Experimental Determination of Dust-Particle Charge in a Discharge Plasma at Elevated Pressures

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The charge of dust particles is determined experimentally in a bulk dc discharge plasma in the pressure range 20–100 Pa. The charge is obtained by two independent methods: one based on an analysis of the particle motion in a stable particle flow and another on an analysis of the transition of the flow to an unstable regime. Molecular-dynamics simulations of the particle charging for conditions similar to those of the experiment are also performed. The results of both experimental methods and the simulations demonstrate good agreement. The charge obtained is several times smaller than predicted by the collisionless orbital motion theory, and thus the results serve as an experimental indication that ion-neutral collisions significantly affect particle charging.

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There is currently considerable interest in understanding the properties of dusty (complex) plasmas—plasmas containing charged micron-size particles (grains). This interest was originally driven by astrophysical topics [1] and industrial plasma applications [2]. It is also recognized that complex plasmas open up the possibility to study a variety of phenomena (e.g., phase transitions, transport, waves, etc.) at the most elementary kinetic level [3,4].

The particle charge is one of the most important parameters of complex plasmas. In gas discharges the (negative) charge on a particle is determined by the balance of electron and ion fluxes to its surface. To calculate these fluxes the collisionless orbital motion limited (OML) theory [5] is typically used on the basis that the electron and ion mean free paths \( l_{e(i)} \) are long compared to the plasma screening length \( \lambda_D \). However, theory has shown that ion-neutral charge exchange collisions in the vicinity of a small probe or dust grain can lead to a substantial increase in the ion current to their surfaces [5–9]. It has been demonstrated that the ion collisions can suppress the particle charge even when \( l_{e(i)} \) is considerably greater than \( \lambda_D \). Another effect for charge reduction is that of “closely packed” grains [10].

So far most of the experimental particle charge determinations were performed in sheath or striation regions of discharges [11–15]. The comparison with theory is complicated here due to the strong plasmas anisotropy and non-neutrality, the presence of “suprathermal” ions and electrons, etc. In addition to the charging model one needs to choose an appropriate model for the sheath, which is itself a sophisticated task. Hence, there is clearly a lack of direct measurements of particle charge in bulk plasmas.

In this Letter, we present experimental results on the dust-particle charge in a plasma at elevated neutral gas pressures. The experiment is performed with particles of radius \( a = 0.6 \, \mu m \) in a horizontal dc discharge tube. For these particles the weak ambipolar radial electric field is sufficient to compensate gravity allowing us to study dust charging in the quasineutral plasma. Highly space and time-resolved measurements of the particle flow and comprehensive probe measurements of plasma parameters make it possible to use theoretical models where the only unknown parameter is the particle charge. This enables us to determine the charge experimentally by two independent methods. The results are then compared with those of molecular-dynamics (MD) simulations.

The experiment is performed in a dc discharge generated in an U-shaped glass tube, the PK-4 facility (see sketch in Fig. 1), and operated in neon at pressures 20–100 Pa and current of 1 mA (voltage of 1 kV). The plasma parameters are measured in the absence of dust...
using a video camera with a field of view of 61°. For our conditions, the electrons are in the collisionless regime and, thus, the Druyvesteyn formula is used to calculate the electron density \( n_e \) and the electron temperature \( T_e \) [16]. The maximum of the first derivative of the probe current is used to estimate the plasma potential [16]. Results of the probe measurements of averaged axial values of \( n_e, T_e, \) and axial electric field \( E \) are presented in Fig. 2. The ion temperature is assumed to be close to the neutral gas temperature, \( T_i \approx T_n \approx 0.03 \) eV, for the pressure range used.

When the dust particles (plastic spheres with mass density of 1.51 g/cm\(^3\)) are injected into the discharge, they charge negatively and drift against the discharge electric field in the horizontal part of the tube (see Fig. 1). The particle flow is illuminated by a laser sheet from the force balance condition using the experimental results of the probe measurements [17]. The images of particle motion just above (1–4 Pa) and at the threshold are recorded and analyzed. In this case the charge can be estimated from a linear dispersion relation describing the transition of the particle flow to the unstable regime at \( p_\ast \). In addition, the force balance condition for pressures above \( p_\ast \) is used to estimate the charge.

Below we present theoretical models for the two methods of charge estimation.

(i) Force balance.— The particle velocity in a stable flow is determined by the balance of the forces acting on the particles: The electric force, \( F_{el} = QE \), the neutral drag force, \( F_n = -m_d \nu_{dn} V_d \), and the ion drag force, \( F_i = m_d \nu_{di} (u_i - V_d) \approx m_d \nu_{di} u_i \). Here \( m_d \) is the dust-particle mass, \( u_i \) is the ion drift velocity, \( \nu_{dn} \) and \( \nu_{di} \) are the momentum transfer frequencies in dust-neutral and dust-ion collisions, respectively. The force balance is

\[
F_{el} + F_i + F_n = 0. \tag{1}
\]

For the momentum transfer in dust-ion collisions we use

\[ \nu_{di} = \frac{eE}{m_d} \]

FIG. 2. Results of probe measurements; Electron temperature (circles), electron density (squares) and electric field (triangles). Dashed lines correspond to linear fits used in the calculations.

