The Change in crystal structure of 3D Yukawa Balls with varying discharge power

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Abstract:

The research covered in this paper involves observation of the changes in the crystal structure while the power in the plasma discharge is modulated. The focus of the research is on the size and symmetry of the ball at higher powers versus lower powers. We present the general trends for these quantities. One of these is an increase in radial cluster size and a change in the particle distribution in the cluster with increased discharge power.

Introduction:

When small, 8.89 micrometer diameter, plastic particles are dropped into plasma formed between two electrodes, they are levitated due to the combined effect of several forces—gravity, thermophoretic forces, ion drag, and the electrostatic force, due to the electrical charge on the dust obtained from the plasma [1]. In the ideal case, the particles will form a two-dimensional crystal on a single plain with hexagonal crystal-symmetry [2]. There are generally particles that do not stay in the same layer or do not have six surrounding particles, however [3]. Much of the research that has currently been accomplished in this field was done on these two-dimensional crystals. There are ways to change the shape of this crystal, however, by using other forces and outside objects. One of these newly shaped crystals is called a “Yukawa ball [4].”

Like the two-dimensional crystals, this “ball” can retain the same hexagonal symmetry, but in three dimensions [5]. This ball forms because the additional radial confinement causes the forces between the charged dust particles to become of comparable magnitude to the external forces [3]. Dust particles also form vertically aligned strings or chains in the plasma, due to the ion wake field effect [6]. By changing the plasma parameters, we hope to study the crystal structure in the ball, and how this might depend on the plasma environment. In order to do this, we modulated the discharge power, inducing changes in the plasma.

Experimental Setup:

The experiments on the Yukawa balls were carried out using argon plasma in a Gaseous Electronics Conference (GEC) vacuum cell [7]. Argon gas is pumped into the cell and kept at low pressures (usually 100-500 mTorr) with a roughing pump. Inside the cell, there are two electrodes (upper and lower), and normally a cutout-plate, which designates the shape of the crystal by providing radial confinement. This cutout is milled in an aluminum disc that sits on top of the lower electrode. For our purposes, the cutout was replaced by a glass box (dimensions: 17mm x 17mm x 20mm), which sat in grooves on top of this disc.

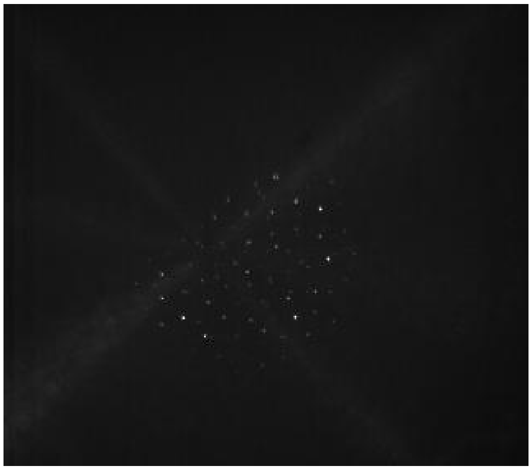
To actually light the gas (create the plasma), an electrical current must be run from the lower electrode to the upper electrode. To do this, the current goes through a series of steps. First, a low-power signal with a frequency of 13.56 MHz is created in an RF generator, which is then run through a variable passive attenuator, which determines the power to which the signal will be amplified. After this, the signal is actually amplified, and is then sent through a filter, so that only a signal with a frequency of 13.56 MHz will get through, and the harmonics of this signal will not, or only with very low amplitude. The signal then travels through a tuning network, in which the reverse power can be modified. Eventually, the signal travels from the lower electrode to the top, which is grounded.

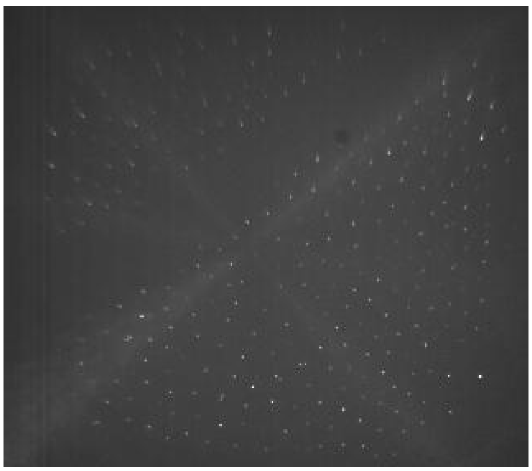
For the experiments on the Yukawa balls, Melamine-Formaldehyde (MF) plastic dust 8.89 micrometers in diameter was used. The pressure inside the cell was kept at 396 mTorr, and the input power at 3.872 Watts, as determined from a Volt reading of 440 mV on the directional bridge (with the reverse power maintained at roughly 10%). For half of the experiments, the natural bias was at -2.65 V, while it was at -3.76 for the others. The variable that did change was the temperature of the lower electrode, which, when heated, creates a thermophoretic force inside of the cell. The highest temperature that was used was 69.3 degrees Celsius, and the lowest was 16 degrees.

