Determination of the Horizontal Potential Well within a 1” Glass Box placed in a GEC Reference Cell

R. K. Moore, L. Matthews, and T. Hyde

***Abstract*—Experiments are performed in which a single dust particle, dropped in a weakly ionized plasma discharge, levitates above a powered electrode and is perturbed with a laser in order to determine the horizontal confinement force acting on the particle within a 1” glass box. Different sized particles are used in conjunction with varied power and pressure settings in order to determine the shape of the potential well for the more recent way of increasing the horizontal confinement force for complex plasma experiments.**

***Index Terms*— Dusty plasmas, glass box, horizontal confinement, weakly-ionized cold plasma.**

I. INTRODUCTION

THE study of dusty plasma became industrially important in the late 1980’s when scientists in the semiconductor industry, while searching for particulate contaminant on semiconductor wafers, came across the substance [1]. A laser used to monitor concentrations of reactive gas by means of weak optical fluorescence when shone into the silicon-wafer-etching plasma was scattered in a startling fashion when it came into contact with micron-sized dust particles. These dust particles were formed in the plasma, and held above the surface of the wafers by means of electromagnetic forces.

Plasma physics has also been of interest to the astrophysics community because it is such a prevalent theme in such a broad range of areas: planet rings, comet tails, ionosphere, and so on [2]. It was also found in the spokes of Saturn’s B ring by the Cassini spacecraft [3].

As a result of these discoveries, and the rich physics they contain, laboratory research on dusty plasmas has been carried out for more than two decades, and is still continuing today.

Recently, members of the scientific community who study dusty plasma physics have used a small 1” tall glass box instead of the traditional 1mm deep machined cut out for providing a horizontal confinement, which ensures that the particles do not fall off of the lower electrode. Because of the greater confinement forces found within the box, the possibility exists for creating particle structures outside of those involving typical horizontal-only interactions. Arrangements which involve vertical alignment can be created; with one particle directly above another, called one-dimensional dust chains.

These chains exhibit unique and interesting characteristics, but some ground work for their interactions and behavior must be laid if a firm understanding of their physics is to be achieved.

Thus, the question, “Is the horizontal confinement within the glass box consistent with that of the lower electrode cut out?” arises. The walls of the glass box charge negatively with the lower electrode which it sits on, and the box itself produces a confinement which is undoubtedly greater than that of the typical cut out. However, using methods previously developed for the well-studied potential well of the cut out, the potential within the glass box can be more precisely examined [4]. A single particle, after being pushed by the radiation force of a laser pulse towards the side of the glass box, will return to its equilibrium position when the laser is off, due to the confining force acting on it. The particle then acts as a way to test how the horizontal potential changes as it moves away from the middle of the box, where its equilibrium point is, by the trajectory that is seen as it does so. At different power and pressure settings, the particle will sit at different places in the glass box, allowing for testing at multiple places within the box.

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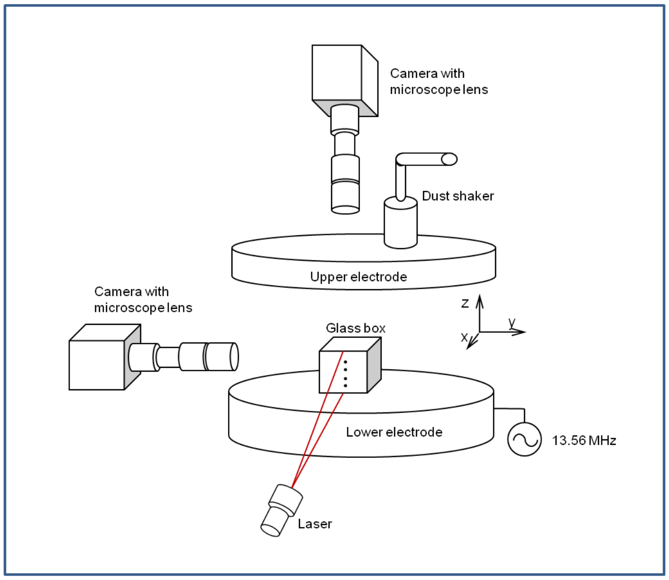

Fig.1.Experiment setup of the Gaseous Electronic Conference (GEC) reference cell for particles within the glass box.

