Ion Beam Characterization by Advanced Plasma Diagnostics with Levitated Particles

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Abstract: **The interaction of powder particles, which are confined in the sheath of an asymmetric capacitively coupled rf-plasma, with an external ion beam has been investigated. In contrast to other experiments where particle displacement and oscillations are excited by electric fields or laser radiation, respectively, we excite the particles by additional energetic ions. By this suitable diagnostics, also an optimization and adjustment of ion beam sources for space thrusters can be provided. By observing the position and movement of the particles in dependence on the discharge parameters we obtained information on the electric field ($2.5\times10^{3}\,Vm^{-1}$) in front of the electrode as well as on the ion drag ($1\ldots5\times10^{-14}N$).**

Nomenclature

D = diameter
T_S = surface temperature
t = time
F_g = gravitational force
F_{el} = electric field force
F_n = neutral drag force
F_{ion} = ion drag force
z = vertical distance
m_d = mass of probe particles
r_d = radius of probe particles
n_i = ion plasma density
m_i = ion mass
v_i = ion velocity
j_i = ion flux density
E = electric field strength
V_{beam} = beam voltage
V_{bias} = bias voltage
Q_d = charge of probe particles

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I. Introduction

OPTIMIZATION of thrust and life time of electric propulsion engines is only possible by a validated modeling on the basis of suitable diagnostics. Common methods for plasma and ion beam characterization do not allow measurements of all related physical parameters, for example, it is very complicated to measure the contribution of fast neutrals in the ion beam, the plasma sheath on the screen grid or the ion thrust itself. In order to overcome these problems, we use non-conventional methods for plasma and beam characterization.

For example, the ion beam profile has been visualized by the interaction of the ions with a micro-disperse particle cloud which has been charged and confined in an additional rf-plasma[1,2]. By this method, the thrust effect of the ions (momentum transfer, ion drag) as well as inhomogeneities in the beam can be observed and estimated.

If dust particles are injected into a plasma, they become negatively charged by the currents towards the particles and can be confined in the discharge. The spatial distribution and motion of the dust particles in a low-temperature plasma is a consequence of several forces acting on the particles. Among the different forces the ion drag force is an important issue under investigation.

In order to simulate the ion effect in the experiments the influence of an external ion beam (additional ion drag) supplied by an ECR ion source has been investigated.

The superposition of the electrostatic field force in front of the rf-electrode, the gravity and the ion drag force results in a typical particle arrangement, whereas the effect of the ion beam is threefold:

- change of the sheath structure and the electric field,
- different charging of the dust particles,
- variation of the ion drag force / thrust.

By means of the particle displacement and its evaluation by the force balance it is possible to obtain the ion force acting on micro-sized probe particles in the range of $10^{-15}...10^{-13} N$. Hence, this method can be efficiently used as a novel method for thrust balance in the μN-regime.

II. Experimental

In order to monitor the interaction of confined powder particles with the surrounding plasma and the external ion beam a common asymmetric, capacitively coupled rf-discharge was employed[3]. The experiments have been performed in the reactor *PULVA II*, which is schematically drawn in Fig.1.

