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Application of dust grains and Langmuir probe for plasma diagnostics

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Abstract – This paper presents the results of the analysis of the experimentally measured width of the dust-free region around a single electric probe in a dusty plasma of glow discharge. The experimental results were compared with the data of a theoretical study on the basis of the balance equation of the dust particles thermal energy and their electrostatic interaction energy with the probe. An alternative method for the determination of the buffer plasma parameters was developed by measuring the dust-free region area around the probe. Using this method the temperature and the concentration of electrons in an argon glow discharge plasma in the pressure range from $P = 0.6$ to $P = 0.8$ torr were determined.

Introduction. – A single electric probe is an universal tool for the diagnostics of the low-temperature gas-discharge plasma. The list of the physical properties, measured by the Langmuir probe, is quite large and this method is easier than other methods of diagnostics. For these reasons it is still of great interest and finds new applications. Among them the application of an electrical probe in dusty plasmas should be noted. Dusty plasma is a usual plasma, which contains small particles of condensed matter [1]. The presence of the relatively large particles, which acquire in the plasma environment the charge of thousands of electrons, strongly modifies the properties of the buffer plasma [2,3]. Therefore, the diagnostics of such systems requires a new approach.

In ref. [4], the trajectory of a single dust particle in the disturbed region around the probe on a strict theoretical basis was firstly considered. Equations for the motion of the individual dust grain in the double layer of the negatively charged cylindrical probe in a glow discharge plasma were derived and solved numerically. The trajectories of grains with different initial energies and impact parameters were considered. An analysis of the grain trajectories showed that high-energy grains can be recharged; *i.e.*, at a certain distance from the probe the grain charge can change sign. Experimental confirmation of this phenomenon and the comparison with the numerical results are presented in ref. [5]. In this work in the equations of the dust particle motion only the electrostatic force acting on the particle from the probe was taken into account. In [6] the ion drag and the neutral friction forces were introduced. In order to determine the effect of the ion drag force and the neutral friction force the experiments were carried out in different discharge conditions, in particular at different values of the pressure in the discharge tube. The analysis of the experimental data showed that, with increase in pressure, the particles are more strongly attracted to the Langmuir probe, and even stick to the probe. Trajectories calculated with taking into account the ion drag and neutral friction forces in the equations of motion are in good agreement with the experimentally obtained trajectories of dust particles at high pressures. Based on the above-mentioned results, in ref. [7], a new method for the determination of the particle charge was constructed. The method is based on the analysis of the trajectories of dust particles around an electrical probe. The experimental tracks of charged particles were digitized and by solving the inverse problem the charge of the dust particles was found. This method allows to determine the charge of the dust particles in the disturbed area and outside of it.

Apart from the study of the interaction of the electric probe with individual dust particles there is great interest in the investigation of the interaction of the plasma-dust structures with the electrical probe. In [8] the radius of the dust-free region around an electrical probe in the high-frequency discharge under microgravity conditions was measured. It was noted that the dust particles had levitated at some distance from the probe due to the balance between the electrical and ion drag forces. The formation of the dust-free region was compared with the formation of "voids" in the complex plasma under microgravity [9,10].

The radius of the dust-free region was also measured in a dusty plasma of argon glow discharge [11]. The free region has a cylindrical shape. In this paper the dependence of the dust-free region size on the negative potential of the electrical probe has been considered. A mathematical model describing this phenomenon was based on the balance between the electrical interaction force of the charged dust particles with negatively charged probe and the ion drag force.

The correct analysis of the behavior of the plasma-dust structures [12] near the electrodes regions allows to use them as diagnostic tools for complex plasmas. In [13–15] the dust particles were used as thermal, electrical, and force probes. Using a conventional method, such as the visual identification of the dust particles, the dust component temperature, local electric field, momentum of high ion flux and power flow on the particles were estimated on the basis of simple calculations.

In all these works very interesting results were obtained. They are important and useful not only in the study of the characteristics of complex plasma and plasma-dust formation, but can be also used in the determination of the characteristics of the background plasma.

