PARTICLE CHARGING IN BEAM-PLASMA SYSTEMS

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The particle charging in an electron beam-plasma discharge is studied by means of the classical orbit motion limited approximation and on the basis of a discrete charging model. The particle charge fluctuations due to the stochastic nature of charging process are considered. The Fokker-Planck description of the particle charging has been presented. An analytical expression for the charge distribution function has been derived taking into account the processes of the collection of plasma electrons and ions by the dust grain and secondary electron emission from it.

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INTRODUCTION

The generation of particles ranging in the size from several microns to a few hundred microns has been observed in many technological vacuum-plasma processes such as vacuum arc methods for depositing decorative and hardening coatings [1]. The presence of particles in the plasma flow worsens the coating parameters. This is a serious detriment which must be avoided.

We recently studied the behaviour of the floating electric potential of a macroparticle in an electron beam-plasma system in the framework of the orbit motion limited (OML) approach [2] with account of secondary electron emission [3]. We have used a "continuous charging model" which assumes that the steady-state potential to which a dust grain is charged has been determined by the balance of the currents that are collected by the grain surface and emitted from it [4]. This paper extends our previous work to include the effect of discreteness of the electrostatic charges that make these currents.

1. CONTINUOUS CHARGING MODEL

Let us consider a beam-plasma discharge in which the number density of dust grains is low and the average intergrain distance l is much larger than the Debye length λ_d in plasma. This allows us to consider the plasma with isolated dust grains [5]. Dust grain of radius $a << \lambda_d << l$ behaves like a spherical electric probe at floating potential φ_f [6]. The charge on a dust particle is the result of the net effect of all possible currents to the particle surface. The charging of dust grain mainly occurs by the collection of electrons and ions from the plasma. In addition to this, dust grains are exposed to high-energy electron beam, which releases electrons by secondary electron emission process. The dust particle acquires instantaneous charge $q = ze$ (with e the elementary charge and z an integer).

The charging of a dust particle is governed by the following equation

$$\frac{dz}{dt} = \sum_j I_j \,,\; j = e,i,b,s \,, \qquad (1)$$

where the sum is taken over all the fluxes I_j of charged particles collected or emitted by the dust particle. Index j here represents the various species: e – indicates plasma electrons; i – plasma ions; b – beam electrons; s – secondary electrons.

The ion, plasma-electron and beam-electron fluxes flowing onto the dust grain surface in the framework of OML model are

$$\begin{aligned}
I_i &= \sqrt{8\pi}a^2 n_0 v_{Ti}\left(1-\frac{z_i e\varphi_s}{kT_i}\right), \varphi_s < 0\,,\\
I_i &= \sqrt{8\pi}a^2 n_0 v_{Ti}\exp\left(-\frac{z_i e\varphi_s}{kT_i}\right), \varphi_s > 0\,,\\
I_e &= \sqrt{8\pi}a^2 n_0 v_{Te}\exp\left(\frac{e\varphi_s}{kT_e}\right), \varphi_s < 0\,,\\
I_e &= \sqrt{8\pi}a^2 n_0 v_{Te}\left(1+\frac{e\varphi_s}{kT_e}\right), \varphi_s > 0\,,\\
I_b &= \pi a^2 n_b v_{eb}\left(1-\frac{e\varphi_s}{\varepsilon_b}\right), \varphi_s < 0\,,\\
I_b &= \pi a^2 n_b v_{eb}\left(1+\frac{e\varphi_s}{\varepsilon_b}\right), \varphi_s > 0\,,
\end{aligned} \qquad (2)$$

Where $-e$ is the electronic charge, $z_i e$ is the ionic charge, φ_s is the dust grain surface potential, a is the dust grain radius (for arc plasmas, this radius is usually from a few hundred nanometers to several tens of microns) , n_0 (n_b) is the plasma (beam electron) density, T_e (T_i) is the electron (ion) temperature, $v_{Te} = \sqrt{\frac{kT_e}{m_e}}$, $\left(v_{Ti} = \sqrt{\frac{kT_i}{m_i}}\right)$ is the electron (ion) thermal velocity, m_e (m_i) is the electron (ion) mass, k is the Boltzmann constant, $v_{eb} = \sqrt{\frac{2\varepsilon_b}{m_e}}$ is the beam electron velocity , ε_b is the energy of beam electrons. For $\varphi_s > 0$ and $kT_i << e\varphi_s$, the ion flux to the grain surface can be ignored.