For larger \( N_d \) the transition to unstable flow with a clear wave behavior occurs at a certain threshold pressure \( p_\ast \) (see Fig. 3). The transition is a manifestation of the ion-dust streaming instability, caused by the relative drift between the dust and the ion components. The transition can be found experimentally with an accuracy of \( \sim 1 \) Pa. The value of \( p_\ast \) depends strongly on \( N_d \) (shifting towards higher pressures when \( N_d \) is increased). An upper value of \( N_d \) corresponds to \( n_d = 4 \times 10^5 \) cm\(^{-3}\) gives an upper limit of \( p_\ast \) of approximately 60 Pa. This value of \( n_d \) is chosen to ensure that the discharge parameters are not strongly modified by the presence of dust and we can use the results of the probe measurements [17]. The images of the particle motion just above (1–4 Pa) and at the threshold are recorded and analyzed. In this case the charge can be estimated from a linear dispersion relation describing the transition of the particle flow to the unstable regime at \( p_\ast \). In addition, the force balance condition for pressures above \( p_\ast \) is used to estimate the charge.

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For the momentum transfer in dust-ion collisions we use
\[
m_d v_{di} = \frac{8}{3} \sqrt{2\pi} a^2 n m v_{T_i} \left( 1 + \frac{1}{2} \frac{R_C}{a} + \frac{1}{4} \frac{R_C^2}{a^2} \lambda \right),
\]

where \( R_C = |Q| e / T_i \) is the Coulomb radius for ion-dust collisions, \( m_i \) is the ion mass, \( v_{T_i} = \sqrt{T_i / m_i} \) is the ion thermal velocity, and \( \lambda \) is the modified Coulomb logarithm [Eq. (12) of Ref. [18]]. In deriving Eq. (2) a subtherm al ion drift (\( u_i \leq v_{T_i} \)) is assumed, which means that the effective screening length is close to the ion Debye radius, \( \lambda_D \approx \lambda_D = \sqrt{T_i / 4\pi e^2 n_i} \) [19]. From momentum conservation we have \( v_{id} = v_{di} (m_d n_d / m_i n_i) \), where \( v_{id} \) is the momentum loss frequency of the ions in ion-dust collisions. The momentum transfer in dust-neutral collisions is \( m_d v_{dn} = (8\sqrt{2\pi/3}) \delta a^2 n m v_{T_i} \), where \( m_d, n_d, \) and \( v_{T_i} \) are the mass, density, and thermal velocity of neutrals, respectively. The numerical factor \( \delta = 1 + \pi/8 \approx 1.4 \), corresponding to diffuse scattering with full accommodation is chosen in accordance with recent experimental results [20]. The ion drift velocity is determined by ion-neutral and ion-dust collisions, \( u_i \approx eE/m_i v_{iT_i} \), where \( v_{iT_i} = v_{in} + v_{id} \). The frequency \( v_{id} \) is given above. For \( v_{in} \) we use an estimate \( v_{in} = n_i \sigma_{in} v_{T_i} \), with the effective momentum transfer cross section taking into account both charge exchange and polarization interaction, \( \sigma_{in} \approx 10^{-14} \text{ cm}^2 \) [21,22].

(ii) Linear dispersion relation.—Though linear theory might not be applicable to describe the wave mode observed in the experiment (e.g., wave number and frequency), it should be adequate to predict the onset of self-excited waves at \( p_e \). In the derivation of a dispersion relation the following effects are taken into account: Electron, ion, and dust collisions with neutrals, ion-dust collisions, and drifts of the electron, ion, and dust components relative to the stationary neutral gas. We also assume “warm” electrons and ions and “cold” dust. Using the hydrodynamic approach we get

\[
\frac{1 + \omega^2}{k^2 v_{T_e}^2 - ku_e (i\nu_{en} + ku_e)} + \frac{\omega^2_{pi}}{k^2 v_{T_i}^2 + ku_i (i\nu_{ei} - ku_i)} - \frac{\omega^2_{pd}}{\omega (\omega + i\nu_{dn})} = 0,
\]

where \( k \) and \( \omega \) are the wave number and frequency, \( \omega_{pi(e)} = v_{T_{i(e)}} / \lambda_{D(e)} \) is the ion (electron) plasma frequency, and \( \omega_{pd} = \sqrt{4\pi Q^2 n_d / m_d} \) is the dust plasma frequency. The electron-neutral collision frequency and electron drift velocity are given by \( \nu_{en} = n_e \sigma_{en} v_{T_e} \) and \( u_e = eE / m_e v_{en} \), respectively. In a neon plasma with \( T_e \approx 1 \text{ eV} \), we have \( \sigma_{en} \approx 2 \times 10^{-16} \text{ cm}^2 \) [23].

