Out-of-plane mode in 2D complex plasma crystals

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Introduction

In 2D complex plasmas, two in-plane wave modes can be sustained. In crystals, both modes have an acoustic dispersion, one of them is longitudinal, another is transverse. Since the strength of the vertical confinement in such systems is finite, there is a third fundamental wave mode associated with the out-of- plane oscillations. Theory predicts that this mode has a negative (or inverse) optical dispersion [1]. In the presence of strong flow of the ambient plasma the screening cloud around each charged particle becomes highly asymmetric. These "plasma wakes" play the role of an (external) "third body" in the interparticle interaction and hence make it non-reciprocal. It affects dust-lattice (DL) modes and the resonance between DL wave modes can trigger the mode-coupling instability which, in turn, can cause the crystal melting [1, 2].

Experimental set-up

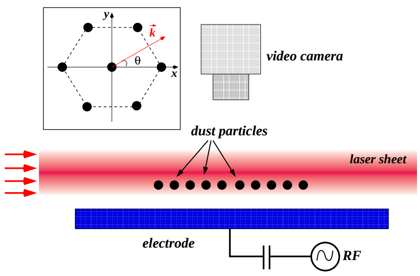

Figure 1: Sketch of the experimental set-up. Microparticles are confined above the rf electrode and are illuminated with a horizontal laser sheet having a Gaussian profile in the vertical direction. The monolayer is levitated well below the peak of the laser intensity. Inset shows elementary cell of the hexagonal lattice and the frame of reference chosen in this paper, the orientation of the wave vector **k** is measured in respect to the x axis.

We used a capacitively coupled RF glow discharge at 13.56 MHz (Fig. 1). The argon pressure p was between 0.5 Pa and 1 Pa and the RF peak-to-peak voltage was between 175 V and 310 V (which corresponds to a forward RF power P between 5 W and 20 W). The self-bias voltage was between -60 V and -130 V. The plasma parameters in the bulk discharge were electron temperature $T_e = 2.5$ eV and electron density $n_e = 2 \times 10^9$ cm^{-3} at p =0.66 Pa and

P=20 W. A 2D particle suspension was formed by levitating melamine formaldehyde microspheres in the sheath above the RF electrode. The particles had a diameter of 8.77 ± 0.14 μm or 9.15 ± 0.14 μm. The diameter of the obtained crystalline structure was about 50–60 mm, depending on the number of injected particles. The microparticles were illuminated by a horizontal laser sheet which had a Gaussian profile in the vertical direction with a standard deviation $\sigma \simeq 75$ μm. The sheet thickness was approximately constant across the whole crystal. The particles were imaged through a window at the top of the chamber by a CCD camera at a speed of 250 frames per second. The horizontal coordinates x and y as well as velocity components v_x and v_y of individual particles were then extracted with sub-pixel resolution in each frame. An additional side-view camera was used to verify that our experiments were carried out with a single layer of particles. In order to extract the vertical position z and velocity v_z of individual particles, we needed to employ a very different technique. The position of the laser sheet intensity maximum was set about 100 μm above the levitation height and then the vertical displacement was deduced from the relative variation of the scattered light intensity [3].

Results

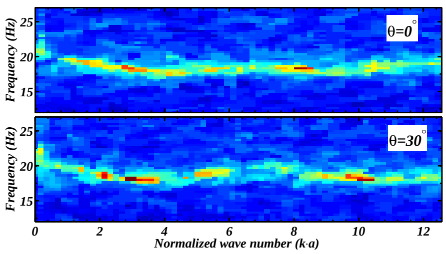

Figure 2: Fluctuation spectra of the naturally excited out-of- plane DL waves in a 2D crystal. The fluctuation amplitude is color coded linearly, from dark blue (10^{-3} a.u.) to dark red (1 a.u.), revealing the optical dispersion of the mode. The results are for a pressure of 0.8 Pa and rf power of 15 W with particles of 8.77 μm diameter. The wave vector $\mathbf{k}$ pointed along the principal lattice axes, $\theta = 0^\circ$ (upper panel) and $\theta = 30^\circ$ (lower panel) (see Fig. 1). The wave number is normalized by the inverse lattice constant a^{-1}.

By performing the Fourier transform in time and space of the determined particle velocities, the dispersion relations $f(\mathbf{k})$ (both in-plane and out-of-plane) can then be obtained for a 2D crystal. The resulting fluctuation spectra of the out-of-plane waves are shown in Fig. 2 for two principal orientations of the wave vector, at $\theta = 0^\circ$ and 30°. The spectra represent the wave energy distribution in the $(f, \mathbf{k})$ space, so that the "ridge" of this distribution yields the wave dispersion relation. The most conspicuous feature of the measurements is the optical character of the dispersion relation. Moreover, the dispersion at long wavelengths is negative, i.e., the wave frequency falls off as the wave number increases. At larger $|\mathbf{k}|$, the wave dispersion is different for $\theta = 0^\circ$ and 30°. Figure 2 shows that the wave frequency as the function of the wave vector $\mathbf{k}$ changes in a narrow interval. Our method also allowed us to measure all three wave modes of a 2D plasma crystal in a single experimental run. In Fig. 3 we show the fluctuation spectra of out-of-plane and in-plane wave modes.

