Plasma sheath diagnostics by micro-particles of different sizes

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Introduction

The interface between a plasma and its surrounding surfaces (walls, electrodes, substrates) is formed by a self-organised structure, called the plasma-sheath. In plasma diagnostics a relatively large uncertainty exists for the determination of the structure of these plasma sheaths near the surface. To gain additional insight, micro-sized particles can be used as electrostatic probes. Due to electron and ion fluxes in the plasma, these particles acquire a negative surface charge, allowing for trapping them within the plasma sheath. A multitude of forces act on the particles, which have been discussed extensively in literature [1]. The particles will attain an equilibrium position, where the sum of all acting forces vanishes. In our case, the system is dominated by gravitational and electrostatic forces, while neutral and ion drag, thermophoresis and photophoresis are of minor importance. The levitated particles react sensitively to changes in the plasma sheath [2], making them suitable electrostatic probes. This approach has been successfully demonstrated in front of the powered electrode of a capacitively coupled rf-discharge [3]. In the present work, we focus on the behaviour of dust grains in front of the grounded electrode. We determine their equilibrium position and resonance frequency, whereby we calculate the electric field and particle charge. The sheath structure in front of a grounded surface is of importance in plasma technology for the treatment of substrate surfaces.

Experiment

The experimental setup is shown in figure 1. A typical asymmetric, capacitively coupled rf-plasma in argon (1- 10 Pa) is employed to charge the particles which are spherical melamine-formaldehyde (MF) particles of 0.5, 1, 5, and 10μm in diameter. The cylindrical reactor vessel with 40 cm in diameter and 50 cm in height contains two electrodes (diameter 13 cm) in a distance of 10 cm. The upper electrode is rf driven with a power of 10 W. The lower electrode is a so called adaptive electrode (AE). It consists of 101 identical square segments (7×7 mm^2) surrounded by 4 larger segments and an outer ring electrode. Each segment can be biased independently with dc and/or ac voltage of up to $\pm$100 V and frequencies of maximum 50 Hz. This arrangement allows distinct local manipulations of the plasma sheath to create different static

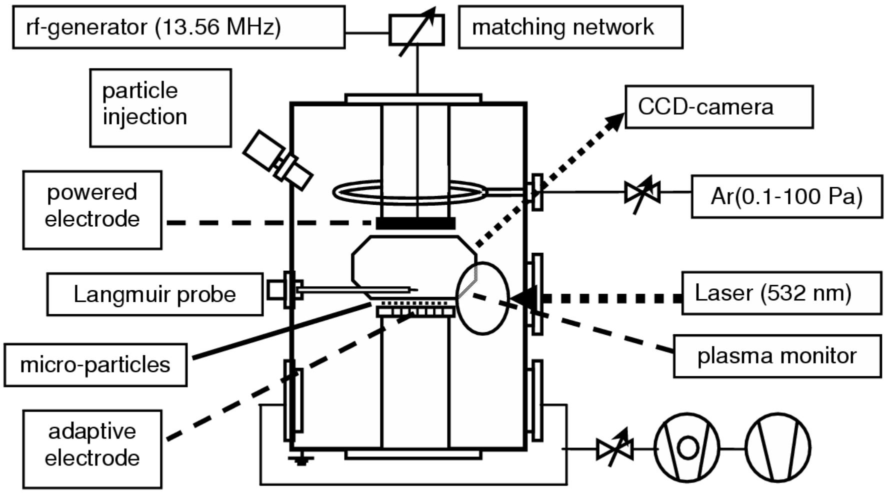

Figure 1: Experimental setup (PULVA-INP)

or time dependent forms of horizontal confinement of suspended particles. An rf-compensated Langmuir probe was used to measure the plasma parameters 1.5 cm above the adaptive electrode as a function of the horizontal position [4]. 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.

The different ions (Ar^+, Ar^{++}, Ar_2^+, ArH^+) and their kinetic energy at the grounded surface were investigated by energy resolved mass spectrometry. In the pressure range from 1 to 10 Pa we observed a higher (about 20 eV) and a lower (about 8 eV) energetic ion group in the energy spectrum. This result reflects the transition from a collisionless to a collisional sheath. The main energy of the higher energetic ion group provides a value of sheath voltage which corresponds to the measured plasma potential.

The injected particles were illuminated using a laser at 532 nm. Their position and motion as well as the total emission of the plasma were monitored by means of a CCD camera. We studied the intensity of plasma emission as function of the height above the centre of the AE to determine the sheath thickness. The intensity profile reveals a distinct bend. We defined this bend as the position of the plasma sheath edge which agrees well with the position of 0.5 μm MF particles which were levitated at the sheath edge [3].

Results

The equilibrium position of a negatively charged particle (charge $-q(z)$) is determined by $q(z)E(z) = mg$, if both drag forces and phoresis effects are neglected. Here m denotes the particle's mass, $E(z)$ and g the absolute values of the electric field at position z and the acceleration of gravity respectively (cf. figure 2, left). A sinusoidal variation of the bias voltage at the central