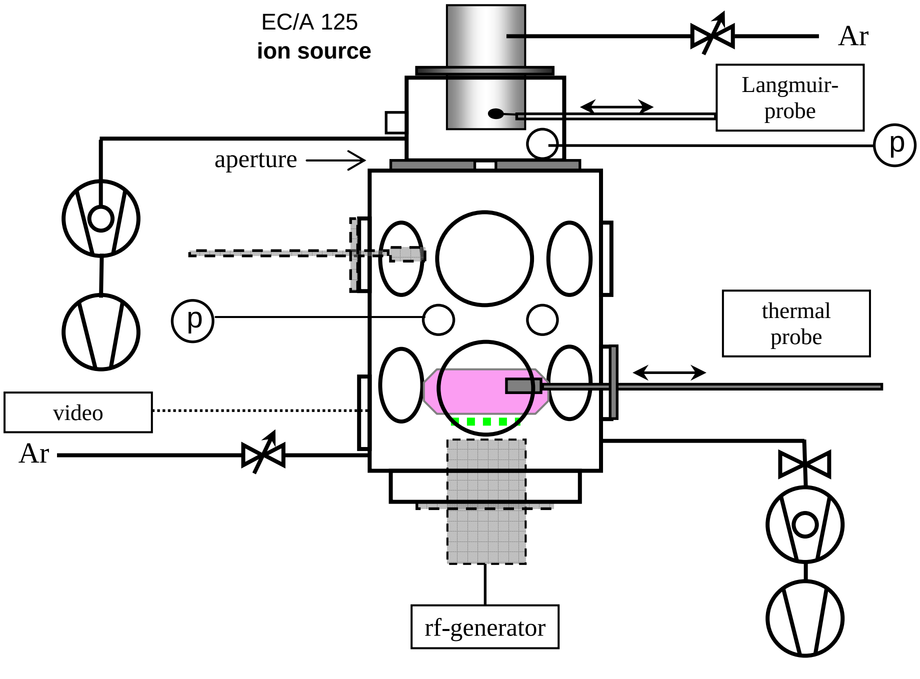

Figure 1. Schematic of the experimental set-up PULVA II

The plasma glow is located in the region between the planar aluminium rf-electrode (*D=130 mm*) and the upper part of the cylindrically shaped reactor vessel (*D=400 mm*), which serves as grounded electrode, see Figure 1. A copper ring was placed on the electrode to confine the injected dust particles (SiO_2, *0,8μm*) by a parabolic potential trap. The *13.56MHz* rf-power (*10W*) is supplied by a generator (Dressler Cesar 1310) in combination with an automatic matching network (Dressler VM700). Depending on the gas pressure the rf-plasma induced a self-bias of *60 … 300V* at the bottom electrode. The turbo-pump which allows for a base pressure of $5\ 10^{-5}Pa$, was connected to the vessel by a butterfly valve; the argon gas pressure was varied between *0.5* and *6Pa* using the valve and a flow controller (MKS).

For the determination of the plasma parameters the experiments were carried out both with and without dust particles as well as with and without ion beam operation. The injected powder particles are charged and confined in the rf- plasma near the sheath edge (~ *10mm*) where they can be observed by light scattering of an illuminating laser fan (*532nm*). A video camera (Nikon FastCam PCI R2) at *125 frames per second* with a filter at the laser wave length was taken to observe the location and movement of the confined particles.

The ion beam source (EC/A 125, IOM Leipzig)[4] is mounted on top of the vessel opposite to the rf-electrode (Figure 2). The power of about *120W* was supplied by a generator (Aalter SM 445) via a microwave antenna. At *87,5mT* and *2.4GHz* the electrons are strongly accelerated by the electron cyclotron resonance and ionize efficiently the argon atoms. The generated ions are extracted by a molybdenum grid system (diameter: *125mm*), and accelerated by the beam voltage which was varied between *400* and *1400V*. The second turbo pump (Leybold) at the ion source allows for base pressure of $10^{-4}Pa$, during ion beam operation the gas pressure was $6\times10^{-2}Pa$ by using another flow controller (MKS). The corresponding gas flow is *8sccm*.

