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Charging of micro-particles in plasma–dust interaction

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Abstract

A microphysical description of the charging of dust grains in a plasma is presented. The model which is based on plasma–wall interaction processes predicts the dependence of the grain charge on the particle radius and on the particle temperature better than the commonly used assumptions of a spherical capacitor.

The results of the model are compared with measurements of the particle charge which were performed in different discharge configurations.

Keywords: Dusty plasmas; Plasma–wall interactions; Charging; Plasma processing

1. Introduction

In the last decades, experimental and theoretical studies on the behaviour of dust particles in plasma environments [1–4] have attracted a lot of attention. The growing interest arises from a wide variety of scientific and technological fields like processes in interstellar clouds [5], in cometary tails [6], in planetary magnetospheres [7], and in the upper atmosphere of the earth [8] as well as from disturbing side effects in industrials plasmas for semiconductor processing [9,10] or the growth and modification of powders for technological applications [11], respectively. In a pointed sentence, one may emphasize: there exist strong connections between Saturn's rings and plasma etching of microchips.

Since the electrostatic energy of interacting particles in a plasma can strongly exceed their thermal energy the particles form ordered plasma crystal lattices [12–15]. In addition to the basic research of dusty plasmas and plasma crystals, the different interactions between plasmas and injected micro-disperse powder particles can also be used as diagnostic tools for the characterisation of

- electric fields in the plasma sheath (particles as electrostatic micro-probes) [16,17],
- energy fluxes in the plasma and towards surfaces (particles as micro-calorimeters) [18,19],
- plasma–wall interaction (particles as micro-substrates) [20,21].

By observing the position and movement of the particles dependent on the discharge parameters information can be obtained on the electric field and the potential distribution in front of electrodes and substrate surfaces where other plasma diagnostic methods fail. Hence, powder particles can be used as a kind of electrostatic micro-probes for the determination of plasma parameters. However, the particle charge Q is a crucial quantity which has to be determined as exactly as possible.

The gravitational force F_g and the electrostatic force F_{el} caused by the field E in front of the electrode mainly act on a confined micro-particle under typical low-pressure plasma process conditions. In order to trap such a particle, the responding electric field force F_{el} must have the same value:

$$F_g = mg = F_{el} = QE(z_0) \qquad (1)$$

This simple balance equation implies the determination of the field strength at the trapping position z_0 of the particles with the mass m. It is obvious that the mechanism of dust particle charging in a plasma is one of the main tasks to be studied. The determination of the net charge is very important in all experiments and applications cited above.

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In general, if microscopic dust particles are injected into a plasma, they become negatively charged up to the floating potential V_{fl} by the currents towards the particles and, hence, can be confined in the discharge. For the determination of the grain charge Q, different methods have been developed by several authors, as for example:

- resonance of the driven particle oscillation about equilibrium by superposition of an external low-frequency voltage [22,23],
- trajectory mapping of natural oscillations of injected particles [23],
- laser-induced photodetachment of charges and subsequent detection by microwave interference methods [24] or probes [25],
- analysis of waves excited by Mach cones of fast moving dust particles [26],
- measurement of the change in electron density of the surrounding plasma during particle injection by probes [27] or by self-excited electron resonance spectroscopy (SEERS) [16,28], respectively,
- analysis of the returning trajectory of a single particle which is removed from a dust cloud by means of a focused laser beam [12],
- estimation by model assumptions based on the particles spherical capacity [29] or on the currents of charge carriers towards the grains [16], respectively,
- Fourier analysis of the so called "heart beat" frequency of the void in a plasma crystal under microgravity conditions [30],
- examination of the inner shell coupling and rotation of particle rings [31],
- response of a simply ordered dust particle chain on a periodical disturbance by an external laser beam [32],
- observation of particle trajectories in binary collisions [33],
- measurement of the charge of single particles flowing through a plasma by a Faraday cup [34,38],
- study of charging/decharging mechanisms of suspended particles in a modified quadrupole trap (electrodynamic suspension) [35],
- behaviour of a dust vortex [36].

A qualitative description and modelling of particle charging is mostly based on the assumption of a spherical capacitor at floating potential V_{fl}:

$$Q = 4\pi\varepsilon r V_{fl} \tag{2}$$

where ε is dielectric constant and r is particle radius.

This assumption predicts a linear increase of the particle charge with its radius r. However, experiments have recently been performed where the dependence of the charge in a wide range of grain sizes was found to be quite nonlinear. For example, Tomme et al. [17] measured a square dependence ($Q \sim r^2$), whereas Fortov et al. [12] obtained a dependence of $Q \sim r^{1,69}$ and $Q \sim r^{1,86}$, respectively. Walch et al. [34,38] reported a nonlinear dependence of the charge on the particle size for rather small radii (<20 μm) and a linear increase for relatively large particle radii (>20 μm) It is of great interest to understand the nonlinear behaviour, which has been observed experimentally, and to model the obvious transition between the different charging mechanisms which result in a different size dependence.

