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The new method for measuring of dust particles charge in glow discharge plasma

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Abstract – A new method for measuring of the dust particle charge in a glow discharge plasma is described. The inverse problem of the restoration of the particle charge on the basis of its videotaped trajectory around the electric probe was solved. The obtained results of dust parameters can be used for the development of new methods for dusty plasma diagnostic.

Introduction. – Dusty plasma is an ionized gas containing particles of condensed matter. The presence of macroscopic particles can significantly affect the properties of low-temperature plasma, and also leads to a system of new parameters, in particular, such important parameter as the charge of dust particles, which depends on its material and size, as well as on the local parameters of the surrounding plasma. In works [1–3] the study of the particle charging processes in a wide range of experimental parameters is performed. Many works were devoted to the theoretical investigation of this problem, for example [4–6].

There are various methods for the determination of the charge of dust particles. Methods based on the balance of gravity and the electric field acting on charged dust particles in a vertical discharge tube (see ref. [7]) are often used for the estimation of their charge.

The magnitude of the electric field at the point of the dust particle localization can be estimated by visible light intensity of strata or by performing of complex calculations associated with the solution of many equations (see refs. [8,9]). In the first case, the error is introduced due to the fact that the distributions of the strata luminosity and electric field are somewhat shifted relative to each other. In the second case, the error of calculations related to the complexity of the investigated system and the equations describing it.

In the investigation of dusty plasma properties the external stimuli of different nature are widely applied (see refs. [10,11]). For example, external fields, the slope of the discharge tube, particle beams and lasers, and others. Today, the use of external influences for the creation and diagnostics of dust structures is seen as a new area of research. Methods for the particle charge measuring by its reaction on external influence, which can be high power laser beam (see [11]), are widely known. Under the influence of a focused laser beam on the particle this particle can move along the beam. Then it is easy, on the basis of the deviation and the applied forces, to calculate the particle charge. But this method can be effectively applied only to the chains of particles.

The aim of our study is to develop a new method of experimental determination of the charge of dust particles in a glow discharge plasma with an electric probe.

It is known that the use of a Langmuir probe is an effective way of measuring plasma parameters in a gas discharge, for example, see [12]. According to the current-voltage characteristics (CVC) of the probe, the concentration of electrons, electron temperature is determined. The same probe can be used to determine the dust particle charge. Near a negatively charged Langmuir probe there is a dust-free region, as was shown in [13], and the authors of the present paper observed it too. Such region corresponds to the ionic sheath near the probe. In this paper we report on measuring of the charge of dust particles moving in the sheath of the negative Langmuir probe on the basis of the analysis of their trajectories obtained in experiment. Such particles have sufficient energy to enter into the sheath. Calculations show that charges of dusty particles penetrating the sheath

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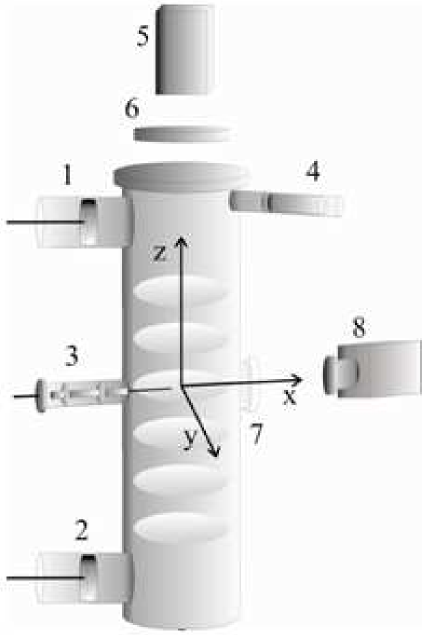

Fig. 1: Outline of the experimental dc installation for the investigation of dusty plasma; 1) anode, 2) cathode, 3) probe, 4) the container with the particles, 5) laser, 6) lens, 7) window for observing, 8) CCD camera.