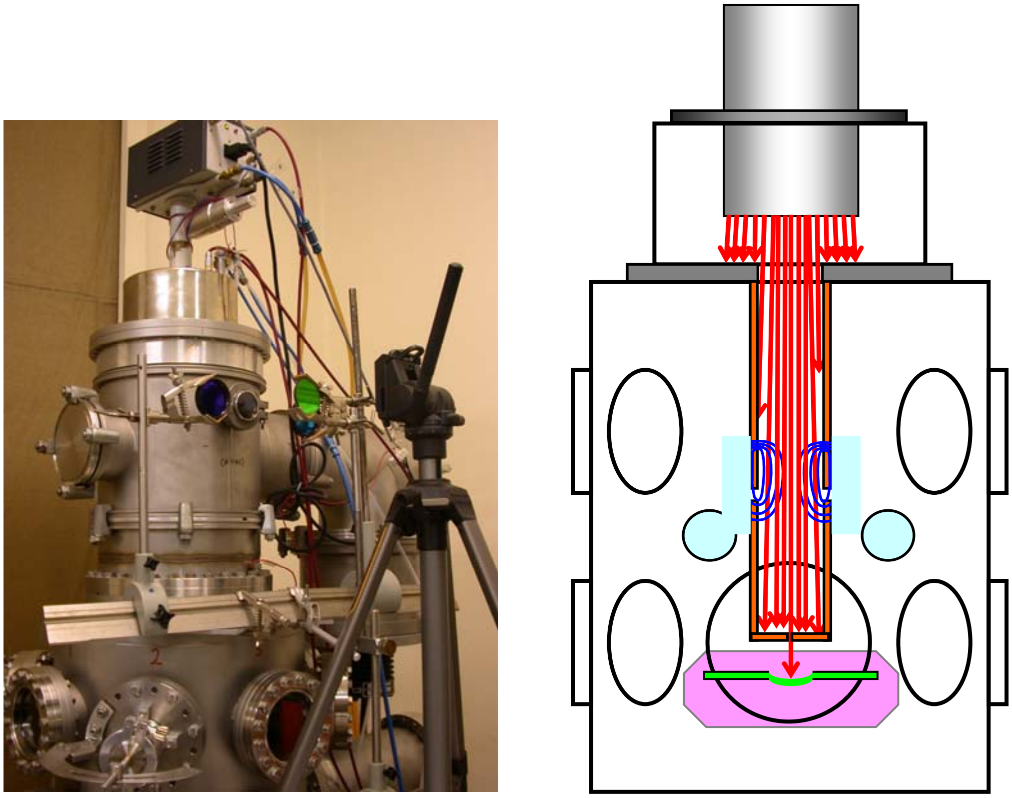

Figure 2. Photograph (left) and schematic (right) of the of reactor chamber. The ion beam source is on top of the vessel and the "beam tube" (red) is shown.

The distance of the levitated particle cloud to the extraction grid system of the ion source was about *640mm*. In order to get a good separation of the ion beam source (at lower pressure) and the plasma-particle interaction region in front of the rf-electrode (at higher pressure), a tube of *75mm* diameter has been used, see Figure 2. At the bottom of the "beam tube" is a hole (*D=5mm*) where the ions leave the tube for interaction with the confined particles. By this method, thermalization of the ions on their way from the extraction grid to the particles can be minimized.

In addition to Langmuir-probe measurements and optical emission spectroscopy[3] the integral energy flux from the ion beam towards the particles was measured by means of a thermal probe which has been described elsewhere[5]. The probe (copper, diameter: *5mm*) is mounted on a manipulator arm to allow for radial scans along the beam diameter below the hole. The heat flux measurements are carried out by monitoring the rate of temperature change dT_S/dt during "beam on" and "beam off". The radial profile of the energy influx (Figure 3) reflects the profile of the escaping ion beam through the hole and its divergence due to the interaction with the rf-plasma at higher pressure. The maximum energy influx of $0.06\ J/cm^2s$ in the centre of the beam corresponds at a beam voltage of *800V* and a pressure of *3Pa* to an ion current density of $75\mu A/cm^2$.

