Frequency clustering in self-excited dust density waves under microgravity conditions

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Self-excited dust density waves (DDWs) are well known from many different types of gas discharges, e.g. [1, 2, 3]. They emerge spontaneously at low gas pressures and high dust densities [1] and are driven by a Buneman-like instability between the dust particles and flowing ions [4]. In recent experiments under microgravity conditions [7] complicated three-dimensional wave patterns were observed with phase defects and spatially varying wavelength. It was found that the propagation of the wave is strongly affected by the local plasma properties [3, 5], which significantly vary over the extension of the dust cloud. The high modulation depth with narrow high-density wave crests but broad wave troughs that contain almost no dust particles, leads to a strong non-sinusoidal shape of the wave. Other experiments show that the DDW significantly affects the plasma glow and consequently the plasma properties [6]. These observations lead to the conclusion that self-excited dust density waves are not small disturbances of a dusty plasma that can be treated by simple linear models. Rather we expect that nonlinear effects play a significant role in the dynamics of the observed waves. In this contribution we investigate nonlinear synchronization phenomena in extended three-dimensional dust clouds under microgravity conditions.

The experiments were performed on parabolic flights in the IMPF-K2 device. The chamber is mostly identical to the device described in Ref. [3] except for the simplified electrode setup which we used here [Fig. 1(a)]. It is a symmetric parallel plate rf discharge with circular electrodes of 8 cm diameter which form a gap of 3 cm. The discharge was operated in push-pull mode with an rf voltage of $U_{\mathrm{rf}} = 48$ V$_{\mathrm{pp}}$ at 13.56 MHz. The self-bias was suppressed by means of shunt resistors. We used argon as working gas at a pressure of 15 Pa and injected monodisperse spherical melamine-formaldehyde (MF) particles of (9.55 ± 0.13) μm diameter into the discharge. A thin vertical section through the center of the dust cloud was illuminated by a laser sheet. A digital CCD camera observed the scattered laser light from the dust particles at right angle. It was equipped with a narrow bandwidth interference filter matching the wavelength of the illumination laser in order to suppress the plasma glow. The camera field of view (FoV) is marked by a rectangle in Fig. 1(a) and measured (47.4×21.6) mm^2 in the plane of the laser sheet. The camera was operated at a frame rate of 100 frames per second and had a spatial resolution of 910×400 pixel inside the FoV.

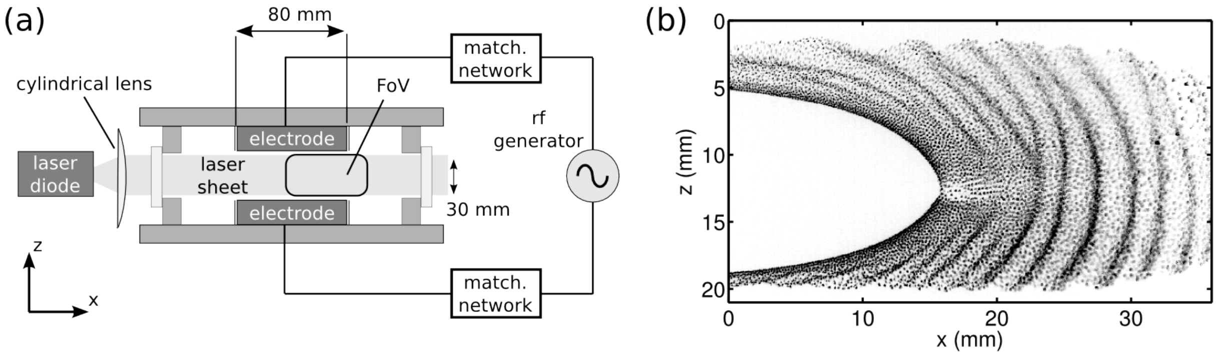

Figure 1: (a) Schematic vertical section through the IMPF-K2 chamber. (b) Snapshot of the dust cloud. Self-excited dust density waves are propagating from the void edge outwards.

