A Consistent Model of Plasma-Dust Interactions: The Potential in a Glass Box

Lori Scott, Lorin S. Matthews, and Truell Hyde

Abstract—**Numerical modeling has become a valuable diagnostic tool for experiments in the modern physical world. In modeling the dynamics of dust particles confined in a glass box placed on the lower electrode of a GEC cell, many interactions between the dust, plasma, and boundaries need to be accounted for accurately. The negatively charged lower electrode affects the plasma conditions in the sheath, altering the electron and ion densities. These local variations in the plasma determine the charge accumulated on the surface of the glass box and the resulting electrostatic potential within it. This work describes the steps taken to build a consistent model of the relationship between the plasma conditions and the confining electric potential due to the glass box in order to more accurately model the charging and dynamics of dust clusters and strings.**

***Index Terms*—Bias, Complex Plasma, Electrostatic Potential, Numeric Modeling, Orbital Motion Limited Theory.**

I. Introduction

MODELING the interactions of dust particles within a glass box is a vital link between the theoretical and experimental communities of plasma physics. Numerical modeling allows one to verify the results of an experiment as well as predict new results for varying experimental parameters. Ultimately, the goal of this research is to be able to simulate the charging and dynamics of a chain or cluster of dust particles confined within a glass box. We currently have a *Dust Chains Dynamics* code to model dust configurations in plasma, but we would like to refine it to be more accurate with specific plasma conditions. The electrostatic potential is the major factor in determining the confinement and subsequent particle motion within the box. This paper presents a method to model this potential to be able to more accurately account for the motion of the particles within the box.

First, background information on the charging of surfaces in plasma using Orbital Motion Limited Theory will be presented. In section III, the numerical model used to calculate the charge on the walls of the box will be presented, and the fluid model used to calculate the plasma conditions within the sheath will be described. Results will be given in section IV with concluding remarks given in section V.

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II. Background Information

A. Orbital Motion Limited Theory and Line of Sight Approximation

Orbital Motion Limited (OML) theory is one of the most common ways to describe the charging of particles immersed in a plasma environment. The fundamental concept behind this theory believes objects in a plasma environment become charged by collecting particles of the surrounding plasma [1]. Another important energy and angular momentum are conserved throughout the experiment. The current to a given object is

$$J_\alpha(t) = n_\alpha q_\alpha \int_{v_m(t)}^{\infty} f_\alpha\,(v_\alpha) v_\alpha^3 dv_\alpha \times \iint \cos(\theta) d\Omega \qquad (1)$$

where α is for either electrons or ions, n is the numeric density, q is the charge of the particles, f is the velocity distribution function, v is the velocity, and θ is the visible angles from line of sight. This current is used to calculate the charge on objects within the plasma.

The Line of Sight (LOS) approximation takes into account the geometry of the objects within the fluid. The ions are less likely to attach to the object if there is another particle blocking the direct path due to their slower velocity. Another inhibitor is when there are fewer paths statistically available for the electrons to take to get to a patch on the object. OML theory states that the orbit of a plasma particle has to connect back to infinity. If the path of a particle is blocked, it won't be able to go back where it came from. For example, in this experiment the electrons will have less ability to hit a corner of the box versus the middle of a face because the 'lines of sight' open to a point in a corner is only a quarter of the 'lines of sight' open to a point in the middle of a face. Using these approximations, we can change the last term in (1) to be a specific factor of π based on the location of the patch or particle.

B. Debye Shielding

Debye shielding is the effective shielding of the plasma on a charged particle. The Debye length is the length that the charged particle is effective without the plasma interfering. This is important in plasma because the order of magnitude of size of the dust particles is so small compared to the order of magnitude of the length of the box. It is because the length of

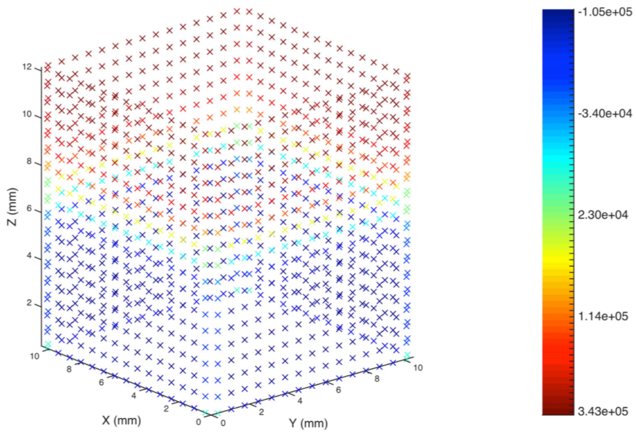

Fig. 1. A half-inch glass box with 1,080 points. The color is proportional to the number of electrons on that point. The number of electrons per point increases with height. The power is 60 Vrf, V, the pressure is 150 mTorr, and the lower electrode has a bias of -40V.

