

On the electrical charging of dust particles in a capacitively coupled rf plasma

U. Kortshagen and G. Mümken

Institut für Experimentalphysik II, Ruhr-Universität Bochum, D-44780 Bochum, Germany

Experimental results on the electric charge of dust particles hovering at the lower sheath boundary of a capacitively coupled plasma are presented. They are interpreted on the basis of a simple theoretical model. The particle charge turns out to be barely dependent on the rf power. More significant changes of the particle charge are observed on variation of the neutral gas pressure. The theoretical model reproduces both trends. Moreover, the measured particle charges are in reasonable agreement with the theoretical predictions.

I. Introduction

Detailed information about the electrical charging of dust particles in low temperature plasmas is important, e. g., for the qualitative and quantitative understanding of the spatial distribution of particles or the transition to Coulomb liquids or crystals. Different theoretical approaches to the particle charging have been proposed [1-4], which usually employ several more or less crude approximations. A verification of these approaches requires a comparison to experimental data. Unfortunately, present experimental results don't offer a very consistent picture. For similar experimental setups the particles charges differ about more than a factor of 30.

II. Experimental method

In the present contribution we have used an experimental method which was recently proposed by Melzer et al. [5,6]. It is based on the determination of the resonance frequency of externally excited low frequency oscillation performed by test particles in the discharge. The discharge vessel consists of two aluminum plates with a glass ring between them. The discharge volume has a diameter of 15 cm and a height of 5.6 cm. The lower plate is grounded, the upper acts as the powered electrode. Test particles are injected through a small hole in the upper electrode into the

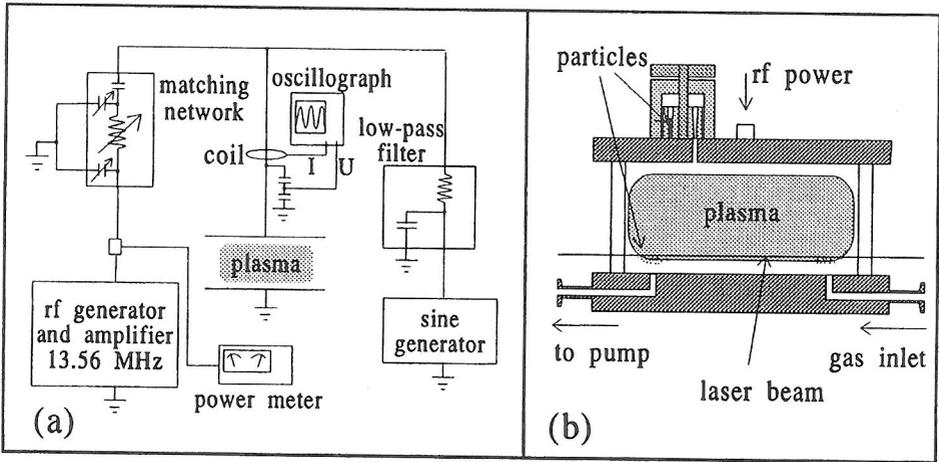


Fig. 1: (a) The electric setup. (b) The discharge vessel.

active discharge. During their passage through the plasma the particles charge up negatively and are repelled by the electrode sheaths. They then hover over the lower electrode. Their horizontal motion is restricted by a washer placed on the lower electrode, which induces a small potential perturbation. First test particles consisting of polyacetate with a mass density of 1410 kg m^{-3} have been used. We were able to observe individual particles over a long time. Due to their irregular shape and the large uncertainty in the determination of their size and mass, in later measurements particles of yellow toner as used for photocopiers have been injected. The size distribution and shape of these particles has been determined with a microscope. The particles are shaped slightly irregular but they can be treated as spheres in good approximation. The largest of them have a radius of $r_p = 8 \mu\text{m}$, while particles with radii below $4 \mu\text{m}$ are found only in a small number. The mass density ρ_p of the material was determined to be approximately 1100 kg m^{-3} . Usually a large number of particles have been injected at the same time. The particles moved constantly so that it was not possible to observe a single particle for a longer period of time. Since it is known that the particle arrange vertically in the sheath according to their mass, the radius of the lowest particles can assumed to be about $8 \mu\text{m}$.