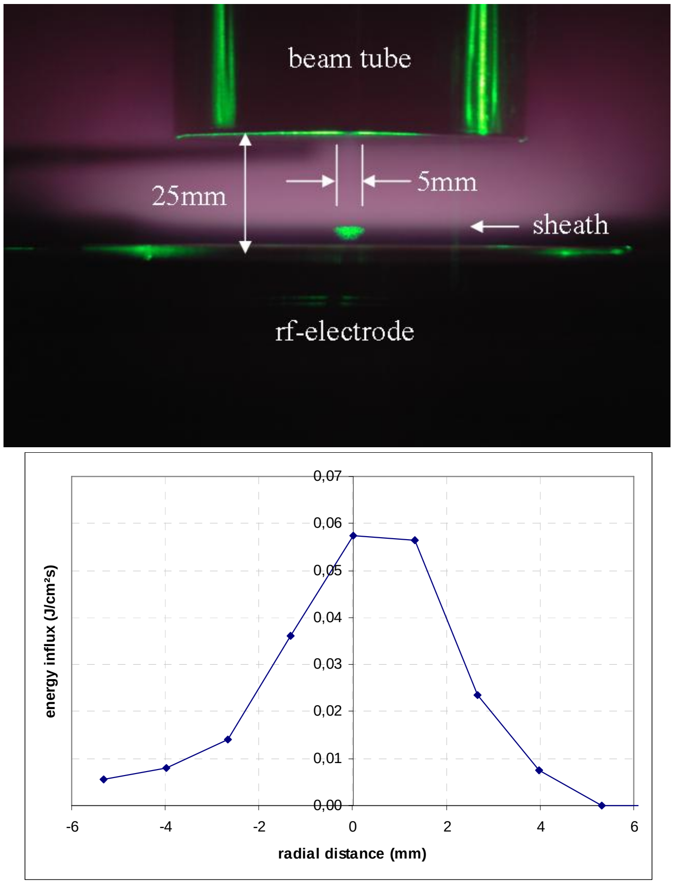

Figure 3. Escaping ion beam through the hole (top) and the measured profile of the energy influx (bottom). The small particle cloud can be recognized underneath the hole.

III. Results and Discussion

The experimental studies have been conducted under static conditions. "Static conditions" means the particle interaction with a constant ion beam. The deformation of a levitated 2D particle dust cloud under broad beam ion operation has already been observed and described elsewhere[1,3,6]. If the beam is switched on, the shape of the particle cloud has been changed in characteristic manner due to inhomogeneities and divergence in the beam. The acting forces onto the particles can easily be seen in Figure 4.