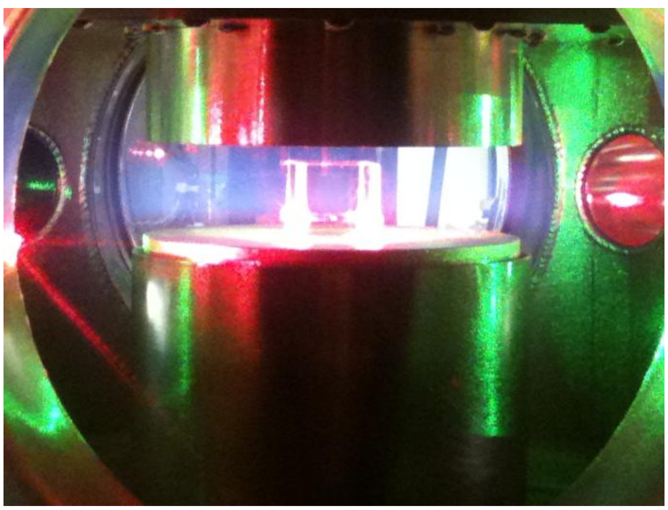

Fig.2. Photograph showing inside of CASPER GEC reference Cell 1 with 1" glass box and Verdi laser on.

II. EXPERIMENTAL PROCEDURES

A. CASPER GEC Reference Cell

The complex plasma experiments discussed in this paper were carried out in the Center for Astrophysics, Space Physics, and Engineering Research (CASPER) Gaseous Electronics Conference (GEC) Cell with the setup as seen in Figure 1, and is photographed in Figure 2 [5][6]. Within this cell are a grounded upper electrode and a powered lower electrode which is capacitively coupled and driven at the standard frequency of 13.56 MHz. The experiments were executed in argon plasma at pressures that were varied between 60 and 100 mTorr. The confining force of the particles, of course, came from the glass box constructed of four glass plates about 3mm thick. The power of the RF signal was also varied between 1 and 3.5 W, and for consistency, a Kepco external DC power supply was used to maintain a -15V DC bias on the lower electrode.

Melamine-formaldehyde (MF) particles with a mass density of 1.510 g/cm^3 and diameters of 6.48, 8.89, and 11.80 μm were dropped from a container with a micron-sized mesh bottom cover in order to achieve the task of dropping one particle at a time.

The different sized particles, even at equal power and pressure settings sit at different levels above the electrode because of their respective masses, according to the force equation:

$$qE = mg \tag{1}$$

B. Powers and Pressures

Variations in the power settings for the lower electrode influences the amount of negative charge found on the walls of the glass box. As power is increased, the particle will typically not be held as high. The voltage used on the lower electrode was between 440 and 830 mV, which when converted to power is about 1 to 3.5 W. Specifically, experiments were carried out at 1, 2, 2.7 and 3.5 W.

Pressure was also varied in these experiments. The pressure inside the cell influences the number of neutral argon particles that increase resistance on the negatively charged dust particle. As a result, an increase in pressure in the cell results in a decrease in the height at which the particle sits above the electrode. The pressures used in this project were 60, 80, and 100 mTorr, controlled by a MKS Throttle Valve controller, and the laser used to push the particle is a Coherent® Verdi laser, capable of a 5 W beam.

C. High Speed Camera Analysis and ImageJ

The motion of the particle was captured by a camera fitted with a microscope lens, which had a frame rate of 120 frames per second (fps). The camera was fixed in place, vertically, over the top of the GEC cell. The camera tracked the y-direction in a three-dimensional coordinate system, in order to see that the particle was pushed in one coordinate direction only. This allowed for a quantitative measurement of the particle movement to be determined. The free software, ImageJ, coupled with the plugin "Particle Tracker", (available in the public domain) was utilized to track the trajectory of the particle, as it was pushed by the radiation pressure of the laser, and while the laser was off and the particle returned to its place of lowest potential energy, its equilibrium point.

Figure 3 is a sample image of the photo from the camera shows the view from the top camera's perspective.

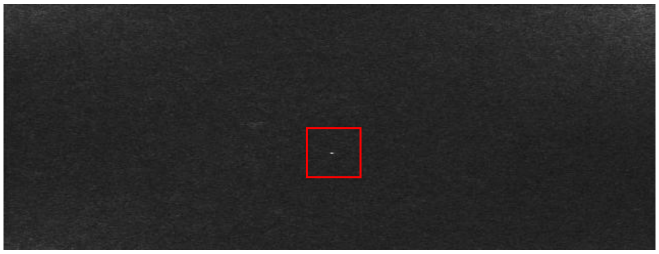

Fig.3. ImageJ tracking of single particle

Once the images had been analyzed using the ImageJ plug-in, Particle Tracker, a set of coordinates for the movement of the particle was created. This can be graphed in order to see the change in position with respect to time, as shown in Figure 4.