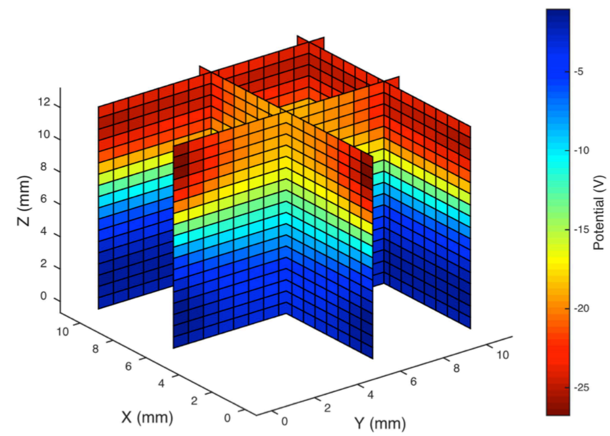

Fig. 2. The potential slices within a half-inch box. The potential is symmetric in the X and Y direction. The power is 60 Vrf, V, the pressure is 150 mTorr, and the lower electrode has a bias of -40V.

the box is large compared to the Debye length of the plasma. The resulting potential is

$$V_{Debye} = \frac{1}{4\pi\epsilon_0}\frac{q}{r}\, e^{-\frac{\lambda}{r}} \tag{2}$$

where ε_0 is the permittivity constant, q is the charge, r is the distance from the point, and λ is the Debye length. The charge on the box from one side will not greatly affect the charge on the opposite side when the distance is significantly greater than the Debye length of the plasma.

III. Research Methods

A. Fluid Model

The fluid model is a self-consistent model that simulates the plasma parameters. A complete description of the fluid model is given in [2]. The purpose of the fluid model is to characterize the plasma conditions for specific operating powers and pressures. These parameters include the plasma potential, Debye length, electron and ion densities, and electron temperature, all as a function of height from the lower electrode. The main use of the fluid model in this simulation is to account for the changing plasma densities and potential as the height increases from the lower electrode [3].

B. Numerical Model

The experiments run in the CASPER laboratory use a half-inch box (10.5 x 10.5 x 12.5 mm) placed on the lower electrode of the GEC rf cell. The charge accumulated on the surface of the box can be numerically modeled.

Each side of the glass box is divided into square patches. The number of sections determines the resolution of the charge distribution on the surface of box and the simulation time needed to obtain an overall equilibrium charge. To account for the LOS theory three distinct types of surface patches were defined: the corners, the edges, and the rest of the faces. The corners and edges were distinguished by the first or the last patch within the divisions. OML theory was implemented by calculating the current to each patch using (1) and multiplying by the area of the patch, the time step, and the LOS factor. This net charge on a patch is calculated by adding the current density of ions and electrons together.

The potential at the center of each patch is calculated as the sum of the potential due to all other patches on the box.

$$V_{self} = \frac{\sigma}{2\pi\epsilon_0}\, l\, \log(17 + 12\sqrt{2}) \tag{3}$$

$$V_{patch\ j} = \sum_{i\neq j}^{n} V_{i_{Debye}} + V_{self\ j} + V_{electrode} \tag{4}$$

where σ is the charge density, ε_0 is the permittivity constant, l is the length of the patch, n is the number of patches, and $V_{\text{electrode}}$ is the bias on the lower electrode. Including the lower electrode's potential is important to account for the potential that naturally occurs on the lower electrode when the plasma's power and pressure are set experimentally.

This potential is used to calculate the electron and ion current to the center of each patch, and the amount of charge accumulated in the time Δt is then calculated. This process is iterated until equilibrium is reached, defined by taking the percent difference from the last and current time step. If the percent difference is less than 0.05%, we assume equilibrium is reached.

IV. Results

Upon plotting the charge of each patch on the surface of the box, there is a distinct height where the charge on the box changes from positive to negative (Fig. 1). The box is sitting on the negatively biased lower electrode, which repels electrons and attracts the ions. This transition region is where the numeric densities become equal. This is also the limit to how deep in the box dust particles can levitate.