A typical snapshot of the dust cloud is shown in Fig. 1(b). Dust density waves appear spontaneously at the chosen discharge parameters and propagate with phase velocities of $v_{\mathrm{ph}} = (10-30)$ mm s^{-1} from the boundary of the central dust-free "void" region outwards. The waves are seen as a clearly modulated dust density in the snapshot. The wavelength is not constant, but increases from a typical value of $\lambda_{\mathrm{DDW}} \approx 1.5$ mm close to the void up to $\lambda_{\mathrm{DDW}} \approx 3$ mm in the outer regions of the dust cloud. Obviously, the waves deviate from a sinusoidal shape and phase defects are present, i.e., wave fronts merge or split on their way to the periphery of the cloud.

To analyze the temporal evolution of the wave field, in a first step, we blurred the video frames by means of a Gaussian filter, which yields a measure of the local dust density. In a second step, we applied a Hilbert transform to the intensity time series at each pixel coordinate (x,z) to derive the instantaneous phase $\phi(x,z,t)$ of the wave at time t. Finally, we obtain the spatial frequency distribution inside the wave field by averaging the time derivative of the instantaneous phase $f(x,z) =< d\phi(x,z,t)/dt >_t$ over an interval of approximately 10 wave periods. A more detailed description of this method is described in Ref. [12]. The resulting frequency map of the wave field is shown in Fig. 2. Accordingly, the frequency is not constant in the entire cloud, but decreases from $f \approx 8$ Hz at the void edge to $f \approx 5$ Hz at the periphery of the could. Further, the frequency varies not continuously but in discrete steps, which results in distinct regions, so-called clusters, of almost constant frequency. For the three marked clusters, i.e., positions marked 1 to 3, we find the corresponding average frequencies as $f_1 = 7.6$ Hz, $f_2 = 6.5$ Hz, and $f_3 = 5.7$ Hz. The positions where phase defects appear in the recorded video are marked by small black circles in Fig. 2. Their positions were derived from the instantaneous phase as described in Ref. [7]. Obviously, defects appear exclusively at the boundary between two frequency clusters, but never inside a cluster. The large number of defects close to the void are due to irregular wave motion in that region.

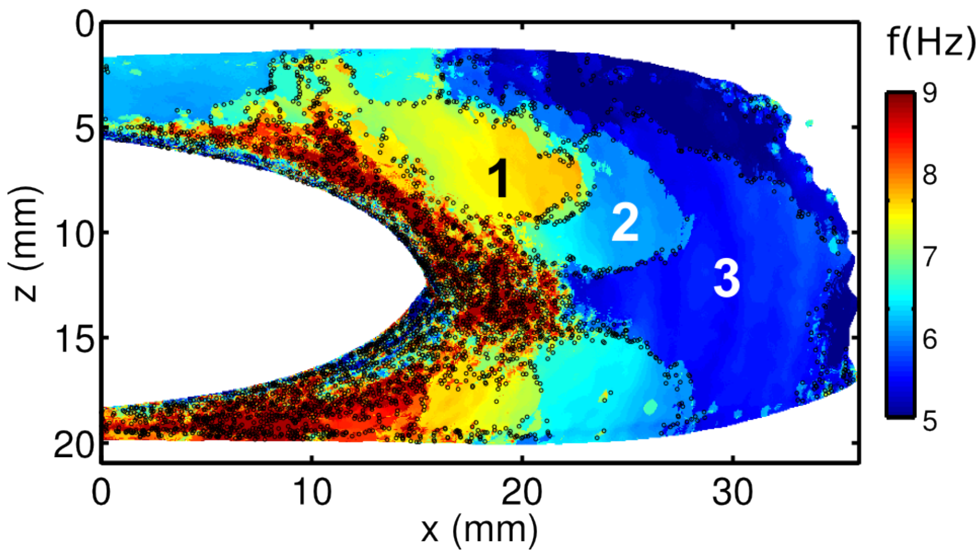

Figure 2: Frequency distribution inside the wave field. Phase defects are marked by small black circles.