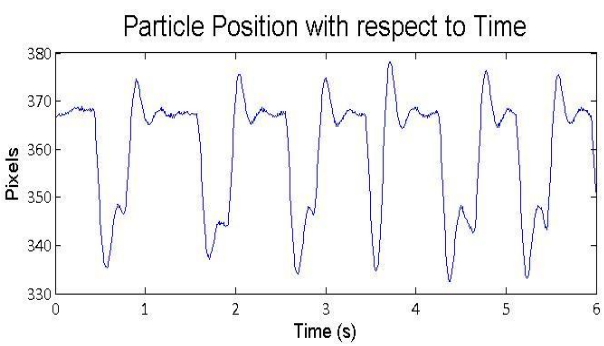

Fig.4. Position vs. Time Plot for a 11.80 μm particle at 100mTorr and approximately 2 W.

D. Analysis

The set of coordinates extracted from the ImageJ analysis can be placed into an array in MATLAB®. From this, variables like velocity and acceleration are calculated with a simple version of code. Using the method outlined by B. Liu [4], it was possible to use the data to calculate the horizontal potential as the particle moved away from the equilibrium point, according to Equation 2.

$$U\big(x(t)\big) = U_0 - \frac{M\dot{x}^2}{2} - R\int_1^t \dot{x}(\tau)^2 d\tau \qquad (2)$$

III. Results

The goal of these experiments was to determine the shape of the horizontal potential well, using the method described earlier in the paper. This was achieved and the data collected indicates that the potential, in the same fashion as the lower electrode cutout, has a parabolic horizontal potential well. This means that as the particle moves farther and farther away from the equilibrium position, the forces acting to constrain its movement towards the side of the box increase greatly.

During the course of ensuring that multiple particle heights were tested, an interesting trend was found. All particles decreased height as the pressure increased, at constant power, as expected, as shown in Figure 5.

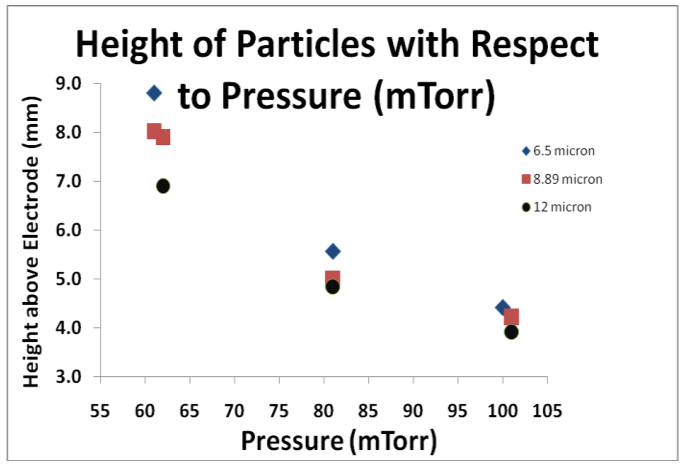

Fig.5. Graph shows three different size particles (6.48, 8.89, and 11.80 μm) all at approximately 2W and their height above the lower electrode at different pressure settings.

However, for increased power settings and a constant pressure of 100 mTorr, not all of the particle sizes dropped lower in the glass box. The 11.80 μm particle, in contrast to the others, lifted up higher in the glass box for increased power settings, as seen in Figure 6.

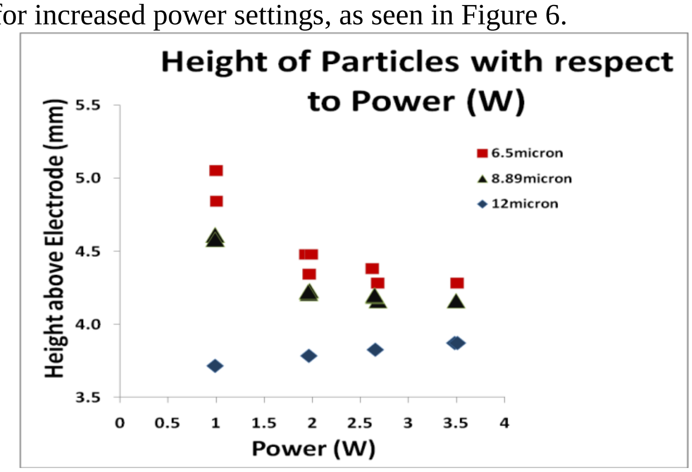

Fig.6. Three different size particles (6.48, 8.89, and 11.80 μm) at 100 mTorr and their height above lower electrode at varied power settings.