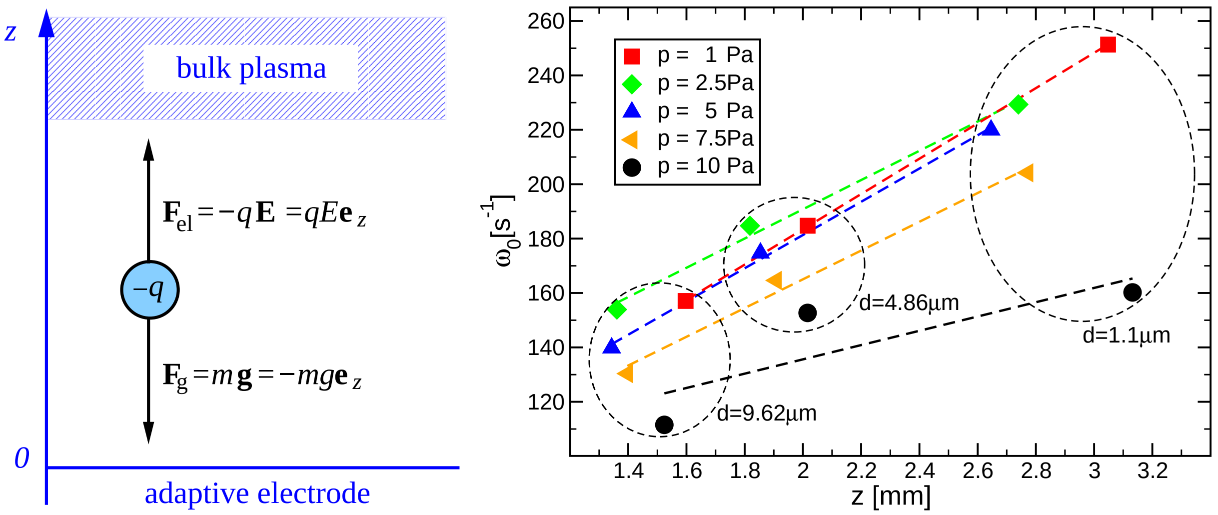

Figure 2: Left: Forces acting on a particle within the plasma sheath. Right: Dependance of the resonance frequency ω_0 on the equilibrium position z for different pressures p and particle diameters d. The dashed lines are least square fits of $\omega_0 = a_1 z + a_0$ to the data.

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. Within this approximation of a driven harmonic oscillator, the particle's resonance frequency at position z_0 is given by $\omega_0^2(z_0) = -\frac{q(z_0)}{m}\frac{dE}{dz}\Big|_{z_0}$. Combining this equation with the equilibrium condition, m can be eliminated, and the resulting differential equation can be solved by separation. Formal integration yields

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

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 the AE.

For a further evaluation we need to know the relation between resonance frequency and equilibrium position throughout the whole sheath. To get this information we confined single MF-particles of different diameters above the central segment of the AE and applied a sinusoidal voltage of variable frequency to this segment. The frequency which causes the maximum amplitude of the particle oscillation is extracted as the resonance frequency. Experimental data (cf. figure 2, right) suggests a linear behaviour from 1.3 mm to the sheath edge for low and moderate pressures ($p \leq 7.5$ Pa). For $p = 10$ Pa, the available data and the assumption of a linear relation between ω_0 and z agree only poorly. Using a linear ansatz for ω_0 in equation 1, we obtained the electric field in the sheath of the grounded electrode for different pressures as presented in figure 3.

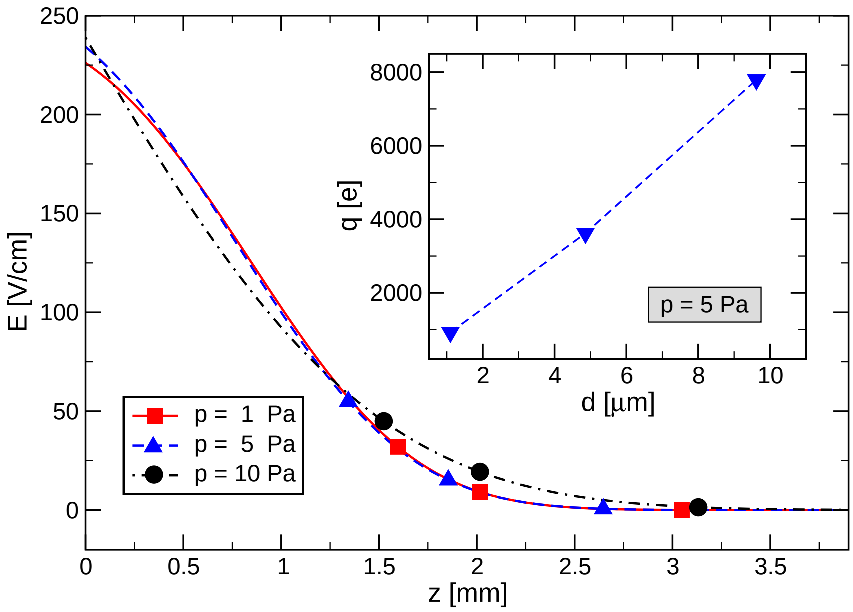

Figure 3: Absolute value of the electric field E as a function of distance z from the AE for different pressures p. Inset: Absolute value of particle charge q in units of elementary charge e as a function of particle diameter d for $p = 5$ Pa.

Furthermore, with the knowledge of the electric field the particle charge can be directly obtained from the equilibrium condition.

Conclusion

The experiments show clearly that the electric field structure can be determined by means of charged micro-particle probes also in front of grounded or additionally biased surfaces. To get further information about the relation between resonance frequency and equilibrium position closer to the electrode, additional measurements with larger particles, which are levitated lower, are necessary.

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References

[1] A. Bouchoule (editor), "Dusty Plasmas", J.Wiley & Sons, New York (1999)

[2] B. M. Annaratone, M. Glier, T. Stuffler, M. Raif, H. M. Thomas and G. E. Morfill, New Journal of Physics **5**, 92 (2003)

[3] A. A. Samarian and B. W. James, Plasma Phys. Control. Fusion **47**, B629 (2005)

[4] M. Tatanova, G. Thieme, R. Basner, M. Hannemann, Y. B. Golubovskii and H. Kersten, Plasma Sources Sci. Technol. **15**, 507 (2006)