The formation of frequency clusters becomes even more pronounced in the spatial distribution of the standard deviation of the frequency [see Fig. 3] within a 5×5 pixel vicinity of each coordinate. Accordingly, the frequency variation inside the individual frequency clusters is almost zero, whereas the cluster boundaries are very sharply marked by a strongly increased value of the standard deviation.

The observed formation of frequency clusters is unexpected in the context of waves in dusty plasmas. However, frequency clusters are known from various calculations and numerical simulations of extended systems of coupled non-linear oscillators, e.g., Refs. [8, 9, 10, 11]. Accordingly, frequency clusters appear, if the natural frequency of the individual oscillators varies in space. The coupled oscillators are able to synchronize with their neighbors within a certain proximity. In such systems the cluster size increases with the coupling strength and the degree of nonlinearity, but decreases with the gradient of the natural frequencies. A more detailed analysis of our data [12] reveals the same dependence for frequency clusters in dusty plasmas.

Consequently, our experiment suggests an alternative interpretation of the nature of self-excited dust density waves: We consider a dusty plasmas as a system of nonlinear self-sustained oscillators, whose natural frequencies are defined by the local plasma parameters, i.e., electron and ion densities, as well as by the particle properties, i.e., its mass and size. Due to gradients in the plasma parameters, the natural frequencies of the individual oscillators vary in space. The coupling between the oscillators leads to a synchronization with neighbors, which results in the observed formation of frequency clusters. We note, that the mentioned theoretical models assume diffusive coupling, i.e., symmetric nearest neighbor coupling, between the individual

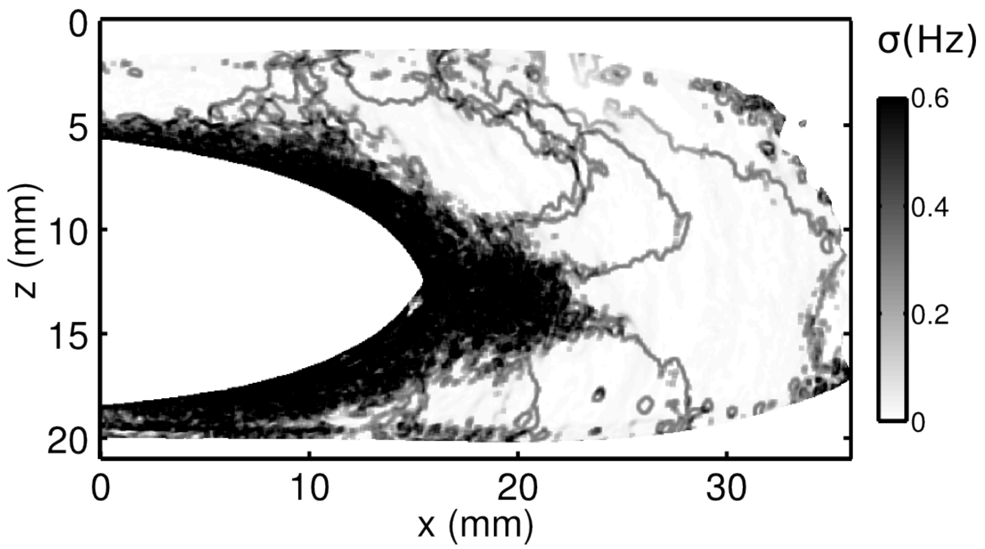

Figure 3: Map of the standard deviation of the wave frequency.

oscillators. This assumption may not be valid in a dusty plasma, where, e.g., quickly streaming ions can cause a non-isotropic interaction between the particles. A systematic study of different coupling types on the formation of frequency clusters is still lacking. Further experiments and calculations are planned to investigate the phenomenon of frequency clustering in dusty plasmas in more detail.

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