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THREE-DIMENSIONAL STRUCTURE OF DUST CLOUDS AND WAVE FRONTS IN AN ANODIC PLASMA

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Dust density waves [1] are naturally excited modes in current carrying dusty plasmas [2]. The wave fronts appear as bright regions in scattered laser light. Because of their low frequency (15-40 Hz) these modes are ideally suited for studies with digital video cameras. The dispersion relation of these modes for dust trapped in an anodic plasma was studied before and compared with a fluid model [3] and kinetic theory [4]. While the earlier investigations were made in dust clouds that were larger than 3-4 wavelengths, which justifies the assumption of nealy plane waves and the comparison with models for a homogeneous and infinitely large system, the present investigation is concerned with the quantitative measurement of the wavefronts in smaller systems.

The experiments were performed in the magnetized radio-frequency discharge described in [4]. The argon plasma ($p = 2$ Pa) has a density $n_e \approx 10^{15}\mathrm{m}^{-3}$, and electron temperature $T_e = 3$ eV. In the magnetic field ($B = 20$ mT) the electrons are magnetized and the ions unmagnetized. The different Hall parameters are responsible for the formation of a radial electric field that provides dust confinement. The anodic plasmas forms in front of a small disk electrode of 30 mm diameter that is held at a high positive potential of $60 \ldots 75$ V (see Fig. 1). A cloud with an ellipsoidal shape containing spherical melamine particles of $(0.97 \pm 0.05)\mu$m diameter is trapped inside the anodic plasma. Its axial confinement is a balance of the ion drag force and the axial electric field force [4]. The dust particles are observed with the combination of a horizontal sheet of laser light ($\lambda = 532$ nm, 200 mW) and a fast CCD video camera with 640×480 pixel and up to 150 frames per second. The camera and laser sheet can be moved vertically to record the particle motion in a series of horizontal slices.

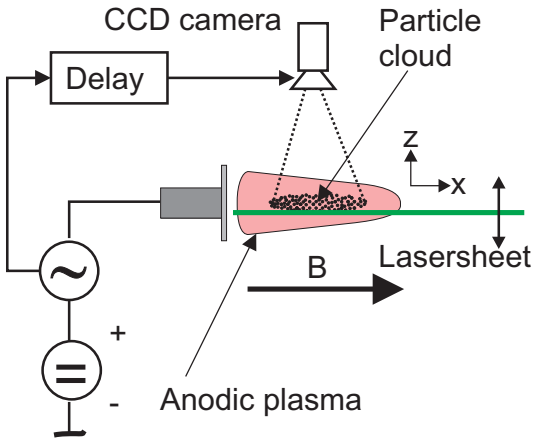

Figure 1: Experimental arrangement. The waves are observed with a fast video camera and a horizontal laser sheet.

Dust density waves are excited by the axial ion flow through the dust cloud. The frequency

of these waves can be locked by a sinusoidal modulation of the anode voltage [3, 4]. In the first set of experiments, the shutter of the video camera is triggered synchronously with the modulation voltage. This produces a series of stroboscopic images at the same phase of the wave. By averaging over 100 samples we obtain the dust density distribution in the wave from the intensity of the scattered light. Fig. 2 shows a series of horizontal sections at various vertical positions $z = (-3 \ldots -9)$ mm. $z = 0$ mm corresponds to the center of the anode disk. The wave frequency is $f = 25$ Hz.