The dominating forces acting on particles of this size in the discharge are gravity and the electric force. The ion drag force plays a role only for particles which stay directly near the sheath edge. The thermophoretic force and force by gas flow are minimized by experimental measures. Hence, the vertical position of the particles is given by the balance of gravity and the electrical force in the lower sheath. If a low voltage - low frequency signal is superimposed to the rf power, the particles

perform a motion that can be described in good approximation by the equation of a driven damped harmonic oscillator [5]:

$$\ddot{x}(t) + 2\delta\dot{x}(t) + \omega_0^2x(t) = F_a(t)/m_p,$$

where $F_a(t)$ is the stimulating force and m_p is the particle mass. The resonance frequency is given by

$$\omega_0 = \left(\frac{Q_p}{m_p} \frac{\partial E(x)}{\partial x} \right)^{1/2},$$

where Q_p is the absolute particle charge and $E(x)$ the time averaged electric field in the sheath. The measurement of the damping constant (spherical particles, diffuse scattering)

$$\delta = \frac{52}{9\pi} \frac{p}{v_{th,N}} \frac{1}{r_p \rho_p},$$

which is determined by the friction force of the particle moving in the neutral gas, gives an additional estimate of the particle size (p : pressure, $v_{th,N}$: thermal velocity of gas atoms). The values for ω_0 and δ are measured by optical observation of the motion of particles, which are illuminated by a dispersed HeNe laser beam, through a long distance microscope with a magnification of 50. The oscillation amplitude can be determined by means of a scale in the optics of the microscope. From the observed amplitudes at different stimulation frequencies, a best fit for the resonance curve can be calculated and thus the resonance frequency ω_0 and the damping constant δ . The time averaged electric field in the plasma sheath is assumed to be linearly increasing from the sheath edge towards the electrode. For sufficiently large amplitude of the rf voltage it can be approximated by

$$E(x) = \frac{2\hat{U}_{RF}}{\pi d^2} x.$$

At the sheath edge ($x=0$) the value of the electric field is about zero. So two ways to obtain information about the particle charge are possible: first, it can be determined by measuring the particle position in the sheath, second, it can be obtained from the resonance frequency of the particles. Uncertainties in the determination of the sheath edge lead to considerable errors in the charge determination via the particle position. Therefore, here only results obtained by measurement of the resonance frequencies are presented.

III. Calculation of the particle charge

The theoretical approach to determine the particle charge used here bases on the orbital motion limited (OML) probe theory [7]. Additionally, it is taken into consideration that only for a fraction α of rf period electrons are present at the particle

position in the sheath. Furthermore, a realistic electron energy distribution function (EEDF) $f_E(E, x, t)$ has been assumed to calculate the electron flux to the particle, unlike many other publications, which employ Maxwellian EEDFs. The EEDFs, which are considerably less populated in the high energy part compared to a Maxwellian, are determined by the numerical solution of the spatially inhomogeneous Boltzmann equation in the nonlocal approximation [8]. Besides the supposition that the electron density in the sheath switches between zero and the value of the ion density, according to the actual extension of the sheath, no time dependence of the EEDF is assumed. For the determination of the ion current one has to multiply the ion current density, which can be derived from sheath voltage and sheath thickness by a modified Child-Langmuir law following Lieberman [9], with the OML cross section of the particle. This cross section depends on the ion energy which is given by the time averaged potential at the particle position added to the Bohm energy. So the time averaged electron flux and the ion flux are given as:

$$I_e = \alpha \int_0^{\infty} dE f_E(E, x) e n_i(x) \pi r_p^2 \left(1 + \frac{eV_p}{E}\right) \left(\frac{2E}{m_e}\right)^{1/2},$$

$$I_i = j_i r_p^2 \left(1 - \frac{eV_p}{E_i(x)}\right).$$

By equating the electron and ion current the particle floating potential can be determined numerically. It should be noted, that no dependence of the floating potential from the particle size shows up within the validity range of the above equations ($r_p \ll$ Debye length $\lambda_D = \mathcal{O}(100 \mu\text{m})$).

IV. Results and discussion

First, measurements with single polyacetate particles in an argon discharge were performed. The results for varying gas pressure and rf power are shown in Figs. 2 and 3. Due to the large uncertainty in the particle mass here the ratio of particle charge and mass is presented in the graphs. In Fig. 2 it can be clearly seen that the particle charge decreases while gas pressure raises. At pressures above 10 Pa the charge approaches a limiting value that amounts to about 60% of the charge measured at the lowest pressure of 6 Pa. Figure 3 demonstrates a weak dependence of charge on the rf power. The shown scope of rf voltages between 120 and 640 V corresponds to a variation of measured forward power between 5 and 100 W.

