NUMERICAL DESCRIPTION OF DUST PARTICLES IN PLASMA SHEATH

R. Basner[1], G. Thieme[1], J. Blazek[2], M. Wolter[3], H. Kersten[3]

[1]*INP Greifswald, 17489 Greifswald, Germany*

[2]*Department of Physics, U of South Bohemia, 37115 Ceske Budejovice, Czech Republic*

[3]*IEAP, University of Kiel, 24098 Kiel, Germany*

Introduction

The interface between plasma and its surrounding surfaces (walls, electrodes, substrates) is formed by a self-organizing structure, called the plasma-sheath. To gain additional insight, micro-sized particles can be used as electrostatic probes. Due to charge carrier fluxes these particles acquire a negative surface charge, allowing for trapping them within the plasma sheath. The particles attain an equilibrium position, where the sum of all acting forces vanishes. In our case, the system is dominated by gravitational force, electrostatic force and ion drag, while neutral drag, thermophoresis and photophoresis are of minor importance. The approach of suitable electrostatic particle probes has been successfully demonstrated in front of the powered electrode of a capacitively coupled rf discharge [1]. In the present work we focus on the behaviour of micro-particles of different sizes in front of a grounded or additional biased adaptive electrode, which is not the powered electrode.

Experimental

The experimental setup is shown in figure 1. A typical asymmetric, capacitively coupled rf plasma (*13.56 MHz*) in argon (*1-10 Pa*) is employed to charge the particles which are spherical melamine-formaldehyde (MF) particles of different diameter. The upper electrode is rf driven with a power of 10 W. The lower electrode is the so called adaptive electrode (AE). It consists of 101 identical square segments surrounded by 4 larger segments and an outer ring electrode. Each segment can be biased independently with dc and/or ac voltage. This arrangement allows distinct local manipulations of the plasma sheath to create different static or time dependent shapes of horizontal confinement of suspended particles. In dependence on the discharge conditions we measured electron densities of $10^9 - 10^{11}\ cm^{-3}$, electron temperatures of $0.8 - 2.8\ eV$, and plasma potentials with respect to ground of $20 - 30\ V$ for the pristine plasma [2]. The injected particles were illuminated using a laser at *532 nm*, position, motion as well as the total plasma emission were monitored with a CCD camera.

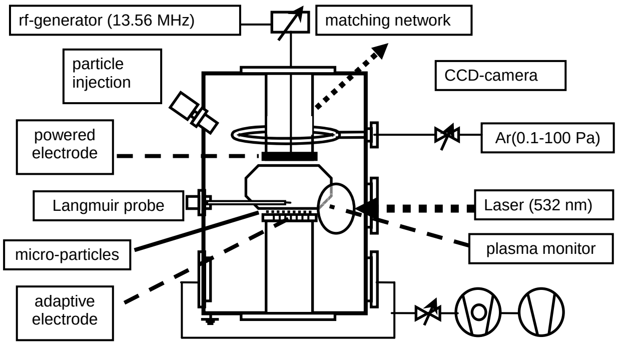

Fig. 1: The experimental setup (PULVA-INP).

For the evaluation we measured the relation between resonance frequency f_0 and equilibrium position x_0 of single MF-particles of different diameters at different positions above the central segment of the AE as shown in figure 2.

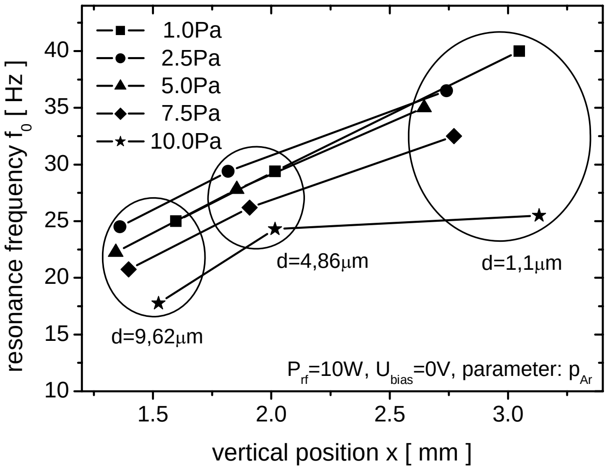

Fig. 2: Dependence of the measured resonance frequency on the equilibrium position for different pressures and particle diameters above the grounded AE.

Sheath model for adaptive electrode

The equilibrium position of a negatively charged particle (x_0) is given by $q(x_0)E(x_0) = mg$, if drag forces and phoretic effects are neglected. Here m denotes particle's mass, $E(x)$ the electric field strength at position x, and g the acceleration of gravity. A sinusoidal variation of the bias voltage at the central segment of the AE 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_o is given by $\omega_o^2(x_o) = [(-q(x_o)/m)\ (dE/dx)]_{xo}$. 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. Formal integration yields:

$$E(x) = E(0)\exp\left\{-\frac{1}{g}\int_0^x \omega_0^2(\zeta)\,d\zeta\right\} \tag{1}$$

Equating the negative integral over the electric field across the sheath with the sheath voltage fixes the value of *E(0)* at the surface of AE.

