Comparison of non-invasive diagnostics for particle charge and screening length for flat dust clusters in rf discharges

J. Carstensen, F. Greiner, A. Piel

Institut für Experimentelle und Angewandte Physik, Christian-Albrechts-Universität, D-24098 Kiel, Germany

Introduction

Dusty plasma experiments with flat dust clusters are often performed in radio frequency discharges at typical gas pressures of 1 Pa to 100 Pa. The interaction of the dust grains is usually assumed to be of Yukawa type, which is determined by the particle charge and the screening length. For the experimental determination of these quantities methods are advantageous, which do not require prior knowledge of the plasma parameters. In this contribution, the results of two such methods are compared. In [1] we have proposed a new diagnostic for grain charge and screening length based on the application of centrifugal forces. For the case of low gas pressures the observation of normal modes can be used as an alternative diagnostic [2]. The findings of these two methods are compared and the results are discussed.

Experimental setup

The experiments presented were performed in a 13.56 MHz, capacitively-coupled parallel plate rf discharge (Fig. 1). The powered lower electrode has a diameter of 10 cm and is radially terminated by a grounded Faraday shield, which is separated from the driven electrode by a gap filled with a PTFE dielectric. The upper grounded electrode is placed 5 cm above the driven electrode. For dust confinement, a cylindrical cavity of 20 mm diameter and 2 mm depth was milled into the center of the lower electrode. The particles used in these experiments are monodisperse melamine formaldehyde spheres with a radius of either $(10 \pm 0.1)\ \mu$m or $(6 \pm 0.1)\ \mu$m. They

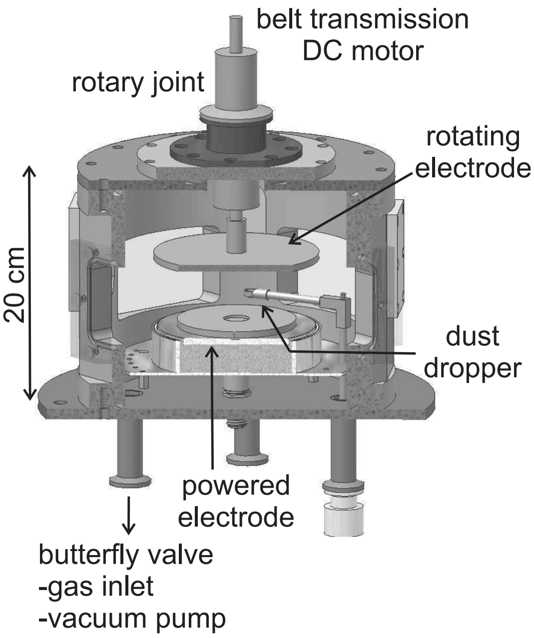

Figure 1: Sketch of the experimental arrangement. An argon plasma is established between the driven lower electrode and the grounded upper electrode, which is attached to a rotary joint.

are illuminated by a laser fan (200 mW@532 nm) and can be be observed side-on by two video cameras under an angle of 90°. The dust grains are confined in a layer typically (5–10) mm above the electrode.

In order to expose dust particles to centrifugal forces, the upper electrode is connected to a DC-motor outside the vacuum vessel, which allows rotation frequencies of the electrode up to approximately $30\,\mathrm{s}^{-1}$. This causes a laminar rotational motion of the neutral gas with a vertical shear. The flow velocity decreases towards the lower electrode due to gas viscosity [3]. Close to the rotation axis, a layer of gas rotates as a rigid body with constant angular velocity. At the position of the dust cluster, rotation frequencies up to $3\,\mathrm{s}^{-1}$ can be obtained.

Experimental results

In this contribution, the focus lies on two-particle clusters. In the following, it will be assumed that these two particles have the same mass and the same charge number Z. Further, it is assumed that the particles are confined in a harmonic potential well and interact through a shielded Coulomb (Yukawa) potential, depending on an effective particle charge number Z_{eff} and the screening length λ_{D}. The effective charge number Z_{eff} can be somewhat larger than the actual grain charge Z, because of weak ion shielding close to the grain [4].

Normal Mode Analysis (NMA)

This two-particle system can exhibit a breathing and sloshing oscillation about its equilibrium position. The sloshing motion occurs at the eigenfrequency of the confining potential well and is independent of the number of particles. The screening length λ_{D} and the grain charge number Z_{eff} can be determined from the mode frequency of the sloshing mode and the equilibrium interparticle distance [2].

The experiments were performed at 4 Pa gas pressure and at a rf peak-to-peak voltage of $200\,V_{\mathrm{PP}}$. The thermal motion of a two-particle cluster was tracked with the two cameras from the side at 100 frames per second for a total observation time of 3000 s. This allows to reconstruct the time evolution of the interparticle distance and of the center of mass of the cluster. The sloshing and breathing frequencies were obtained from the power spectrum of this time series. In Fig. 2(a) the power spectrum for both modes for $6\,\mu$m particles are shown. The line widths of the peaks is a result of the neutral gas friction. The experimentally determined effective charge numbers and screening lengths for $6\,\mu$m and $10\,\mu$m particles are summarized in Tab. 1.

