Wave Modes and Mode Coupling in Bulk Complex Plasma Crystals

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1 Introduction-

Complex (dusty) plasmas are an interesting area of study not only for their real world applications, where they are found in proto-planet formation and in the process of plasma etching, but also because they provide a useful analog to other, more conventional, condensed matter systems [6]. The advantage to complex plasmas is that they provide an atomistic demonstration of strongly coupled dynamics on a length scale that can be imaged via normal video microscopy [6].

A complex plasma consists of weakly ionized plasma with dust particles injected into the plasma, these dust particles acquire a charge by colliding with the ions and electrons in the plasma. The electrons are much more mobile than the ions, therefore they collide with the dust particles much more often than the ions and the dust particles accumulate a negative charge. In most complex plasma experiments on earth, the charged dust particles then levitate in the plasma sheath at the balance point between the electric field and gravity [1]. The particles are confined in the horizontal direction by adding a radial component to the electric field[6]. Alternatively, a glass box can be placed on the electron which confines the particles to the interior of the box[6].

The normal Coulombic interaction between the charged dust grains is screened by the presence of the ions. The resulting potential in the horizontal direction is usually modeled by a Debye-Hükel or Yukawa potential [6] and has the form

$$V \propto \frac{1}{r} e^{\frac{-r}{\lambda}}$$

where λ is called the Debye length or screening length and it characterizes the length scale over which the interactions between particles are relevant. All of this causes the charged dust grains to condense into a hexagonal crystal [6].

In the area of the plasma known as the sheath the ions stream down towards the lower electrode and when they interact with the levitated dust particles create an effect known as the ion wake stream effect. When a streaming ion passes a negatively charged dust particle the on is attracted to the particle and deflects its path towards the particle. This creates an area of higher positive charge directly downstream from each particle and modifies how the oscillating particles interact with each other [2].

It is well accepted that there are three possible wave modes for the system to occupy. In the plane of the crystal the system can oscillate in the transverse or longitudinal direction. These are termed the transverse acoustic (TA) and longitudinal acoustic (LA) modes, respectively[3]. The system can also oscillate out of the plane in a mode that is called the transverse optical (TO) mode [3]. The optical and acoustic modes are distinguished from one another because the frequency of an acoustic mode will increase with increasing wave number, whereas the frequency of an optical mode will decrease as wave number increases (Figure 1).

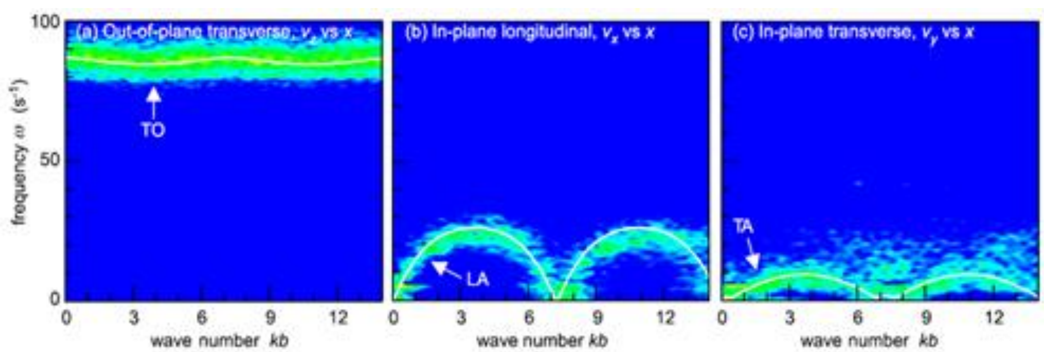


Figure 1: The dispersion relations for all three normal wave modes available to complex plasma crystals. From left to right the modes are the transverse optical, longitudinal acoustic, and transverse acoustic. Figure taken from [10]

When the dispersion relations of the different wave modes overlap then the overlapping modes are considered to be ‘coupled’ and this can cause several different results. The modes can become coupled because of the quasi particles generated by the ion wakefield. The dust particles interact with the quasi particles and the in plane and out of plane modes are no longer independent[]. The first of these is an increase in the energy of the overlapping region. This increase in energy causes an instability in the crystal that will melt the hexagonal lattice in the center of the crystal. Outside of the central instability the crystal will still be in its solid state. When two of the modes become coupled they will also produce an effect at the intersection between the two intersecting modes. This mode is sometimes referred to as the Non Dispersive (ND) mode [5]. The ND mode is a hybrid mode and it is not confined to exclusively the longitudinal or transverse directions[10].

