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An investigation of dust particles orbiting a Langmuir probe

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Abstract
In the present work, the behavior of dust particles near an attracting Langmuir cylindrical probe in glow discharge plasma was investigated experimentally. Trajectories of dust particles for different initial kinetic energies and impact parameters were analyzed numerically. The comparision between experimental and simulation results are made. The results obtained can be used for the development of new dusty plasma diagnostic techniques.

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(Some figures in this article are in colour only in the electronic version)

1. Introduction

Probe diagnostics are of considerable interest for experimental investigation of dusty (complex) plasmas [1–5]. They provide local measurements of the main plasma parameters (the electron and ion densities, the plasma temperature and the electron energy distribution function). The presence of dust particles in gas discharge plasma influences current–voltage characteristics of the probe because they are strongly affected by the third charged component—dust particles. On the other hand, the presence of a probe electric field plays an important role in dust behavior, since the dust particles receiving a large charge by plasma currents are strongly affected by the sheath field. Dust particle charge depends on both the particle size and the local parameters of the surrounding plasma. Earlier in [3], a dust particle's central motion in the double layer of a negatively charged cylindrical probe was investigated numerically. In this case a dust grain with a negative charge of about $10^3 e$ is strongly repulsed by the probe electric field. In the present work, the behavior of dust particles near the attracting Langmuir cylindrical probe in glow discharge plasma was investigated experimentally. The motion of dust particles in the perturbed plasma region near the probe was observed. In order to analyze experimental results obtained the approach used in [3] was modified and trajectories of dust particles were traced at the parameters of the experiments.

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2. Experimental setup

The setup on the basis of dc discharge was used in which dust particles take negative charge and levitate in the positive column striations [6]. The discharge was created in argon in a vertically oriented cylindrical glass tube with cold electrodes. Measurements were carried out at gas pressures 0.1–0.5 Torr and discharge currents 0.5–2 mA. A single cylindrical Langmuir probe was used: tungsten cylindrical wire of ∼0.1 mm in diameter and ∼2 mm long. The probe was immersed in the striation in the central part of the discharge perpendicularly to the discharge axis. In the experiments, two types of particles were used: polydisperse Al_2O_3 particles with diameters 2–6 μm and monodisperse micron-sized melamine formaldehyde spheres. In order to illuminate the dust particles we used a diode laser beam with wavelength 532 nm. The observations were performed by CCD camera at a frame rate of 25 fps. In the experiments with the probe immersed in dust structures a collection of dust particles by the probe was observed, i.e. at a negative potential with respect to the local plasma. In this case particles moved from the dust structures directly to the probe and could either repulse from it or adhere to its probe surface. Particles falling from the top of the discharge to the probe region can collide with the probe at some impact parameter. In this case particles trapped on infinite orbits by probe and even particles orbited probe with 1–2 periods. Analysis of orbiting particle trajectories was made and velocities of particles near the probe were obtained.

3. Simulation model

To describe completely the dusty particle's motion in the perturbed area near the probe one needs to solve the set of equations consisting of the equation of motion for a dusty particle, the equation for kinetics of particle charging and the equation for a plasma layer, which gives us a potential distribution in the disturbed area. The dusty particle moves in a central symmetry electric field in the disturbed area near the probe. Therefore, the equation of motion for the particles under central forces, well known from mechanics, can be used. Introducing polar coordinates r and θ in the plan of the trajectory and considering the center of the probe as a center of the reference system, the equation of motion can be written as [3]

$$\frac{\mathrm{d}^2 r}{\mathrm{d}t^2} = -\frac{eZ_d}{M_d}\frac{\mathrm{d}U(r)}{\mathrm{d}t} + \frac{2K_0 p^2}{M_d r^3}, \tag{1}$$

$$\frac{\mathrm{d}\theta}{\mathrm{d}t} = \frac{p}{r^2}\left(\frac{2K_0}{M_d}\right)^{1/2}, \tag{2}$$

where $U(r)$ is the potential of the probe field at the point r, p is an impact parameter, K_0 is the initial kinetic energy of a dust particle, M_d is its mass, Z_d is its charge and e is elementary charge. The motion of dust particles was considered in the whole perturbed zone including both the quasi-neutral part of the plasma and the volume charge area where potential changes sharply. Electrical potential distribution was calculated with the Poisson equation

