Micro-Particles as Electrostatic Probes for Plasma Sheath Diagnostics

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Abstract

An interesting aspect in the research of complex (dusty) plasmas is the experimental study of the interaction of micro-particles of different sizes with the surrounding plasma for diagnostic purpose. In the plasma micro-disperse particles are negatively charged and confined in the sheath. They are trapped by an equilibrium of gravity, electric field force and ion drag force. From the equilibrium position and motion of the particles, local electric fields can be determined, e.g. particles are used as electrostatic probes. In combination with additional measurements of the plasma parameters with Langmuir probes and thermal probes as well as by comparison with an analytical sheath model, the structure of the sheath can be described.

Experimental

For the experiments a typical asymmetric, capacitively coupled rf plasma (13.56 MHz) with argon (1-10 Pa) is used. The particles are spherical melamine-formaldehyde (MF) particles of different diameter (10 μm, 18 μm). The lower electrode is driven by an rf power between 10 to 50 W. In the center of the powered electrode a spherical dip is situated with a diameter of 10 mm and a depth of 3 mm. This electrode forms a special local plasma environment which is useful for particle trapping. The injected particles are illuminated by using a laser at 665 nm with 20 mW. Their position and motion as well as the total emission of the plasma were monitored with a CCD camera. An additional biased "mini electrode" with a diameter of 20 mm can be inserted from the top of the vacuum vessel and is located above the center of the powered electrode in an axial distance of 40 mm.

In dependence on the discharge conditions electron densities of $n_e = 10^9...10^{11}$ cm^{-3}, electron temperatures of $k_B T_e$ =0.8...3.8 eV, and plasma potentials with respect to ground of 20 V to 30 V for the pristine plasma has been measured.

The equilibrium position (x) of a negatively charged particle is given by $q(x)E(x) = mg$, if drag forces and photophoretic effects are neglected. Here m denotes particle's mass, $E(x)$ the electric field strength at position x, and $q(x)$ the particle charge.

A sinusoidal variation of the bias voltage at the "mini electrode" induces the particle to vertically oscillate around its equilibrium position. For small amplitudes this oscillation is harmonic and the particle's charge is approximately constant. The resonance frequency of the particle at position x is given by $\omega_0^2(x) = [(-q(x)/m)(dE/dx)]_x$. Combining this equation with the equilibrium condition, m can be eliminated and the resulting simple differential equation can be solved by separation to determine the electric field strength.

For a further evaluation we measured the relation between resonance frequency and equilibrium position of single MF-particles of different diameters at different positions beneath the "mini electrode".

Sheath model

The potential U in the sheath is given by Poisson's equation and the electrons are assumed to be Maxwellian, their density is given by the Boltzmann relation. The ions are considered cold, i.e. their thermal energy is negligible in comparison with their kinetic energy in the sheath. Their behavior in the sheath is described by ion continuity and ion motion. The sheath thickness s is determined by additional boundary condition $\left\langle \frac{\partial U(t,s)}{\partial x} \right\rangle = \frac{k_B T_e}{e\lambda_i}$ with λ_i the ion mean free path. The total current density J_0 at the electrode consists of electron (J_e) and ion (J_i) part: $J_0(t) = J_e(t) - J_i$ where: $J_e(t) = 1/4 e n_e(t,0)\sqrt{8k_B T_e/m_e}$ and $J_i = e n_s v_B$ with v_B the Bohm velocity. The electron density n_e at the electrode is determined from the Boltzmann distribution function. In the case of a capacitively coupled rf discharge the average of total current has to be zero.

