

LASER-EXCITED WAVES IN A PLASMA CRYSTAL

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Plasma crystals can serve as powerful model systems for the investigation of strongly coupled plasmas as well as for solid-liquid phase transitions. They consist of micrometer sized particles which are usually trapped in the sheath of rf discharges where the electric field in the sheath balances the weight of the particles. Due to the collection of electrons and ions, the particles have a negative charge Z of several thousand elementary charges. By means of their mutual Coulomb repulsion these dust particles can form regular lattices of hexagonal order [1, 2, 3], the so called plasma crystal. The dust particles are strongly coupled, i.e the coupling parameter $\Gamma = Z^2 e^2 / (4\pi\epsilon_0 b k T_d) \gg 1$ which means that the electrostatic interaction of neighboring particles (with distance b) by far exceeds their thermal energy $k T_d$. The presence of ions and electrons in the rf sheath reduces the particle–particle interaction due to shielding. Simulations show that, in a multilayer crystal, the shielding properties are anisotropic in the vertical direction due to the ion flow in the sheath [4, 5, 6], but rather isotropic in the horizontal plane.

The excitation of waves in these crystals is a very useful method to determine the shielding properties of plasma crystals. To exclude complications from the vertical anisotropy, here only single layer crystals will be studied. Hence it can be assumed that the particles interact by a Debye-Hückel potential

$$\phi(r) = \frac{Ze}{4\pi\epsilon_0 r} \exp(-\kappa r/b) \quad \kappa = b/\lambda_D \quad (1)$$

where λ_D is the Debye length and κ denotes the screening strength.

In literature there exist two possible types of waves in plasma crystals: the dust lattice wave (DLW) and the dust acoustic wave (DAW). In the dust lattice wave the dust particles directly interact by means of their shielded Coulomb repulsion. The dispersion relation $\omega(q)$ for a linear chain of dust particles was discussed in [7]. The extension to the 2D case including friction (with the Epstein friction constant ν) is given in [8]:

$$\omega^2 + i\nu\omega = 4 \sum_{m=1}^{N_m} \sum_{n=-N_n}^{N_n} \frac{k_{mn}^{00}}{m_d} \sin^2 \left(\frac{q x_0^{mn}}{2} \right) \quad (2)$$

with

$$k_{mn}^{jl} = \frac{Z^2 e^2}{4\pi\epsilon_0 r^5} \exp \left(-\kappa \frac{r}{b} \right) \left[(x_0^{jl} - x_0^{mn})^2 \left(3 + 3\kappa \frac{r}{b} + \left(\kappa \frac{r}{b} \right)^2 \right) - r^2 \left(1 + \kappa \frac{r}{b} \right) \right] \quad (3)$$

The waves propagate in the x -direction. This dispersion can then be calculated for a given crystal structure where the particle mn is located at (x_0^{mn}, y_0^{mn}) and r denotes the distance between particle jl and mn . The linear chain result is recovered for $N_n = 0$.

The DAW is the analog to the ion acoustic wave where the pressure is provided by ions and electrons and the inertia by the dust particles here. The dispersion relation including friction

then reads [9, 10]

$$\omega^2 + i\nu\omega = \frac{\omega_{\text{pd}}^2 q^2 b^2}{\kappa^2 + q^2 b^2} \quad (4)$$

with $\omega_{\text{pd}}^2 = Z^2 e^2 n_d / (\epsilon_0 m_d)$ denoting the dust plasma frequency where n_d, m_d are the dust density and mass, respectively. For both dispersion relations (DLW and DAW) one should keep in mind that for a driven system ω is real and $q = q_r + iq_i$ has to be taken as complex.

