Micron-sized particle-charge measurements in an inductive rf gas-discharge plasma using gravity-driven probe grains

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A method for measuring the interactions of charged dust particles within a three-dimensional dust cloud in a plasma is presented. The measurements have been performed with the help of gravity-driven heavy charged probe particles, which moved through a dust cloud levitating at the diffuse edge of an inductively coupled rf discharge plasma. Assuming a screened Coulomb potential surrounding each particle, both the particle charge and the effective screening length were calculated from an analysis of the elastic particle interactions for 20, 30, and 50 Pa of neon pressure. The basic parameters of the bulk discharge plasma have been diagnosed with a Langmuir probe to compare the experimental data with those deriving from different theoretical approaches. The observed discrepancies are discussed.

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I. INTRODUCTION

A micrometer-size particle put into a plasma quickly acquires an electric charge due to absorption of electron and ion fluxes by its surface. This charge is a crucial parameter of colloidal (dusty) plasmas; namely due to the presence of the electric charge on the dust grains, dusty plasmas exhibit numerous specific phenomena such as spatial structurization and different kinds of dust waves and instabilities [1–3]. So knowledge of this parameter is quite important for understanding different physical processes in dusty plasmas.

To the present time, a number of experimental techniques have been developed to evaluate the charge on a dust grain immersed in a plasma [4–11]. Nevertheless, most of the reported techniques are intended to determine the charge of only the particles levitating in the plasma sheath region of a rf capacitive planar discharge and do not permit one to measure the charge of a free particle in a bulk plasma. In addition, these experimental results are very sensitive to the theoretical model used of the sheath structure. Recently, the authors [11] have shown a strong influence of suprathermal electrons on the charging of the macroscopic particles levitating in the plasma sheath. So a more detailed model for the sheath region is required for interpretation of the mentioned measurements of the particle charge.

Research into the charging processes requires the most simplified experimental conditions, such as well-diagnosed uniform background plasma, spherical dust particles, etc. To our knowledge, there is only one work [12] in which the charge was measured for the particles levitating in a bulk plasma. These measurements were provided in a stratum of a dc glow discharge using an aperiodic particle oscillation in an axial discharge tube electric field. Unfortunately, the strata region has also a significant nonuniformity of the main plasma parameters, especially of the electron temperature, which is important for the charging.

The main purpose of the present work is to determine the electric charge of the spherical dust particles immersed in a possibly more uniform plasma and to compare the obtained results with known theoretical approaches. For this reason the charge measurements were performed at the diffuse edge of an inductive rf discharge plasma. This region features more uniformity [13] in comparison with the plasma sheath [9,10] or the stratum [12] regions. For example, the electron temperature at the edge is uniform within 5 cm along the discharge axis for the given discharge parameters. In comparison, the electron temperature changes within 2–10 eV at the dc strata; the suprathermal electrons in the plasma sheath can lead to a two-temperature electron distribution and unpredictably disturb the particle charge [11]. The electric field strength at the edge ranges from 1 to 4 V/cm [13]. In comparison, the electric field strength at the plasma sheath ranges from 5 to 22 V/cm [10]. The obtained values of particle charges will be compared with those calculated in the orbital motion limited (OLM) approximation [14,15] and using the self-consistent molecular dynamics simulation (MDS) for collisional plasma [16]. It is shown that charge exchange collisions of plasma ions with neutral atoms lead to a considerable suppression of the particle charge even when the ion free path is considerably greater than the screening length. Nevertheless, additional arguments should be considered to explain the small value of the measured charges.

II. EXPERIMENTAL SETUP AND METHOD

The scheme of the experiment is shown on Fig. 1. The measurements were performed in a vertically installed glass tube with 28 mm inner diameter and 60 cm length. The tube was filled by neon in the pressure range of 20–50 Pa. An inductive rf discharge was excited in the tube by a two-circle coil inductor with 35 mm diameter powered by a rf voltage with a frequency of 100 MHz. The length of the glow was about 10 cm. Two containers with dust powders were suspended in the upper part of the glass tube. The bottoms of the containers were made from thin grids. The upper container was filled by monodisperse spherical polymeric (melamine formaldehyde, $\rho = 1.51\ \mathrm{g/cm^3}$) particles with $d_1 = 1.87 \pm 0.04\ \mu\mathrm{m}$ diameter, while the lower container was