Results and discussion

From the measured trapping position of the particles in the plasma sheath the simulation program yields the plasma parameters like electron and ion density and temperature, the force balance for the particles, the dust charge, dust and plasma potential and the electric field strength. An additional control parameter is the resonance frequency of the particles. It is possible to measure this frequency by video microscopy form the experiment and calculate the values by the simulation programm. The experimental results show a good agreement with the theoretical predictions, e.g. the measured height of the particles is between 6 and 7 mm, depending on the bias voltage and the rf power, respectively (see fig. 1a). The simulation yields a height of nearly the same trapping positions (1b). For typical experimental conditions (8 Pa argon pressure, 135 V rf bias, 9.55 μm particle diameter) the electron density is 8.9$\cdot 10^{14}$ m^3, the electron temperature is 2.6 eV, the particle charge is 16355 elementary charges and the electric field strength is 5200 V/m at particle position.

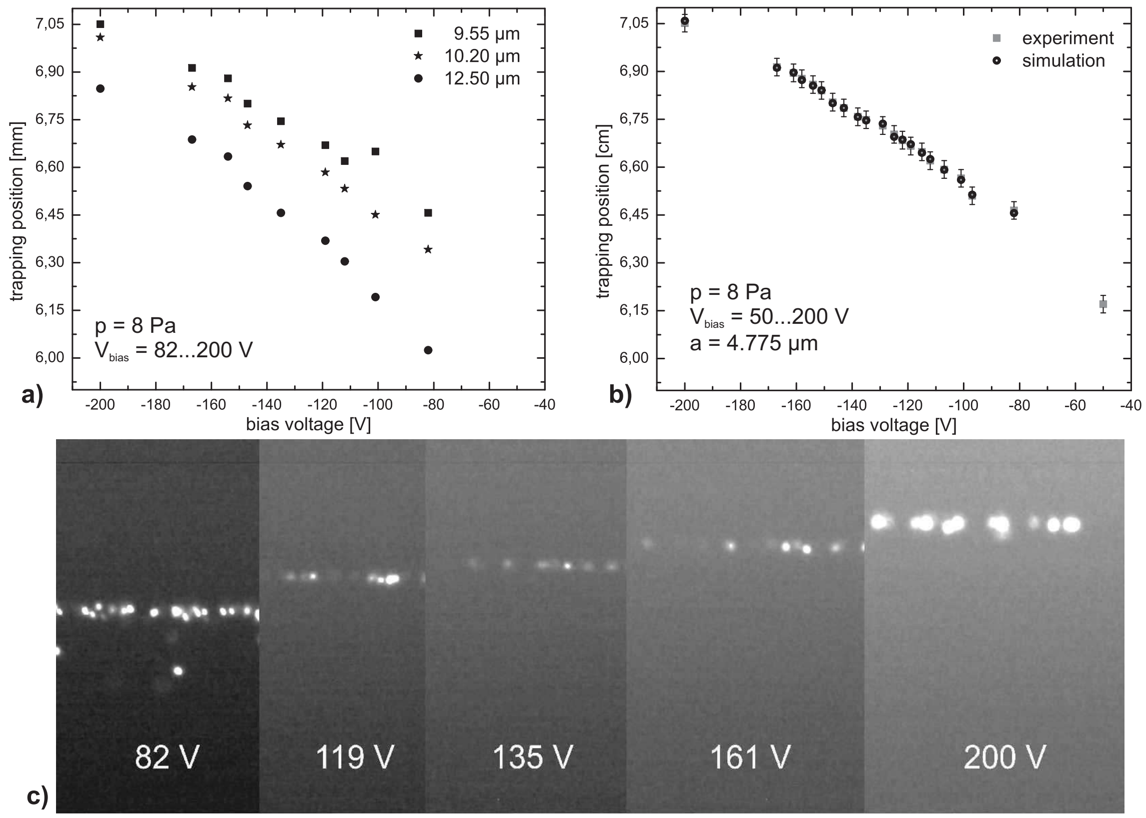

Figure 1: Particle trapping in dependence of the rf bias voltage. Figure a) shows the measured height of the particle position for three different particle diameters. In figure b) a comparison between the experimental results (■) and the simulation (○) for 8 Pa argon, 9.55 μm particle diameter and bias variation from 50 V to 200 V are shown. The photograph in c) are experimental observation for at different bias voltages.