In this paper, a microphysical description for the charging of dust particles on the basis of plasma–wall interaction processes is presented. The frequently occurring assumption of a spherical capacitor in contrast to the assumption of our simple model of surface charge densities based on plasma–wall interaction shall be tested in this context. However, the determination of the surface concentration of charge carriers on solid surfaces [39,40] as well as of the electric field strength near the surface [41] is not easy and, therefore, dust particles are welcome supplements for the study of plasma surface interactions and sheath diagnostics.

2. Theory

The injected particles acquire a negative charge in the plasma. The resulting electrostatic interactions can lead to a spatial arrangement of the particles and, for example, into patterns which are known as Coulomb crystals [13]. The formation and structure of the confined powder depend on the internal plasma parameters which can be influenced by the rf-power, gas pressure, and particle properties like their size and size distribution.

The equilibrium net charge Q of a powder particle, which is reached only after a very short time, is a result of the charge carrier fluxes. Under the considered experimental conditions, where the diameter $2r_p$ of the particles ($\sim 10^{-5}$ m) is small or comparable to the Debye length λ_D ($\sim 10^{-4}$ m) and the mean free path λ_{mfp} ($\sim 10^{-2}$ m), the orbital motion limited (OML) theory for a spherical particle holds [42,43]. Daugherty et al. [37] could even show that for particles of a size which is comparable to the Debye length ($r_p \sim \lambda_D$) the OML approximation is accurately valid.

The quantitative treatment of the problem will be carried out in an approach by taking into account the influx of charge carriers towards the particles and the resulting variation of the particle's floating potential. A more detailed description needs an extensive kinetic solution of the problem [41,45,49,50]. However, such an attempt is not the goal of this paper.

The electron flux density j_e for a Maxwellian EEDF can be calculated by:

$$j_e = n_e \sqrt{\frac{kT_e}{2\pi m_e}} \exp\left(\frac{-e_0 V_{fl}}{kT_e}\right) \tag{3}$$

while the ion flux density j_i may be obtained by

$$j_i = n_i \sqrt{\frac{kT_i}{2\pi m_i}} \left(1 + \frac{e_0 V_{fl}}{kT_i}\right) \tag{4}$$

where m_e and m_i are the electron and ion masses, respectively, T_e is electron temperature and T_i is ion temperature.

The dust particles always rest at floating potential V_{fl} in respect to the plasma potential V_{pl}. In this equilibrium state, the electron and ion currents towards the particles are equal: $j_e = j_i$. Hence, the dust potential V_{fl} can be implicitly obtained from the current balance of electrons and ions:

$$\sqrt{\frac{m_i T_e}{m_e T_i}}\frac{n_e}{n_i} = \left(1 + \frac{e_0 V_{fl}}{kT_i}\right)\exp\left(\frac{e_0 V_{fl}}{kT_e}\right) \quad (5)$$

The proposed model for the explanation of charging of "insulated" dust particles based on studies for insulating surfaces [39] includes the following elementary processes at the surface: adsorption of incoming charge carriers, desorption of charge carriers, and surface recombination of the incoming charge carriers including the concept of their surface diffusion. Modelling of the plasma particle interaction is performed in the framework of a "two-dimensional surface plasma" as proposed by Emeleus and Coulter [40]. This means that the ions at the particle surface are considered to be fixed and the electrons move along the surface by diffusion. This concept includes the same formalism and physical treatment as commonly used for adsorption, diffusion and desorption of neutrals [46]. However, the desorption energies and residence times for neutrals and ions differ. This difference was determined, for example by Hughes et al. [47], where the residence times of Rb neutrals and ions on clean tungsten were measured. For the polymer material which was used in the experiments considered here no data on residence times could be found.

In the stationary case, there is an equilibrium between the adsorbed charge carriers and those which desorb again or recombine, respectively. Hence, the balance equations of the adsorbed particles on a dust grain may be written as follows [16,39,41]:

$$\frac{d\sigma_e}{dt} = S_e j_e - \frac{\sigma_e}{\tau_e} - \alpha_R \sigma_e \sigma_i, \quad (6)$$

$$\frac{d\sigma_i}{dt} = S_i j_i - \frac{\sigma_i}{\tau_i} - \alpha_R \sigma_e \sigma_i, \quad (7)$$

where σ_e and σ_i are the electron and ion surface densities on the particle, j_e and j_i are the current densities towards the particle, S_e and S_i are the sticking probabilities, τ_e and τ_i are the residence times of adsorbed electrons and ions, respectively, and α_R is the coefficient for recombination/neutralization. The treatment of the mechanisms in the framework of this model is a relatively new view for describing the surface processes of charge carriers. But we try to use the formalism for a more macroscopic description of the overall surface charging process which includes microscopic (elementary) mechanisms—in detail, solid state effects like Auger-processes, mirror charges etc., might contribute to total charging. However, those elementary mechanisms are already manifest in the macroscopic surface model which is supported by the experimental measurement of the real particle charge.

