# Dependence of the Dust-Particle Charge on Its Size in a Glow-Discharge Plasma

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Measurements of the charge of dust grains have been performed in a quasineutral plasma over a wide range of grain sizes. A new method was established for measuring the charge on grains levitating in the striations of a dc glow discharge. A single dust particle is moved out of a dust cloud with the help of a focused laser beam. When it leaves the beam it returns back to the cloud, and the charge on the grain is derived from the analysis of the returning trajectory. The obtained dependence of the dust-grain charge on its size was found to be strongly nonlinear in the experimental conditions.

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The problem of the charging of dust particles in a plasma is one of the main tasks to be studied. In a plasma dust particles acquire a charge (typically it is negative), interact with each other, and their presence may lead to a significant change of the plasma properties. Since the electrostatic energy of interacting particles strongly exceeds their thermal energy, the particles can form an ordered lattice. The so-called plasma crystals have been widely studied with respect to lattice formation [1,2], phase transitions [3], and waves and instabilities [4]. The determination of the grain's charge is very important in all of these experiments in order to reveal whether the dust system is strongly or weakly coupled [5]. The charge of the dust grains is of great interest to understand the behavior of particulates in processing plasmas used for thin-film production, in processes of growing particles in the gas phase by nucleation and aggregation [6] as well as for the study of space plasmas, e.g., interstellar clouds and planetary rings [7].

There is a requirement to obtain reliable experimental data on the value of the dust-particle charge over a wide range of grain sizes and plasma parameters. However, no methods for measuring the charge on the dust particles were proposed for the direct current (dc) discharge dusty plasma.

For rf discharge plasmas several methods have been developed. In the first method, initiated by [8,9] the charge is derived from a response of a simple ordered system (chain, monolayer, etc.) of dust particles on a periodical disturbance. In the second method [10], the charge was determined from the trajectories of the particles in binary collisions. In the third method [11], Mach cones were excited in a 2D crystal by the fast dust particles, and the charge was derived from the analysis of these waves. However, the crucial condition for the application of these methods is low neutral gas pressure (of the order of $10^{-2}$–$10^{-1}$ torr).

In this Letter, we present the results of the measurements of the charge on dust grains in the striations of a dc discharge obtained with a new method. The experiments were carried out in a glass discharge tube [12] of 36 mm diameter and 40 cm interelectrode distance. The glow discharge with cold electrodes was produced in neon in the range of pressures 0.5–1.5 torr. The discharge current varied from 0.4 to 3 mA. In this range of parameters, regimes with standing striations existed. Dust particles were stored in a container with a grid at the bottom, positioned above the anode. Through the shaking of the container, the particles were dispersed into the plasma region then levitated in the striations where they formed ordered structures. Melamine-formaldehyde particles of 1.87, 4.82, and 13.57 $\mu$m diameter were used. A 50 mW diode laser was used for the illumination of the particles. The scattered light was observed by a CCD video camera.

The specificity of the striations of a dc glow discharge is such that a stable levitation of dust particles occurs at relatively high pressures (0.5–2 torr). At lower pressures self-excited waves are developing in the dusty plasma structures [4], making the measurement of the charge with the techniques, cited above, impossible.

In the present work, the measurements of the charge were conducted in the following way (Fig. 1). The light beam from an $Ar^+$ laser was focused onto a single particle in the structure. The beam power was up

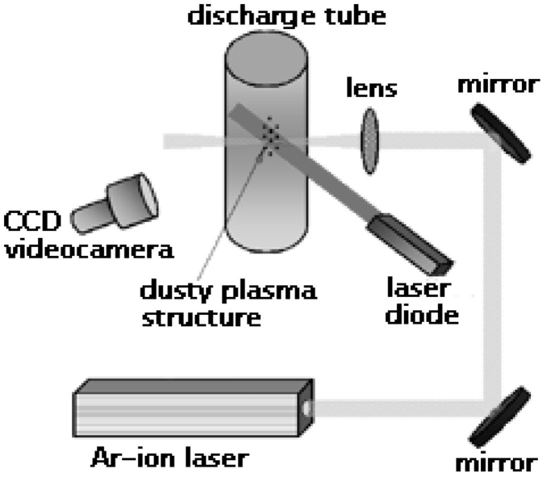

FIG. 1. Scheme of the setup for measuring the charge on dust particles.

