PARTICLES AS MICRO-PROBES IN PLASMAS

Holger Kersten

IEAP, University of Kiel, Germany

kersten@physik.uni-kiel.de

Complex (dusty) plasmas, which can form plasma or Coulomb crystals are at recent a topical research subject in plasma physics [1]. The complexity of dusty plasmas results in complicated interactions at different scales in energy, space, time and mass. Experimental and theoretical studies initiated the idea of using externally injected small particles, which are negatively charged and affected by several forces in plasmas, as micro-probes. From the behaviour of the particles in the surrounding plasma local electric fields can be determined ('particles as electrostatic probes') [2]. Moreover, momentum fluxes in energetic ion beams ('particles as force probes') [3] as well as energy fluxes towards the particles ('particles as thermal probes') [4] are worth studying.

Particles as electrostatic probes in a plasma sheath

In dusty plasma experiments, fine particles usually levitate in the horizontal plane above a electrode and show a spatial distribution, which depends on the electric field structure above the electrode. Under some conditions, vortices appear and the micro-particles move in the plasma.

According to the balance of gravitational force, electrostatic force, ion drag, neutral drag, thermophoresis and Coulomb interaction, micro-particles disperse in a relatively small region of the plasma sheath depending on their size and charge. Commonly, the electrostatic and gravitational forces are important. Superposition of the two forces results in a harmonic potential trap around an equilibrium position. From the particle behaviour, conclusions about the surrounding plasma and sheath properties can be obtained, e.g. field strength and structure.

In order to influence the particles and to simulate different electrostatic surface conditions, a segmented adaptive electrode (AE) has been used as an essential part of a capacitively coupled asymmetric rf-plasma [5], see fig.1.

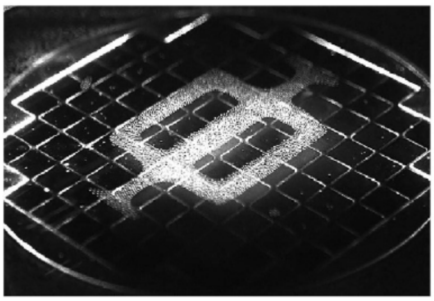

Fig. 1: Pattern of dust particles (d = 9.6µm) which are charged in an rf-plasma and levitated in front of the AE due to different pixel biasing.

As the plasma potential is positive with respect to grounded surfaces the electric field is directed towards the AE. Applying a local bias to some pixels of the AE influences the potential structure in the sheath and, thus, locally changes the direction and magnitude of the electric field. In this way, we can tailor confinement potentials for particles, which are levitating above the AE, see fig.1. Using a cloud of probe particles, which will arrange such that their potential energy is minimized, the spatial variation of the potential can be mapped.

For precise experiments, a single probe particle is confined above the centre pixel of the AE and its equilibrium position z_0 is measured. An additional sinusoidal voltage applied to the centre pixel, causes the particle to oscillate around z_0. Recording the oscillation amplitudes for different driving frequencies allows for a determination of its resonance frequency ω_0, see fig. 2. Using particles of different sizes, the corresponding equilibrium positions cover a wide range of the sheath and allow for a thorough characterization of the particle charge and the electric field in the sheath [5].

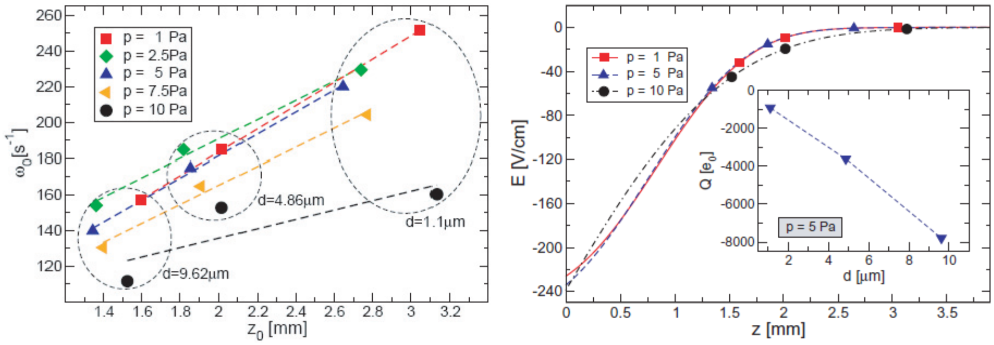

Fig. 1: Left: Probe particles in the sheath in front of the AE: measured relation between the resonance frequency ω_0 and the equilibrium position z_0 for different particle diameters d and neutral gas pressures p. Right: Calculated electric field E as a function of distance z from the AE for different neutral gas pressures p. Inset: particle charge Q as a function of particle diameter d for $p = 5\ Pa$.

However, by the method described above one can only determine the electric field at certain positions where just the equilibrium between field E-field and gravity holds. In order to measure the electric field structure at any position in the plasma sheath without the plasma being changed or disturbed an additional, non-electric, force has been introduced which does not alter the plasma conditions, but which does allow for manipulation of the particle position through the sheath: hyper-gravity, induced by a centrifuge. Consequently, the electric field and the particle charge can be determined as function of the position in the sheath. The experimental details are described elsewhere [6].

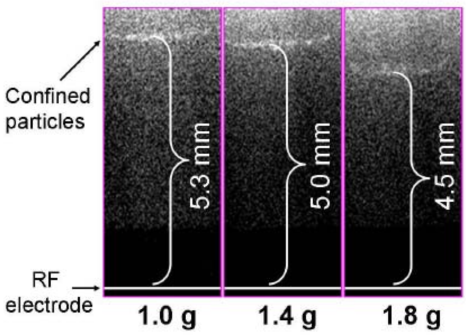

Fig. 3: Images illustrating the changing particle equilibrium position under hyper gravity conditions, obtained by on-board CCD camera on the centrifuge.

