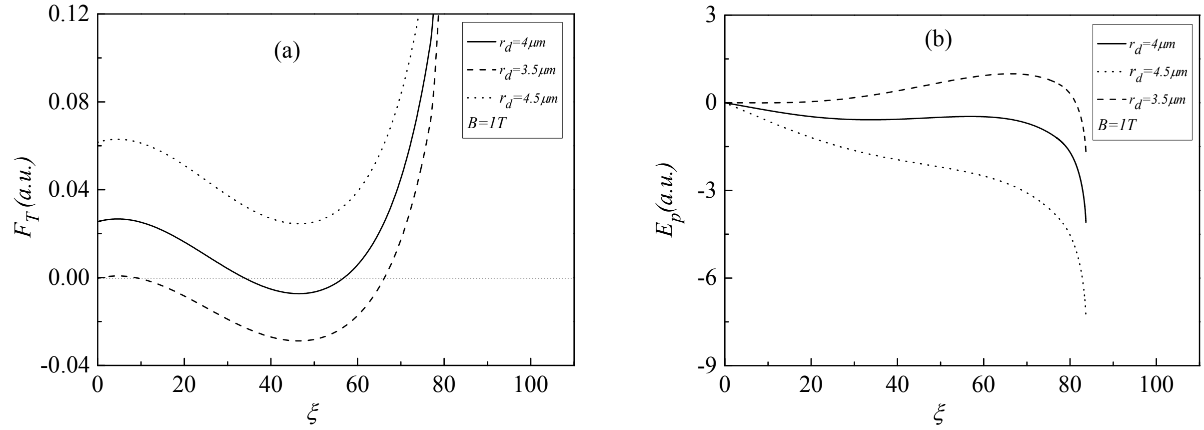

Figure 1: Total force acting on the dust F_T (a) and potential energy E_p (b) as function of $\xi = z / \lambda_{Di}$.

First, we have checked that the presence of magnetic field reduces the sheath thickness. Furthermore, the contribution of the neutral drag force in the total force acting on the dust grains is negligible. However, the contribution of the gravity force is important only for micrometer particles. Thus, the dust grains levitation in the sheath is possible only for a small radius interval around $r_d \approx 4\mu m$, for which the electrostatic force is balanced by the ion drag and gravity forces.

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