The flux I_s of secondary electrons is connected to flux I_b of beam electrons through the secondary emission coefficient δ :

$$I_s = \delta I_b. \quad (3)$$

The coefficient δ is described by the empirical dependence connected to the energy of primary electrons reaching the grain surface [3]:

$$\delta = 7.4\delta_m \frac{\varepsilon_b}{\varepsilon_{bm}} \exp\left(-2\sqrt{\frac{\varepsilon_b - e\varphi_s}{\varepsilon_{bm}}}\right). \quad (4)$$

Here ε_{bm} is the primary electron energy at which the secondary electron emission coefficient reaches the value δ_m.

The floating potential φ_f can be found from the balance of the particle fluxes to/from its surface.

$$\sum_j I_j = 0. \quad (5)$$

The charge on a grain q is related to the dust potential by:

$$q = C\varphi_s, \quad (6)$$

in which an isolated dust grain is considered as a spherical capacitor C of radius a. For a spherical dust grain satisfying $a << \lambda_d$, in vacuum the capacitance is given by [7]

$$C = 4\pi\varepsilon_0 a. \quad (7)$$

Hence, if one knows the potential of the dust grain and its radius, it is easy to determine its charge

$$q = 4\pi\varepsilon_0 a\varphi_s. \quad (8)$$

Let define the charging time τ, which indicates how fast a grain can charge up in a plasma, as an RC time.

$$\tau = RC. \quad (9)$$

The resistor R is related to the slope of the characteristic of a spherical probe at floating potential φ_f. Therefore,

$$-\frac{1}{R} = \frac{d}{d\varphi_s} \sum_j I_j \Bigg|_{\varphi_f}. \quad (10)$$

Thus, we choose τ as the linear charge relaxation time required for the grain charge to approach its equilibrium value within one e-fold.

For example, when $e\varphi_s << \varepsilon_{bm}$, the dust particle acquires a positive charge during

$$\tau = \varepsilon_0\sqrt{\pi k T_e} \Big/ \sqrt{2} e^2 a n_0 \left(1 + (1+\delta)\frac{n_b}{2n_0}\sqrt{\frac{\pi k T_e}{\varepsilon_b}}\right). \quad (11)$$

The fact that relaxation time τ is inversely proportional to both size of the dust grain and plasma density means that the fastest charge relaxation occurs for large grains and high plasma densities. Also the relaxation time depends on electron temperature and secondary electron emission coefficient δ.

2. DISCRETE CHARGING MODEL

The currents collected by the grain surface and emitted from it actually consist of individual electrons and ions. Let assume that all the ions carry a single charge. Electrons and ions arrive at the particle's surface at random times. Upon collision with plasma particles and with beam electrons, the particle charge undergoes a stepwise change $z_i - z_{i-1} = \pm 1$. The charge losses are due to secondary electron emission and absorption of plasma ions, while the increase in charge of negatively charged particles is due to absorption of plasma electrons. The generation and loss of a unit elementary charge is a one-step Markov process for which transition from state z can only go to either state $z-1$ or state $z+1$. The probability for one charging event does not depend on the history previous events. This Markovian property enables us to write a so-called Fokker-Planck equation for the distribution function f_Z [8]:

$$\frac{\partial f_z}{\partial t} = -\frac{\partial}{\partial z}[A(z) f_z(z,t)] + \frac{1}{2}\frac{\partial^2}{\partial z^2}[B(z) f_z(z,t)] \quad (12)$$

where

$$A(z) = \overline{\frac{\Delta z}{\Delta t}}\Bigg|_{\Delta t \to 0} \quad (13)$$

and

$$B(z) = \overline{\frac{\Delta z^2}{\Delta t}}\Bigg|_{\Delta t \to 0}. \quad (14)$$

The distribution function f_Z is interpreted as the fraction of the particles that carry the discrete elementary charge z. It is normalized by

$$\int_{-\infty}^{\infty} f_z dz = 1. \quad (15)$$

Also, we have made use of the fact that f_Z must be "slow" function of the charge.

A Fokker-Planck equation is identical to the continuous equation. The equation (12) can be rewritten as

$$\frac{\partial f_z}{\partial t} = -\frac{\partial j}{\partial z}. \quad (16)$$

Here "flux" is given by

$$j = A(z) f_z(z,t) - \frac{1}{2}\frac{\partial}{\partial z}[B(z) f_z(z,t)]. \quad (17)$$

For case $j = 0$, we have equilibrium distribution

$$f(z) = \frac{C}{B(z)} \exp\left[2\int \frac{A(z)}{B(z)} dz\right], \quad (18)$$

where C is the constant, calculated from condition (15).