to 200 mW, the waist thickness was about 60 $\mu$m, and the corresponding power density was of the order of $10^3$ W/cm$^2$. Under the effect of the laser light, the particle moves 1.5–3 mm out of the structure, then leaves the beam and returns back into the structure. The deflection of a macroparticle is definitely horizontal. That means that the laser light does not affect the charge on the dust particle. When returning back into the structure, the dust grain is experiencing mainly the radial electric force and the neutral drag force. The radial electric field is derived from the ambipolar diffusion condition [13]:

$$E_r = \frac{\epsilon}{ne} \frac{\partial n}{\partial r}, \tag{1}$$

where $\epsilon$ is the local value of the average electron energy, $n$ is the plasma density, and $r$ is the current radius. The radial distribution of the plasma density is known to be described by the zero order Bessel function [13]:

$$n = n_0 J_0\left(\frac{2.4r}{R}\right), \tag{2}$$

where $n_0$ is the plasma density in the center of the tube, and $R$ is the tube radius. Since the deflection of the particle is small compared to the tube radius (18 mm) the linear approximation of the radial electric field can be used:

$$E_r = \left(\frac{2.4}{R}\right)^2 \frac{\epsilon r}{2e}. \tag{3}$$

Then the motion of a macroparticle can be described by the harmonic oscillator equation as it is done in [14]:

$$\ddot{r} + 2\beta\dot{r} + \omega^2 r = 0, \tag{4}$$

where $\beta$ is the damping factor, arising from the neutral drag:

$$\beta = \frac{8\sqrt{\pi}}{3} \frac{pa^2}{mv_{\text{th}}} \tag{5}$$

($a$ is the dust particle radius, $p$ is the gas pressure, $m$ is the particle mass, $v_{\text{th}}$ is the thermal velocity of the gas atoms) and $\omega$ is the natural frequency of a dust particle in the radial field of the discharge:

$$\omega^2 = \left(\frac{2.4}{R}\right)^2 \frac{\epsilon}{2em}. \tag{6}$$

*Epstein* formula [15] for the neutral drag force is supposed here since the mean free path of neon atoms at the maximal pressure used (1.5 torr) equals 32 $\mu$m. This is about 4.6 times larger than the maximal dust grain radius.

As follows from the observation, the particle performs an aperiodical motion. This distinguishes the present work from [14], where periodic oscillations of dust grains were observed under rather low neutral gas pressure conditions (0.03 torr). Starting its way back with the zero radial velocity, the particle is first accelerated by the electric force and then, while its velocity increases and the electric field decreases towards the tube center, neutral drag starts to prevail and the particle is slowed down. In the point of the velocity maximum the radial electric force must be balanced by the neutral drag:

$$E_r q = \frac{16\sqrt{\pi}}{3} pa^2 \frac{v_m}{v_{\text{th}}} \tag{7}$$

($v_m$ is the maximal particle velocity). This equation gives the possibility to determine the charge:

$$\epsilon q = \frac{32\sqrt{\pi}}{3} pa^2 \frac{v_m}{v_{\text{th}}} \left(\frac{R}{2.4}\right)^2 \frac{e}{r_m}, \tag{8}$$

where $r_m$ is the radial position, at which the velocity maximum occurs.

The dust-particle velocity is determined from the frame-by-frame analysis of the 25 fps video recording. It takes 5–8 frames for a dust grain to return back. The maximal velocity $v_m$ equals the maximal distance the particle passes between two frames divided by the interframe time interval (1/25 s). The position $r_m$ is attributed to the middle between the dust particle positions on the two frames. The errors of $v_m$ and $r_m$ determination contribute to the total error of the $\epsilon q$ product measurements which are estimated not to exceed 40%.

Note that measurements of the local values of the electron temperature $T_e$ (average electron energy $\epsilon$) and electron density $n_e$ in standing striations of a glow discharge are impossible with the known techniques (e.g., Langmuir probe methods). Therefore we calculated $T_e$ [13] for a uniform positive column with the same plasma conditions. From the measurements of the plasma parameters in the moving striations [16,17] it is known that $\epsilon$ changes along the striation about a factor of 2. At the same time, there is evidence for the similarity of the properties of standing and moving striations at the same discharge conditions [18]. The value of $T_e$ for the uniform positive column corresponds to the minimal $\epsilon$ value for the striation. For the pressure $p = 0.5$ torr, $\epsilon = 3$–$6$ eV, and for the pressure $p = 1.5$ torr, $\epsilon = 2$–$4$ eV. The results of the charge determination are shown in Fig. 2. It is clearly seen that the dependence of the charge on the particle size is quite a nonlinear one. Dependence of the charge on the particle radius can be rather accurately approximated by the power function $q \sim a^{1.87}$ for the pressure 0.5 torr and $q \sim a^{1.69}$ for the pressure 1.5 torr.

