Variation in Particle Levitation Height with Respect to System Potential in a Complex Plasma

Megan D. Johnson, Bernard Smith, Lorin S. Matthews, and Truell W. Hyde, *Member, IEEE*

***Abstract*—Dust is a common component in plasma systems, from silicon chip manufacturing to comet tails. Dust particle clouds in each of these systems can contaminate synthesis techniques or define the properties of protostellar clouds. Experiments have been conducted to describe the crystal structure within the plasma potential well, but more work needs to be done in order to describe the effect of DC bias on the shape of the potential well and the height of the layers within the potential well. By varying the DC bias in the cell, the height was found to vary experimentally as $V_{DC}{}^{2}$ by experimental and numerical methods, but as $V_{DC}{}^{1/2}$ for a theoretical approach. The cause of this discrepancy is yet unknown but may lie in dust charge variance or faulty assumptions. Characterization of the potential well allows for greater control of the conditions created by the applied voltage when manipulating the particles.**

Index Terms— Complex plasmas; Coulomb crystals; Dusty plasmas; Potential variation

I. INTRODUCTION

DUST is a common contaminant in many synthetic and naturally occurring plasmas. Within the semiconductor industry, plasma contamination due to dust results in manufacturing defects in integrated circuits. [1] Dusty plasmas, or complex plasmas, are also found in many environments in space including Saturn's rings, [2] comet tails, and proto-planetary nebula. Dust particles can coagulate to form fluffy aggregates, the initial step in planetary formation. [3]

A complex, or dusty, plasma is one with nanometer or micrometer sized particles suspended within the plasma. Plasma is an ionized gas composed of electrons, slower moving ions, and neutral gas molecules. Plasmas are sensitive to the application of an external electromagnetic field because of their relatively free-moving charges. Dust within a dusty plasma is charged and not necessarily distributed uniformly throughout the plasma. Dust particles within a plasma can form Coulomb crystals, particle arrays with structure partially determined by repulsion amongst the charged dust particles. The positioning properties of the dust are subject to the parameters of the system. One of these parameters is DC bias, the net potential applied across the region of interest. DC bias has a clearly observable effect on dust particle levitation height, but the nature of that effect necessitates further research, some of which will be discussed in this work.

II. EQUIPMENT AND METHODOLOGY

A. GEC Radio Frequency Reference Cell

The Gaseous Electronics Conference (GEC) radio frequency reference cell is a controlled environment in which plasma can be safely and consistently generated. [4] The cell is a vacuum chamber consisting of a parallel-plate electrode system, with a voltage applied to the lower electrode. This voltage ignites an argon-based plasma in the cell. The lower electrode consists of a 10.2 cm flat circular disc with a 2.54 cm circular cutout in the center. With a depth of 1 mm, this cutout allows for the formation of a potential well and the confinement of the dust particles allowed to enter the system.

Manuscript received July 17,2009. This work was supported in part by the National Science Foundation under the Research Experience for Undergraduates program.

Megan D. Johnson was with Baylor University. She is now with Rice University, Houston, TX (e-mail: mdj1@rice.edu).

Bernard Smith is with the Center for Astrophysics, Space Physics, and Engineering Research, Baylor University, Waco, TX 76798 (e-mail: Bernard_Smith@baylor.edu).

Lorin S. Matthews is with the Physics department at Baylor University, Waco, TX 76798 (email: Lorin_Matthews@baylor.edu).

Truell W. Hyde, corresponding author, is with the Center for Astrophysics, Space Physics & Engineering Research, Baylor University, One Bear Place #97310, Waco, TX. 76798 USA (phone: 254-710-3763, fax: 254-710-7309, e-mail: Truell_Hyde@baylor.edu).

B. Melamine formaldehyde Dust

A complex (or “dusty”) plasma is a colloidal mixture of dust and plasma. The dust used to obtain the following data was melamine formaldehyde (4.5, 6.5, 8.9, and 12μm diameter) and nile blue fluorescing melamine formaldehyde (6.4 and 8.8 μm diameter). When the dust particle is released into the system, it falls through the region of plasma within the cell and obtains a negative charge. [1] The negatively charged lower electrode then repels the negatively charged dust particles and the dust is suspended within the cell as a result of the balancing of gravity with electrostatic repulsion. [5] [6] The suspended particles form a coulomb crystal where the forces acting on the particles are balanced by the interparticle repulsion resulting in a hexagonal ion lattice crystal structure. [7]-[9] The particle cloud can be manipulated by the application of varying voltages to the lower electrode or the variation in pressure of the cell.

