31st EPS Conference on Plasma Phys. London, 28 June - 2 July 2004 ECA Vol.**28G**, O-4.12 (2004)

Three-dimensional dust clouds in a capacitively coupled rf-discharge

O. Arp[1], D. Block[1], A. Piel[1], and A. Melzer[2]

1. *Institut für Experimentelle und Angewandte Physik, Christian-Albrechts-Universität Kiel, Germany*

2. *Institut für Physik, Ernst-Moritz-Arndt-Universität Greifswald, Germany*

For a system consisting of particles with charge *Ze* the Coulomb interaction and the thermal energy of the particle have severe influence on the overall system. If the interaction energy of neighbouring particles at a distance *b* is larger than their thermal energy, i.e.

$$\Gamma = \frac{Z^2 e^2}{4\pi \epsilon_0 b k T} \gg 1 \qquad (1)$$

matter is said to be strongly coupled. In such systems order phenomena and dynamic properties differ from weakly coupled systems. An example of a strongly coupled system are plasma crystals. If micrometer sized particles are immersed into a plasma enviroment they are immediately charged up to several thousand elementary charges and, even at room temperature Γ can become much larger than unity. Usually, because of gravity, the heavy dust particles sediment to the bottom of the plasma near the electrode, where they are levitated in the electric field of the plasma sheath. Several experiments have shown that the dust particles can form two-dimensional crystalline systems [1], which can be investigated by means of simple video microscopy, e.g., with respect to phase transitions [2], fluid motions [3], and a variety of wave phenomena [4]. Therefore, these investigations have proven that plasma crystals are a convinient and powerful model system to study strong coupling effects.

However, the electric fields near the electrode have severe implications on the crystal structure. First, gravitation limits the formation of three dimensional plasma crystals to the rather small sheath region and second, the strong electric field causes a directed ion flow which results in an anisotropic, aligned crystal order [5,6]. Attempts to overcome this limitation, e.g., by using thermophoretic forces [7] or by microgravity conditions [8], were hampered by the appearance of dust-free regions (voids). In the following we present first experimental results on void-free 'Coulomb balls'. We show that it is possible to create spherical particle clouds with homogeneous particle density under laboratory conditions.

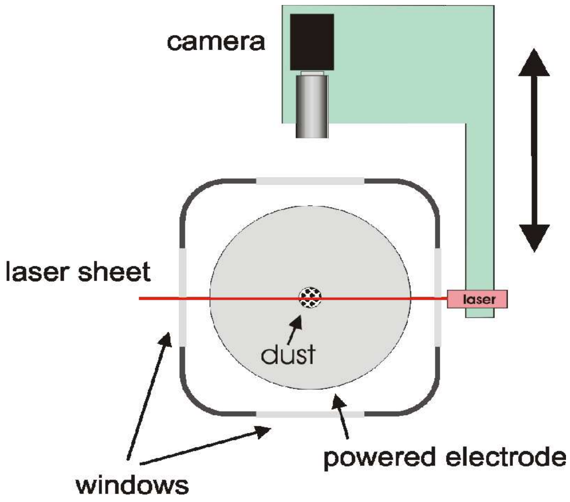

FIG. 1: Experimental setup to obtain 3D particle position. The camera is focused to the plane of the vertically oriented laser fan. Both are mounted on a common positioning system to allow for axial scans.

The experiments are performed in a capacitively coupled parallel plate discharge at 13.56 MHz. For gas pressure (argon) of (50 -150) Pa and discharge voltages (40 – 60) V_{pp} it is possible to create Coulomb balls. With respect to the standard setup for 2D plasma crystal generation [6], some modifications are applied. First, the lower electrode is heated to (30 – 80) °C. This causes a thermophoretic force, which is directed towards the upper electrode and provides an improved levitation of the dust particles. The maximum temperature is carefully choosen to avoid the onset of neutral gas convection. Second, a short glass tube with square cross section is inserted into the discharge. In this way the discharge is operated with a higher plasma density in the outer zone. Hence, compared to the standard setup, the direction of the ion drag force is reversed and confines the dust in the center of the discharge. Finally, the diagnostics with standard video microscopy is modified to measure the 3D particle positions. For this purpose a vertical laser fan is used to illuminate a thin cross section of the dust cloud. The thickness of this illuminated layer is about 500 μm. Further the laser system and the camera are mounted on a translational stage to perform axial scans with a resolution of 10 μm (Fig. 1). Typical images of a dust cloud are shown in Fig. 2. In the first image (Fig. 2a), the laser fan just touches the front of the dust cloud, while for the subsequent images the cross section is moved with 880μm steps towards the back of the dust cloud. Already in Fig. 2a and Fig. 2f it is seen that the surface of the dust cloud is in a well ordered state. In both cases the central particle has six nearest neighbours. In Fig. 2c and Fig. 2d, the almost spherical shape of the particle cloud becomes visible. Further, the particles do not arrange in vertical chains as they do in the sheath region. Rather they seem to form nested shells. To analyse this in more detail, Fig. 3 shows the radial particle distribution with respect to the