We solve Eqs. (1) and (3) numerically for the plasma parameters taken from probe measurements. The ion density is obtained from the quasineutrality condition \( n_e = Z_d n_d = n_i \), where \( Z_d = |Q| / e \) is the particle charge number. As discussed above, we assume that \( n_e \) is unaffected by the presence of dust [17], but \( n_i \) is increased. Hence, in our calculations \( n_i, v_{di}, v_{id}, u_i, \omega_{pi}, \) and \( \omega_{pd} \) are functions of the particle charge only. Equation (1) is solved directly, yielding the particle charge. Solution of the dispersion relation (3) gives the dependence of \( \omega = \omega_i + i\omega_i \) on the wave number \( k \) for a given particle charge. The charge is then determined by matching the experimental observations: Stable mode (\( \omega_i < 0 \) for all \( k \)) above the threshold pressure \( p_e \) and unstable mode (\( \omega_i > 0 \) for a range of \( k \), corresponding to experimentally found wavelengths) below \( p_e \). An illustration of such a solution is shown in Fig. 4. The results of both methods are presented in Fig. 5 and demonstrate good agreement. The error bars correspond to the uncertainties in \( n_d \) (50%), \( n_e \) (30%), \( E \) (10%), and \( V_d \) (15%). Both methods are quite insensitive to the value of \( T_e \).

To have an independent verification of the charge estimates described above, MD simulations of particle charging have been carried out for conditions similar to those of the experiment. The simulations are performed using a code originally developed by Zobnin et al. [6] to study the effect of ion-neutral collisions on the particle charging. As seen from Fig. 5 the charge found from the simulations is in good agreement with the results of both experimental methods. Some discrepancies can be attributed to the fact that the conditions used in the simulations are not completely identical to those of the experiment (e.g., weak plasma anisotropy, ion losses to the tube walls, ion-neutral polarization interaction are not taken into account).

![FIG. 4 (color online). Numerical solution of the linear dispersion relation (3). The dust number density and threshold pressure correspond to those of Fig. 3. Real and imaginary parts of wave frequency \( \omega \) are given by solid and dashed lines, respectively (note that the imaginary parts are multiplied by a factor 10). Red/blue (light gray/dark gray) lines correspond to \( p = 53 \) (56) Pa. Particle charge number in this calculation is \( Z_d = 2 \times 10^3 \).](image-url)
the effect of ion-neutral collisions. For the lowest pressure range investigated.

Experiments with a smaller combination of all the effects mentioned above. Some difference still exists and can be caused by a wards the OML values, as expected from theory [5,6].

The two dotted lines correspond to the charge given by the OML model for Havnes parameters between $P = 0.2$ (upper line) and $P = 3$ (lower line).

Figure 5 shows the results of charge calculations using the OML theory for the range of the Havnes parameter, $0.2 \leq P = Z_d n_d/n_e \leq 3$, estimated from experimentally determined charges. We use the OML expression modified to take into account the contribution of dust to the quasinutrality condition, $v_T \exp (-Z_d e^2/4 T_e) = v_T (1 + Z_d e^2/4 T_e)(1 + P)$ [4]. The difference between OML theory and the charges found from experiments and MD simulations is most significant at higher pressures. At $p \sim 100$ Pa we have $P \approx 0.2$, $\Delta/\lambda_D \approx 3.6$ (where $\Delta$ is the intergrain distance), and $l_i/\lambda_D \approx 0.6$. This means that the quasineutrality is weakly affected by the dust, the effect of “closely packed” grains is insignificant, and, therefore, we attribute the dramatic charge suppression (up to 5 times) at higher pressures to the effect of ion-neutral collisions. For the lowest pressures investigated, $l_i/\lambda_D \approx 3$ and the charge tends towards the OML values, as expected from theory [5,6]. Some difference still exists and can be caused by a combination of all the effects mentioned above. Experiments with a smaller $N_d$ (low dust density) as well as MD simulations show a decrease of charge with pressure. This can be mainly due to an increase in ion collisionality [6] (it is unreasonable to expect more than a $30\%$ effect due to decrease in $T_e$, see Fig. 2). Experiments with a larger $N_d$ reveal the opposite tendency which might be explained by some modifications of the plasma parameters at high dust number densities. These tendencies are not strongly pronounced, however, especially taking into account the experimental uncertainties, and $Z_d \approx 1500 \pm 500$ is a reasonable estimate for the whole pressure range investigated.

In conclusion, we have determined the charge of dust particles in a bulk dc discharge plasma under the conditions when the ion mean free path is comparable to the plasma screening length. Two independent experimental methods and MD simulations agree well with each other and yield a charge which is considerably smaller than that predicted by OML. Thus our results prove experimentally the significant effect of ion-neutral collisions on particle charging in plasmas.

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