For data analysis, pictures had to be taken of the dust crystals from both the top and the side. To do this, cameras were put in these locations, and two lasers (which were equipped with lenses to form thin laser sheets) were shone perpendicular to the direction of the camera such that a plane of dust would be illuminated, allowing the camera to take pictures. These pictures were then analyzed using the ImageJ imaging software and the MATLAB data analysis program.

Method:

High-speed cameras were used to take pictures from both the top and the side (they were set to 250 frames per second, and were run for approximately 12 seconds). Two runs were done, one for each camera view, in which the power was modulated between 5.962 Watts and 3.872 Watts, as determined from a Volt reading on the directional bridge of 546 mV and 440 mV. After this, two more runs were done with the powers at 7.2 W and 3.872 W, as determined from a Volt reading of 600 and 440 mV, and finally, the last two were run at 9.522 W and 3.872 W, as determined from a Volt reading of 690 and 440 mV.





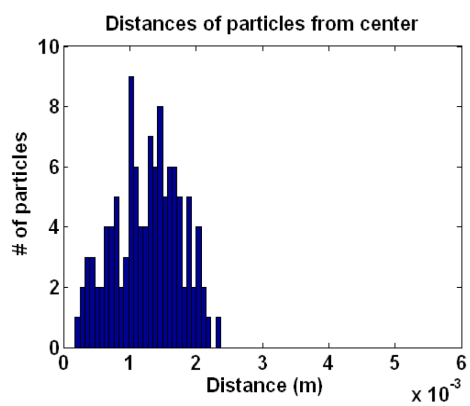
(Top) picture taken at 440 mV of run #4, and (Bottom) picture taken at 600 mV of the same run. Images were cropped using ImageJ.

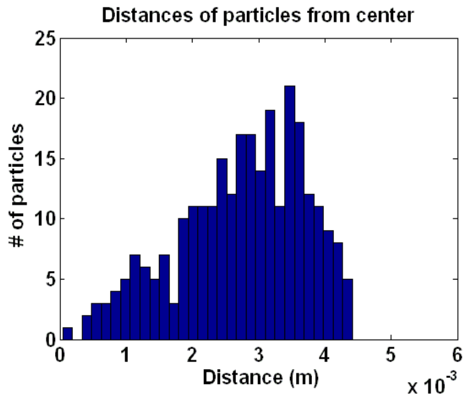
The obtained sets of pictures were imported into ImageJ, and two pictures from each set (one at the higher power, and one at the lower) were selected on the basis of which picture most clearly showed the particle locations.

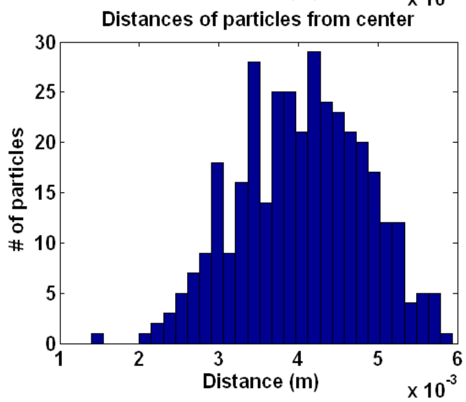
The particle detector plug-in on ImageJ was used to find the exact locations of each dust particle, and these locations were imported into MATLAB. The MATLAB program was written so that a plot of the particles would be made, along with two voronoi plots, a graph showing the number of particle neighbors, and graph showing the distance of a particle from the center.

Results:

After the data was run through MATLAB, clear results showed that there was a large difference in crystal structure after the modulation of power in the GEC cell. It is, however, impossible to compare the last set of data (at 9.522 W and 3.872 W) to the rest of the data, due to the fact that more particles accidentally fell into the crystal. In the first two groups of runs, particles at the low power were, on average, about 1 to 1.5 mm from the center of the crystal, and most of the particles had either 5 or 6 neighboring particles. When the power was increased to 5.962 W (546 mV), however, most particles moved to about 2.5/3.5 mm from the center.