This behavior can be understood by considering the EEDF in the discharge. With increasing gas pressure, usually the population of high energy electrons (above the first excitation level) decreases, since the diffusion losses are diminished and thus the ionization has to decrease, too. Thus the fraction of high energy electrons which contribute to the electron flux to the particle decreases significantly if the gas pressure raises. This behavior is exemplified in Fig. 4.

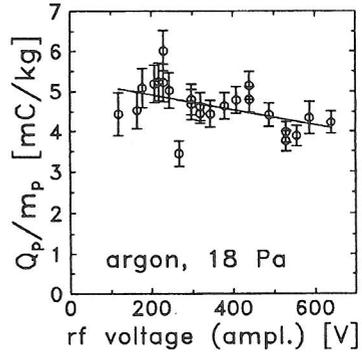
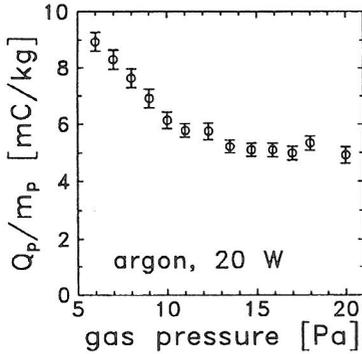


Fig. 2: Particle charge vs. gas pressure. Fig. 3: Particle charge vs. rf amplitude.

In contrast to the described pressure dependence of the EEDF a variation of rf power only weakly changes the shape of the EEDF, as far as Coulomb collisions are unimportant. Then the absolute values of electron and ion density are changed in the same way so that the resulting particle charge remains constant.

Information about the absolute particle charge and the floating potential is obtained from measurements of toner particles. Measurements of the damping constant of the lowest particles yield radii between 8 and 12 μm for these particles, which is consistent with the microscope measurements of the particle size distribution. Fig. 5 shows the charge and potential obtained for these particles (open circles). The closed circles show the numerically calculated values, where the measured particle position, the sheath thickness and voltage are input parameters of the model. It can be seen that the calculations are in qualitative agreement to the measurements. Keeping

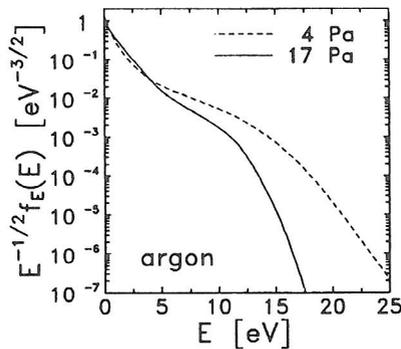


Fig. 4: Normalized EEDF for different pressures in argon.

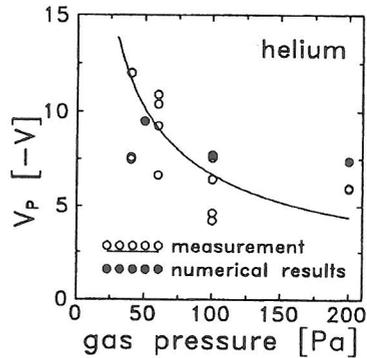
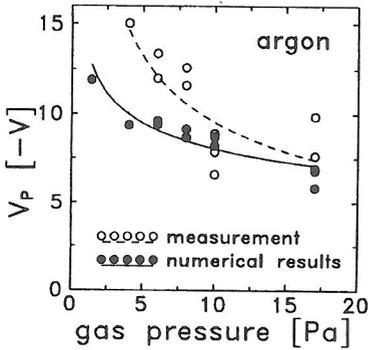


Fig. 5: Toner particles in an argon discharge. Fig. 6: Toner in a helium discharge.

in mind the uncertainty the charge measurement of nearly 50% the quantitative differences between calculations and measurements are explicable. In Fig. 6 results for a discharge in helium are demonstrated. In contrast to the supposition that for reasons of the higher ionization energy of helium the charging of particles should be stronger, here similar values of charge as in argon are measured. This is caused by the higher ambipolar potentials in the discharge which lead to a higher cut-off in the nonlocal EEDF so that the resulting EEDF at the particle position is nearly the same as in argon.

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VI. References

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