The potential U in the sheath is given by Poisson's equation:

$$\frac{\partial^2 U(t,x)}{\partial x^2} = -\frac{e\left[n_\mathrm{i}(x) - n_\mathrm{e}(t,x)\right]}{\varepsilon_0} \tag{2}$$

with boundary conditions $U(t,0)=U_0(t)$ and $U(t,s)=0$, where n_i and n_e are local ion and electron number densities, respectively. The coordinate x is oriented upward from the AE to the plasma. We relate the zero potential to the sheath edge at $x=s$. Potential $U_0(t)$ of the electrode will be specified later. The electrons are assumed to be Maxwellian, their density is given by the Boltzmann relation: $n_\mathrm{e}(t,x) = n_\mathrm{s}\exp\left(\frac{eU(t,x)}{kT_\mathrm{e}}\right)$ (3)

where n_s is the electron density at the sheath edge. The ions are considered cold, their behavior in the sheath is described by ion continuity and ion motion:

$$n_\mathrm{i}(x)\,v_\mathrm{i}(x) = \text{const.} \qquad m_\mathrm{i}\,v_\mathrm{i}\frac{\mathrm{d}v_\mathrm{i}}{\mathrm{d}x} = \left\langle -e\frac{\partial U}{\partial x}\right\rangle + \frac{1}{\lambda_\mathrm{i}}m_\mathrm{i}v_\mathrm{i}^2 \tag{4}$$

with boundary conditions $n_\mathrm{i}(s) = n_\mathrm{s}$, $v_\mathrm{i}(s) = -v_\mathrm{B}$. Here λ_i is the ion mean free path and $v_\mathrm{B} = \sqrt{kT_\mathrm{e}/m_\mathrm{i}}$ is the Bohm velocity. The sheath thickness s is determined by additional boundary condition: $\left\langle\frac{\partial U(t,s)}{\partial x}\right\rangle = \frac{kT_\mathrm{e}}{e\lambda_\mathrm{i}}$ (5)

The total current density at the electrode consists of electron and ion part: $J_0(t) = J_\mathrm{e}(t) - J_\mathrm{i}$.

$$J_\mathrm{e}(t) = \frac{1}{4}e\,n_\mathrm{e}(t,0)\sqrt{\frac{8kT_\mathrm{e}}{m_\mathrm{e}}}, \qquad J_\mathrm{i} = e\,n_\mathrm{s}v_\mathrm{B}. \tag{6}$$

The electron density n_e at the electrode is determined from the Boltzmann distribution function. In the case of capacitively coupled rf discharge the average of total current has to be zero but additional voltage brought to the electrode pixel violates this condition.

For the pixel voltage $U_0(t)$ and current density $J_0(t)$ we take their average values from measurement: $\langle U_0(t)\rangle = U_\mathrm{dc}$, $\langle J_0(t)\rangle = J_\mathrm{dc}$. (7)

Neglecting higher harmonics we approximate the time behavior of $U_0(t)$ by sinusoidal: $U_0(t) = A_0 + A_1\sin(\omega t)$, with coefficients A_0, A_1 uniquely determined by eq.(7).

We get immediately $A_0 = U_\mathrm{dc}$. Coefficient A_1 is obtained by eq.(8) (I_0: Bessel function):

$$\ln I_0\left(\frac{A_1}{kT_\mathrm{e}}\right)=\frac{1}{2}\ln\left(\frac{2\pi\, m_\mathrm{e}}{m_\mathrm{i}}\right)-\ln\left(1+\frac{J_\mathrm{dc}}{J_\mathrm{i}}\right)-\frac{eU_\mathrm{dc}}{kT_\mathrm{e}} \tag{8}$$

For $J_\mathrm{dc}=0$ the above equation reduces to the standard condition for capacitive rf discharges.

Results and discussion

In figure 3 experimental and theoretical results for the electric field strength as a function of the position in the plasma sheath above the AE are presented. Te small MF particle of *1.1 μm* diameter is levitated at positions of low electric field near the sheath edge and the heavy particle (*9.62 μm*) at positions around the middle of the sheath.

The experimental results as well as the theoretical curves demonstrate the expected expansion of the plasma sheath with increasing negative dc bias voltage. As can be seen, the predicted expansion of the calculations is obviously smaller than the values obtained from experiments. The theoretical curve for dc bias of *-60 V* appears approximately at the same position as the experimental values for *-40 V*. However, each of both data sets shows nearly an equidistant shift of position with increasing negative bias of constant steps and the shape of the curves remains almost unchanged.

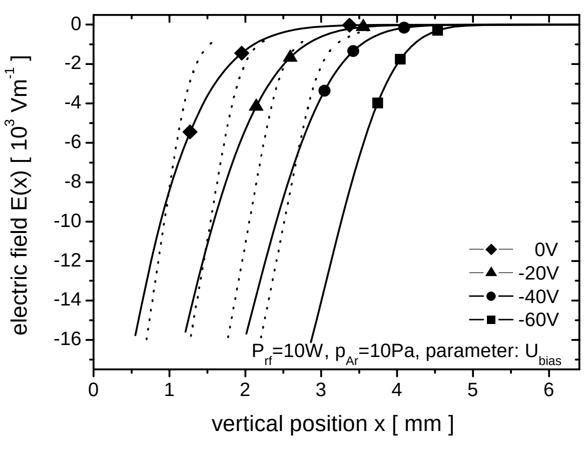

Fig. 3: Electric field strength from experiments (symbols) for different negative dc bias voltages together with the corresponding calculated curves (dotted) above the AE.

Furthermore, the experiment shows that the electric field strength at different positions of the particles of same size is nearly constant. We can conclude that the particle charge is unchanged and the charged particle simply moves with increasing negative bias voltage to new position where the electric field satisfies the equilibrium condition.

References

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[2] M. Tatanova, G.Thieme, R. Basner, et.al., Plasma Sourc.Sci.Technol. 15(2006) 507.