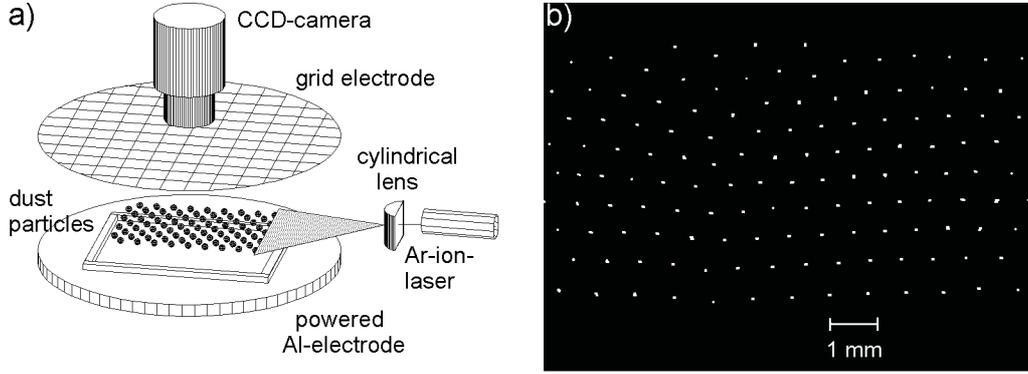


Figure 1. a) Scheme of the experimental setup for the laser excitation of waves in the plasma crystal. b) Top view of the single layer plasma crystal.

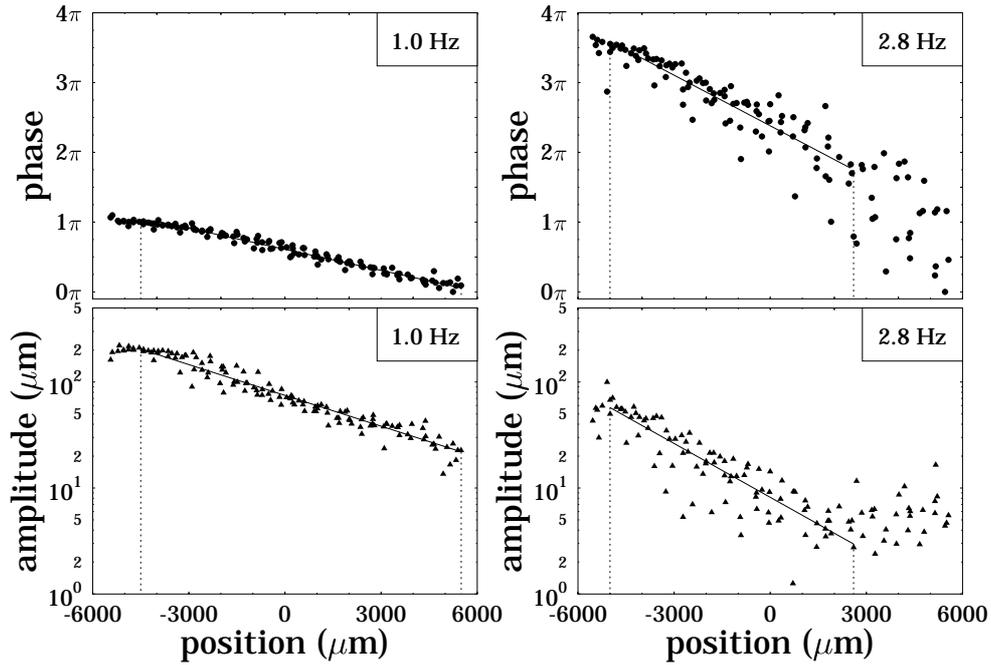


Figure 2. Phases and amplitudes of the particle oscillations as a function of position in the crystal for an excitation frequency of 1.0 Hz and 2.8 Hz at a gas pressure of 27 Pa.

The experiments are performed in a parallel plate rf discharge at 13.56 MHz operated in helium [see Fig. 1a)]. The discharge pressure is controlled in the range between 10 and 50 Pa and the discharge power is around 10 W. 150 to 160 monodisperse melamine formaldehyde particles of $9.4 \mu\text{m}$ in diameter are trapped in the sheath of the discharge. A rectangular barrier of 35 mm width and 60 mm length is placed onto the electrode for horizontal confinement of the particles.