The map of the potential within the glass box (Fig. 2) shows the symmetry between the X and Y directions. The negatively charged dust particles can only levitate in yellow or red regions, so this essentially cuts off half of the box. The

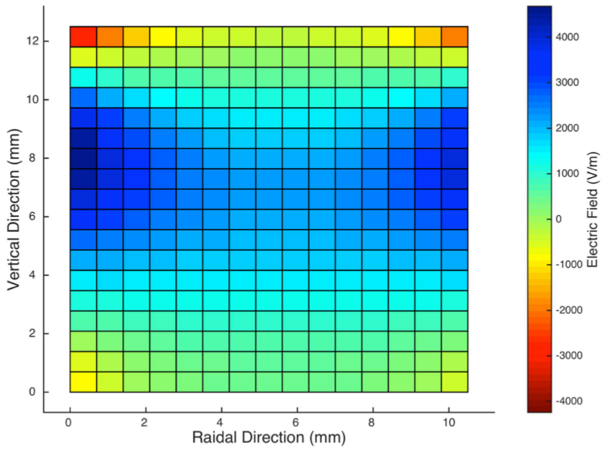

Fig. 3. The vertical electric field slice through the center of the box. The power is 60 Vrf, V, the pressure is 150 mTorr, and the lower electrode has a bias of -40V.

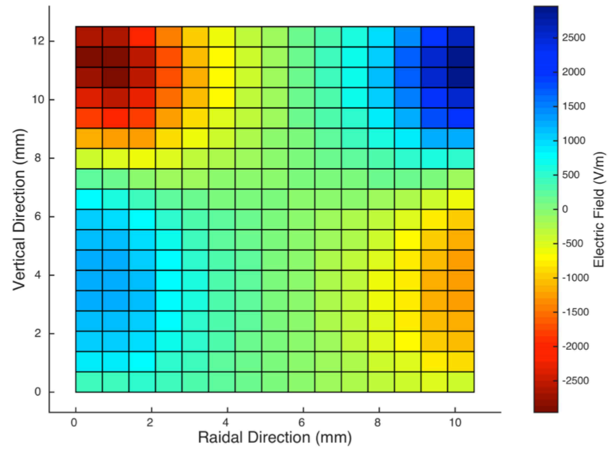

Fig. 4. The radial electric field slice through the center of the box. The power is 60 Vrf, V, the pressure is 150 mTorr, and the lower electrode has a bias of -40V.

transition line from negative to positive electrostatic potential shifts upward as the bias increases.

The map of the vertical electric field within the glass box tends to match previous experimental results. The contour diagrams (Fig. 3) of the Electric Field in the vertical direction match those previously published by CASPER. Negative dust particles can only be in the negative electric field region, which limits their levitation to most upper divisions of the box.

Fig. 4 shows the strong points near the corners and transition edge that appear when taking the radial electric field's contour plot. Both of the strong electric fields confine negative dust chains to the center of the box, which confirms experimental results.

The magnitude of the vertical electric field along the midline of the box (Fig. 5) shows the significant effect that changing the lower electrode's bias has on the confinement region for the particles. This figure also shows the effects that the box has on the electric field versus the fluid model, which is an open plasma environment within the GEC cell.

Fig. 6 shows the magnitude of the radial electric field at three distinct heights in the box. This shows where the dust particles are allowed to levitate. The dust particles need an increasing slope from the side in order for the particles to stay in the center of the box, which in this simulation is above the halfway point.

V. Discussion

The dust particles within the box are limited to levitating in a negatively charged region of the box. Since the particles are charged negatively, the negative box has an inward repulsion which confines the particles. As the magnitude of the bias on the lower electrode is increased, the transition height from positive to negatively charged points on the box is raised. This limits the region where dust particle levitation can exist. At a bias of -49V, the entire box is charged positively, so particles would be able to enter but they would attract to the faces of the box immediately, with no levitations in the center.