In this paper the method for determination of the temperature and concentration of the buffer plasma on the basis of the experimental measurement of the radius of the dust-free region around an electrical probe in the positive column of a glow discharge is presented. The novelty is the use of equations based on the equality of the thermal energy of the dust particles and the energy of the electrostatic interaction of particles with the probe and further use of a theory of the probe potential for plasma diagnostics based on measuring the dust-free region.

Experiment. – The experiments have been performed in the positive column of a glow discharge in argon. The discharge was obtained in a glass tube with a length of 550 mm, and a diameter of 46 mm. The measurements have been carried out on an experimental setup (fig. 1), it includes: a special discharge tube, which provides inserters for the anode (1) and cathode (2), probe (3), the container with the particles (4), a laser for illumination (5), a PC (6), the systems of observation and visualization (7,8). The typical experimental value of the discharge voltage is in the range 0.9–1.2 kV, the discharge current is 0.5–3 mA in the pressure range 0.6–0.8 torr. A single cylindrical Langmuir probe has been inserted in the plasma perpendicularly to the positive column. The probe was made of a tungsten wire with a length of 1 mm and a diameter of about 150 μm. Recording is carried out using a CCD camera at 25 frames per second. The measurement error of the width of the dust-free region is about 8–10%.

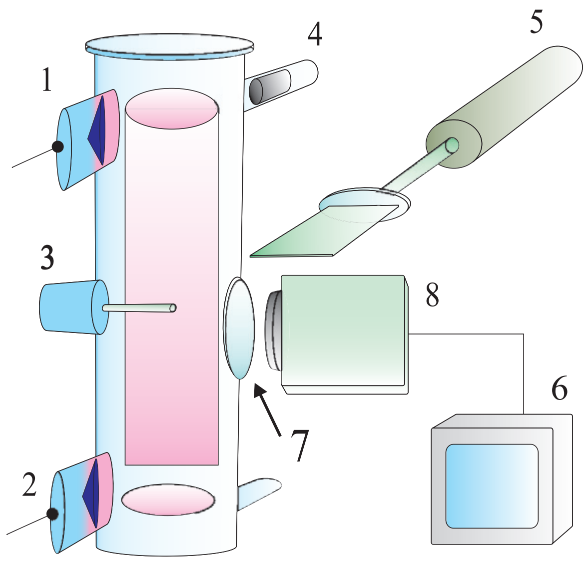

Fig. 1: (Colour on-line) Experimental setup: anode (1), cathode (2), probe (3), container with the dust particles (4), laser for illumination (5), PC (6), the systems of observation and visualization (7,8).

Once the probe circuit had been turned on, a voltage U_p, which was negative relatively to the plasma, was applied on the probe. The probe field is screened by the plasma charged particles around the probe and the screening length is much smaller than the size of the discharge tube. Therefore, we assume that in general the discharge parameters do not change significantly upon introducing the probe. Dust particles of Al_2O_3 with diameter 10 μm were injected into the plasma from the container, which had been located on the top of the discharge tube.

After inserting the probe a layer of positive charge was formed around it. The dust particles fell down until they reached the region near the probe. Then the particles with a relatively high kinetic energy overcame the barriers of the ion layer moving toward the probe along different trajectories in this region. Some of them performed rotations around the probe and fell on the probe surface [5,6]. The particles that had a low thermal energy kept levitating at some distance from the upper probe. So, some region near the probe was free from dust particles. The dimensions of this region depend on the voltage, on the probe, and on the parameters of the surrounding plasma. When the absolute value of the voltage U_p decreases, the distance between the probe and the cloud of dust particles decreases too. At a certain potential in the circuit diagram of the probe, dust particles were attracted by the probe and fell on the probe surface. Photos of the probe and dust structure on the probe, which were taken at different values of the probe potential U_p and constant pressure, are shown in fig. 2. Here, the potential at which the dust particles fall on the probe surface is equal to $U_p = -80$ V.