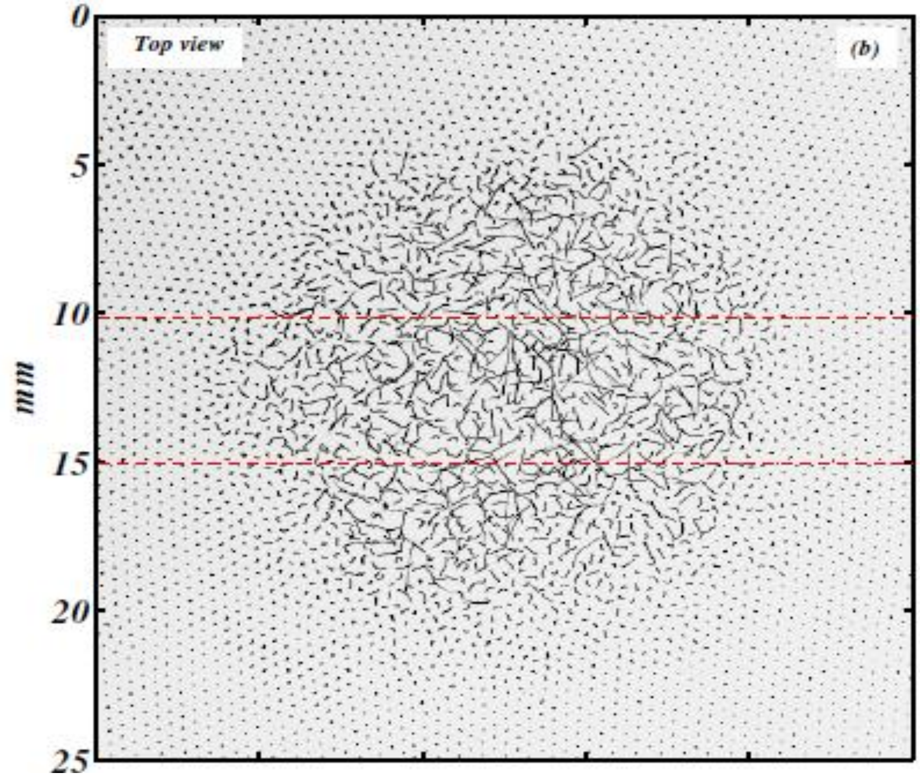
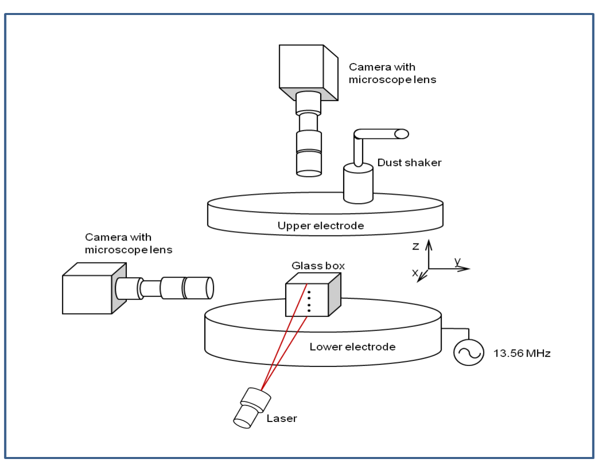


Figure 2: A crystal that shows the melting instability that is evidence of coupling between its wave modes. The center of the crystal is in a liquid phase, the particles are not bound to a lattice and their average velocity is much higher than if they were in a solid state. The particles towards the edge of the crystal are still bound on a hexagonal lattice. Figure taken from [2]

In this experiment extended crystals consisting of more than ≈500 particles were formed to study the oscillation modes available to the system and the coupling between them. The goal of this project was to compare the results that this experiment obtained with the expected behavior, and to provide a jumping off point to start looking at these kinds of behaviors in clusters of 3-10 particles instead of bulk crystals.