Fig. 3 shows CCD camera images of one layer of micro-particles ($r=5.1\ \mu m$) confined in the plasma sheath demonstrating decreasing particle height with increasing values of gravity acceleration. Again, the electric field profile in the sheath of an rf argon plasma is determined from measurements of the equilibrium height and the resonance frequency of plasma-confined micro-particles, but now under hyper gravity conditions in the centrifuge.

Finally, fig. 4 shows the obtained electric field profile in the sheath. As can be observed, the electric field is linear with respect to *z* over a large part of the sheath, which is in agreement with many sheath models. However, close to the sheath edge, the behavior is non-linear and the tangent to the *E(z)* profile is an increasing function of *z*. The shape of this profile corresponds well with profile shapes predicted by Lieberman [7].

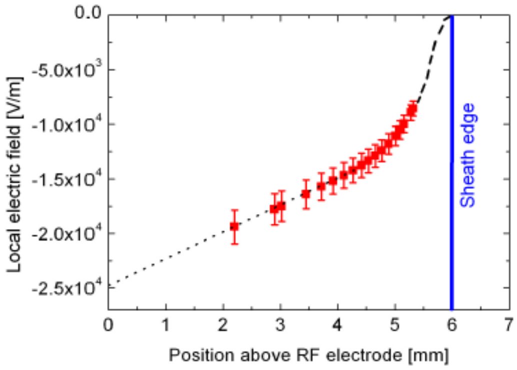

Fig. 4: Obtained electric field profile (squares) together with expected profile (dashed line). The dashed line corresponds to the expected shape of the electric field profile.

Particles as force probes in an energetic ion beam

In another novel experiment micro-particles have been used to study the forces in ion beams. For this purpose, a broad beam ion source provides a vertically upward directed beam wherein *100µm* hollow glass spheres are injected [8]. The particles are illuminated by a stroboscopic diode laser and recorded with a CCD camera. From the observed particle trajectories (fig.5) the acceleration and the net force on the particles are determined. Information on energetic neutral atoms is achieved, which is not accessible by electrostatic methods. The right graph in fig.5 shows the forces acting on the particles for different ion energies obtained from about the trajectories.

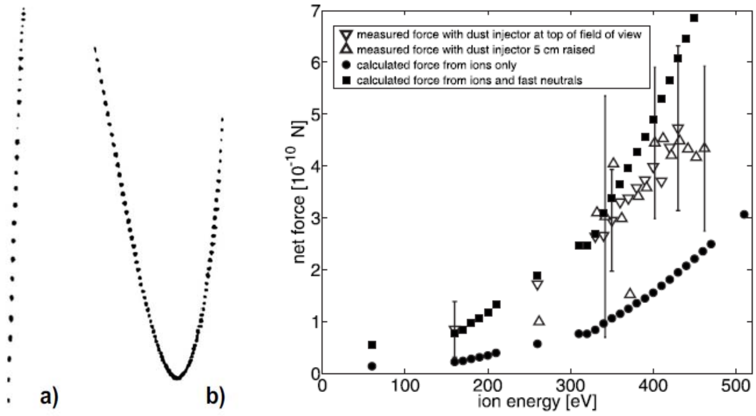

Fig. 5: Left: Particle trajectories (a) of a free falling particle and (b) with a *410 eV* ion beam. Right: Measured net forces on the test particles and calculated forces due to argon ions and fast neutrals based on the ion beam current measurements.

As expected, the net force increases with higher ion energies up to $4.510^{-10}N$ which is comparable with the gravitational force [8]. Measurements with this new technique show results which, compared with the calculated forces from ion beam current measurements, indicated that more than the half of the force is caused by fast neutrals in the ion beam due to charge-exchange collisions.

Particles as thermal probes in plasma

Temperature sensitive features of special phosphor particles were utilized for measuring the temperature T_p of micro-particles, confined in the sheath of a rf-plasma [9]. T_p has been determined by evaluation of characteristic fluorescent lines which exhibit a characteristic temperature dependence. The possibility for obtaining the temperature of micro-particles, levitated inside plasma, give access to the energetic conditions at their surface due to the balance of several contributions of energy gain and loss.

The experiments have been performed again in an asymmetric rf plasma (in argon) in front of the AE in the range from *10* to *50 Pa* and *10* to *100 W*. The temperature increase with rising discharge power in argon is found to be more pronounced at low pressures than at higher pressures, see fig.6. Addition of molecular hydrogen gas to the argon plasma results in a further temperature increase due to additional heating of the particles by hydrogen recombination at the particle surface.

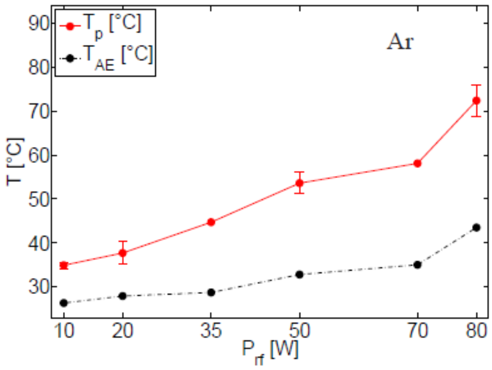

Fig. 6: Particle temperatures as a function of rf-power (solid line) and electrode temperature (dotted line) for a gas pressure of *10 Pa* in argon.

The utilization of charged probe particles in plasma and sheath environments is a promising method for the characterization of electric field structures, forces and energy fluxes. These experiments and models may provide a novel connecting link between sheath diagnostics and plasma–wall interactions.

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