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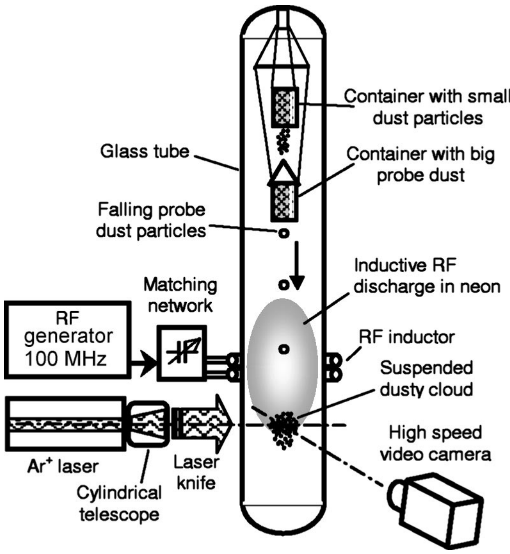

FIG. 1. Scheme of the experiment on charge measurements of grains levitating at the diffuse edge of inductively coupled rf discharge.

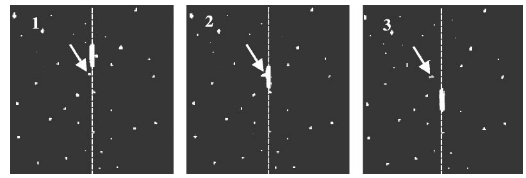

FIG. 2. Interaction of a moving probe particle of 12.74 μm diameter with a levitating dust grain of 1.8 μm diameter. The area shown is about 2×2 mm^2. Frame rate is 1000 frames per second. Dotted vertical line means the trajectory of the probe particle. The arrow indicates the suspended 1.8 μm particle disturbed by the moving probe particle.

filled by particles with $d_2=12.74\pm 0.17$ μm diameter. At the first step, the upper container with small particles was shaken with the help of a magnet. In doing this, the particles penetrated through the grid bottom, fell down, and were partially suspended in the low part of the discharge glow due to a natural electrostatic trap at the diffuse edge. This trap is formed by the combination of the electrostatic fields that result from the ambipolar diffusion and of the charged surface of the tube [17] and it permits one to suspend particles with maximum diameter up to 4 μm. The maximum size of the suspended dust cloud depends on the diameter of the dust spheres used and can achieve about 1.5 cm for particles with 1 μm diameter [18]. In present work the size of the created cloud was made sufficiently small (about $3\times\varnothing 2$ mm^2) to prevent a reduction of the electron density n_e within the cloud due to the electron absorption on the particles. The number of particles in the cloud was about 500 with the mean dust particle density $n_d\sim 5\times 10^4$ cm^{-3} and with the mean intergrain spacing about 300 μm. In spite of using particles with a known diameter, the size of the levitating particles was independently measured using the light scattering technique *in situ* [18]. It was found that the average diameter of the levitated particles is a little bit less than its original size and consists of about 1.80 ± 0.03 μm. This occurred because the particles with a smaller diameter have a greater probability to be captured in the electrostatic trap than the heavy ones.

At the second step, the low container with big particles was shaken, and the heavy probe particles dropped down to the levitating cloud with the light particles and collided with them. The dusty cloud was illuminated by a "laser knife" and the process of particle interactions was recorded by a high-speed video camera at frame rates of 500 or 1000 frames/s. Typical recorded successive video frames are presented in Fig. 2. They show that the falling objects were composed of not only single probe particles, but few-particle clusters also. Since the forces acting on a cluster are different from those acting on a single particle, a selection of the falling particles were carried away by their velocities. It was found that the lowest measured velocities of the falling particles correlated well with the velocities calculated by the Epstein formula [19] for the case of diffuse reflection on neon atoms from the particle surface,

$$F_{fr}=\delta\frac{4\pi}{3}n_n m_n \overline{\upsilon}_{n,th} r_p^2 \upsilon_p = m_p g \tag{1}$$

where $\delta=1.44$ is the numerical factor, n_n and m_n are the neutral gas atom density and the atom mass, respectively, $\overline{\upsilon}_{th,n}$ is the mean thermal velocity of neutral atoms, r_p is the radius of the moving probe particle, υ_p is the probe particle velocity, and m_p is the probe particle mass. Only the slowest probe particles were taken for further data processing. The application of Eq. (1) corresponds to our physical conditions, namely, the mean free path for the neon atoms λ_n is much longer than the dust particle radius r_p.