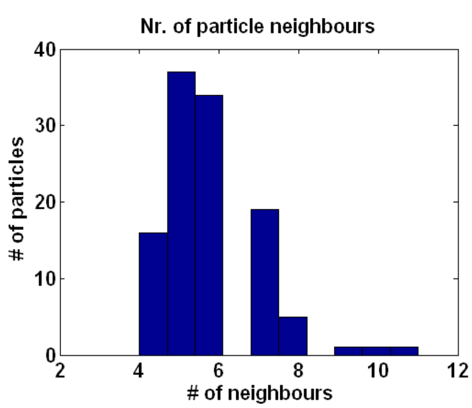


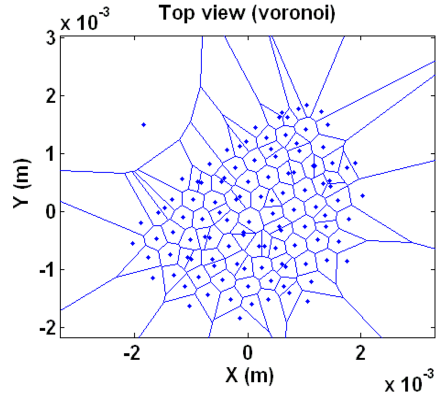


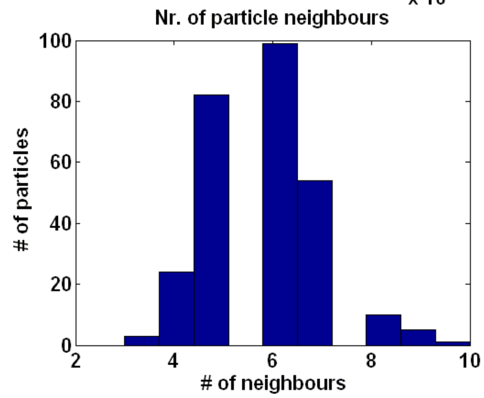


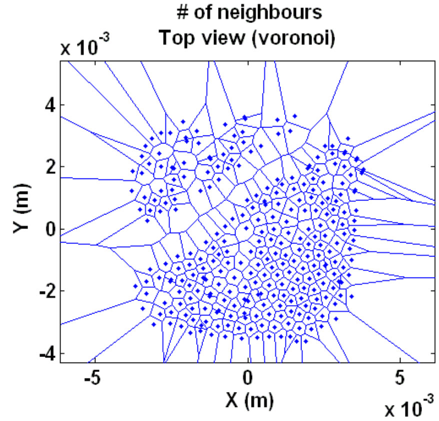
Graphs show the distance of each particle from the center of the Yukawa crystal, and (from top to bottom) are measured at 440 mV, 600 mV, and 690 mV.

Again, when the power was increased to 7.2 W (600 mV), the radius of the crystal increased even more. The data at 9.522 W (690 mV) has an even larger radius, although there were more particles present.









Images are histograms that show the amount of particles that had x amount of neighbors, followed by a voronoi diagram of the same crystal. The first two images are at 440 mV, the last two at 600 mV.

Another aspect of Yukawa balls that was observed was the crystal symmetry of a cross section of the ball. This was calculated by producing the graphs pictured above, which show the amount of neighbors each particle has. At 440 mV, most of the particles had 5-6 neighbors, with some having 4-8. As the ball expanded (when power was increased), this symmetry remained largely the same. Most particles still had 5-6 neighbors, and some had 4-8. This stayed true for all of the runs that were observed, ranging from 3.872 W to 7.2 W. Due to the fact that extra particles fell into the crystal during the final two runs, a void was formed in the middle of the crystal, which means that some particles are read into the particle detector as having only half of the neighbors that they should. Because of this, the symmetry of the run at 9.522 W was not used.

Discussion/Conclusion:

The data presented here, shows us that with increasing power the radius of the dust crystal increases as well. While it has this effect, the crystal symmetry remains mainly hexagonal. Due to a lack of time, this data has yet to be analyzed completely to find the effect of power modulation on each particle. The initial question on the general effects of power modulation was answered, however. While the last set of data was not consistent with the two before, the trend of crystal expansion with increasing power still continues. The results of this research will hopefully cause more interest into the study of Yukawa balls so that more could be learned about a three-dimensional crystal, rather than only a two-dimensional one.

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