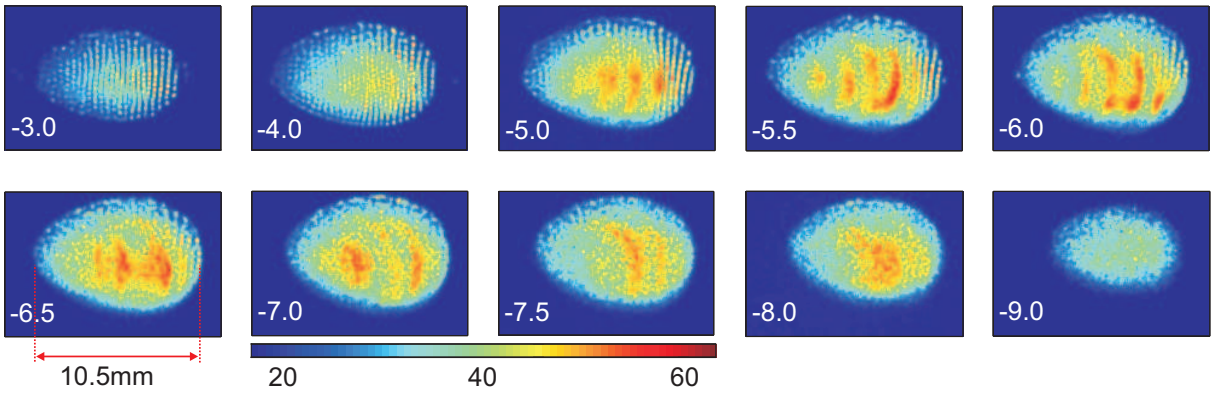

Figure 2: A series of horizontal sections obtained by the stroboscopic recording of the dust density fluctuations in the wave.

Obviously a dust cloud of 10.5 mm length and 7.3 mm diameter is trapped in the lower half of the anode disk, where a stronger radial electric field exists. The top of the dust cloud ($z = -3$ mm) shows that the dust particles are arranged in a set of parallel stripes. These stripes are perpendicular to the magnetic field direction and apparently the stripes do not move in axial direction, which can be seen from the sharp image in the average over 4 s. In transverse direction the image is slightly blurred but still individual particles can be recognized. The distance of the stripes is the same as the interparticle distance d. In a hexagonal lattice the distance would be $0.86d$. This crystalline order gradually disappears when we compare with sections taken at lower positions (see Fig. 4).

The dust density waves can be seen as strong periodic density modulations in the regime $z = -5 \ldots -8$ mm. By changing the trigger delay we have verified that the waves move from left to right, i.e. in the direction of the axial ion flow away from the anode disc. The wave fronts are curved and apparently emanate from a point-like source at the left side of the dust cloud. The wave amplitude increases during propagation but is already saturated in the center of the cloud. The wave amplitude falls to zero at the right edge of the cloud.

The stroboscopic method has the disadvantage that wave fronts can only be seen in terms of the wave crests. A more refined analysis can be made from long movies of the density wave in the case that wave frequency and frame rate of the camera are incommensurate. For this purpose we have recorded a movie with 8192 frames at 473 frames per second. A FFT-analysis of the intensity fluctuations in a cluster of 21×21 pixels in the center of the cloud shows that the spectrum has only sharp lines at 25 Hz and its harmonics. The fundamental has an intensity that is 20 dB higher than the incoherent background. Hence the wave is highly coherent. Therefore, we can determine the complex wavefunction $C(x,y) + \mathrm{i}S(x,y)$ by projecting the intensity distribution $B_i(x,y)$ in the frames $i = 0 \ldots N-1$ on the dominant Fourier component at the fundamental frequency $\omega_0/2\pi = 25$ Hz.

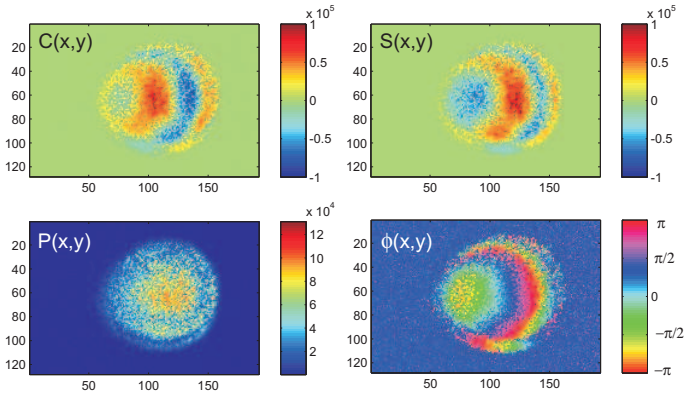

Figure 3: Complex wave function, wave energy density and phase evolution. The axis labels give x and y-coordinates in pixels.