$$\frac{1}{r}\frac{\mathrm{d}}{\mathrm{d}r}\left(r\frac{\mathrm{d}U}{\mathrm{d}r}\right) = -4\pi e[n_i(r) - n_e(r)] \tag{3}$$

where n_e, n_i are the number density of electrons and ions. Electron number density is distributed by the Boltzman law

$$n_e = n_0 \exp\left[\frac{eU(r)}{kT_e}\right] \tag{4}$$

where n_0 is the plasma density; T_e is the temperature of electrons. Distribution of ions is significantly nonuniform. Hence, the Boltzmann distribution is not applicable for ion density. For a large cylindrical probe ($R_p \gg r_d$), the distribution of ions is determined by the following expression [7, 8]:

$$n_i = n_0 \left\{ 1 - \frac{1}{\pi} \arcsin \frac{r_l}{r} \left[\frac{E_{0n} + eU(r_l)}{E_{0n} + eU(r)} \right]^{1/2} \right\} \qquad \text{for} \quad r > r_l, \tag{5}$$

$$n_i = \frac{n_0}{\pi} \arcsin \frac{r_l}{r} \left[\frac{E_{0n} + eU(r_l)}{E_{0n} + eU(r)} \right]^{1/2} \qquad \text{for} \quad r < r_l, \tag{6}$$

where E_{0n} is a quantity that approximately equals the ion temperature in plasma; r_l is the so-called limiting radius which is determined by the local maximum of the effective ion potential energy [7]. Charge of the dust particle near the probe is determined by electron and ion fluxes on the surface of this particle

$$e\frac{\mathrm{d}Z_d}{\mathrm{d}t} = I_e + I_i. \tag{7}$$

Expressions for electron and ion currents obtained in the framework of orbit motion limited theory [1, 3].

The obtained system of equations (1)–(7) with initial and boundary conditions [3] allowed us to describe numerically the motion of a dusty particle in the perturbed region near the probe. The system of equations was rewritten in dimensionless form in order to simplify the solution. Limiting radius r_l and Debye radius $r_d = \sqrt{kT_e/(4\pi n_0 e^2)}$ were taken as scales of length. The temperature of electrons kT_e was taken as a scale of energy, whereas kT_e/e was taken as a scale of potential. Dimensionless parameters were used

$$x = \frac{r}{r_l}, \qquad \gamma = \frac{T_i}{T_e}, \qquad \gamma_d = \frac{K_0}{kT_e}, \qquad \varphi = \frac{eU(r)}{kT_e}. \tag{8}$$

It should be mentioned that all the lengths on the graphs are normalized to the Debye radius r_d.

4. Numerical and experimental results

Numerical calculations were performed for a dust particle with radius 1.5 μm, mass of 1.7×10^{-10} g, and Ar plasma ($\mathrm{m_i} = 6.63 \times 10^{-23}$ g) at energy of electrons 5 eV, at room temperature for ions ($\mathrm{Ti/Te} = 0.0069$), the Debye radius $r_d = 0.006$ cm. The result of numerical calculations of the electric field potential distribution near the probe is presented in figure 1 below. Density distributions n_e, n_i are presented in figure 2.

If the dust particle acquires enough energy to penetrate into the double layer it will move on the trajectory shown in figure 3. In this connection it is possible to determine the charge of the dust particle from analysis of the trajectory. For this purpose, by detecting the experimental trajectories of the moving particles and comparing with numerical ones that coincide with it one can determine the initial kinetic energies of the dust particle and impact parameters. Hence, it is possible to determine the charge of a dust grain in any moment of its movement in the framework of OML theory. Figure 3 presents trajectories of particles in the vicinity of the probe: those obtained experimentally are compared with those calculated for the same parameters using the algorithm described in section 3. The figures show good agreement between the model and experiment.

It is shown in figure 3 that at certain parameters the dust particles are attracted to the probe. In order to answer the question of how a negatively charged dust particle is attracted to

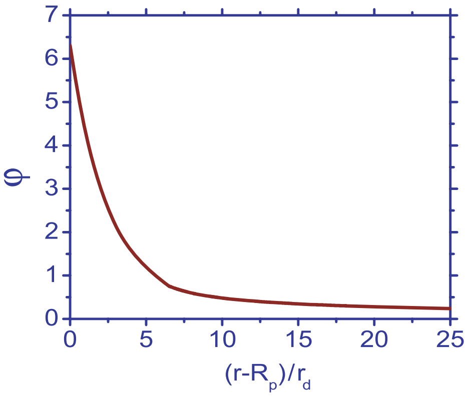

Figure 1. Potential distribution near the cylindrical probe.