2 Methods-

The plasma is formed by ionizing argon gas between two electrodes in what is called a Gaseous Electronic Conference (GEC) reference cell[4]. In this cell a radio frequency signal is oscillated between the electrodes at a frequency of 13.56 MHz. In order to get the transverse optical (TO) and longitudinal acoustic (LA) modes to cross the interparticle spacing needs to be minimized so that the ion wakefield has a strong enough interaction with the other particles. To



this end, crystals were created using ~500 particles, because inserting a large number of particles into the interior of the cutout will shrink the interparticle spacing.. The pressure in the cell is, on average, around 25 mT to keep the damping minimal.

To illuminate the particles a laser that is turned into a horizontal sheet by a line generator is shone onto the particles. The laser is low enough energy that it does not disturb the motion of the particles. The crystals are then imaged via video microscopy. The top and side view cameras are both Sony XC HR50 cameras. On the top view camera there is a navitar 7000 zoom lens and the side view camera has a KC/S2 lens. The images are taken at a rate of 60 frames per second and each data set consists of 1000 frames.

Data on the positions of the particles is obtained by using a software package called polyparticletracker that was developed by S.S. Rogers et al [7]. This program tracks the movement of the particles throughout different frames and records the coordinates of each frame. To calculate the velocities of the particles the image is divided vertically into bins. In each frame the velocities of each particle in the X, Y, and Z directions is averaged together with the velocities of the others. The resulting matrix is a relation between the velocity of each particle and the current time. When this matrix is Fourier transformed it results in a matrix of wave numbers and angular frequencies.