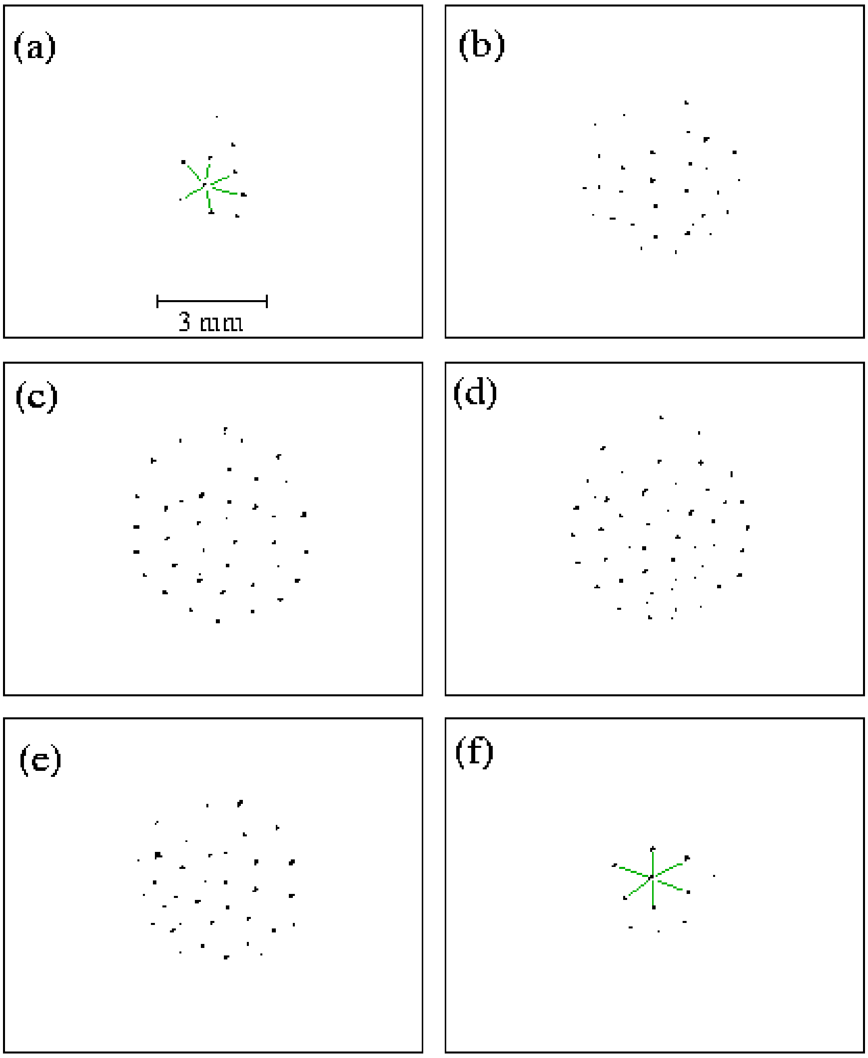

FIG. 2: Series of inverted images of vertical cross sections through the dust cloud. All pictures use the same scaling denoted in (a). The axial distance between subsequent images is about 880µm.

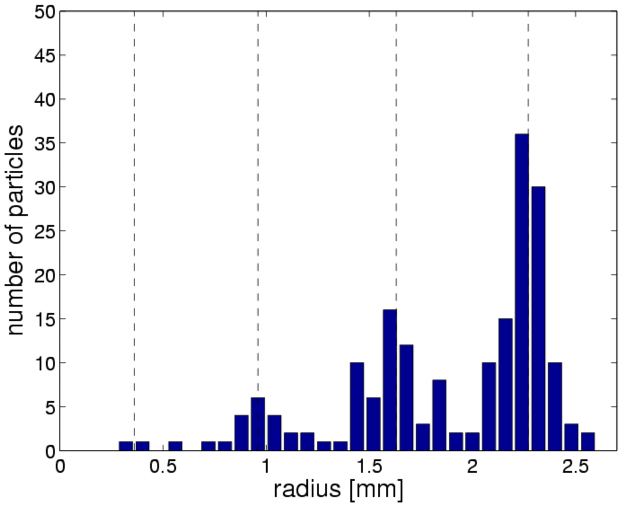

FIG. 3: Radial particle distribution of a dust cloud containing 190 particles. The peaks indicate a concentric shell structure. The dashed lines indicate the average shell radii.

center of the dust cloud. We find that the dust cloud consists of four shells with occupation numbers 2, 21, 60, and 107. This has to be compared with molecular dynamics simulation of Coulomb clusters [9]. Hasse et al. give the occupation number for a 192 particle cluster as 1, 18, 59 and 114, which is in good agreement with our experiments. For the distance between shells we measure about 630 μm. If this is compared to the typical nearest neighbour distance of 715 μm again a good agreement is found with the simulation results.

To conclude, we have shown that it is possible to create void-free three dimensional dust clouds in a capacitively coupled discharge. Within these dust clouds the particles arrange in nested shells and indications for hexagonal ordering within shells are found. Further analysis is needed to reveal the full shell structure and to demonstrate that the dust cloud is in a crystalline state.

[1] J.H. Chu and L. I, Physica A **205**, 183 (1994); H. Thomas *et al.*, Phys. Rev. Lett. **73**, 652 (1994); Y. Hayashi and K. Tachibana, Jpn. J. Appl. Phys. **33**, l804 (1994).

[2] A. Melzer, A. Homann, and A. Piel, Phys. Rev. E **53**,2757 (1996); H. Thomas and G.E. Morfill, Nature **379**, 806 (1996).

[3] L. I, W.-T. Juan, C.-H. Chiang, and J.H. Chu, Science **272**, 1626 (1996)

[4] A. Piel and A. Melzer, Plasma Phys. Control. Fusion **44,**R1 (2002)

[5] N. Nambu, S.V. Vladimirov, and P.K. Shukla, Phys. Lett. A **203**, 40 (1995)

[6] A. Melzer *et al.,* Phys. Rev. E **54**, R46 (1996)

[7] H. Rothermel *et al.*, Phys. Rev. Lett. **89**, 175001 (2002)

[8] G.E. Morfill *et al.*, Phys. Rev. Lett. **83**, 1598 (1999)

[9] R.W. Hasse, Phys. Rev A **44**, 4506 (1991)