In figure 2 the variation in the particle charge for three different particle sizes for bias voltage variation is shown. For example, the calculated particle charge for a dust grain with a diameter of 12.50 μm is 25500 elementary charges at a rf bias voltage of 135 V. From the OML-theory [2] a maximum charge for an isolated dust grain of this size is given by 32600 elementary charges. The collision reduced model [3] gives a value of 19700 elementary charges. In comparison to this models, our es-

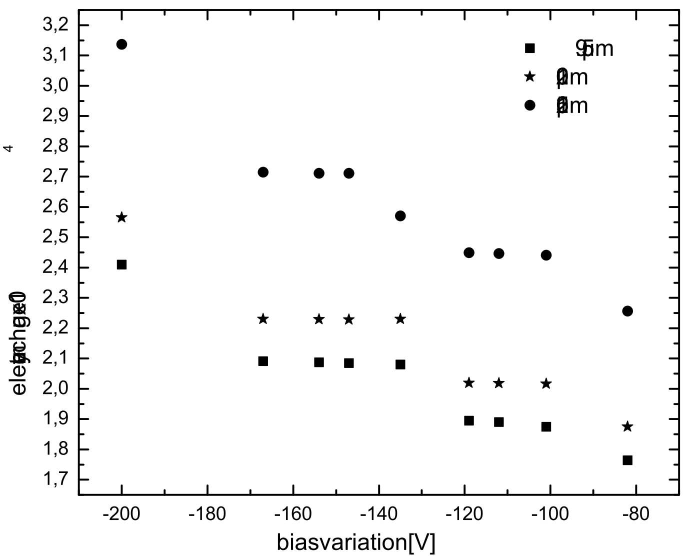

Figure 2: Calculated particle charge in units of the elementary charge for three different dust grain diameters as a function of rf bias voltage. The argon pressure is 8 Pa.

timation of the particle charge is in the same range.

In figure 3 the dependence of the electron density and the electron temperature against the bias variation is shown.

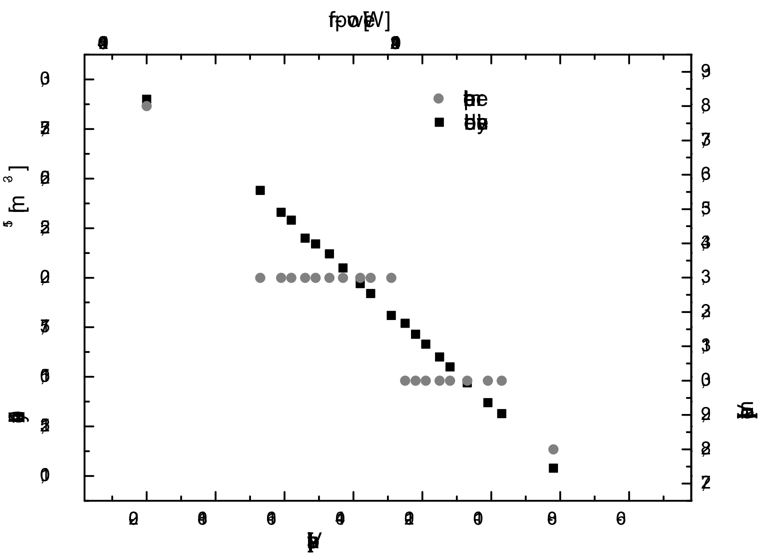

Figure 3: Calculated electron density (■) and electron temperature (○) over the variation of the rf bias voltage. The argon pressure is 8 Pa and the particle diameter is 9.55 μm.

In addition to the rf bias voltage the associated rf power is plotted. In comparable experiments [4] similar values for the electron density and temperature have been obtained.

The measured trapping height of the used dust grains above the powered electrode done by video microscopy in combination with the simulation model provides a method to obtain the plasma parameters without disturbance of the local plasma environment in contrast to commonly used (Langmuir) probe measurements.

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