Since the dust grains at floating potential (V_{fl}), the currents are equal and $j_e = j_i = j$ can be assumed. The temperature dependence of the residence times are given by the Frenkel equation as:

$$\tau_l = \tau_{l0}\exp\left(\frac{E_{des,l}}{kT_p}\right),\ l = e, i \quad (8)$$

where T_p denotes the particle temperature, k is the Boltzmann constant, τ_{e0} and τ_{i0} are the vibration periods of the adsorbed electrons and ions, and $E_{des,e}$ and $E_{des,i}$ are the corresponding desorption energies. The negative particle charge Q, finally, is given by the net charge $\Delta\sigma_e$:

$$\Delta\sigma_e = \sigma_e - \sigma_i = \frac{Q}{A_p}, \quad (9)$$

where A_p denotes the surface area of the powder particle. It is interesting to note that by means of this model the negative net wall charge—of a given plasma–dust particle system—is only influenced by

- the fluxes j_e, j_i of charge carriers and their sticking behaviour to the particle, and
- the particle temperature T_p.

The particle temperature is a result of the different heat fluxes towards and from the grains which undergo a thermal balance. The balance takes several contributions as kinetic energy of electrons and ions, ion recombination energy, thermal conduction and radiation into account. Measurement of the particle temperature T_p yields valuable information on these different fluxes [18]. Especially, the kinetic energy of the incoming ions is an essential contribution to particle heating. A certain part of the mean kinetic energy which is given by the difference between plasma potential and floating potential of the dust grains (about −15 V) is transferred to the particle body by collision and subsequent adsorption of an ion. This is the reason why the particles to be measured are hotter than the gaseous environment [18,28]. Only a very small percentage of the transferred kinetic energy is related to the binding energy of the ions to the grain surface.

The performed model is applied to the description of the experimentally obtained charging of melamine-formaldehyde (MF) particles in helium [44], neon [12], and argon [17] plasmas, respectively.

The values for the surface data listed in the following table were taken from the literature [16,39,41] and were in some cases slightly modified. Commonly, the adsorption probability of ions is assumed to be in order of unity ($S_i = 1$). This assumption is also taken for the electrons ($S_e = 0.95$) [41]. The desorption energy E_{des} which is assumed for the ions is in the order of the energy of the related neutrals. Since the adsorbate is an insulating and not perfectly clean material (MF particles), the E_{des} is one order of magnitude smaller than for metals. The assumed values are related to the energies obtained for the adsorption/desorption on glass

Table 1
The values of the used elementary surface data

Pre-exponential factors for residence times	$\tau_{e0} = 3 \times 10^{-9}$ s, $\tau_{i0} = 1 \times 10^{-11}$ s
Desorption energies	$E_{des,e} = 0.185$ eV, $E_{des,i} = 0.1$ eV
Sticking coefficients	$S_e = 0.95$, $S_i = 1$
Recombination coefficient	$\alpha_R = 0.3\,cm^{-2}\,s^{-1}$ [16,39,41]

[45,48]. The adsorption residence time of electrons τ_e is in the order of 10^{-6} s, while τ_i for the ions is in the order of 10^{-10} s. The values of the used elementary surface data are given in the Table 1.

3. Available experimental data

In order to computate the charge carrier fluxes to dust grains and, hence, the grain charge a quantitative treatment of the model requires the knowledge of several plasma parameters. The data for the charging of melamine-formaldehyde (MF) particles in a helium plasma, as described in Ref. [44], were used at first. The particle charges were determined by Melzer et al. in dependence on the discharge power (5 ... 60 W) and He gas pressure (40 ... 120 Pa) by means of the resonance (oscillation) method. The diameter of the used MF particles was 4,7 μm. The plasma parameters (n_e, kT_e) are obtained by Langmuir probe measurements, the experimental results are summarized in Table 2.

Secondly, the plasma data for the charging of MF particles in neon and argon plasma are taken from Fortov et al. [12] and Allen and coworkers [17], respectively. The authors varied power, pressure and the MF particle size in their experiments (see Table 3 and figure captions). The determination of the particle charge has been done by means of the force balance between the radial electric force and the neutral drag in the first case, and by the balance between the axial electrostatic force and gravitation in the latter case. While the measurements in [17,44] are carried out in commonly used capacitively coupled weak rf-discharges, the experiments described in [12] are made in a striated dc-glow discharge. However, observations on plasma–dust interactions in dc-glow discharges are rarely reported. The experimental conditions also differ partly and this fact makes it somewhat difficult to compare the results in general. The experimental data which are used for the modelling are summarized in Tables 2 and 3.