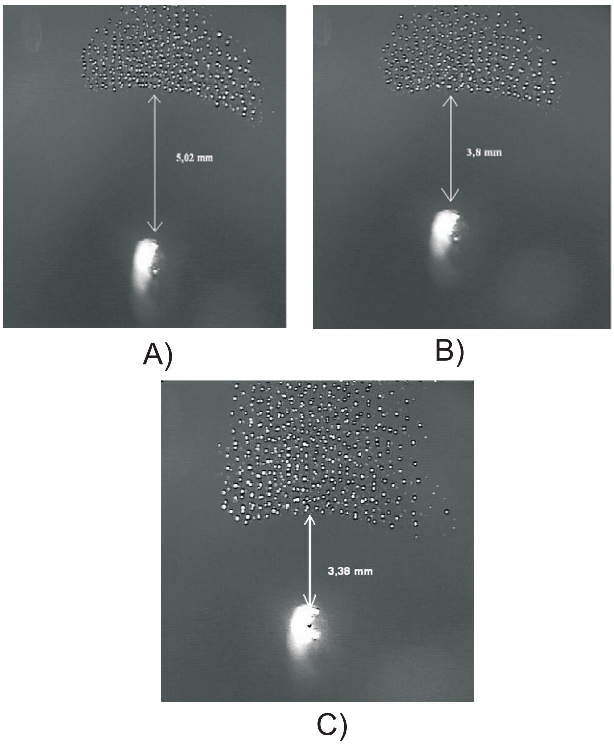

Fig. 2: Dust-free region around the electric probe. The distance between probe and dust particles is (A) $r_f = 5.02\,\mathrm{mm}$, probe potential $U_p = -580\,\mathrm{V}$; (B) $r_f = 3.80\,\mathrm{mm}$, probe potential $U_p = -420\,\mathrm{V}$; (C) $r_f = 3.38\,\mathrm{mm}$, probe potential $U_p = -280\,\mathrm{V}$. Pressure in the discharge tube $P = 0.6\,\mathrm{torr}$.

The experimental data were obtained under different conditions of discharge. It was observed that with the increase in the discharge current or (and) decrease in the gas pressure the distance between the probe and the dust particles decreases: the radius of the dust-free region increases from 6.5 mm to 8 mm with an increase in pressure in the discharge tube from 0.3 torr to 0.42 torr [16]. Usually, the particles follow the sheath in front of the electrode which decreases with increasing pressure (see, for example, [17]). But in our case, the increase of the dust-free region size with the growth in gas pressure in the discharge tube is probably due to the increase in particle charge, which leads to a strong repulsion between the negatively charged microparticles and the probe. The temperature of the dust particles T_d was determined using the video recording of the experiment. After processing the video files the distribution function of the dust particles levitating above the probe had been built. Then, on the basis of the maximum of the velocity distribution function the most probable velocity of the dust particles ϑ_p, which was used to obtain their temperature, was determined according to the following formula:

$$\vartheta_p = \sqrt{\frac{2k_B T_d}{m_d}}. \tag{1}$$

Here, k_B is the Boltzmann constant, T_d is the dust particles temperature, m_d is the mass of the dust particles. It should be noted that the temperature T_d in eq. (1) is a thermodynamic temperature. According to the works [18–20] in the plasma-dust structures formed in the gas discharges a Maxwellian velocity distribution of dust particles was observed. In our experiments we found that the velocity distribution was Maxwellian too. The observed large temperature in energetic units is due to the relatively large mass m_d of dust particles.