The condition of the aperiodic motion ($\beta > \omega$) is satisfied with the measured charge values, e.g., when $\epsilon = 3$ eV, $p = 1$ torr for $a = 1.87$ $\mu$m, $q = 3 \times 10^3 e$, $\beta = 339.5$ s$^{-1}$, $\omega = 49.9$ s$^{-1}$ and for $a = 13.57$ $\mu$m, $q = 1.1 \times 10^5 e$, $\beta = 46.8$ s$^{-1}$, $\omega = 15.5$ s$^{-1}$.

From the dust-particle levitation condition the axial electric field $E$ required for the levitation can be determined:

$$E = mg/q. \tag{9}$$

Table I shows the range of $E$ values for the macroparticles we measured the charge on. The uncertainty in the electric field value arises from the uncertainty of $\epsilon$ and indicates that the dust grains of the same size levitate at different

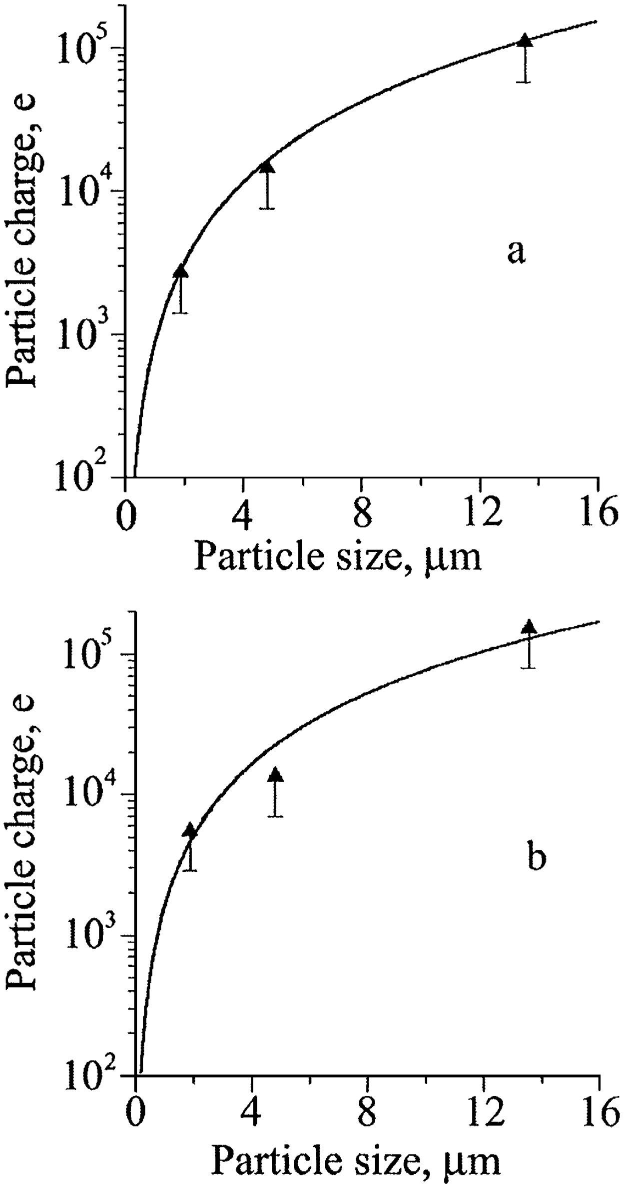

FIG. 2. Results of the charge measurements. Triangles show experimental points for the minimal $\epsilon$ value. Negatively directed error bars indicate the charge value discrepancy due to the uncertainty of the average electron energy. (a) Neon pressure 0.5 torr, minimal $\epsilon = 3$ eV, power fit $q \sim a^{1.87}$; (b) neon pressure 1.5 torr, minimal $\epsilon = 2$ eV, power fit $q \sim a^{1.69}$.

plasma conditions. The structures, we observed, were up to 1 cm long. Since the region of the drastic change of the plasma parameters has the length of about 1.6 cm, large gradients of the plasma parameters may be expected along the dusty plasma structures. The values in Table I are in agreement with the experimental measurements of the electric field in striations [16].

TABLE I. Electric fields, required for the levitation of the dust particles of different sizes.

| $a$ µm | $E$ ($p = 0.5$ torr) V/cm | $E$ ($p = 1.5$ torr) V/cm |
|---|---|---|
| 1.87 | 1.2 ÷ 2.4 | 0.5 ÷ 1.0 |
| 4.82 | 4.6 ÷ 9.2 | 3.9 ÷ 7.8 |
| 13.57 | 12.0 ÷ 24.0 | 8.1 ÷ 16.2 |