4. Results and discussion

The same surface data were used for all gases and plasma conditions for the ion component at the surface for the calculation of the particle charge on the basis of the plasma–wall interaction model as described in Section 2. This assumption is reliable. Despite of the importance of the ions for ambipolar diffusion towards the particle surface the charging itself is mainly caused by the electrons, which is also reflected by the ratio of the surface charge densities: $\sigma_e/\sigma_i \sim 10^3$. In this respect, the ion component is only a "correction term". Since in all experiments MF particles were used, the surface data for the electron component are surely assumed to be the same.

Figs. 1–6 show the results of the calculations for MF particle charging in different plasmas compared with the measurements provided in [12,17,44], respectively. In the following paragraphs, the results are discussed in more detail.

In Fig. 1, the experimentally obtained charge values of MF particles in a helium rf-plasma in dependence on the plasma power (taken from [44]) are compared with the calculations based on the suggested model by using the related plasma

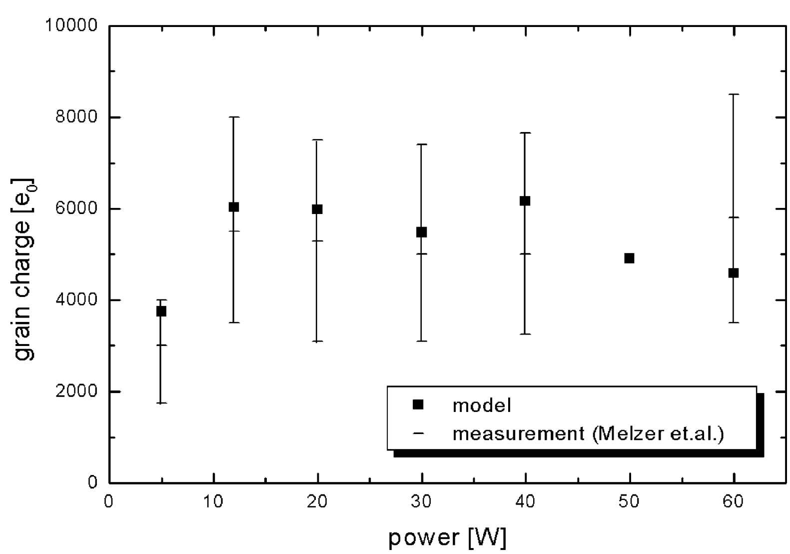

Fig. 1. Charge of the MF particles in dependence on the rf-power ($p = 102$ Pa) [44].

Table 2
Available experimental data [44], resulting charge carrier fluxes towards the particles and Debye lengths

Power, P (W)	Pressure of He, p (Pa)	Electron temperature, kT_e (eV)	Ion temperature, kT_i (eV)	Particles floating potential, V_{fl} (V)	Electron, ion density n_e, n_i (cm^{-3})	Electron, ion flux j_e, j_i ($cm^{-2}\,s^{-1}$)	Debye length, λ_{De} (μm)	Debye length, λ_{Di} (μm)	Debye length λ_D (μm)	Particle temperature, T_p (K)
5	100	1.50	0.030	−2.79	3.3×10^8	1.05×10^{15}	5.01×10^2	7.09×10^1	7.02×10^1	345
12	100	2.20	0.040	−4.02	6.2×10^8	2.46×10^{15}	4.43×10^2	5.97×10^1	5.92×10^1	365
20	100	1.70	0.035	−3.16	9.0×10^8	3.03×10^{15}	3.23×10^2	4.70×10^1	4.65×10^1	385
30	100	1.28	0.036	−2.55	1.2×10^9	3.15×10^{15}	2.43×10^2	4.07×10^1	4.02×10^1	390
40	100	1.20	0.038	−2.42	1.5×10^9	3.68×10^{15}	2.10×10^2	3.74×10^1	3.68×10^1	398
50	100	1.00	0.039	−2.08	1.4×10^9	2.93×10^{15}	1.99×10^2	3.92×10^1	3.85×10^1	398
60	100	0.80	0.040	−1.73	1.6×10^9	2.76×10^{15}	1.66×10^2	3.72×10^1	3.63×10^1	395
12	30	2.20	0.030	−3.82	2.6×10^8	1.04×10^{15}	6.84×10^2	7.99×10^1	7.93×10^1	295
12	40	2.20	0.030	−3.82	4.0×10^8	1.74×10^{15}	5.51×10^2	6.44×10^1	6.39×10^1	300
12	60	2.20	0.030	−3.82	4.8×10^8	2.09×10^{15}	5.03×10^2	5.88×10^1	5.84×10^1	309
12	80	2.20	0.036	−3.95	5.2×10^8	2.14×10^{15}	4.84×10^2	6.19×10^1	6.14×10^1	330
12	100	2.20	0.040	−4.02	6.2×10^8	2.46×10^{15}	4.43×10^2	5.97×10^1	5.92×10^1	365
12	120	2.20	0.040	−4.02	8.0×10^8	3.18×10^{15}	3.90×10^2	5.26×10^1	5.21×10^1	405

The MF particle size is 4.7 μm.

