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SYNCHRONIZATION OF DUST DENSITY WAVES IN ANODIC PLASMAS

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It is well known that self-excited dust density waves [1, 2] in current carrying dusty plasmas can apparently be "synchronized" by an external periodic modulation of the discharge voltage [3]. This method was used to measure the dispersion relation of the dust-density wave [3, 4]. However, little is known about the detailed mechanism behind the synchronization. The present investigation is concerned with the response of the dust cloud to modulation of the discharge voltage over a wide frequency range.

Our experiments were performed in the magnetized radio-frequency discharge described in [4]. The argon plasma ($p = 2$ Pa) has a density $n_e \approx 10^{15}$ 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 radial dust confinement. The anodic plasma forms in front of a small disk electrode of 30 mm diameter that is held at a high positive potential of 60...75 V. Figure 1(a) shows the potential contours measured with an emissive probe [4]. A cloud with an ellipsoidal shape containing spherical melamine particles (0.97 ± 0.05 μm diameter) is trapped inside this anodic plasma. The axial confinement is a balance of the ion drag force F_{ion} and the axial electric field force F_C, which form an effective potential that traps the dust as shown in Fig. 1(b). The hatching marks the region in which dust can be trapped, which agrees with the position and width of the dust cloud.

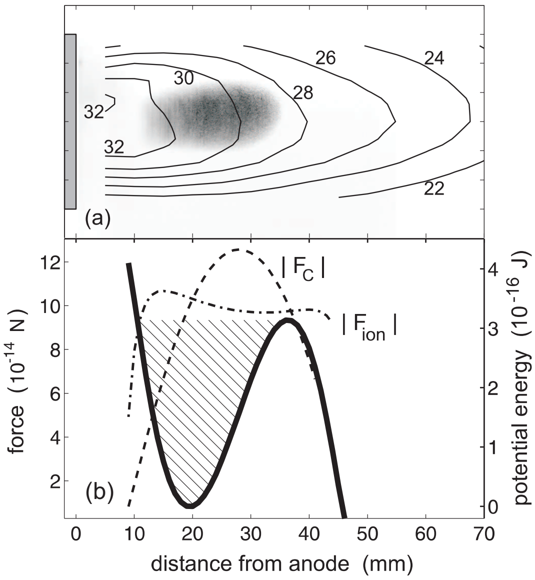

Figure 1: (a) Dust cloud and electric potential contours in a horizontal section, (b) effective potential well formed by ion drag and electric field force.

The dust particles are observed with the combination of a horizontal sheet of laser light ($\lambda = 532$ nm, 200 mW), positioned in the midplane of the dust cloud, and a fast CCD video camera. Self-excited waves are only found in dust clouds, which exceed a minimum size of ≈ 5 mm. These self-excited waves have frequencies of $f = (25 \ldots 30)$ Hz and can be stimulated by modulating the anode bias with external frequencies f_{mod}.

Our first series of investigations was focused on the response of stable small dust clouds to external modulation in the frequency range (1 – 20) Hz. We find that, at low frequencies, the dust cloud performs a sloshing and stretching motion (Fig. 2), which is analyzed in the following way: The dust density information is obtained from the intensity distribution $B_{ij}(t)$ of scattered laser light in each frame of the video recording after subtracting the signal background in a dark frame. Herefrom we deduce the "center of mass" position in each frame

$$x_{c.o.m.}(t) = \frac{1}{B_{tot}(t)} \sum_{i=0}^{N-1} \sum_{j=0}^{M-1} j B_{ij}(t) \ , \qquad (1)$$

where $B_{tot}(t) = \sum_i \sum_j B_{ij}(t)$ is the total intensity in that frame.