As one can see on Fig. 2, the probe particle passes a levitated particle much more quickly than it is possible to resolve with the current frame rate, and the levitated particle is repulsed from the probe particle in the horizontal direction. Because of this a detailed picture of particle interaction will not be considered in this work. Typical trajectories of the disturbed levitating particles for the different impact parameters h are shown on Fig. 3. The mechanical pulse Δp acquired by a levitating particle during a "collision" was calculated using a linear approximation of the first 2–5 points of the particle shift after the disturbance. The result of the measurements of the acquired pulses Δp for $p=51$ Pa is presented on Fig. 4. The same kind of plots were built for the other neon pressures used (20 and 30 Pa) also. The range of the investigated impact parameters h was about 40–250 μm.

The interpretation of the obtained results for the pulses $\Delta p=\Delta p(h)$ was performed in the follow manner. The falling probe particle had straight trajectory with the impact parameter h (Fig. 5). Due to an interparticle repulsion during the process of interaction the levitated particle gains a final mechanical pulse Δp perpendicular to the probe particle trajectory. As soon as the levitating particle does not shift substantially during the period of particle interaction, the gained impulse can be written as

$$\Delta p = 2\frac{h}{\upsilon_p}\int_h^{\infty}\frac{F(r)}{\sqrt{r^2-h^2}}dr \tag{2}$$

where r is the current distance between the particles, and $F(r)$ is the particle interaction force as a function of the

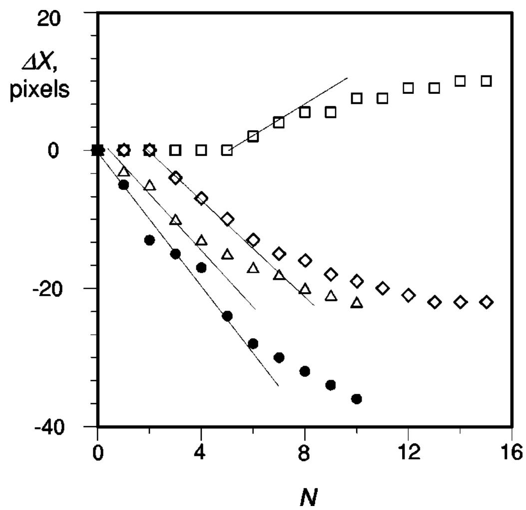

FIG. 3. Shifts ΔX of the levitating particles vs the number N of successive video frames and a linear approximation of the initial parts of the trajectories.

distance r. Assuming the particle interaction potential to be a screened Coulomb one [8,20]

$$U(r) = (Q_1 Q_2/r)\exp(-r/r_{scr}), \tag{3}$$

where Q_1 and Q_2 are the electrical charges of the levitated and probe particles, respectively, and r_{scr} is the effective dust screening length, Eq. (2) can be rewritten as

$$\Delta p = \frac{Q_1 Q_2}{\upsilon_p r_{scr}} P\left(\frac{h}{r_{scr}}\right) \tag{4}$$

where

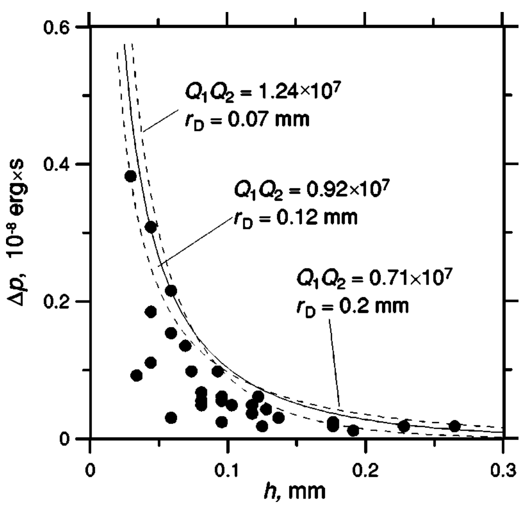

FIG. 4. The measured pulses Δp of the levitating particles vs the impact parameter h and the three approximations of the data with Eqs. (4) and (5). Solid line is the best approximation; dashed lines are an illustration of sensitivity of the method.

