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Comparison of 2D Plasma Profiles and Particle Distributions in Complex Plasmas under Microgravity

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Abstract

The equilibrium position of dust particles in a gas discharge is studied under varying plasma conditions in the absence of gravity. Two-dimensional plasma parameter profiles, obtained from Langmuir probe measurements and simulations, are used to calculate the expected dust position considering the electric field force and ion drag force. Different models for the ion drag are taken into account for comparison with the observations.

Experiment and Observations

Dust particles immersed in a plasma charge up negatively and therefore experience a number of forces, that determine their motion or equilibrium position. While, in the laboratory, the gravitational forces is normally dominant and confines the particles to the lower boundary of the plasma, under microgravity the effect of more feeble forces becomes evident. An example is the formation of a central dust-free region ("void") that has been observed in experiments and simulations (e.g. [1]). The void is understood as an effect ion drag, exerting an outward directed force on the particles and the electric field force, that confines the negative dust grains in the positive plasma bulk. Here, the variation of the void size under manipulated plasma conditions is studied and compared to calculations based an probe measurements or discharge simulations. The experiments have been performed in the IMPF plasma chamber, developed

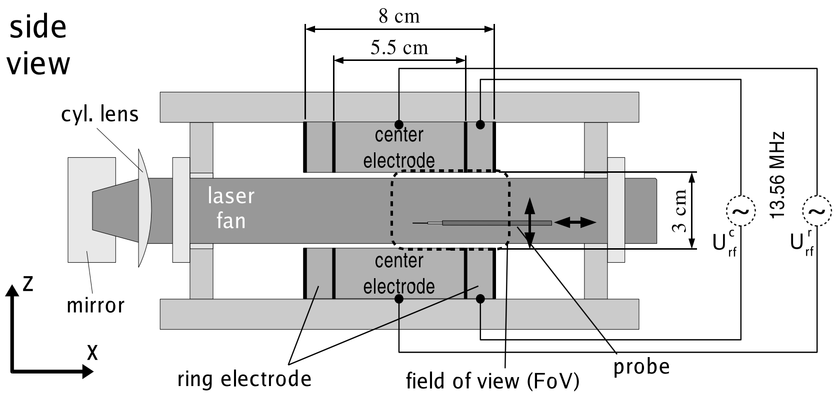

Figure 1: Scheme of the IMPF plasma chamber with the field of view of the camera.

by Kayser-Threde GmbH, Munich and MPE, Garching, which is a preliminary study for the projected IMPACT-experiment on board the ISS. To obtain microgravity, the setup has been flown on parabolic flights. The IMPF chamber is a capacitively coupled rf-discharge vessel with two symmetrical electrodes separated by a gap of 30 mm (Fig. 1). Each electrode consists of a central disk and a surrounding ring electrode. Different rf voltages can be applied between the two center electrodes (c) and ring (r) electrodes. This allows to shape the plasma profile. Typical argon discharge parameters are 15-60 Pa gas pressure and rf voltages $U_{rf}^{c,r}$ of 30 to 100 V_{pp} at 13.56 MHz. The injected dust consists of monodisperse spherical plastic particles with a diameter of 3.4 μm. Trapped particles in the plasma are illuminated by a laser fan and recorded by a CCD video camera. To measure plasma parameter profiles, a Langmuir probe allows to scan a meridional (2D) section of the discharge. Besides the tip of 4 mm length and 25 μm radius, the probe design includes a large area reference electrode for passive rf compensation. Simulations of the discharge have been performed with SIGLO [2], a three-moment fluid code.