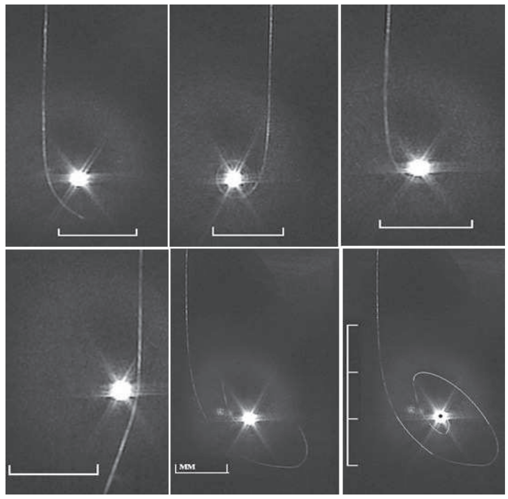

Fig. 2: Trajectory of dust particles near the electric probe.

can change the sing from negative (out of the sheath) to positive (in the sheath) due to the prevailing of ions in the probe sheath.

In the present work the ion drag force acting on the dust particle was not taken into account. Although, it is known that the ion drag force sufficiently effects the dust particles but this force cannot explain their sticking to probe. In work [14] it was shown that the particles far from the negatively biased wire are attracted to the probe by the deflection of the ion drag but the near particles are repelled by the electrostatic force that prevails over the saturated ion drag.

In some experiments the phenomenon of recharging of dusty particles was observed. Thus, the first experiment on the recharging of dust particles in complex plasma under the condition of microgravity was carried out in work [15].

Experiment. – The measurements were carried out in an experimental setup (fig. 1), which includes: a special discharge tube, which provides inserters for the anode (1) and cathode (2), probe (3), high voltage power supply, the container with the particles (4), a laser for illumination (5), lens (6), the systems of observing and visualization (7, 8). Glow discharge in the tube was observed at working gas (argon) pressures of 0.08–0.2 torr and discharge current of 0.5–1.5 mA, see ref. [16]. A single cylindrical Langmuir probe was used: a tungsten cylindrical wire of about 0.1 mm in diameter and about 2 mm long, inserted in the plasma from the special appendix on the glass tube.

Recording is carried out using a CCD camera at 25 frames per second. Figure 2 shows the photographic images of dust particles trajectories near the probe in the discharge plasma.

It is visible in fig. 2 that some dust particles passing near the probe are attracted to it and even make a centrally circular motion around it. Such motion seems odd, because the probe and the macroparticles in the plasma have a negative charge. To explain this phenomenon in work [17] theoretical investigations of the behavior and charge of the solitary dust particle in the probe sheath were carried out.

Theory. – The proposed method for the determination of dust particle charge is based on the following idea: to calculate the values of the particle charge, which depends on the distance from probe r, by means of the substitution of the digitized coordinates of dust particle obtained from its experimental trajectory into the system of dust particle motion equations.

We assumed that a solitary dust particle near the probe moves under the action of only the electrostatic force. Since its motion across the axis of the tube is negligible, then the problem is reduced to a two-dimensional one in the vertical plane. Introducing the polar coordinates r and θ in the trajectory plane and taking the origin center of the probe, the equation of such motion can be written in the form

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

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

where $K_0 = M_d V_0^2/2$ is the initial kinetic energy of the dust particle, the initial velocity V_0 can be estimated by the ratio of the initial displacement to the time interval corresponding to this displacement, M_d is the macroparticle's mass, and ρ is the impact parameter, $U(r)$

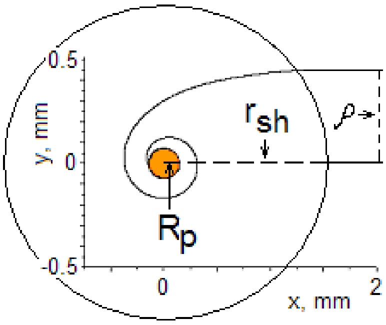

Fig. 3: (Colour on-line) Trajectory and impact parameter of dust particles near the electric probe.

is the potential of the probe at the point r. The electric field distribution near the probe is determined by the Poisson equation, which has the form ($\varepsilon = 1$)

$$\frac{1}{r}\frac{\mathrm{d}}{\mathrm{d}r}\left(r\frac{\mathrm{d}U(r)}{\mathrm{d}r}\right) = -4\pi e[n_i(r) - n_e(r)]. \qquad (2)$$

For the electron density the Boltzmann distribution may by applied. Unlike electrons, the distribution of ions is substantially nonequilibrated due to the absorbing action of the probe. So, the Boltzmann distribution is no longer applicable to the concentration of ions. To calculate the density distribution of ions a special approach with an absorbing surface was used. About it and boundary conditions for eq. (2) one can find information in refs. [17,18].