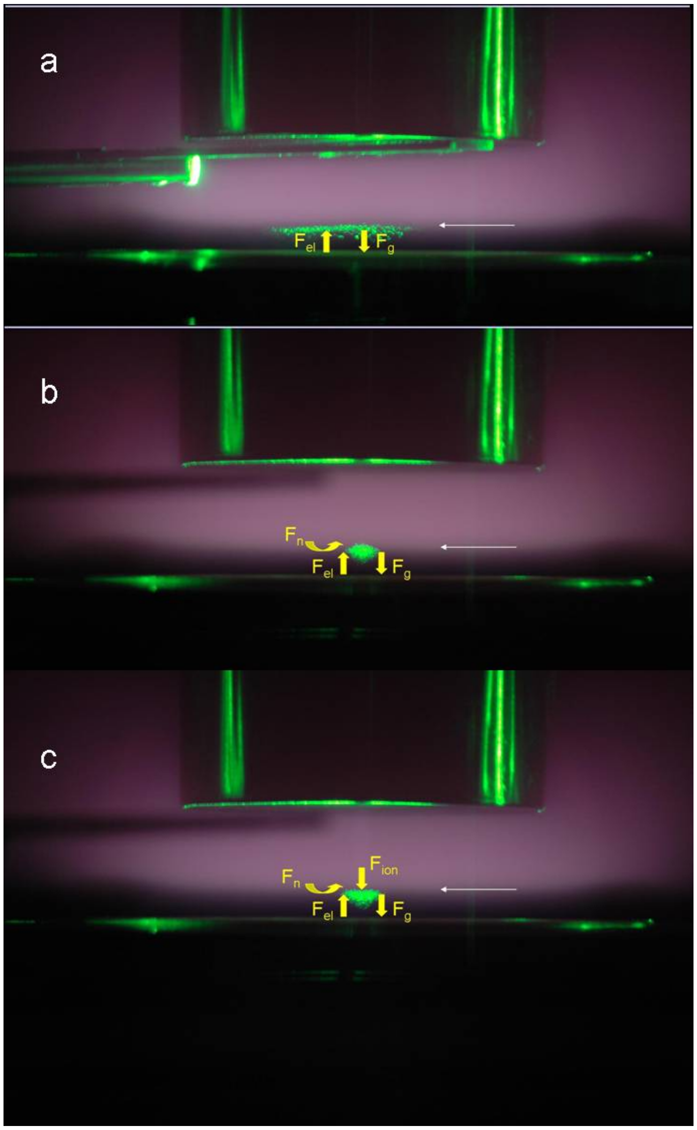

Figure 4. Particle interaction with the plasma and the ion beam at p=3Pa and V_{bias}=146V.
a) hole covered, b) hole open, c) ion beam (V_{beam}=1300V) on.

When the hole of the beam tube is closed by a shutter (Figure 4a), the common situation of complex plasma is realized. The particles are levitated due to the force balance between gravity F_g and electrostatic force F_{el} by the electric field in front of the rf-electrode. If the shutter is removed and, thus, the hole is open there exist a strong pressure gradient between the rf-plasma region (*3Pa*) and the beam region inside the tube (*0.1Pa*). The result is a neutral drag F_n by the gas flow which changes the shape of the originally flat dust cloud into a dome-like structure, see Figure 4b. The additional force F_n acts in radial as well as in vertical direction due to the pressure gradient and the dust cloud structure can be explained by the flow patterns which can easily be simulated. Finally, if the ion beam is switched on the dome is distorted again by the pushing ion drag force F_{ion} (Figure 4c). Since the electric field in the rf-sheath varies strongly with varying distance z from the electrode, the upper layers of the particle cloud are more likely influenced by the ion beam. Therefore, the displacement of the particle dome (e.g. top of the cloud) which looks like an indentation has been taken as measured quality.

For levitated particles of mass m_d and charge Q_d in steady state the force balance in vertical z-direction can be written as:

$$F(z) = F_{el}(z) + F_n(z) - F_g - F_{ion}(z) \approx Q_d(z)E(z) + F_n(z) - m_d g - F_{ion}(z) = 0 \qquad (1)$$

The ion drag force consists of two components: the orbital force and the collection force[7,8]. The orbital force corresponds to the momentum transfer due to Coulomb scattering and the collection force is a consequence of direct collisions between the beam ions and the particle. Since the directed kinetic energy of the supersonic ions is much larger than the potential of the dust particles the particle cross section πr_d^2 can be regarded as collection impact parameter. Then the ion drag force becomes

$$F_{ion} = n_i m_i v_i^2 \pi r_d^2 = \pi r_d^2 j_i \sqrt{\frac{2m_i}{e_0}} \sqrt{V_{beam}} \quad , \qquad (2)$$

where n_i is the density of the ions of mass m_i and directed velocity v_i which can also be written in terms of the ion flux density j_i and the beam voltage V_{beam}. For typical experimental conditions as given above the ion drag force is in the order of $1 \ldots 5 \times 10^{-14} N$, depending on beam voltage.