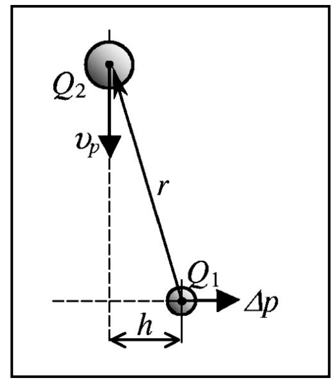

FIG. 5. Scheme of the particle interaction.

$$P\left(\frac{h}{r_{scr}}\right) = 2\frac{h}{r_{scr}}\int_{h/r_{scr}}^{\infty} \frac{e^{-t}(t+1)}{t^2\sqrt{t^2 - h^2/r_{scr}^2}}dt$$
$$\simeq \left(0.74 + 1.72\, r_{scr}/h + 0\,.\,92\sqrt{\frac{r_{scr}}{h}}\right)e^{-1.05\, h/r_{scr}}. \tag{5}$$

The last equation is valid within an accuracy of 1% at $0.02 < h/r_{scr} < 4$. Thus, there are two fitting parameters, the product Q_1Q_2 and the effective dust screening length r_{scr}, to fit the measured impulses $\Delta p(h)$ by the function of Eq. (3). This fitting procedure will be correct if we use a set of the measured data $\Delta p(h)$ for a wide range of the impact parameters h.

As one can see in Fig. 4, many experimental points lie below the approximating curves $\Delta p = h(\Delta p)$. These points originate from those collisions when striking particles moved at some angle to the plane of the "laser knife." During the fitting procedures only the points with maximum measured impulses Δp at a given impact distance h were taken into account. The fitting procedures had a good convergence and the unique final parameters Q_1Q_2 and r_{scr}. Three fitting curves are shown on Fig. 4—the best fit by Eq. (4) (solid line) and two illustrating fits with $[r_{scr}]_{best} \pm 50\%$ for a comparison. The resulting data on the product Q_1Q_2 and the screening length r_{scr} for the three neon pressures are presented in Table I. The accuracy of determination of the fitting parameters Q_1Q_2 and r_{scr} was estimated to be 30% and 40%, respectively.

To compare the obtained results with known theoretical models of particle charging and particle interaction in plasma, the basic plasma parameters such as electron temperature T_e, electron number density n_e, and permanent electric field strength E were measured with the help of the probe measurements. The details of the probe measurements have been described in [13]. The results are presented at Table I. The electron distribution function was found to be the Boltzmann one. The measured strength of the permanent electric field of the ambipolar diffusion in the region of a dust cloud levitation was $E_0 \cong 2$ V/cm. The ion temperature T_i was not measured because of a very low value of the measured probe ion current. Under our experimental conditions the ion temperature is close to the temperature of neutral atoms (T_n

TABLE I. The parameters Q_1Q_2 and r_{scr} of the best fit of the experimental data on the acquired pulses Δp with the Eqs. (4) and (5) and the results of the probe measurements of the electron concentration n_e and the electron temperature T_e at the edge region; u_i and u_{Ti} are is the drift and thermal ion velocities; T_i is the ion temperature estimated by Eq. (6); λ_{Di} and λ_{De} are the electron and ion Debye radii, calculated on the basis of the probe data.

Neon pressure p (Pa)	Q_1Q_2 (10^6 e^2)	r_{scr} (μm)	n_e (cm^{-3})	T_e (eV)	u_i (cm/s)	T_i (K)	u_{Ti} (cm/s)	λ_{Di} (μm)	λ_{De} (μm)
20	23	160	3×10^8	4.5	3.7×10^4	407	6.6×10^4	80	910
30	17	150	3×10^8	3.8	2.6×10^4	353	6.1×10^4	75	840
50	9.2	120	4×10^8	3.5	1.6×10^4	319	5.6×10^4	62	700

=298 K); at low neon pressures the T_i is increasing due to the ion heating in the ambipolar diffusion field E_0 and results in 2/3 of the mean energy of ions drifting in the electrical field,

$$T_i = T_n + \frac{m_i u_i^2}{3}, \tag{6}$$

where m_i and $u_i=\mu_i E_0$ are the ion mass and drift velocity respectively, and μ_i is the neon ion mobility. The results of calculation are presented at Table I. As one can see there, the ion drift velocity u_i is less than the ion thermal velocity u_{Ti} in the whole pressure range being studied. Hence, the ambient plasma can be considered as anisotropic in theoretical simulations of the particle charging. Using the measured plasma parameters, the electron and ion Debye lengths were calculated also.

III. RESULTS AND DISCUSSION

To extract the charges Q_1 and Q_2 from the measured product Q_1Q_2, first we should consider two questions, the charging time τ for the probe particle and the dependence of the particle charge Q vs its radius r_p at constant ambient plasma conditions.