3 Results-

3.1 Wave Modes-

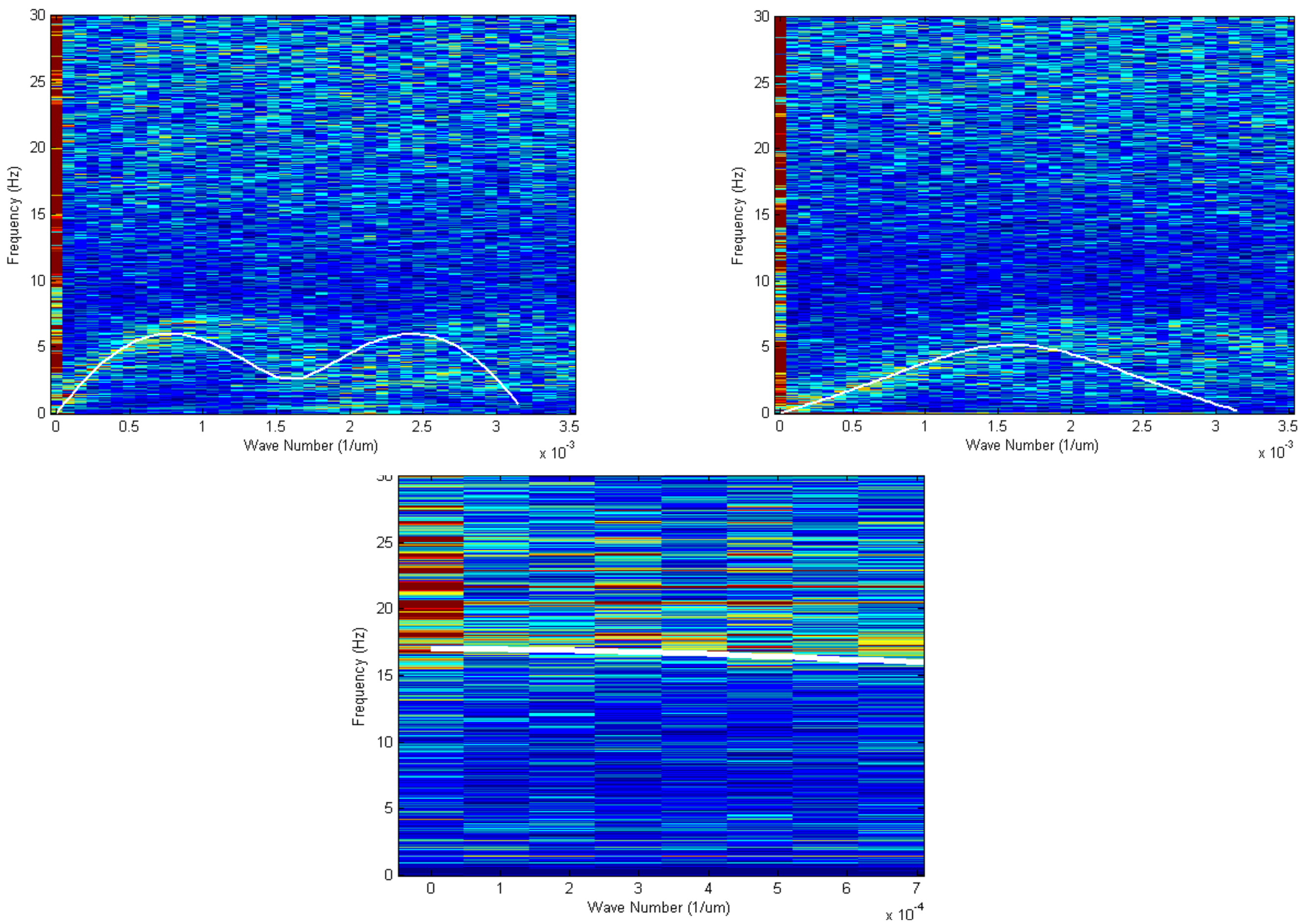


Figure 4: Dispersion relations for the longitudinal acoustic (top) and transverse acoustic (bottom). The white line is the theoretical prediction for the dispersion relation based on the interparticle spacing, mass of the particles, charge on each particle, and the debye length.

Data was collected at a pressures varying from 20 mT to 30 mT, powers from 250 mV to 500 mV, and interparticle spacings from 500 μm to 700 μm. The dispersion relations that were obtained for the LA, TA, and TO wave modes agree well with the theoretical predictions as shown in figure 4. The power in the cell for these crystals was 457 mV and the pressure was 20 mT. The theoretical dispersion relations depend on the mass, interparticle spacing, charge on the particles (q), and the debye (λ) length. The interparticle spacing and the mass of each particle are both parameters that can be computed. The theoretical fit provides a method for estimating the particle charge and Debye length. For this data set the particle charge was determined to be 20000 times the elementary charge and the Debye length was determined to be 300 μm.