Table 3
Different experimental conditions [12,17], calculated charge carrier fluxes towards the particles and Debye lengths

Pressure, p (Pa)	Electron temperature, kT_e (eV)	Ion temperature, kT_i (eV)	Particles floating potential, V_{fl} (V)	Electron, ion density n_e, n_i (cm^{-3})	Electron, ion flux j_e, j_i (cm^{-2} s^{-1})	Debye length, λ_{De} (μm)	Debye length, λ_{Di} (μm)	Debye length λ_D (μm)	Particle temperature, T_p (K)
6.67 Ar	3.7	0.03	−8.65	1.70×10^9	5.28×10^{15}	3.42×10^2	3.12×10^1	3.11×10^1	347
13.33 Ar	3.9	0.03	−9.00	2.40×10^9	7.80×10^{15}	3.00×10^2	2.63×10^1	2.62×10^1	360
200 Ne	3.0	0.03	−6.5	2.5×10^8	8.25×10^{14}	8.14×10^2	8.14×10^1	8.10×10^1	300
67 Ne	5.5	0.03	−10.9	5.0×10^8	2.73×10^{15}	7.80×10^2	5.76×10^1	5.74×10^1	330

The dust particle size has been varied to a maximum of 16 μm.

data, see Section 3 and Table 2. The model calculations well agree with the measurements including the weak maximum of Q at about 12 W. For a small discharge power ($P < 12$ W), the electron and ion fluxes to the grains increase with the power which results in an increasing particle net charge. The almost constant charge of about 5500e_0 for $P > 20$ W is due to the nearly unchanged charge carrier fluxes j_e and j_i to the particles with further increasing discharge power.

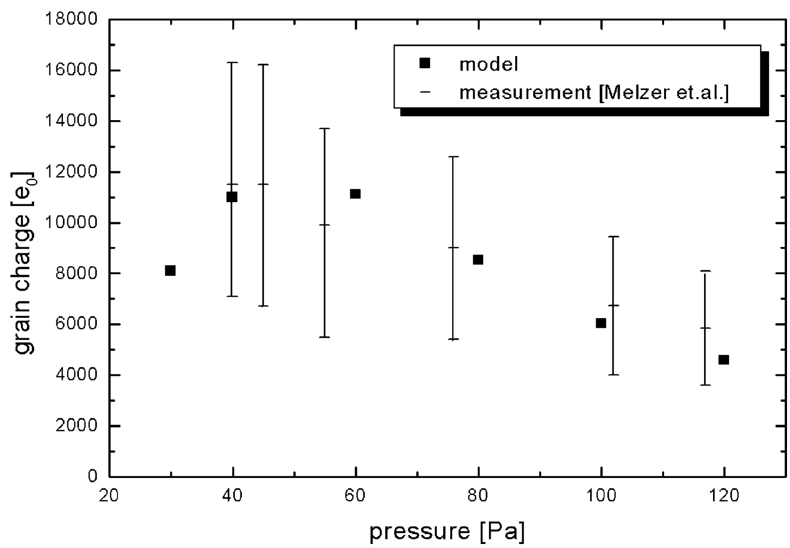

Fig. 2. Charge of MF particles in dependence on He gas pressure ($P = 12$ W) [44].

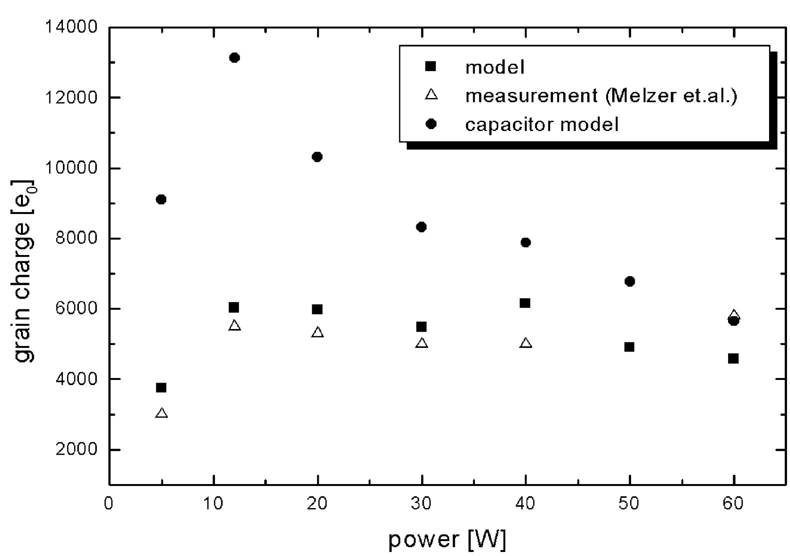

Fig. 3. Comparison of the determined particle charge Q by means of the capacitor method, our surface model, and experimental data [44] for different experimental conditions (see Fig. 1).