The potential of the box in the vertical direction is symmetric from all sides (Fig 2). This indicates that the *Dust*

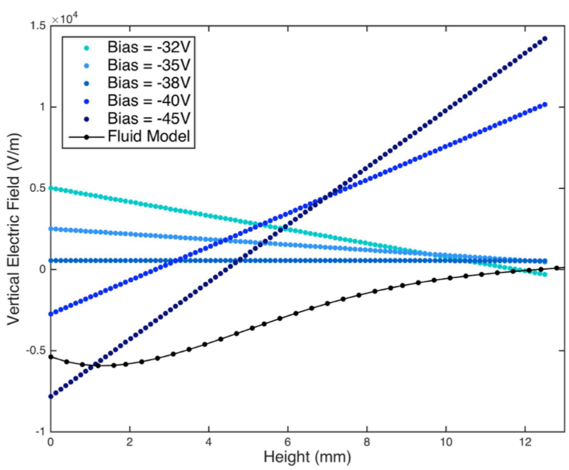

Fig. 5. The vertical electric field strength at the center of the box with varying biases on the lower electrode. The black line is the electric field found from the fluid model shown for comparison. The power is 60 Vrf, V, the pressure is 150 mTorr.

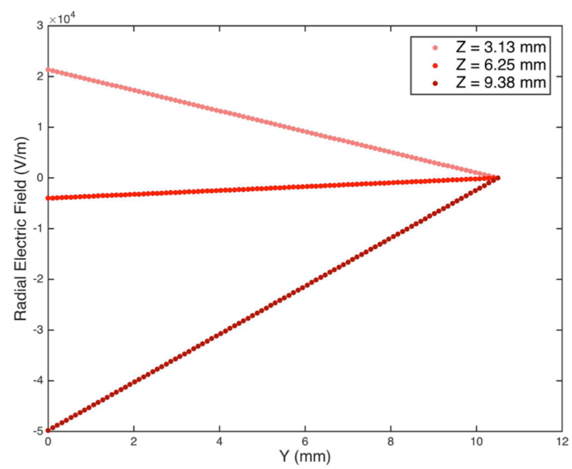

Fig. 6. The strength of the radial electric field at varying heights. This signifies that the particles can only levitate from the half point (Z = 6.25mm) upwards because of the slope of the electric field. The power is 60 Vrf, V, the pressure is 150 mTorr, and the lower electrode has a bias of -40V.

Chains Dynamics code's two variables for the confinement are correct. The *Dynamics* code assumes radial and a vertical electrostatic confinement, both of which can be numerically calculated from the electrostatic potential modeled for the box. The radial confinement is the strength from the side of the box and the vertical confinement defines the height at which the vertical electric force balances gravity.

The vertical electric field as shown in Fig. 3 is promising for the continued modeling with the *Dust Chains Dynamics* code. The vertical potential has a specific limited region where negative particles can exist and this region shrinks as the magnitude of the lower electrode bias is increased. This is important for the *Dust Chains Dynamics* code because it limits the motion that the particles are able to experience. While we have known about the electrostatic potential, we haven't taken the significance into enough consideration previously, allowing the particles to levitate throughout the whole box instead of just a small fraction of the upper box.

The vertical electric field within the plasma is directed downward, towards the negative bias of the lower electrode. However, when the box is added, the electric field is directed upwards within the box since the negative charges are at greater heights (Fig. 3). Previously, we have assumed the box would only be a perturbation in the overall effect of the plasma on the particles. However, this negation of magnitude is significant enough to adjust the parameters within the *Dust Chains Dynamics* code to see what new motion a particle will receive with the increase of the electric field.

The radial electric field has darker sections near the corners and transition region, as seen in Fig. 4. The dust particles require a positive radial electric field slope in order to levitate within the region, so in this case the chain could only exist above 6.25 mm. As the lower electrode bias increases, the transition height rises which shrinks the effective area where the dust particles are allowed to levitate. This result is important to keep in consideration when adjusting the magnitude of the lower electrode.

When the magnitude of the bias is increased, the slope of the electric field increases (Fig. 5). In previous CASPER experiments, there has occasionally been difficulty with the box allowing the dust to levitate inside. Results from the current effort have shown that if the magnitude of the bias was too high, then the box charges positively, attracting the dust particles instead of confining them to the center. There is a range of bias that the experiments can run with, and this helps verify that range.

VI. Future Work

Future work with these results will include merging this new information regarding the confinement of the box back into the *Dust Chains Dynamics* numeric code. This will help the *Dynamics* model more closely emulate the experimental setups by reducing the number of required input parameters. Ultimately we wish to have the model only use initial variables of power and pressure.

Other work can include applying the model to a different kind of box, one where the faces are coated with indium tin oxide (ITO), which causes each face of the box to charge with an electric potential differently. The ITO box is used by CASPER in the GEC cell for other experiments.

References

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