The left column of Fig. 2 presents a series of dust arrangements under microgravity while the ring electrode voltage U_{rf}^{r} is increased from 27 to 69 V_{pp}. Obviously, a thin layer of particles clearly visualizes the boundary of the void, that begins to appear. Assuming that the influence of the small amount of injected dust is negligible, the simulations and plasmas scanned by the probe do not contain particles. It is seen from Fig. 2, that the corresponding plasma density profiles tend to elongate horizontally with increasing U_{rf}^{r}. The probe measurements show an earlier constriction of the profile from a convex to a hollow shape (row (b)) than visible in the simulations (row (d)). Comparing profiles and dust arrangement, the particles seem to be balanced at an equilibrium position that closely follows a contour line of the plasma profile. Further enhancement of U_{rf}^{r} leads to the transformation of the dust arrangement from the oblate spheroid to a toroid (see Fig. 2(e)).

Force Model and Discussion

In order to prove the dominance of electric field force ($\vec{F}_E$) and ion drag force ($\vec{F}_i$) as driving mechanism of the void formation, the experimental and simulated potential, electron temperature and density profiles served as input for the calculation of the confining potential for dust particles. The field force is obtained directly from the plasma potential and the particle charge that is derived from the OML model. Two ion drag model have been accounted for: the formula from Barnes *et al.* [3] and the recent model of Khrapak *et al.* [4]. With the Barnes model a Coulomb cut-off radius on the order of the electron Debye length has to be used to estimate the outward driving drag force in order to create a void [5]. The calculations yield a 2D-profile with residual absolute force $|\vec{F}_E - \vec{F}_i|$ on the particles for each combination of driving voltages. Figure 3 shows the radial position of the minimum residual force deduced from the numerical models in comparison with the video observation of the particle equilibrium position. Obviously, the linear increase of the radial void size as function of U_{rf}^{r} is reproduced by both ion drag models calculated on plasma simulations or probe measurements. While the