The first drift coefficient of the Fokker-Planck equation is the definition of the particle flux. Then, this coefficient reads

$$A(z) = \sum_j I_j \quad (19)$$

To determine the second diffusive coefficient $B(z)$, we also use the analogy to a capacitor charging through a resistor R following Einstein's model for the thermal noise in an electric circuit [9]:

$$\overline{\frac{\Delta q^2}{\Delta t}}\Bigg|_{\Delta t \to 0} = \frac{2kT_e}{R}. \quad (20)$$

Therefore, an expression for the second drift coefficient $B(z)$ is

$$B(z) = \frac{2kT_e}{e^2 R}. \quad (21)$$

Figs. 1 and 2 show the charge distribution function at small values of secondary electron emission coefficients for typical laboratory plasma conditions: hydrogen

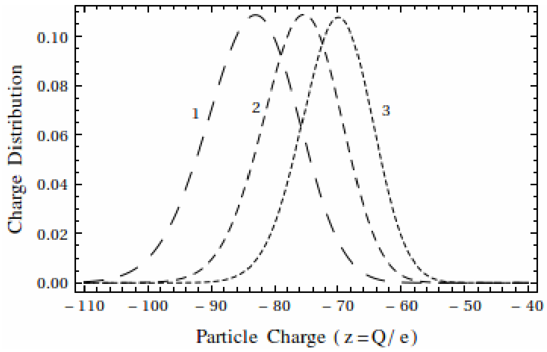

Fig. 1. Charge distribution function of dust particles with plasma density $n_0 = 10^9$ cm^{-3} and different beam electron energy: 1 – ε_b = 70 eV; 2 – ε_b = 50 eV; 3 – ε_b = 25 eV

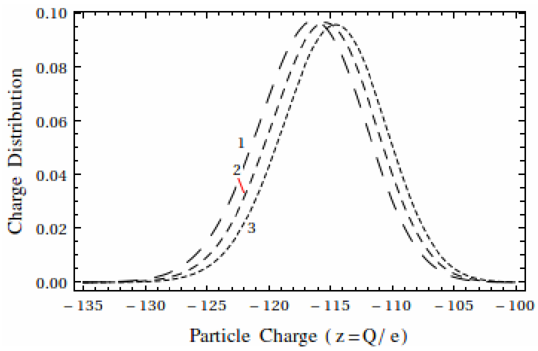

Fig. 2. Charge distribution function of dust particles with plasma density $n_0 = 10^{10}$ cm^{-3} and different beam electron energy: 1 – ε_b = 70 eV; 2 – ε_b = 50 eV; 3 – without electron beam

plasma with a plasma density of, $n_0 = 10^9 \ldots 10^{10}$ cm^{-3}, an electron temperature of, T_e = 10 eV an ion temperature of T_i = 1 eV, grain radii of, a = 1 μ·m beam electron energies of ε_b = 25…100 eV. As the plasma density increases, the effects caused the electron beam become weaker.

CONCLUSIONS

It has been shown that injection of an electron beam into a dusty plasmas can significantly increase the negative potential of a dust grain at small values of secondary electron emission coefficients. This allows to raise the efficiency of plasma purification methods, namely evaporation and Rayleigh decay of macroparticles.

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ЗАРЯДКА ЧАСТИЦЫ В ПУЧКОВО-ПЛАЗМЕННЫХ СИСТЕМАХ

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В рамках классического приближения ограниченного орбитального движения и на основе дискретной модели изучается зарядка частиц в пучково-плазменных разрядах. Рассматриваются флуктуации заряда частиц, связанных со случайностью процесса зарядки. Представлено описание Фоккера-Планка зарядки частиц. Выведено аналитическое выражение для функции распределения заряда с учетом процессов поглощения электронов и ионов плазмы пылевой частицей и с учетом вторичной электронной эмиссии.

ЗАРЯДЖЕННЯ ЧАСТИНКИ В ПУЧКОВО-ПЛАЗМОВИХ СИСТЕМАХ

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У рамках класичного наближення обмеженого орбітального руху та на підставі дискретної моделі вивчається заряджання частинок у пучково-плазмових системах. Розглянуто флуктуації заряджання частинок, пов'язаних з випадковістю процесу заряджання. Представлено опис Фоккера-Планка заряджання частинок. Отримано аналітичний вираз для функції розподілу заряду, з урахуванням процесів поглинання електронів та іонів плазми пиловою частинкою та з урахуванням вторинної електронної емісії.