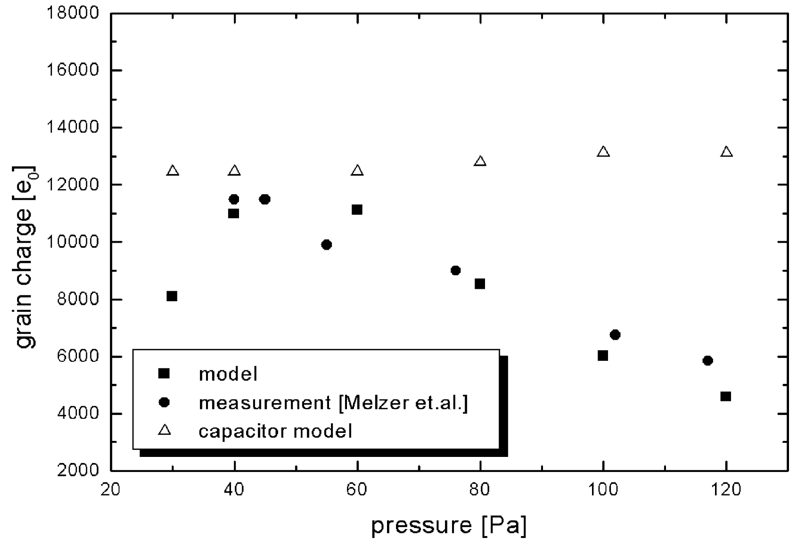

Fig. 4. Comparison of the determined particle charge Q by means of the capacitor method, our surface model, and experimental data [44] for different experimental conditions (see Fig. 2).

A quite similar correlation has been also obtained for the particle potential (V_{fl}) in dependence on the discharge power. However, the influence of the particle temperature T_p results in a modified slope of the net charge on the external plasma parameters, e.g., the “fine structure” of the dependence of the grain charge on the plasma conditions can only be explained by taking elementary surface processes into consideration.

Fig. 2 shows the dependence of the charging mechanisms on the helium gas pressure in experiment and model. Although there is a remarkable increase of the charge carrier flux to the dust grains with increasing pressure, the net charge of the particles decreases with the pressure. This effect can be explained by an essential heating of the particles (295 ... 405 K) by transfer of kinetic energy and recombination (neutralization) [18]. The increased particle temperature T_p causes an increasing desorption of the charge carriers which results in the observed weak decrease of the grain charge with pressure.

Since Melzer et al. [44] used the oscillation method as an independent measurement for determining the particle charge Q, the experimental results can be critically compared with the commonly used theoretical description by the capacitor model:

$$Q = CV_{fl} = 4\pi\varepsilon_0\varepsilon_r r V_{fl} \tag{10}$$

which predicts a linear dependence of the charge on the particle radius ($Q \sim r$). Figs. 3 and 4 illustrate a comparison of the results calculated by the capacitor method on the basis of

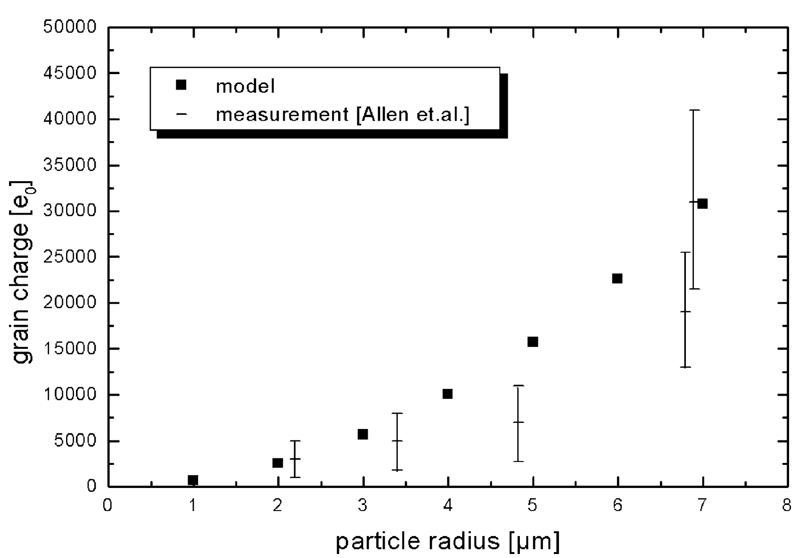

Fig. 5. Variation of the grain charge as a function of the particle radius (Ar, $p = 6.7$ Pa) [17].