The x-direction corresponds to the magnetic field direction. The stretching of the dust cloud is obtained by calculating the second moment of the intensity distribution

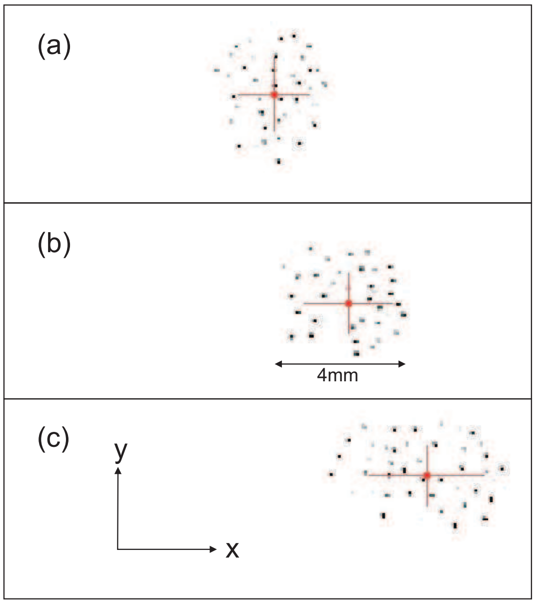

Figure 2: Sloshing and stretching of the dust cloud at low modulation frequency $f_{mod} = 4$ Hz. ($U_a = 70$ V, $U_{mod} = 10$ V$_{pp}$). (a) left turning point, (b) equilibrium position, (c) right turning point.

$$d_x^2 = \frac{1}{B_{tot}(t)} \sum_{i=0}^{N-1} \sum_{j=0}^{M-1} [j - x_{c.o.m.}(t)]^2 B_{ij}(t) \ . \qquad (2)$$

The sloshing amplitude in x-direction is dependent on the applied frequency (full circles) in Fig. 3). The c.o.m. motion at the lowest frequency ($f_{mod} = 1$ Hz) is representative for the static shift of the dust cloud's equilibrium position with applied anode bias U_a. With increasing frequency, the sloshing amplitude becomes larger and attains a maximum at 4 Hz. For even larger frequencies, the sloshing amplitude decreases rapidly. The sloshing motion has obviously a resonant response to the external modulation. A similar behavior with a resonance at the same frequency is found for the stretching of the dust cloud (circles in Fig. 3). In summary, we understand the combined sloshing and stretching as the motion of the dust fluid in an asymmetric potential well whose x-position changes according to the applied modulation.

For small dust clouds no self-excited waves are found in the investigated frequency range (1–60) Hz. Nor does the external modulation excite any propagating density waves, which should become visible in the range $f_{mod} > 20$ Hz, where the sloshing and stretching motion disappears.

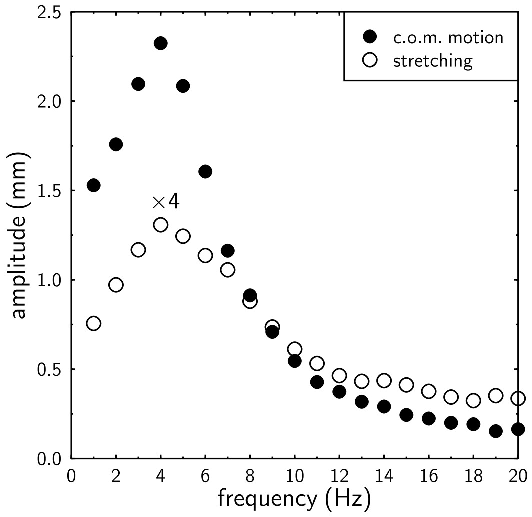

Figure 3: Response of the dust cloud to external modulation.

The self-excited dust density waves found in larger dust clouds represent a spatially amplifying plasma medium. When self-excited waves in such a system are stimulated by an external signal at a different but close-by frequency, the situation resembles the phenomenon of injection locking of lasers [6]. Injection locking can be described by a periodically driven van der Pol-oscillator. This model was also successfully used to describe the spatio-temporal synchronization of plasma waves, e.g., in neon-gas discharges [7] or drift waves [8].