3.2 Melting Instability-

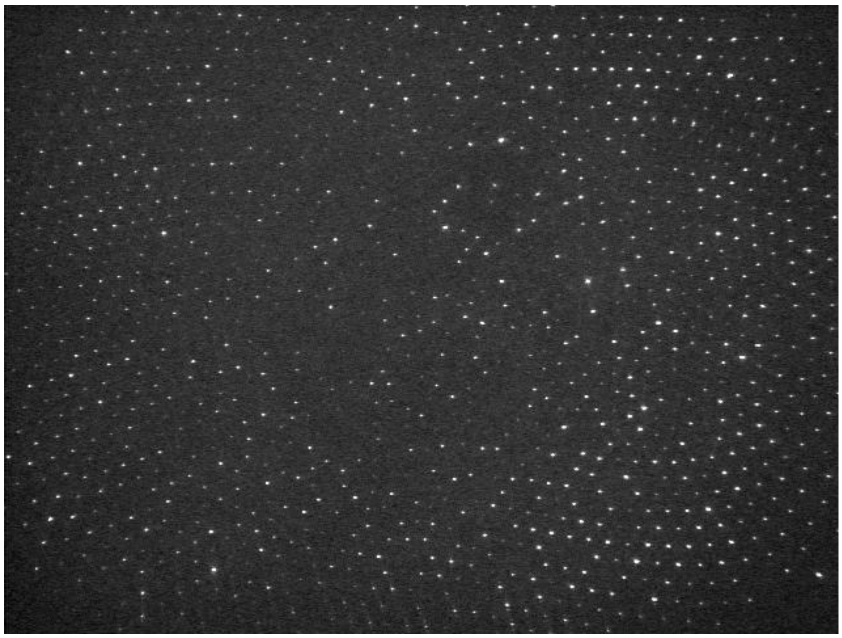


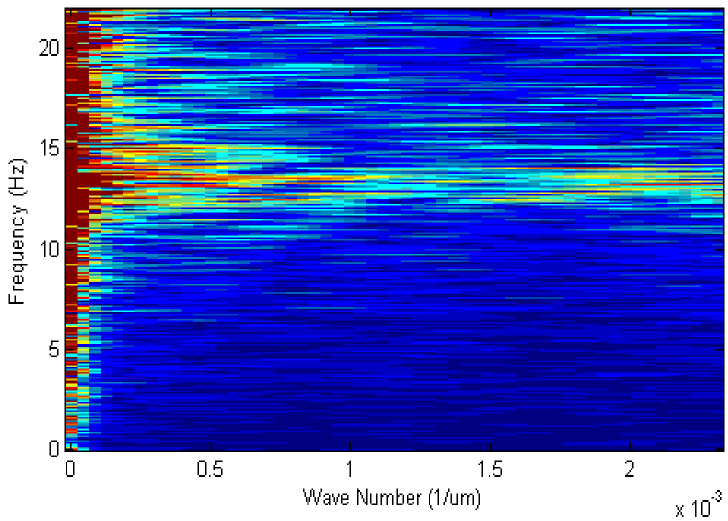
Figure 5: The melting instability in this crystal matches exactly with what is expected. The center of the crystal is in a liquid phase and the edges of the crystal are in the solid phase.

In theory the melting instability occurs because the wave modes have overlapped and caused a certain section of the dispersion relation to increase in energy density. This increase in energy manifests itself as particle velocities. This melts the center of the crystal but, depending on the level of overlap between the modes, it leaves the edges of the crystal in a solid state. Figure 5 shows that the crystals that were formed in this experiment look exactly like they should.

The transition between the fully condensed state and the melted state is sharp and shows a lack of hysteretic behavior. Figure 5 was taken at 457 mV and 21 mT. If the pressure was increased by only a single millitorr the crystal would return to its fully condensed state. Reducing the pressure again would cause the melting instability to reemerge exactly as it was originally.

3.3 Mode Coupling-

Figure 6 shows the dispersion relations for the LA and TO wave modes for one crystal at 467 mV and 28 mT. This crystal displays the melting instability that should indicate the presence of coupling between the modes. Looking at the dispersion relations it is obvious that they come very close to each other, and possibly cross. There is also a bright horizontal band running across the figure at the intersection point which could be the nondispersive mode that should be present if the modes are coupled to each other. If the modes are coupled then the longitudinal acoustic and transverse optical modes are no longer independent of one another and they can form a new hybrid mode. This hybrid mode is the ND mode, because it is a hybrid



