Effect of supra thermal electrons on dust particle charge in RF sheath

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Complex plasmas - plasmas containing macroscopic particles (e.g. colloidal dusts), electrons, ions, and neutrals are open systems. Therefore parameters of the macroscopic particles such as particle charge appear as a function of not only their internal characteristics (e.g. size, shape, material, etc.), but also as a function of external plasma conditions (e.g. plasma density, temperature, etc). Our knowledge in the particle charge is the foundation of our understanding of the self-organized structure, as well as phase transitions observed in complex plasma.

These structures have recently attracted cross-disciplinary attention because of their similarities with processes in condensed matter physics, statistical physics, biophysics, etc. For typical plasma conditions, the charge can be reasonably predicted by the widely adopted 'orbital motion limited' (OML) model, where the dust grain is considered as a spherical probe and the charging is due to plasma currents onto the grain surface [1]. In the simplest approximation, the particle charge is directly proportional to its radius. In most of the experiments, the dust particle structures levitate in the sheath region of radio-frequency (RF) discharge plasma. Sophisticated experimental methods have been recently developed to elucidate the charge on a dust grain. Most of the reported experimental data have demonstrated nonlinear dependency of the particle charge on its size [2-4].

In this paper, we report on the experiments dedicated to clarify the dependence of the dust charge as a function of its size in an rf-discharge plasma. The experiments are accompanied by modeling of the charge behavior of a dust particle in the sheath region. Among the possible contributions to the particle charging, we singled out the effects of suprathermal electrons (STE). We demonstrated that the presence of STE can indeed cause the observed nonlinear behavior of the charge on the size of a levitating particle.

The experiments were carried out in a capacitively coupled rf-discharge in argon. The experimental setup is described in detail in [5]. A compensated single Langmuir probe is used to make measurements of the plasma parameters. The typical plasma parameters in our experiments are the plasma density \( n \sim (2-8) \times 10^8 \text{ cm}^3 \), the temperature...
\( T_e \sim (1-1.5) \text{ eV} \). The dust particles used in our experiments were spherical melamine formaldehyde \((\rho=1.5\text{g/cm}^3, \text{radius } a=1.45, 2.12, 2.83, 3.05, \text{ and } 3.52 \text{ µm})\). The dust particles suspended in the plasma are illuminated using Helium–Neon laser. The laser beam enters the discharge chamber through the side window mounted on the side port. The laser beam is expanded in the vertical directions into sheets of light by a system of cylindrical lens. This allowed us viewing the light scattered by the suspended dust particles. The position of the particles was analyzed with a software program that outputs their vertical coordinates. The charge on the particles was measured by two techniques namely, by the vertical equilibrium technique (VET) and by the vertical resonance technique (VRT).

The VET method operates with the equilibrium height of dust particles levitating in the sheath region [5]. The VRT method uses the sinusoidal voltage (up to 500 mV) applied to the powered lower electrode [6]. The results of these methods are in good agreement. Therefore we present only the values obtained by VET in the diagram below. Circles in Fig. 1 represent experimental dependence of the charge of the levitating melamine formaldehyde particle on its size at 60 W of input power and pressure of 18.3 Pa. The obtained dependency is strongly nonlinear.

![Figure 1](image)

**Figure 1.** Dependence of the charge of the levitating particle on its size. Circles represent experimental results, solid line - results of theoretical modeling with STE, and dashed line - theoretical modeling without STE.

In general, the particle charge can be written as \( Q_d = F(a) \phi_i \), where the function \( F(a) \) is not necessarily linear. On the other hand, the surface potential \( \phi_i \) reflects plasma parameters taken by the particle as a kind of ‘probe’ at the point of levitation.
Indeed, from the current balance equation, the potential appears as $\varphi = f^{\theta}(n_e/n_i, T_e, v_i)$. However, the plasma parameters at the point of levitation are functions of the particle size intrinsically, i.e. $n_e/n_i = f^\alpha(h_e)$, $T_e = f^\Gamma(h_e)$, and $v_i = f^\nu(h_e)$, where levitation height $h_e = f^h(a)$. Thus, the surface potential is

$$\varphi = f^{\theta}(f^\alpha(h_e), f^\Gamma(h_e), f^\nu(h_e)) \quad (1)$$

In an ideal experiment, when all particles are in the same plasma conditions (i.e. $\varphi = \text{Const}$), the charge measurements can in principle give us the functional dependence $F(a)$. In reality, a measurement of a levitating charge $Q_d$ as a function of the size $a$ gives us a mixed dependence

$$Q_d = F(a) f^{\theta}(f^\alpha(h_e), f^\Gamma(h_e), f^\nu(h_e)) \quad (2)$$

From this consideration, we see that the particle charge indeed appears as a complex function of its size via the size dependence of the levitation height and the height dependence of the plasma parameters.

To elucidate the contribution of different functions into the charge dependence on the radius of a levitating particle, we calculated the charge on the basis of the self-consistent hydrodynamic model of the dust levitation and equilibrium in the collisional plasma sheath while taking plasma ionization into account. For more details of the model, see [7]. For the particle levitation in the sheath field, we took into account the sheath electrostatic force, the ion drag force, and gravity. We assumed that the main electron temperature is constant in the whole region of interest. We also added a fraction of STE, with the ratio of the STE density to the ion density at the electrode as a boundary condition. The boundary condition is determined by the secondary emission [8]. Solution of the equation for the balance of forces together with the charging equation gave the dependence of the charge of the grain levitating in the sheath electric field as a function of its size, as shown from the solid line in Fig. 2. Since the results were obtained for the condition in the above experiment, we were able to compare them directly. We noted strong nonlinear dependence for the experimental and simulation curves. As an example of the contribution of STE, dashed line in Figure 2a showed the simulated charge of the levitating particles in the absence of suprathermal electrons.
This effect demonstrates the nonlinear dependence of the levitating particles on the grain size. Bigger and therefore heavier particles levitate deeper into the sheath (and closer to the electrode) where the fraction of energetic electrons is higher because of the secondary emission from the electrode. On the other hand, in the absence of STE, the closer the dust particle is to the electrode, the more deficiency in the thermal electrons because of the electrode's electric field. The analysis of this simulation demonstrates that out of various contributions (Eq.2) to the dependence of $Q_d$ on the particle's size, we can single out the effect of $f^T$. It is common to assume that the main electron temperature is not changing in the sheath region. Therefore the change of $f^T$ is due to an increase in number of STE closer to the electrode. And the observed nonlinear dependencies are due to the different levitation heights of the particles with different sizes (and masses).

Nonlinear dependence of the particle charge on its size observed in experiments can be explained by different plasma conditions in the sheath region where strong inhomogeneities of plasma parameters took place. Among the plasma parameters, the characteristics of the electron distribution appear to be one of the most important for the particle charge. It is shown that the observed experimental data can be explained with good accuracy by the model based on the presence of the supra thermal electrons.

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References