The particles form there a single layer crystal of hexagonal order with an interparticle distance of $b = 740 \mu\text{m}$ [Fig. 1b)]. The particles are illuminated by a horizontally expanded laser fan (40 mW at 690 nm). The scattered light is recorded from top with a CCD camera and stored in a computer for further processing.

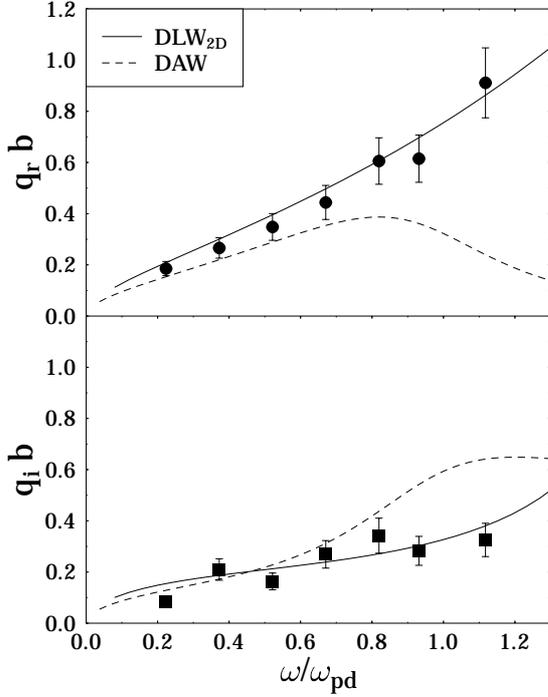


Figure 3. Real and imaginary part of the dispersion relation at a pressure of 31 Pa. Symbols: experimental values, solid line: best fit for the DLW, dashed line: best fit for the DAW.

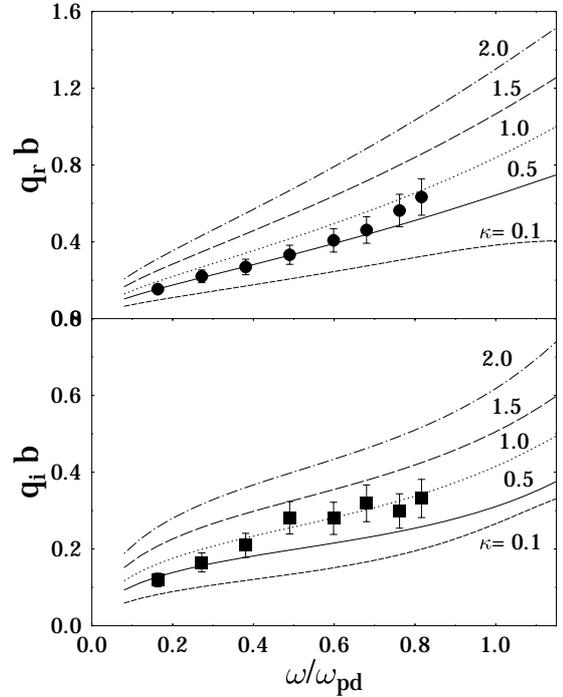


Figure 4. Real and imaginary part of the dispersion relation at a pressure of 27 Pa and theoretical DLW dispersions for different values of κ .

The excitation of waves is achieved by use of an argon ion laser (8 W at 514 nm) in order to minimize the disturbance of the rf sheath environment. The laser beam is expanded by a cylindrical lens in order to hit the plasma crystal in its full width [see Fig. 1a)]. The laser beam is chopped at frequencies below 10 Hz. The radiation pressure of the laser beam pushes the particles into the crystal and the particles relaxate into their equilibrium positions when the laser is blocked. Thus a wave in the plasma crystal is launched.

For analysis, the particles' positions are followed from one video frame to the next. Each particles motion is then seperated into the time averaged crystal position and the oscillatory motion about this equilibrium. Fourier decomposition of these oscillations yield their amplitude and phase. Fig. 2 shows these values for each particle as a function of the x -position in the crystal for two different frequencies. From the linear slope of the phases the wavelength, and thus q_r , is determined. The damping length (inversely proportional to q_i) is obtained from an exponential fit to the amplitudes.