The non-reciprocity of pair interaction in complex plasmas provides a very efficient mechanism of converting the energy of the flowing ions into the kinetic energy of microparticles. Ivlev and Morfill [4] suggested that the resonance between DL wave modes in a 2D plasma crystal can trigger the *mode-coupling instability* which, in turn, can cause the crystal melting.

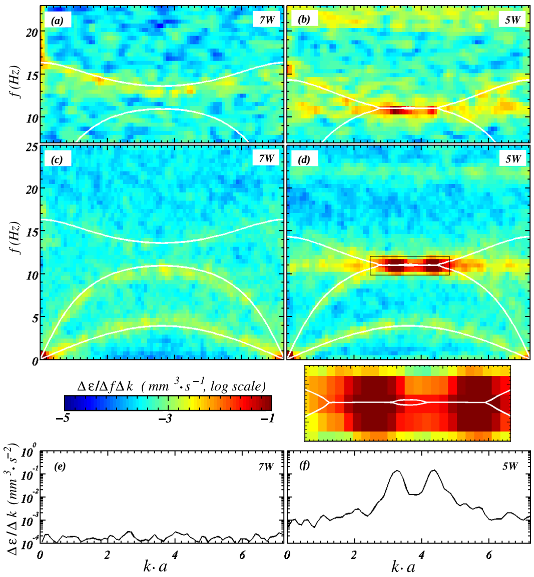

Figure 3: Evolution of the DL dispersion relations near the instability onset (argon pressure of 0.76 Pa with particles of 9.19 μm diameter, at a rf power of 7 W (left column, stable regime) and 5 W (right column, instability onset)). The logarithmic color coding is used for the "fluctuation intensity" $\Delta\varepsilon/\Delta k\Delta f$ (energy density, for unit mass, per unit wave number and frequency); (a) and (b): out-of-plane mode; (c) and (d): pair of in-plane modes. The solid lines are theoretical results [1]. The wave number k is normalized by the inverse interparticle distance a^{-1} (first two Brillouin zones at $\theta = 30^\circ$). Below the fluctuation spectra the magnified hybrid mode in the unstable regime is shown. (e) and (f): distribution of the "fluctuation energy" $\Delta\varepsilon/\Delta k$ at fixed frequency (stable case $f = 12.5$ Hz; instability onset $f = 11$ Hz)

The melting was thus systematically investigated in experiments. One of two different discharge parameters was used as the control parameter for the melting: We gradually decreased the rf power at a constant gas pressure (which lowers the resonance frequency of the vertical confinement), or we decreased the pressure at a constant rf power (which naturally lowers neutral gas friction, but also makes the radial confinement stronger). In Fig. 3, the fluctuation spectra for 2 different powers is plotted (out-of-plane mode (a) and (b) are separate from those for the in-plane modes (c) and (d)), due to different background intensities introduced by the imaging method [3]). As regards the theoretical curves, in each panel we plotted all principle modes that fit the frequency range shown. Fig. 3 summarizes results of our analysis. In the stable regime (left column) the wave modes are well separated and the fluctuation intensity is evenly distributed over the branches. In contrast, the unstable regime (right column) is characterised by the apparent intersection between the out-of-plane and (one of) in-plane branches. The intersection occurs in the vicinity of the first Brillouin zone boundary, resulting in the anomalous energy release (dark-red “hot spots”). For comparison with the experiments we employed the theoretical results for 2D crystals [1]. The theoretical branches are shown in Fig. 3 by solid lines (upper curve: optical out-of-plane mode, the middle and lower curves: acoustic in-plane modes). These curves were calculated for a normalized dipole moment of the wake $\tilde{q}\tilde{\delta}$ (see Ref. [1]) equal to 0.1. We assumed the Yukawa interparticle interaction, with parameters (particle charge and screening length) deduced from the low-k part of in-plane fluctuation spectra. Fig. 3 shows that the theory yields excellent agreement with the experiment, both for the stable and unstable regimes. In the unstable regime (right column) the predicted unstable hybrid mode perfectly coincides with the locations of “hot spots” in the measured fluctuation spectra.

Conclusion

Spectra of phonons with out-of-plane polarisation were studied experimentally in a 2D plasma crystal [3]. The dispersion relation was directly measured for the first time using a novel method of particle imaging that allowed us to resolve the particle motion in 3D. The out-of-plane mode was proven to have negative optical dispersion at small wave number. Comparison with theory showed good agreement. We also observed experimentally the coupling between the out-of-plane mode and one of the in-plane modes predicted by theory [1], which under certain conditions can form hybridised modes and trigger an instability [2].

References

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