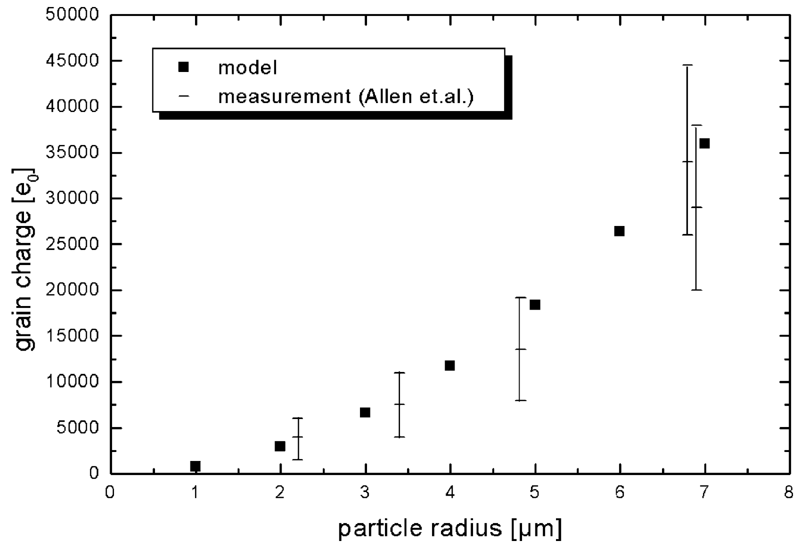

Fig. 6. Variation of the grain charge as a function of the particle radius (Ar, $p = 13$ Pa) [17].

the determined floating potentials (Tables 2 and 3) with the results of our surface method as well as with the independently obtained experiments. Obviously, there is only a quite narrow range of agreement between the methods at about 40 ... 60 Pa for a constant power (12 W) and between 50 and 60 W for a constant pressure (100 Pa). The reason for the discrepancy between measurements and capacitor assumption is obviously due to the fact that this assumption is only valid for an isolated charged body in vacuum. However, in a nonvacuum case (as the plasma surrounding) the situation is more complicated and the surface charge density σ has to be taken into account. Nairn et al. [49] predicted the surface charge density by the gradient of the potential at the surface of the grain, when the grain is at its floating potential.

Another theoretical approach is given by Choi and Kushner [50]. The authors used particle-in-cell simulation and obtained the dust surface potential and the net charge in dependence on the particle diameter. The model simulation was carried out for comparable plasma parameters as in our case, e.g., also for OML conditions, too. However, due to a nearly linear change of the surface potential in dependence on the particle size they also obtained a linear dependence of the charge on the particle diameter in their model. In contrast to these methods, we introduced the concept of charging by elementary surface processes in the present paper.

A modification of the capacity C in Eq. (10) considers the Debye shielding of the particle by the surrounding plasma:

$$C = 4\pi\varepsilon_0\varepsilon_r r\left(1 + \frac{r}{\lambda_D}\right) \tag{11}$$

where λ_D denotes the Debye length. In general, the shielding effect results in an increase of the capacity of a particle due to the plasma. However, for the experiments which are used in this study the particle diameter is much smaller than the Debye length ($r = 5\,\mu$m, $\lambda_D = 100\,\mu$m) and the effect can be neglected. A modification of the capacity by this effect becomes important if $r \gg \lambda_D$, i.e., at much larger particle sizes. In this case, the capacity becomes $C = 4\pi\varepsilon_0\varepsilon_r(r^2/\lambda_D)$ which would result in a dependence of $Q \sim r^2$ for large particle radii. But the listed measurements do show a nonlinear (squared) dependence of the charge on the radius for small particle sizes of a few micrometers. This discrepancy indicates again that the simple capacitor model is mostly not useful for the description of particle charging. But the surface model can reflect the measured dependence.

The calculations for the charging of the particles presented in Figs. 5–8 support the results:

- direct correlation between Q and V_{fl} ($Q \sim V_{fl}$), but a counteract influence of T_p,
- nonlinear dependence of Q on the particle size $Q \sim r^x$ ($x \sim 2$),
- deviations from the $Q \sim r^x$ ($x \sim 2$) dependence at large radii (Fig. 7) due to thermal effects.

Fortunately, the measurements in [12,17] are conducted for different MF particle sizes. Thus, there is an opportunity to test the model in respect to the particle radius. The theory given here implies that for constant plasma conditions the negative net charge $\Delta\sigma_e = Q/A_p$ has a constant value. But for spherical dust particles, the net charge Q on the spherical grains increases with $(\text{size}/2)^2$ (see Figs. 5–8).

As mentioned above, in accordance to the orbital motion limited (OML) theory [42], the ion and electron currents collected by a body are given by:

$$I_i = An_i e_0\sqrt{\frac{kT_i}{2\pi m_i}}\left(1 + \frac{e_0 V_{fl}}{kT_i}\right) \tag{12}$$

$$I_e = An_e e_0\sqrt{\frac{kT_e}{2\pi m_e}}\exp\left(\frac{-e_0 V_{fl}}{kT_e}\right) \tag{13}$$