To check the reliability of the system of eqs. (1), (2), the direct problem of the finding of the particle trajectories with a known value of dust particle's charge with parameters taken from experiments was solved in work [17]. Here, the dust particle charge $Z_d(r)$ was calculated by the currents of electrons and ions on its surface. Since in the probe sheath flows vary and depend on the radial distance to the probe, it turns out that the charge of the dust particle has also a variable value that depends on r. The parameters taken from experiments were the probe radius, $R_p = 150\,\mu$m, the plasma potential, $U_p = -6.3\,$V, the impact parameter ρ, which had values in the range 150–500 μm for different observations of moving particles near the probe. Impact parameters were determined from photographs of the trajectories of the dust particles as shown in fig. 3. Here r_{sh} is the radius of the probe sheath, which is equal to a few electron Debye lengths. The temperature T_e, the density n_e of electrons and the potential of the probe were determined by probe diagnostics, for example, at a pressure equal to 10 Pa, $T_e = 2.8\,$eV, $n_e = 2\cdot 10^9\,\mathrm{cm}^{-3}$. The calculated trajectories on the basis of eqs. (2), (3) are in good agreement with experimental ones (see ref. [17]).

The equation for the inverse problem of the particle charge determination by the experimental trajectory was

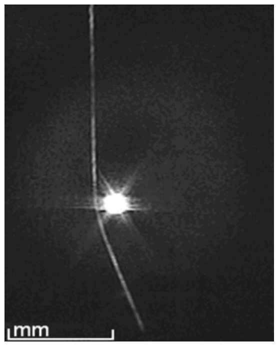

Fig. 4: Trajectory of the dust particle in the probe sheath. Example 1.

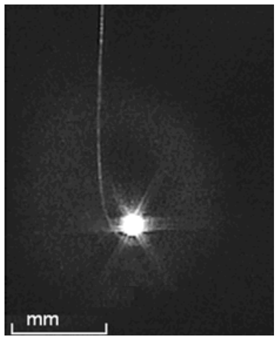

Fig. 5: Trajectory of the dust particle in the probe sheath. Example 2.

obtained from (1) and can be written as follow:

$$Z_d(r) = M_d\frac{r\,(\mathrm{d}\theta/\mathrm{d}t)^2 - (\mathrm{d}^2r/\mathrm{d}t^2)}{e\mathrm{d}U/\mathrm{d}r}. \qquad (3)$$

For eq. (3) the following initial conditions for polar radius r, radial velocity u_r and polar angle θ at $t = 0$ are recorded:

$$r(t=0) = r_0, \quad u_r(t=0) = -\left[2K_0/M_d(1-\rho^2/r_0^2)\right]^{1/2},$$
$$\theta(t=0) = \arcsin(\rho/r_0). \qquad (4)$$

The system of eqs. (2), (3), together with the initial and boundary conditions allows us to calculate the charge of dust particles in the the probe sheath.

Figures 4 and 5 show photos of the trajectories of dust particles moving in an argon plasma near the probe presented at different impact parameters ρ/R_p and reduced initial energies $\gamma_d = K_0/k_bT_e$. Dust particles have a radius $r_d = 1.5\,\mu$m and mass $M_d = 1.7\cdot 10^{-10}\,$g, the electron energy is 3 eV and the ion temperature is equal to room temperature.