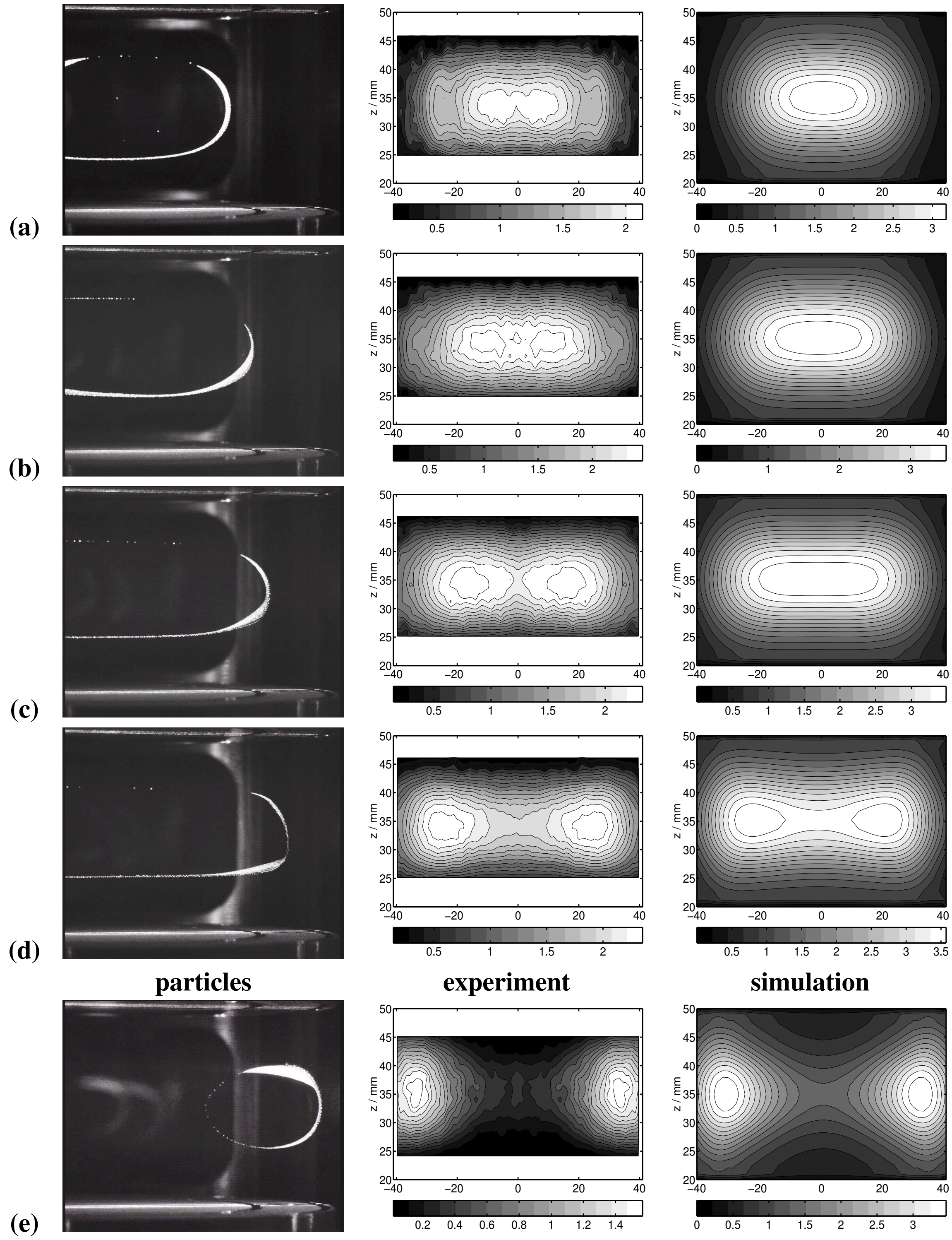

Figure 2: Modification of the density profile and dust arrangement by variation of the rf voltages applied to center/ring electrodes: (a) 50/27 V_{pp}, (b) 54/40 V_{pp}, (c) 55/54 V_{pp}, (d) 56/69 V_{pp}, (e) 41/88 V_{pp}. The left column shows the resulting growth of the void by frames of the observation camera (compare with Fig. 1), the second column provides the corresponding density profiles from probe measurements in a dust-free laboratory plasma, the right column contains the appropriate profiles from simulations for the inter-electrode space of the IMPF-chamber. Plasma densities are normalized by a factor $10^{14}\mathrm{m}^{-3}$, argon pressure is 15 Pa. Video frame (e) shows one poloidal cross section of a dust torus, that is formed under the given conditions.

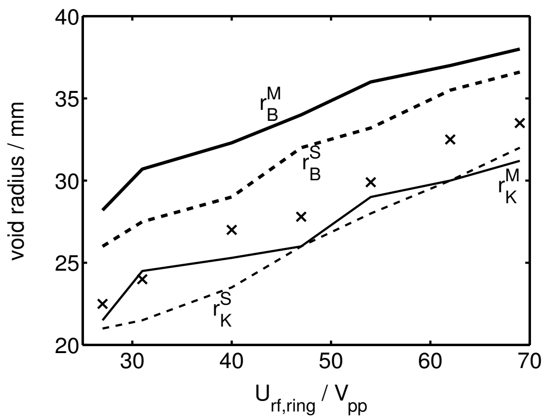

Figure 3: Radial extent of the void as function of the ring electrode voltage U_{rf}^{r}. Crosses mark the observed particle positions, $r_{B,K}^{M}$ are calculated equilibrium positions from probe measurements, using the Barnes formula and Khrapak's model respectively. $r_{B,K}^{S}$ are derived from simulated plasma parameter profiles.

drag force after [4] slightly underestimates the equilibrium position, results from the Barnes model exceed the observations by 4-7 mm. The source of the plasma parameter profiles (simulated or measured) shows less influence on the results and thus demonstrates the consistency of simulations and Langmuir probe measurements.

Thus, probe scans are a useful method to estimate, in advance, the particle motion in complex plasmas and therefore facilitate, for example, the design of microgravity experiments.

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