First we have studied the system response in the vicinity of the naturally excited modes by choosing the modulation frequency in the range $f_{mod} = (15 \ldots 40)$ Hz. Surprisingly, in the entire range, the system response was found as a monochromatic wave at the modulation frequency f_{mod} and its harmonics (see Fig. 4). For a van der Pol-system we would have expected the transition from a quasiperiodic state with the two independent frequencies $f \neq f_{mod}$ to a phase-locked state with $f = f_{mod}$. In other experiments, the phase-locking range had a typical width $2\Delta f_{mod}/f < 0.2$ [9]. Here, the single-frequency response is found over a very much wider frequency range, which sheds doubt on the concept of synchronization in a van der Pol scenario for this system. Rather, the actual system behavior bears similarities with the case of injection seeding, where a seed wave with an amplitude above the noise level sets the proper initial conditions for the wave that subsequently wins the competition with all other noise-excited modes.

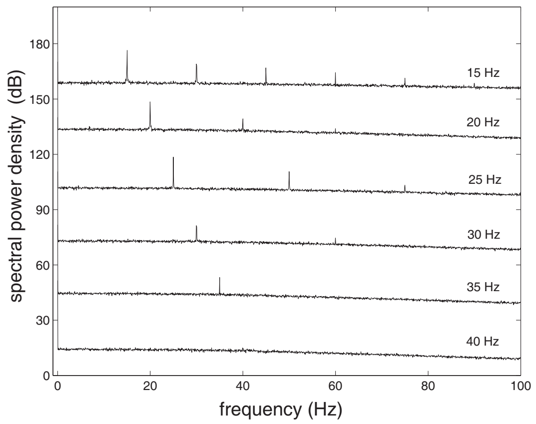

Figure 4: Frequency spectra of the excited waves.

In a second step, we have investigated the system response when the modulation frequency is chosen close to the first harmonic of the naturally excited modes, $f_{mod} \approx 2f$. In this situation we expected superharmonic synchronization, as observed in [9]. For this purpose the wave is recorded by triggering the camera shutter synchronously at $f_{mod}/2$. In this way an entrained wave would give a system of standing phase fronts. An independent mode appears at the beat frequency $f - f_{mod}/2$.

The response of the system, however, did not show any clear entrainment of the natural mode to the modulation signal. A spectral analysis of the beat spectrum (see Fig. 5) shows that it is determined by the natural mode as seen from the reference frame of the modulation signal. A monochromatic natural mode at exactly $f = 29$ Hz would follow the dashed line. The dominant peak in each beat spectrum (full circles) obviously follows this expectation. However, the beat spectrum is more complex with additional peaks (open circles). In summary, the observed waves resemble the phenomenon of injection seeding of pulse lasers, which also do not show the van der Pol behavior found in injection locking of cw lasers.

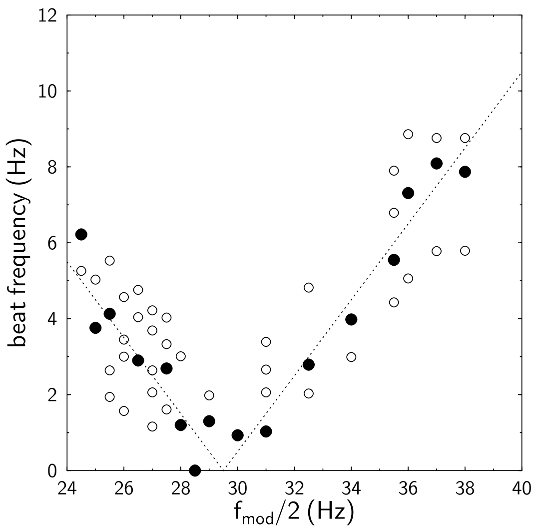

Figure 5: Measured beat spectrum as a function of modulation frequency.

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