$$C(x,y) = \frac{1}{N}\sum_{i=0}^{N-1} B_i(x,y)\cos\omega_0 t \quad ; \quad S(x,y) = \frac{1}{N}\sum_{i=0}^{N-1} B_i(x,y)\sin\omega_0 t \tag{1}$$

From the complex wave amplitude we immediately obtain the distribution of the wave phase $\varphi(x,y) = \arctan[S(x,y)/C(x,y)]$ and wave amplitude $P(x,y) = [S(x,y)^2 + C(x,y)^2]^{1/2}$. These four quantities are compiled in Fig. 3. The wave function confirms the result of the stroboscopic measurement in Fig. 2 that the wave fronts are curved. This curvature and the origin of the wave from a spot on the left hand side of the dust cloud become even more evident in the phase distribution. The wave amplitude decreases towards the edge of the dust cloud. This decrease is counterintuitive because, at first glance, the boundary of the dust cloud could be considered as a free moving surface. Then, waves at the open end of a transmission line should be reflected with the same sign and the amplitude should attain twice the value which it has inside the waveguide. Here, the decrease of the wave amplitude at the boundary hints at reflection with the opposite phase, like in a shortcircuited transmission line. However, we find no evidence for standing waves, which would be expected as the eigenmodes of the spheroidal dust cloud. The obvious dominance of the forward travelling wave can be understood by the ion streaming instability that excites the wave. The wave propagating in the direction of the ion flow is amplified whereas the reflected wave is damped by friction

with the background gas. A tentative explanation for the curved wavefronts and the point-like origin of the waves could be the periodic modulation of the ion current. Ions are produced in the anodic plasma and impinge on the dust cloud, thereby depositing their momentum by Coulomb scattering on the dust particles preferentially within the first few crystal layers. Different from larger dust clouds, which are in a liquid state [4], the smaller dust clouds are crystalline in the upper half, as can be seen from the column (along y) averaged intensity distribution (averaged over 100 frames) for the top layer at $z = -3$ mm and the bottom layer at $z = -9$ mm. The parallel crystal layers become quite evident from the modulation in the plane $z = -3$ mm whereas the structure disappers at $z = -9$ mm. The observed parallel layers that are perpendicular to the magnetic field direction are quite different from the nested spherical shells which are typical of Yukawa balls [5]. The present investigation has further shown that dust density waves can be excited by ion flows even in the solid phase as discussed theoretically by Rosenberg et al. [6] with respect to the coupling of longitudinal and transverse phonons excited by an ion beam.

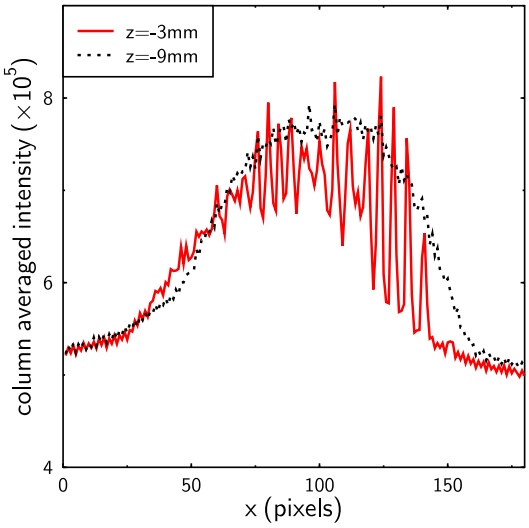

Figure 4: The crystalline structure becomes evident from the modulation of the column averaged intensity, which is pronounced at $z = -3$ mm and disappears at $z = -9$ mm.

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