Theory. – In work [11], the distance between the probe and the dust particles was calculated by the balance between electric and ion-drag forces. We have calculated the radius of the dust-free region on the basis of the equality of the thermal energy of the dust particles and the energy of the electrostatic interaction of particles with the probe:

$$k_B T_d = Z_d e U(r_f), \tag{2}$$

where $Z_d e$ is the charge of the dust particles, $U(r)$ is the electrostatic potential around the probe and r_f is the radius of the dust-free region. In order to correctly describe U_r it is necessary to obtain and solve the equation of the plasma layer. In the case of an isotropic, weakly ionized and rarefied plasma, when the mean free path of the charged particles is much larger than the characteristic dimensions of the probe, the electrostatic potential around the probe is determined by the Poisson equation:

$$\Delta U(\vec{r}) = -4\pi(n_i(\vec{r}) - n_e(\vec{r})). \tag{3}$$

According to work [21] there is an absorbing surface, which differs from the probe surface. The radius of the absorbing surface is the limitation radius, which defines the local maximum of the effective potential energy of the ions:

$$U_{eff}(r) = \frac{l^2}{2m_i r^2} + eU(r), \tag{4}$$

where m_i is the mass of the ions, l is their angular momentum. Then for a large cylindrical probe ($r_p \gg \lambda_d$) when $\lambda \gg r_p$ one can obtain [21]

$$n_i = n_0 \left\{ 1 - \frac{1}{\pi} \arcsin \frac{r_l}{r} \left[\frac{E_0 + eU(r_l)}{E_0 + eU(r)} \right]^{\frac{1}{2}} \right\}, \tag{5}$$

when $r > r_l$

$$n_i = \frac{n_0}{\pi} \arcsin \frac{r_l}{r} \left[\frac{E_0 + eU(r_l)}{E_0 + eU(r)} \right]^{\frac{1}{2}}, \tag{6}$$

when $r < r_l$ (here and below the potential is described by absolute values). Here r_p is the probe radius, λ is the mean free path of the charged particles, λ_d is the Debye length, r_l is the limitation radius, E_0 is equal to the average kinetic energy of the ions in the plasma, n_0 is the ion concentration in the unperturbed plasma region. For the electron numerical density the Boltzmann distribution was taken. Thus, numerically solving eq. (3), we have obtained the curves of the electrostatic potential near the

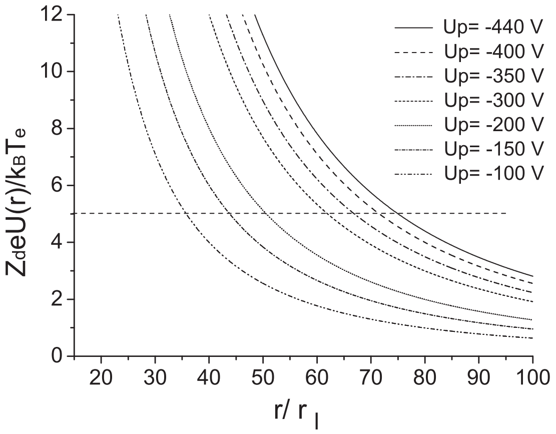

Fig. 3: Interaction energy between the dust particles and the electric probe. The dotted line corresponds to the thermal energy of the dust particles.

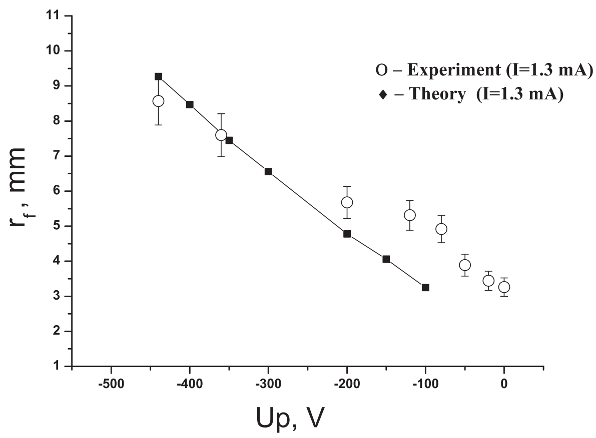

Fig. 4: Comparison of the experimentally measured radius of the dust-free region with theoretical results.

probe for different boundary values of the probe potential U_p on its surface.