Concerning the value of plasma density, it should be noted that in our experiments it is estimated [13] to be in the range (1–5) × $10^8$ $\mathrm{cm}^{-3}$. The ion Debye length, assuming ion temperature $T_i = 300$ K, varies from 56 to 121 $\mu$m. Since the particle radius is much smaller than the ion Debye length, the particle screening length $\lambda_{\mathrm{scr}}$ [19] is close to the value

$$\lambda_{\mathrm{scr}} = (1/\lambda_i^2 + 1/\lambda_e^2)^{-1/2}, \tag{10}$$

where $\lambda_i$ and $\lambda_e$ are the ion and electron Debye lengths, respectively. Under the conditions of these experiments $\lambda_e$ is about 10 times greater than $\lambda_i$. Thus, $\lambda_{\mathrm{scr}}$ is comparable to the ion mean free path (32–96 $\mu$m). Accordingly, the sheath around the dust particle is not collisionless and estimations of the grain charge using the orbit-motion-limited (OML) [20] theory are not valid in the conditions of these experiments.

In Fig. 3 surface potentials, calculated from the measured charges, using the following relation [21],

$$\phi = \frac{q}{a(1 + a/\lambda_{\mathrm{scr}})}, \tag{11}$$

are presented. It is seen that the surface potential of a dust grain increases with an increase of a grain size. In our opinion, this may be due to the effect of ions trapped in the potential well around a negatively charged dust particle [22,23]. Ions undergo occasional charge-exchange collisions near the grain surface, in which the impinging ion

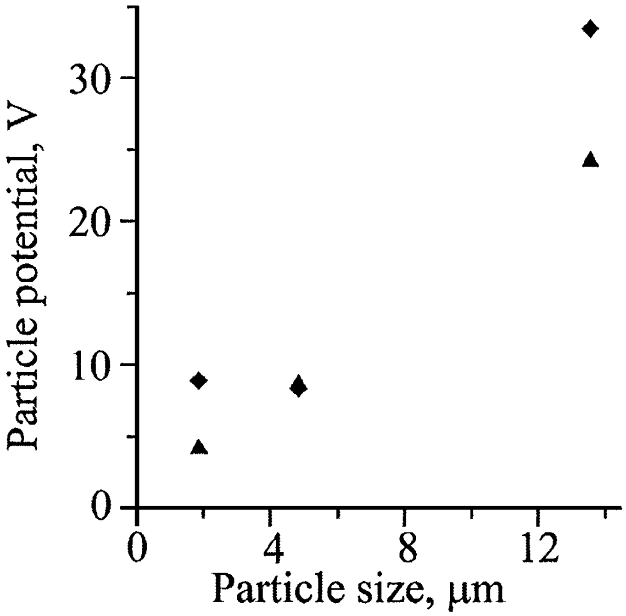

FIG. 3. Surface potentials of the dust particles. Triangles for $p = 0.5$ torr; rhombuses for $p = 1.5$ torr.

disappears and a new ion has thermal velocity. So, effectively ions lose energy in the charge-exchange collisions and, consequently, fall onto the grain creating an additional ion flow. According to [22] when $a/\lambda_{\text{scr}} \geq T_i/\epsilon$, the surface potential increases with the growth of the grain size. This condition is satisfied in our experiments and the dependence of the dust-particle potential on its size is in the qualitative agreement with the calculations in [22]. The detailed comparison of the experimental data with simulation results will be the subject for future studies.

Experiments with 80–170 $\mu$m bronze balls [mass $(0.2-1.8) \times 10^{-4}$ g] in the dc discharge were carried out on board the Mir space station (details of the experiment are to be published). In the positive column of this discharge a cloud of particles, drifting with constant velocity, was observed. From the balance of electric force and viscous friction the charge on a dust particle was determined. Since the particle radius here is comparable to the mean free path of neon atoms (48 $\mu$m) viscous friction is expressed by the formula for the transition regime [24]:

$$Eq = 6\pi\eta a v\left(1 + A\frac{l}{a} + Q\frac{l}{a}e^{-(ba/l)}\right)^{-1}, \qquad (12)$$

where $\eta$ is the gas viscosity, $A = 1.2$, $Q = 0.41$, $b = 0.88$, and $l$ is the mean free path of neon atoms. Taking $E = 3$ V/eV, that is the typical value for the used discharge conditions in neon (current is 0.1 mA, pressure is 1 torr, tube radius is 32 mm), the observed steady-state velocity is 0.3 cm/s, the charge of $(2.0-6.1) \times 10^5$ electrons is acquired, and the corresponding surface potential is 7.2–10.3 V.

In conclusion, we have measured the charge on dust particles levitating in the quasineutral plasma of the dc glow discharge striations by the new method in a wide range of grain sizes. The dependence of the dust particle charge was found to be quite nonlinear. The increase of the surface potential of the dust grains with an increase of the particle size was observed. That is in qualitative agreement with the recent calculations of the spherical grain potential performed in [22,23].

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