On the other hand, the ion drag can be estimated from the force balance at levitating position. Supposing that there is only a weak change in the electric field by the relatively low ion beam flux density in front of the rf-electrode and almost no influence on the particle charge during beam operation, the change in the position of the particles can only be caused by the ion drag (thrust). Under these assumptions, the sum of gravitation and ion drag has to compensate the sum for the electrostatic force and vertical neutral drag. The electrostatic force F_{el} is given by the product of the particle charge Q_d times the electric field strength $E(z_0)$ at trapping position z_0. The field is in the order of $2.5 \times 10^3 Vm^{-1}$ and the charge is about $10^3 e_0$ which results in an electrostatic field force of $1 \ldots 10 \times 10^{-14} N$ depending on the levitation height. The gravitational force F_g is for SiO_2 particles ($m_d \sim 6 \times 10^{-16} kg$) in the order of $6 \times 10^{-15} N$, e.g. about 10% of the opposite electrostatic force. Considering the uncertainties in the determination of the particle charge and the field strength the agreement between the estimation by the force balance and the calculation by Eq.(2) is rather satisfactory. The field strength at position $z=z_0$ has been obtained by a linear extrapolation along the sheath in front of the rf-electrode by measuring the bias voltage V_{bias} and the sheath thickness. Obviously, also the particle charge Q_d is during ion beam operation smaller than for the pure rf-plasma. Moreover, the ion drag by the rf-plasma which is certainly small in comparison to the ion beam drag has been neglected.

The displacement of the particles by the ion beam in dependence on the beam voltage is shown in Figure 5.

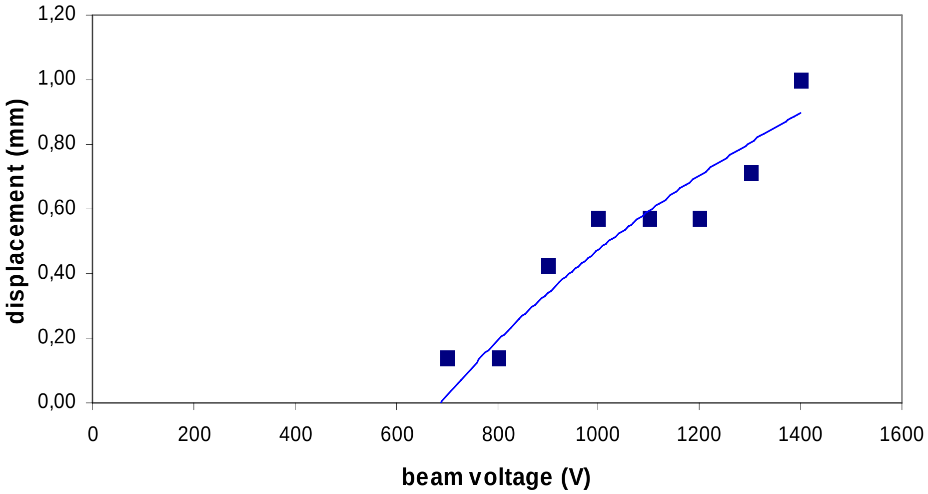

Figure 5. Displacement of the particles from their original position in the sheath of the rf-electrode at ion beam operation (p=4Pa, V_{bias}=100V)).

For small beam voltages ($V_{beam} < 600V$) there is almost no change. When the beam voltage increases, the height of the dust particles decreases. That means the originally dome-like dust cloud forms a more flat shape and moves into the direction of the rf-electrode. For higher beam voltage the ion drag becomes stronger and the particles can deeply penetrate into the sheath and can compensate the influence of the electrostatic field more efficiently.

IV. Conclusion

By the use of micro-sized particle probes, local electric fields and potential distributions in front of electrodes or substrates, respectively, can be visualized. The micro-particles act as a kind of electrostatic probe. Especially, the profile of an external ion beam could be visualized by the interaction of the ions with a confined micro-disperse particle cloud. The displacement of dust particles by the drag force of the additional beam ions has been calculated by the formula for the ion drag as well as by the force balance of the particles. For the used SiO_2 dust grains the obtained value for the ion drag is in the order of $1 \ldots 5 \times 10^{-14} N$ depending on beam voltage. By this experimental method, the thrust effect of the ions (momentum transfer) as well as inhomogeneities in the beam can really be observed and estimated. Hence, measurements of ion-particle interaction in complex plasmas can be used as a tool in development, optimization and diagnostics of ion beam sources for satellite thrusters.

Acknowledgments

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