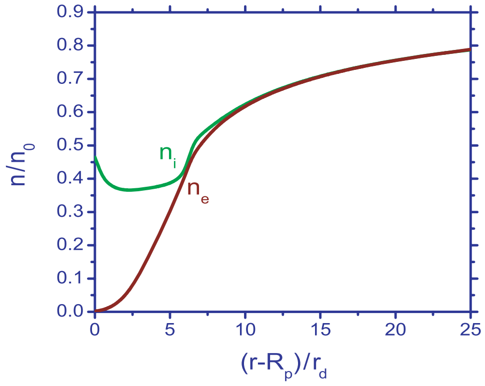

Figure 2. Distribution of electron and ion densities near the cylindrical probe.

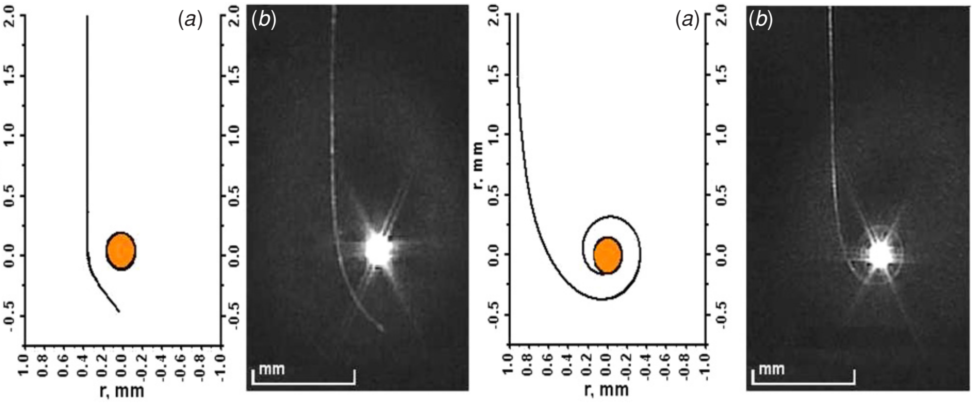

Figure 3. Comparison of theoretical calculations with experiments. Trajectories of the dust particle at different initial kinetic energies and impact parameters. Comparisons of numerical (*a*) and experimental (*b*) results. (1) $p/R_{\mathrm{p}} = 3$; $\gamma_{\mathrm{d}} = 29000$ (2) $p/R_{\mathrm{p}} = 4.5$; $\gamma_{\mathrm{d}} = 33430$.

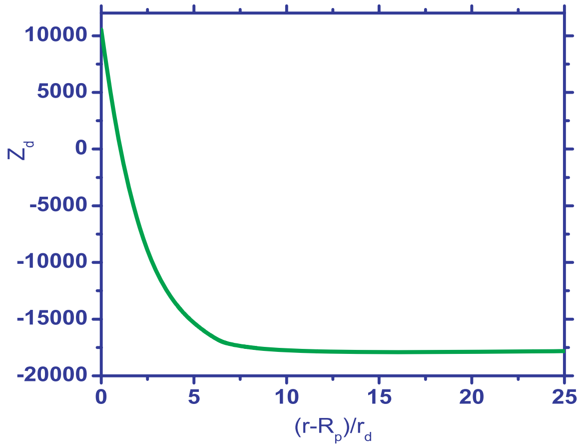

Figure 4. Charge of dust particle versus the distance from the probe.

the negative probe with respect to the plasma, one should experimentally estimate the radius of an ion layer around the probe. In our experiment the magnitude of the radius of the ion layer was about $30r_d \sim 2$ mm. Figure 3 shows that impact parameters of falling dust particles less than the radius of the ion layer, i.e. dust particles decreasing its negative charge by entering into the ion layer. Figure 4 shows how the charge of a dusty particle changes when it is moving near the probe. As is shown in the graph, at the moment when a dust particle reaches a certain location, which is called the distance of the recharging, the charge changes its sign from negative to positive. The recharging process takes place when ion current prevails over electron current.

So, one can conclude that such trajectories can provide information about parameters of the dust and discharge plasma such as the dusty particle's charge from some distance to the probe, the potential of a solitary (individual) dust grain, temperature and number density of the electrons and ions. Therefore it could be used as a new dusty plasma diagnostic technique.

Acknowledgments

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