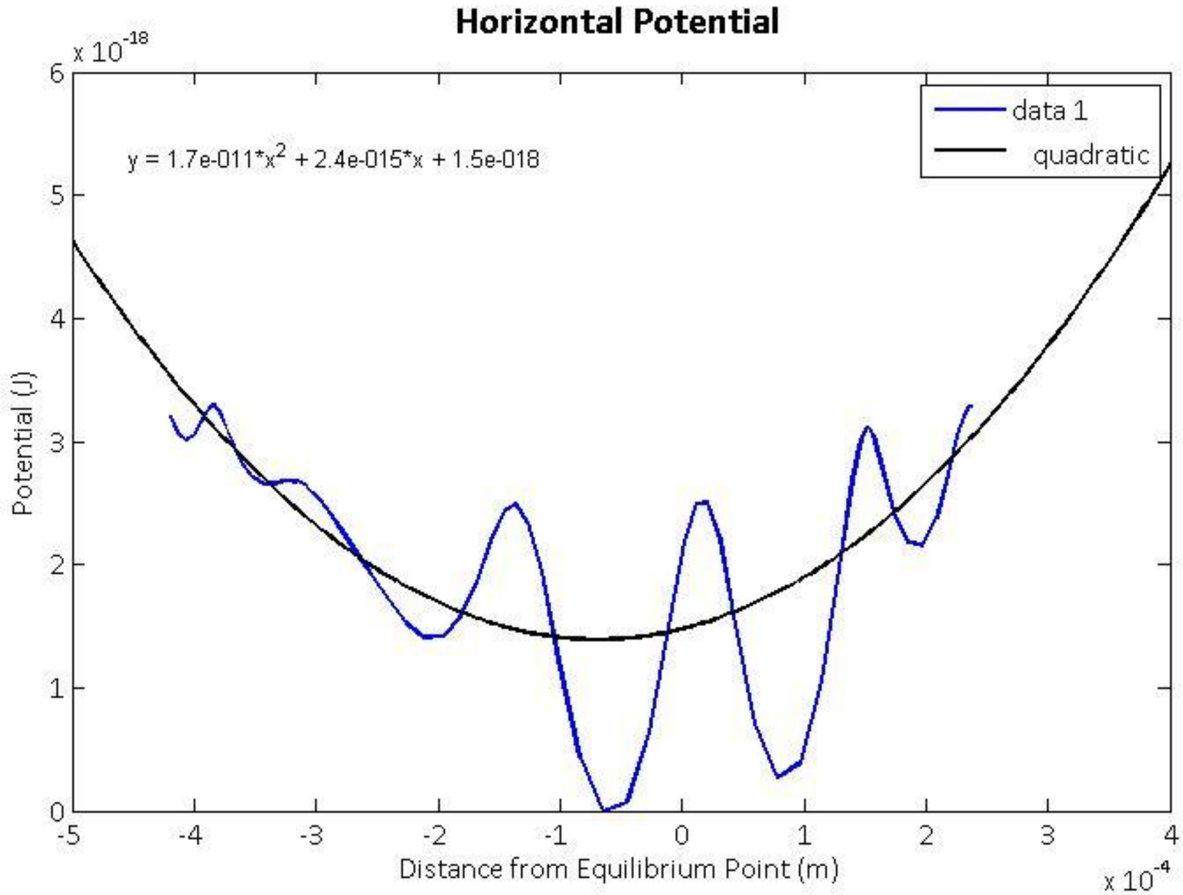

Fig.6. The horizontal potential well shape, as evaluated by the method explained above. An 11.80 µm particle at 100 mTorr and 2 W.

There is still work to be done in order to investigate the cause of such particle movement.

IV. Discussion

The calculated potential well, and the best-fit parabola, as shown in Figure 6, describes the horizontal confinement. It is interesting to note that the confinement is similar to that of the cut out; they are both parabolic in nature. Initially, it was discussed that the potential might be hyperbolic instead of parabolic, because the walls of the glass box literally encase the edges of the area where the particle sits. Using different settings for the laser-push experiment allowed for analysis at varied heights to see if the potential well was parabolic for all heights. Through MATLAB® analysis of that data, it is clear that at all of the particle heights, the potential well was no more than parabolic in nature.

Initially, the variation in particle diameter, power, and pressure settings was intended to construct a full 3-dimensional set of data of the potential well within the box. However, due to time constraints, complete analysis and coding for the construction of this model did not occur. Also, another similar method used for confinement that was not previously mentioned in this paper, the 0.5” glass box, should be similarly investigated to see if the potential well is as consistently parabolic in nature as the 1” box.

V. Conclusion

Particle movements within the glass box can now be viewed in light of this determination of the shape of the confinement forces found during these experiments. However, more work has yet to be done to determine a more complete set of parameters which defines how the potential well changes with varying conditions, such as a larger number of particles, or at greater pressure and power settings. More work should be done in order to put together a more full representation of the precise change that occurs within the box as the pressure or power or particle size is increased.

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