The charging time can be estimated by the formula

$$\tau \sim \frac{Q}{I} \sim \frac{Q}{4\pi r_p^2 n_e \overline{v_e} e \exp(-e\varphi_p/k_B T_e)}, \tag{7}$$

where φ_p is the particle surface potential, and $\overline{v_e}$ is the mean thermal electron velocity. A rough estimation of $Q = 50\,000e^-$ and $\varphi_d=-9$ V using the OLM approach [14,15] shows that for probe particles with the diameter of 12 μm $\tau\sim 2.4$ μs. During this time the moving probe particle with the equilibrium speed $v_p=75$ cm/s passes only 2 μm, i.e., much less than the diameter. Hence, the charge of the falling probe particle can be considered to be in equilibrium with ambient plasma at each point of its trajectory.

To extract the charges Q_1 and Q_2 from the measured product Q_1Q_2 we need to know how the particle charge Q depends on its radius r_p. According to the OLM approach, in a collisionless plasma the surface potential of the spherical particle put into a plasma does not depend on its size. Hence the particle charge will linearly depend on its size, i.e., $Q(r_p)=Ar_p$. The main physical requirement of the OLM approach is $r_p \ll r_D \ll \lambda_i$, where λ_i is the ion mean free path in a plasma. As a rule, these criteria are well satisfied in a laboratory dusty plasma. However, recently it has been shown [16,21] that the charge-exchange collisions of ions with neutrals began to affect the dust particle charge even at pressures corresponding to the $r_D \ll \lambda_i$ criterion, and the particle surface potential φ_p depends on the particle radius r_p. A self-consistent molecular-dynamics simulation shows [16] that for our experimental conditions the difference of the surface potentials φ_p for spherical particles of 1.8 and 12.74 μm diameters consists of about 15% of its value (Table II).

Experimental studies of the dependence of the particle surface potential on its diameter are quite ambiguous. The authors [12] measured the charge of spherical particles with different diameters (1.87, 4.82, and 13.57 μm) levitating in a dc stratum and found the dependences $Q(r_p)\sim r_p^{1.9}$ and $Q(r_p)\sim r_p^{1.7}$ for gas pressures 66 and 200 Pa, respectively. The authors [9] investigated the dependence of the particle charge vs its diameter in the plasma sheath region and found

TABLE II. The experimental data on the charge numbers Z_1 and Z_2 of the spherical particles with diameters of 1.8 μm and 12.7 μm and the corresponding particle surface potentials φ_d in comparison with the charge numbers Z_1 and Z_2 computed in the OLM approximation for collisionless plasma [18] and using the self-consistent molecular dynamics simulation (MDS) for collisional plasma [19], calculated on the basis of the measured plasma parameters.

	Experimental data			OLM [14,15]			MDS [16]			
p(Pa)	Z_1	Z_2	φ_p(V)	Z_1	Z_2	φ_p(V)	Z_1	Z_2	φ_{p1}(V)	φ_{p2}(V)
20	1800	12800	2.9	5880	41600	9.4	3100	24800	5.0	5.6
30	1500	11000	2.5	5000	35400	8.0	2400	19500	3.8	4.4
50	1150	8100	1.8	4560	31700	7.3	2100	16500	3.3	3.7

the sharper power dependences $Q(r_d) \sim r_d^{2.3}$ and $Q(r_p) \sim r_p^{2.5}$ for the gas pressures 7 and 13 Pa, respectively. A nonlinear dependence $Q(r_p) \sim r_p^x (x > 1)$ has also been observed in [10,22]. However, in recent work [11] it was clearly shown that the experimental dependences $Q = Q(r_p)$ measured in the plasma sheath [9,10,22] are the result of different ambient plasma conditions for the particles of different diameters, levitating at different distances from a rf electrode. For example, it was found in [11] that two particles with different diameters of 3.5 and 5.0 μm levitating at the same place in the plasma sheath have the same surface potential within the experimental error of about 15%. As to the research [12] in the dc stratum, the found nonlinear dependence $Q(r_p) \sim r_p^{1.9}$ can also be attributed to the same reason as in the plasma sheath, in particular, to the different electronic temperature at different places of the stratum.

The present experiments on the charge measurements were performed at the diffuse edge of a rf inductive discharge, which is characterized by a more uniform plasma media in comparison with the rf plasma sheath and the dc stratum regions. Thus, to extract the charges Q_1 and Q_2 from the measured product $Q_1 Q_2$ we used the linear dependence $Q = A r_p$. The results of the splitting are presented in Table II. More accurate results on the charges Q_1 and Q_2 can be obtained by using an additional coefficient equal to 1.15, which was found as the ratio of the MDS calculated surface potentials φ_{p1} and φ_{p2} of the 1.8 μm and 12.74 μm particles for our experimental conditions (Table II), i.e., finally, $Q_1/Q_2 = d_{p1}/1.15 d_{p2}$. Nevertheless, this correction is within the experimental errors and will be omitted for simplicity in our present discussion.