Figure 3 shows the distance dependence of the energy of the interaction of the dust particles with the electric probe obtained on the basis of eq. (3) for different values of the probe potential U_p on its surface. The dotted line corresponds to the thermal energy of the dust particles, which in this experiment equals 5 k_BT_e. The dust temperature, as was mentioned above, was determined by the velocity distribution function, which was measured in the experiment. The points of the intersection of the dotted line with the potential curves give us the distances between the dust cloud and the electric probe, that are the radii of the dust-free regions r_f. In fig. 4 the theoretical results were compared with experimental data at the pressure in the discharge tube $P = 0.6\,\text{torr}$, and for a value of the discharge current $I_2 = 1.3\,\text{mA}$. They showed a good agreement.

Determination of the electron temperature and density. – It was shown by the experimental and theoretical results on the radius of the dust-free region that the

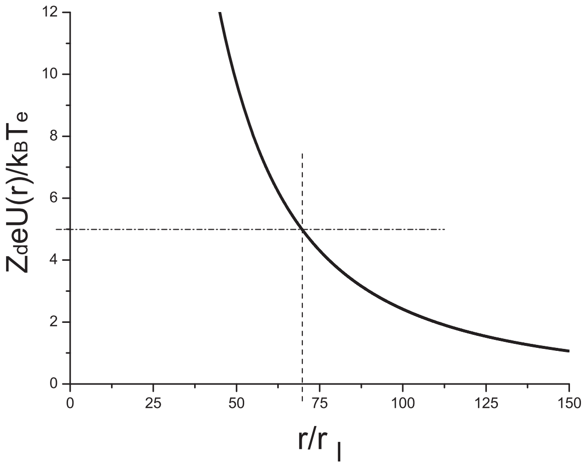

Fig. 5: The interaction energy of the dust particles with the electric probe (solid line) at $U_p = -350\,\text{V}$, the thermal energy of the dust particles (dash-dotted line), and the experimentally determined radius of the dust-free zone (dotted line).

distance between the probe and the dust particles depends on the probe potential and discharge conditions. This allows us to identify important parameters of the plasma, such as temperature and numerical density of the electrons. Let us remind that the distribution of the electric potential around the probe depends on the Debye length, which appears in the solution of the Poisson-Boltzmann equation. To each potential curve in fig. 3 there corresponds some value of the Debye length λ_d. If one assumes that the radius of the dust-free region is known (since it can be easily measured in the experiment) the inverse problem of finding the electron Debye length can be solved. The Debye length is determined by the well-known formula

$$\lambda_d = \sqrt{\frac{k_BT_e}{4\pi n_e e^2}}. \tag{7}$$

Here, T_e is the temperature of the electrons, n_e is the numerical density of the electrons. Figure 5 displays a graphical illustration of the inverse problem.

This illustration shows the thermal energy of the dust particles, marked by a dash-dotted line. Knowing the radius of the dust-free region r_f, one can find the point of the intersection of the line corresponding to the thermal energy of the dust particles and the line corresponding to r_f. Then, the potential curve, passing through this point and corresponding to a certain value of λ_d, can be easily found. Thus, knowing, for example, the electron temperature, the electron numerical density can be determined by eq. (7).

As an example, we can obtain the temperature of the plasma electrons using the equation of the Orbit Motion Limited (OML) theory [22,23]:

$$e^{-\frac{|Z_d|e^2}{aT_e}} - \frac{n_i}{n_e}\sqrt{\frac{m_eT_i}{m_iT_e}}\left(1+\frac{|Z_d|e^2}{aT_i}\right) = 0. \tag{8}$$

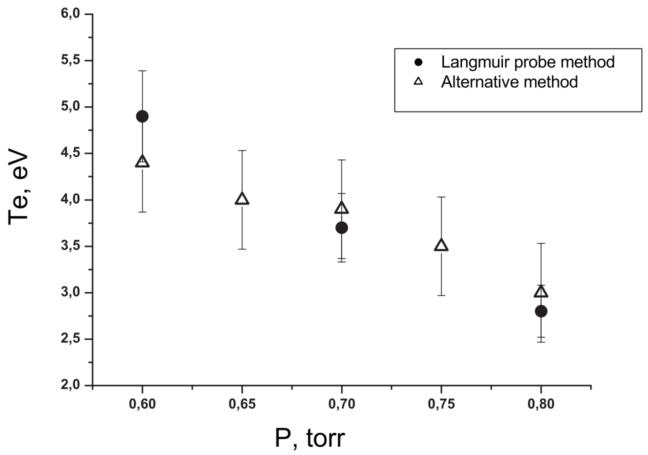

Fig. 6: The temperature of electrons which has been determined by measuring the dust-free region (alternative method) and by Langmuir probe measurements.