Figures 6 and 7 show the results of calculations of the charge of a dust particle as a function of the distance from the probe for the examples presented in figs. 3 and 4, respectively. One can see that the dust away from the probe has a negative charge and in the near-probe region charge sign changes to positive. "Recharge" is due to the fact that close to the surface of the probe the ion

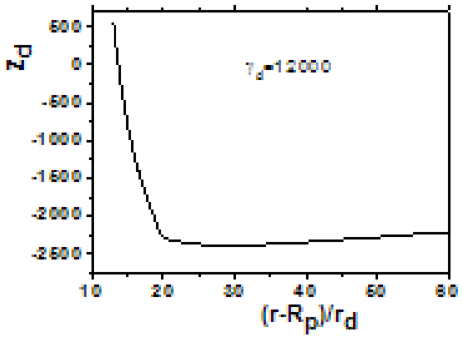

Fig. 6: The dependence of the dust charge on the distance from the probe. Example 1.

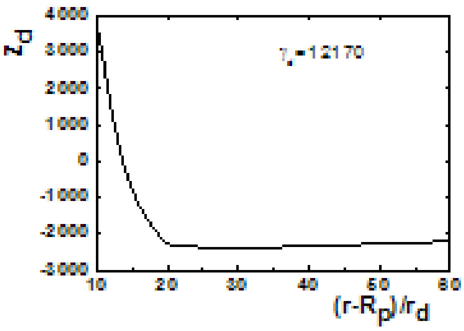

Fig. 7: The dependence of the dust charge on the distance from the probe. Example 2.

current begins to prevail over the electron current. The asymptotic value of the charge away from the probe may be considered as unperturbed charge of dust particles in the glow discharge plasma.

The charge of dust particles in the unperturbed region of plasma can be estimated on the basis of Orbit Motion Limited (OML) theory (see, for example, ref. [4]). In the framework of this theory the equation for dust particle charging in plasma has the following form:

$$\frac{\mathrm{d}z}{\mathrm{d}t^*} = \frac{1}{\sqrt{\mu\tau}}\left[\exp(-z) - \left(\frac{\mu}{\tau}\right)^{1/2}(1+\tau z)\right], \qquad (5)$$

here $z = \frac{|Z_d|e^2}{r_d T_e}$ is the reduced charge, $\tau = \frac{T_e}{T_i}$, $\mu = \frac{m_e}{m_i}$, $t^* = \frac{\omega_{pi}}{\sqrt{2\pi}}(\frac{r_d}{\lambda_{D_i}})t$ is the reduced time and λ_{D_i}, ω_{pi} are the Debye length and plasma frequency of ions. The result of calculation of eq. (5) at the same parameters as in the experiment is presented in fig. 8. As one can see, the value of the charge obtained by OML theory differs from the experimentally obtained one within 5–10 percent.

Conclusion. – In this work a new method for the determination of the charge of dust particles by their motion near an electric probe in the discharge plasma is proposed. Assuming that the particles are monodisperse and of the same material, it is possible to consider

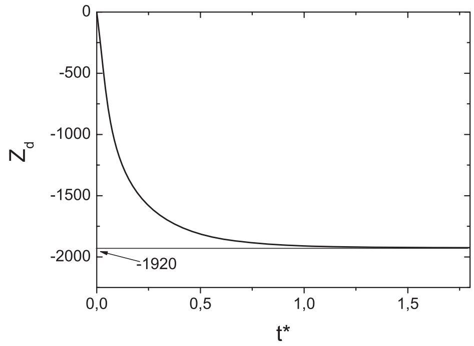

Fig. 8: The time charging of the dust particle in the plasma on the basis of OML theory.

that they have the same charge values on average. As a consequence of this, it is sufficient to determine the charge of one or more test particles in their response to external perturbation. As an external perturbation the electric probe has been chosen. The method includes videotaping of capturing of one of the dust particles by the probe, digitizing the coordinates of dust, the solution of mathematical problems related to the definition of particle charge values (parameter in the equation motion) from the known coordinates of dust. The value of the particle charge on the distance r from the probe is determined by solving the inverse problem with eq. (3).

This method allows to estimate the dust particle charge in a perturbed region near the probe as well as in the unperturbed plasma. The asymptotic value of the charge away from the probe is the founded charge of dust particles in the unperturbed glow discharge plasma.

* * *

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