It is difficult to compare the measured charges with the data from other experimental works [4–12], because all of them were performed in rather different experimental conditions. Therefore here we compare our experimental results on the charges Q_1 and Q_2 only with those computed for a collisionless plasma in the OLM approximation [14,15] and for a collisional plasma using a self-consistent molecular-dynamics simulation [16] on the basis of the measured plasma parameters. In both cases the charges were calculated for an isolated dust particle in anisotropic plasma with the Boltzmann distribution function for n_e and n_i. The results of the computations are presented in Table II. As one can see, the charges Q_1 and Q_2 computed in the OLM approximation are up to four times more than the measured ones. The charges Q_1 and Q_2 computed by the MDS method are much closer to the measured charges, but nevertheless exceed the measured charges about 1.5 times. So our experimental data on the particle charge are in agreement with the thesis [16] of a sufficient enhancement of the ion current flowing to the particle surface in a collisional plasma, but additional arguments should be considered to explain the last discrepancy.

In our experiment, dust concentration effects [23] could not lead to a visible depletion of the electron density n_e within the dust cloud, because the mean free electron path is bigger than the size of the small dust cloud at all considered pressures. In this case, the electron density within the cloud is equal to the electron density in the ambient neon plasma due to electron diffusion. Next, we estimated the values of the 3*S* neon excited atom flow and the resonance vacuum ultraviolet (VUV) photon flow on the particle surface. In doing this, the concentrations of the metastable neon atoms n_m and the resonance neon atoms n_r in the plasma were measured by the emission absorption technique. The full concentration of both n_m and n_r was found to be about 2×10^{10} cm^{-3}. In this case the flow of the excited 3*S* atoms consists of only a few percent of the electron flow on the particle surface. About the same value was found for the VUV resonance photon flow on the particle surface. Taking into account the low efficiency of electron output from the particle surface under bombardment by the excited atoms and the VUV resonance photons, one can conclude that these processes could not diminish the particle charge sufficiently. In our opinion, an additional diminishing of the particle charge can be caused by a partial reflection of the electrons from the particle surface. This effect was widely investigated in the probe technique [24], but was not applied to the dust charging process. Unfortunately, quantitative data on electron reflection from a negatively charged dielectric surface are absent.

Finally, we consider the relation between the values of the measured screening length λ_{scr} and the ion λ_{Di} and the electron λ_{De} Debye lengths computed on the basis of the probe data. As one can see from Table I these values have the relation $\lambda_{Di} > \lambda_{scr} > \lambda_{De}$ for the investigated pressure range. This relation reflects the transition from a particle sheath where the scale length is a linearized Debye length $\lambda_D = (\lambda_{Di}^{-2} + \lambda_{De}^{-2})^{-1/2}$ to one where the scale length is the electron Debye length λ_{De}, which correlates with the numerical calculations in [20].

IV. CONCLUSION

In the present work a method for measuring the macroscopic particle charge and the screening length within a levitating three-dimensional dust cloud has been realized. These measurements were performed at the diffuse edge of a rf inductively coupled discharge within the pressure range 20–50 Pa of neon with the help of gravity-driven probe particles. It is shown that the diffuse region is an ideal uniform medium for investigation of the charging processes and for testing different theoretical models of particle charging and interaction. The obtained experimental results show that particle interactions in the cloud are well described with a screened Debye potential within the range from one-half to a few Debye lengths. The measured screening length was found to be between the ion and electron Debye lengths, which reflects the transition from a particle sheath where the scale length is a linearized Debye length to one where the scale length is the electron Debye length for the used probe particles with 12.7 μm diameter. The measured charges were compared with the calculated ones using the collisionless OLM approach and the self-consistent molecular-dynamics method for collisional plasma. The charges calculated with the collisionless OLM approach exceed the measured ones up to four times. The charges calculated with the self-consistent molecular-dynamics method for a collisional uniform plasma are much closer to the measured ones, but nevertheless exceed the measured charges by 1.5–2 times. The authors have proposed that a partial reflection of the charging electrons from the negatively charged dielectric surface of the suspended dielectric particles can be responsible for this discrepancy.

The reported method can be extended for microgravity conditions using a special "gun" for the probe particle throwing.

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