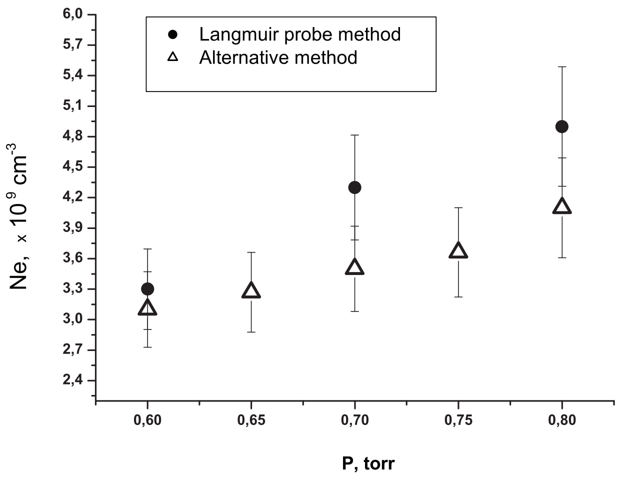

Fig. 7: The numerical density of electrons which has been determined by measuring the dust-free region (alternative method) and by Langmuir probe measurements.

The ratio $\frac{n_i}{n_e} \approx 1$ for Ar plasma of the DC discharge due to the quasi-neutrality of the plasma. The ion temperature equals room temperature.

Dust charge was determined from the pair correlation functions of dust particles according to refs. [24,25]. The first maximum g_{max} of the pair correlation function defined the coupling parameter Γ, then from the following ratio the dust particle charge can be calculated:

$$\Gamma = \frac{(Z_d e)^2}{a_0 k_B T_d}. \tag{9}$$

Here, a_0 is the average interparticle distance.

Dust temperature and the average interparticles distance are easily determined in experiment. Below the data used in one performed experiment are presented. The pressure in the discharge tube was $P = 0.6\,\text{torr}$, and the discharge current was $I = 1.5\,\text{mA}$, the temperature of the dust particles is $T_d = 22\,\text{eV}$, the average interparticle distance $a_0 = 0.09\,\text{cm}$ and the nonideality parameter $\Gamma = 33$, the dust multiple charge $Z_d = 2.1 \cdot 10^4$.

The solution of eq. (8) gives us the electron temperature, which is equal to $T_e = 4.4\,\text{eV}$. Thus, with the following parameters: $T_e = 4.4\,\text{eV}$, $U_p = -350\,\text{V}$, $r_f = 3.65\,\text{mm}$, the Debye length, found by the above-described method, is equal to $\lambda_d = 0.028\,\text{cm}$, and the electron density $n_e = 3.1 \cdot 10^9\,\text{cm}^{-3}$.

Figures 6 and 7 show the results of the determination of the electron temperature and electron numerical density obtained by measuring the dust-free region near the probe under different discharge pressures. As one can see the estimated parameters are in good agreement with the results of Langmuir probe method in DC glow discharges.

Conclusion. – A method for the diagnostics of the buffer plasma based on the study of the dust-free region was proposed. The main deal is only measuring the dust-free region and then applying the special software which calculates the temperature and numerical density of dust, and the electron temperature and numerical density. It should be noted that this method does not use the voltage-current characteristics and can be applied when the construction of the correct *I-V* characteristic in standard probe diagnostics is difficult.

For practical purposes, this method can be used in laboratory to determine the complex plasma parameters, in devices for coating the dust particles surfaces by special materials, in microparticles synthesis in a gas discharge plasma, during the separation of monodisperse powders in a plasma-dust medium etc.

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