Rotating electrode method (REM)

When this system of two particles is set into a rotation about its center of mass, an additional centrifugal force is exerted on the dust grains, which leads to an increased interparticle

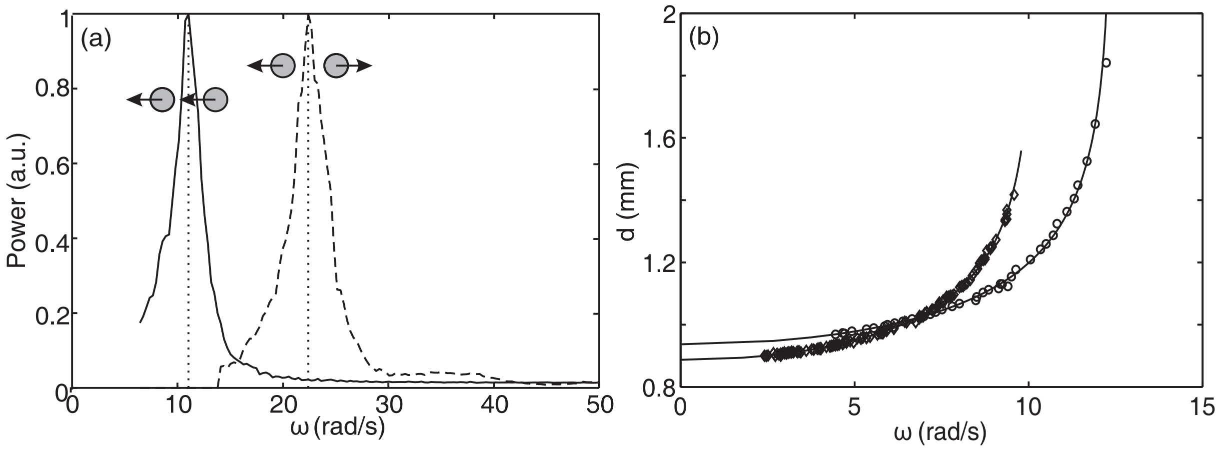

Figure 2: (a) Power spectrum of the center of mass motion (sloshing mode, full line) and of the interparticle distance (breathing modes, dashed line) for a two particle cluster (r_d=6$\,\mu$m).(b) Dependence of the interparticle distance d as a function of rotation frequency ω for particles with 6$\,\mu$m (diamonds) and 12$\,\mu$m radius (circles).

distance. The measurement of the interparticle distance for different rotation frequencies allows the determination of screening length and (effective) charge number [1].

After the observation for the normal modes was completed, the upper electrode, i.e., the two-particle cluster was set into rotation. For a fixed rotation frequency of the cluster, the particle motion was tracked by the two cameras for 60 s. This was done by stepwise increasing the frequencies up to the critical value, where the centrifugal force overcomes the confining force and the dust grains flew radially outwards. In Fig. 2(b) the obtained interparticle distance d is plotted versus the rotation frequency ω. The resulting effective particle charge number and screening length are summarized in Tab. 1.

	NMA		REM	
	$Z_{\rm eff}$	$\lambda_{\rm D}$ (mm)	$Z_{\rm eff}$	$\lambda_{\rm D}$ (mm)
$r_{\rm d} = 6\,\mu$m	20600(±3100)	0.49(±0.11)	19500(±1800)	0.68(±0.18)
$r_{\rm d} = 10\,\mu$m	57500(±13700)	0.86(±0.42)	60300(±8300)	0.6(±0.16)

Table 1: Effective charge number $Z_{\rm eff}$ and screening length $\lambda_{\rm D}$ in mm for different particle radii $r_{\rm d}$ obtained by REM and normal mode analysis (NMA).

Discussion

The obtained values for effective charge number and screening length are in fair agreement with the results from the normal mode analysis. The effective charge numbers obtained by both methods differ by approximately 5%, which is within the given error margin. The difference in the screening length is of the order of 30%, which can be explained by the larger uncertaintiy in $\lambda_{\rm D}$.

The Debye length found is of the order of the interparticle distance, which is a typical result for experiments with flat dust clusters [5, 6]. Furthermore, both methods show a non-linear dependency of particle charge and radius, which is contrary to the standard orbital motion limited theory [7]. Although a comparable behavior is found in other experiments in rf discharges [8, 9], the reason for this strongly enhanced floating potential for larger dust grains is not fully understood.

To conclude, the REM can be used as a non-invasive, reliable diagnostic for the (effective) particle charge and screening length, which does not require prior knowledge of the plasma parameters. In contrast to methods that are based on wave phenomena or particle oscillations, e.g., normal mode analysis, it is also applicable at higher gas pressures up to 100 Pa.

Acknowledgments

This work was supported by the Deutsche Forschungsgemeinschaft DFG in the framework of the SFB-TR24 Greifswald-Kiel, Project A2.

References

[1] J. Carstensen *et al.*, IEEE Trans. on Plas. Sci. **38**, 788 (2010)

[2] A. Melzer *et al.*, Phys. Rev. Lett. **87**, 11 (2001)

[3] J. Carstensen *et al.*, Phys. Plasmas **16**, 013702 (2009)

[4] M. Lampe *et al.*, Phys. Plasmas **7**, 3851 (2000)

[5] V. Nosenko *et al.*, Phys. Rev. E **68**, 056409 (2003)

[6] A. Piel *et al.*, Phys. Plasmas **13**, 042104 (2006)

[7] J. E. Allen, Phys. Scripta. **45**, 497 (1992)

[8] E. B. Tomme *et al.*, Phys. Rev. Lett. **85**, 2518 (2000)

[9] A. A. Samarian *et al.*, Phys. Rev. E **67**, 066404 (2003)