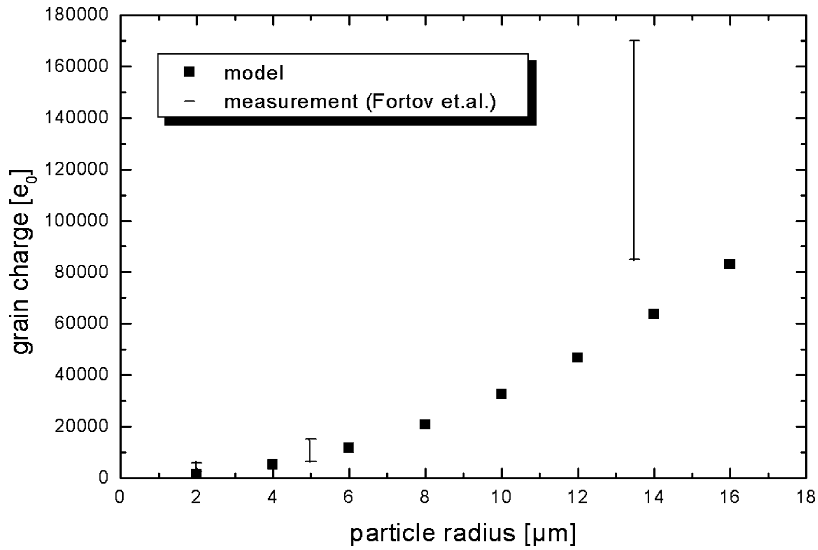

Fig. 7. Variation of the grain charge as a function of the particle radius (Ne, $p = 200$ Pa) [12].

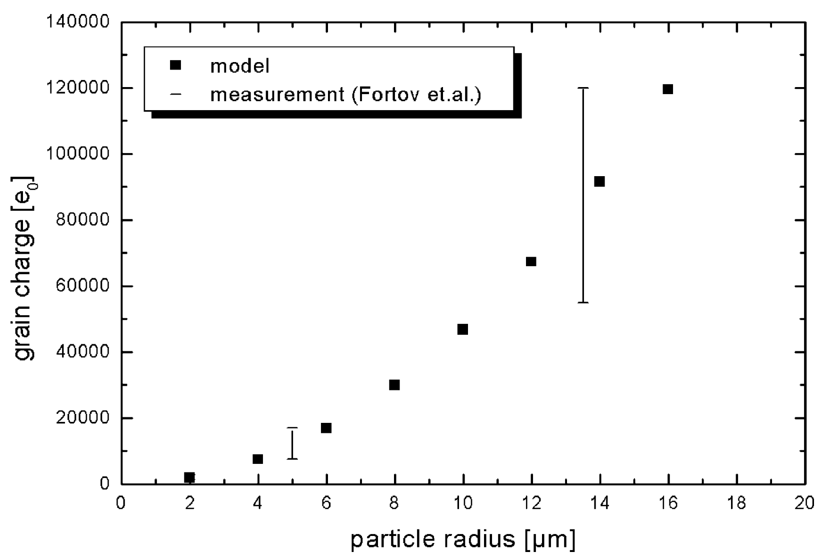

Fig. 8. Variation of the grain charge as a function of the particle radius (Ne $p = 67$ Pa) [12].

where $A = 4\pi r^2$. The OML theory is valid for $r \leq \lambda_D$ [37] which holds in our case as it can be seen in Tables 2 and 3, respectively. The Debye length λ_D itself is given by $\lambda_D^{-2} = \lambda_{Di}^{-2} + \lambda_{De}^{-2}$, where λ_{Di} and λ_{De} are the Debye lengths of the ions and electrons, respectively.

$$\lambda_{Di} = \sqrt{\frac{\varepsilon_0 k T_i}{n_i e_0^2}}, \quad \lambda_{De} = \sqrt{\frac{\varepsilon_0 k T_e}{n_e e_0^2}} \tag{14}$$

Our model represents the dependence $Q \sim r^2$ by taking the OML theory into consideration, e.g., the current density $j = I_e/4\pi r^2 = I_i/4\pi r^2$ does not depend on the particle radius r for these small sizes. The current density is only affected by the plasma parameters and not by the particle size. Therefore, the problem can be treated by plasma disturbing effects in regard to probe theories. The presented study on particle charging clearly shows the effect of the charge carrier fluxes (as expected) and the effect of the dust particle temperature T_p which was not included in earlier investigations. However, this quantity which was treated in the framework of elementary surface processes seems to be a crucial process parameter which can not be neglected in charging.

5. Conclusion

The proposed model which is based on plasma–wall interaction processes at the grain surface predicts the charge dependence on particle radius and particle temperature better than the commonly used assumptions of a spherical capacitor. For example, the model calculations are in a quite better accordance with the experimental data than for the commonly used capacitor assumption.

In addition to the electron and ion fluxes from the plasma towards the particles, it is necessary to consider the temperature-dependent elementary processes as adsorption, desorption and recombination of the charge carriers at the particle surface. Since the charge of small "dusty" substrates can be determined much more precisely these processes can be studied even better than at large solid substrates. Hence, it might be a useful supplementation for the investigation of plasma–wall interaction.

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