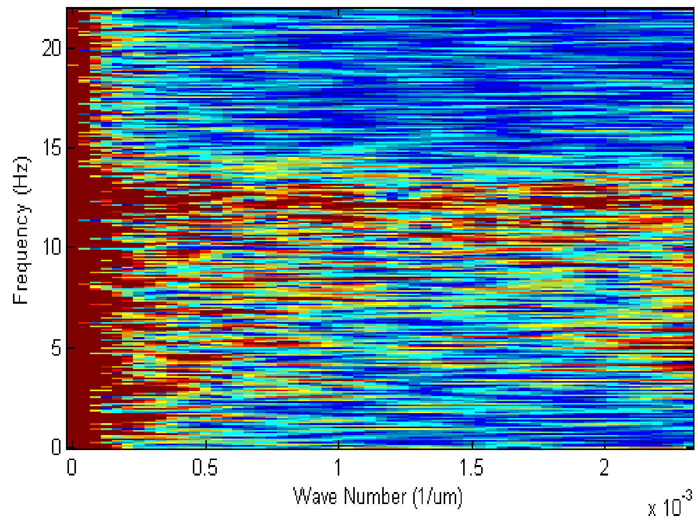


Figure 6: Data taken at 467 mV and 28 mT. The transverse optical (left) and longitudinal acoustic (right) both clearly show a strong band at 13 Hz

of other modes it should show up in the dispersion relation graphs for both the LA and TO modes.

This is interesting when compared to dispersion relations corresponding to other crystals, such as one taken at 18.5 mT and 457 mV. Other crystals also display a perfect looking melting instability, but in looking at their dispersion relations there is no clear sign that the LA and TO modes touch and that the ND mode present at the intersection.

4 Discussion-

It is clear that dispersion relations for the longitudinal acoustic and transverse acoustic agree very well with the theoretical predictions, up until about the wave numbers around 1.5 x 10^{-3}. After those values of the wave number the signal becomes very noisy and it becomes difficult to tell what the dispersion relation is doing. In general, signal noise presented a large problem in this experiment. Often the noise arises because the crystal that was created was not a pure single layer. If any of the particles that are dropped into the cell are fragments of other, whole particles then their mass will be less than the mass of the other particles and therefore they will levitate higher than the other particles. This is an issue because these fragments levitate close enough to the crystal to interact with the particles in the crystal. They are also not bound into a lattice so they are free to travel from one end of the cut out to the other. As they travel above the crystal they introduce extra motion into the particles in the crystal. Once a fragment has fallen into the cell there is no way to get it out, and the crystal either needs to be dropped entirely or data can be taken knowing that the fragment is there.

The level of the noise also makes determining if figure 7 is displaying mode coupling. It is clear that the dispersion relations at least come close to each other. It also looks like there is a ND mode present as well. Unfortunately, one good indicator of mode coupling, the melting instability, also makes it much more difficult to extract data from the images. The increased velocity of the particles in the instability makes it impossible to track any of those particles. The transition from a fully solidified state to a state with the melting instability present is very sharp. Within a single milli-torr the crystal can go from being in a complete solid state to having a melting instability that takes up a large portion of the crystal. It may be that finer control of the pressure in the cell would allow crystals to be created that have a melting instability while at the same time keeping that melting instability small, in order to maximize the number of trackable particles in the solidified section of the crystal.

Another point of interest is that some of the crystals that were created have melting instability, but the mode coupling is clearly absent. The dispersion relations on from these crystals come close to each other, but it is clear that they do not touch. It is possible to have mode coupling without having the melting instability, if the damping is high enough then the crystal will not be allowed to melt, but if the melting instability is present then the modes should be coupled. It is possible that this is occurring because, while the crystal is a single layer, the crystal is bulged toward the center. If the crystal is no longer completely flat then the particles are no longer interacting with each other in the typical manner and this may be enough to stop the modes from coupling.

5 Conclusion-

The longitudinal acoustic, transverse acoustic, and transverse optical dispersion relations obtained from this experiment all show excellent agreement with theoretical predictions. The melting instability in these crystals behaves exactly as it is expected. The crystal can transition from a fully condensed state to a state with the melting instability when the pressure is reduced by only a single millitorr. If the pressure is increased again the crystal will return to its original state. It is unclear why the melting instability should be behaving exactly as expected and yet there is no conclusive evidence of coupling between the modes. While no crystals showed conclusive evidence of mode coupling on data set shows enough characteristics of mode coupling to reasonably conclude that the modes are coupled in that data set. All of this has laid the groundwork to move on and look at mode coupling in clusters of 10-20 dust particles instead of bulk crystals.

6 References-

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