Determining in this way the real and imaginary parts of the wave vector for several frequencies, the dispersion relation of the plasma crystal waves is measured (see Fig. 3). One can see a linear increase of q_r at lower excitation frequencies ($\omega < 0.6\omega_{pd}$) and a stronger

increase at higher ones. The damping length is almost constant over frequency. The measured dispersion is then compared to those of a DLW and a DAW. For that purpose, the dust charge was determined independently from the resonance technique [3, 11] to be $Z = 11\,000$. The friction constant ν and the screening strength κ were then used to fit the real and imaginary part of the theoretical dispersions simultaneously to the experimental data. As shown in Fig. 3 the best fit of a DLW is in close agreement with the experimental data. The friction constant is then found to be $\nu = 11\text{ s}^{-1}$, which agrees well with the Epstein friction for that pressure. The best fit reveals a screening strength of $\kappa = 0.8$.

Even the best fit of a DAW, however, shows strong deviations from the data points. The best fit is obtained also for $\nu = 11\text{ s}^{-1}$ and $\kappa = 0.5$, which is a little smaller than that determined from the DLW. The low frequency part ($\omega < 0.6\omega_{\text{pd}}$) is well represented, but at higher frequencies the DAW shows a roll over to long wavelengths which is in contrast to the experimental data. When fitting all parameters of a DAW (Z, ν, κ) the best fit also shows quite good agreement with the measured points, but the fitted charge is far beyond the experimental value [8].

Having identified the plasma crystal waves as a DLW it is now possible to give detailed values for the screening strength. Fig. 4 shows the data points and the theoretical DLW for different values of κ . One can see that good agreement between theory and experiment is found for a screening strength in the range $\kappa = 0.5 \dots 1.5$ for the imaginary part and $\kappa = 0.5 \dots 1.0$ for the real part of the wave vector. The best fit gives $\kappa = 0.8$. Thus a screening strength of $\kappa = 0.8 \pm 0.4$ is determined from the measured dispersion. The screening length λ_{D} is therefore of the order of the interparticle distance b . This screening length is in quantitative agreement with the Debye length of energetic ions in the rf sheath [8].

Summarizing, we have presented experiments on waves in plasma crystals. The laser radiation allows for a controllable excitation of waves and does not disturb the sheath environment. The dispersion of waves in plasma crystals has been measured up to frequencies close to the dust plasma frequency. The dust lattice wave model is in good agreement with the measured dispersion relation whereas dust acoustic waves show strong deviations. From the fit of a DLW to the experimental data the screening length was determined to be of the order of the interparticle distance. This shielding length can be attributed to energetic ions in the sheath.

References

- [1] J.H. Chu and L. I: Phys. Rev. Lett. **72**, 4009 (1994)
- [2] H. Thomas et al.: Phys. Rev. Lett. **73**, 652 (1994)
- [3] A. Melzer, T. Trottenberg, and A. Piel: Phys. Lett. A **191**, 301 (1994)
- [4] F. Melandsø and J. Goree: Phys. Rev. E **52**, 5312 (1995)
- [5] A. Melzer et al.: Phys. Rev. E **54**, 46 (1996)
- [6] V. A. Schweigert et al.: Phys. Rev. E **54**, 4155 (1996)
- [7] F. Melandsø: Phys. Plasmas **3**, 3890 (1996)
- [8] A. Homann, A. Melzer, R. Madani, and A. Piel: Phys. Lett. A **242**, 173 (1998)
- [9] N. N. Rao, P. K. Shukla, and M. Y. Yu: Planet. Space Sci. **38**, 543 (1990)
- [10] J. Pieper, J. Goree, and R. Quinn: J. Vac. Sci. Technol. A **14**, 519 (1996)
- [11] T. Trottenberg, A. Melzer, and A. Piel: Plasma Sources Sci. Technol. **4**, 450 (1995)