C. Experimental Technique- Image Capture

Data were collected by both numerical and optical techniques. For each trial, an electronic log was made of the power, DC bias, and reverse power as well as the motor position of various experimental apparatus. Photographs captured during each trial were the most important form of data used for the analysis of the crystalline state and the interparticle forces. When illuminated by a diode laser, the dust particles refract the laser beam and the positions become easily visible. Using a 30 or 60 Hz CCD camera, these images were captured to document the position and movement of the particles.

D. Analysis Techniques

Each collection of images was analyzed using a series of programs in MATLAB. Analysis yielded results in a variety of forms.

1) Pair Correlation Function: The pair correlation function, g(r), or the radial density distribution, shows the probability that the center of another particle will be found at a specific position. Pair correlation functions are useful when determining the phases of a crystal or examining the “packing” of particles in a structure. The function is normalized to the average distance between nearest neighbors. When plotted, the pair correlation function yields a series of peaks of decreasing magnitude with increasing distance from the particle center. For a perfect hexagonal lattice, for instance, the graph of the pair correlation function versus distance would have its largest peak at the normalized nearest neighbor distance of 1, two smaller peaks at $\sqrt{3}$ and 2, extending to describe the distance from the center of each particle to the centers of all the others.

2) Peak Detection for Position: Images were collected from the side of the crystal in order to reveal the separation of horizontal layers. An analysis program was used to determine the relative positioning of the layers for these images. This program allowed for the detection of peaks within an image, or set of images, and a numerical determination of the peak’s position within the cell.

E. Experimental Method

In order to determine the effect of varying voltage on the height at which a crystal levitates, data were collected across a range of applied biases with different particles sizes. In varying the bias, the potential difference between the lower electrode and the plasma changes, altering the conditions in the sheath region, the region below the plasma and above the lower electrode. These altered conditions change where the crystal sits and this level can be captured by photography and analyzed by position. Images were captured for each of the voltages and particle sizes for analysis.

III. RESULTS

A. Theoretical Results

Assuming that the potential in the sheath region is parabolic, that the potential of the lower electrode is V_{DC}, and that the potential at the edge of the sheath is 0, the voltage, V, as a function of height, z, above the electrode can be described by the equation

$$V(z) = \frac{V_{DC}}{d^2} z^2 - \frac{2V_{DC}}{d} z + V_{DC} \tag{1}$$

where d is the distance from the lower electrode to the bottom of the sheath. The electric field, E, is then

$$E(z) = -\frac{2V_{DC}}{d^2} z + \frac{2V_{DC}}{d} \tag{2}$$

and the electrostatic force, F_E, is

(3)

$$F_E(z) = -\frac{2V_{DC}Q}{d^2}z + \frac{2V_{DC}Q}{d}$$

where Q is the average charge of a single dust particle.

At the equilibrium point, h, where downward gravitational force balances the electrostatic force,

$$mg = -\frac{2V_{DC}Q}{d^2}h + \frac{2V_{DC}Q}{d}, \qquad (4)$$

where m is the mass of the dust particle. This allows a description of position, h, as a function of electrode potential, V_{DC}.

$$h(V_{DC}) = \frac{mgd^2}{2V_{DC}Q} + d \qquad (5)$$

This equation has the component, d, which is not a constant, but rather, varies with V_{DC}. According to the Child-Langmuir law of space-charge-limited current in a plane diode,

$$J = en_0u_0 = \frac{4}{9}\left(\frac{2e}{M}\right)^{1/2}\frac{\varepsilon_0|V_{DC}|^{3/2}}{d^2}, \qquad (6)$$

in which J is the ion current into the electrode, e is the electronic charge, n_0, is the plasma density, u_0 is the ion drift velocity, and M is the average ion mass. Solving for d in (6) and substituting back into (5) yields

$$h(V_{DC}) = \frac{2^{3/2}mg\varepsilon_0V_{DC}^{1/2}}{9(eM)^{1/2}n_0u_0Q} + \frac{2^{5/4}\varepsilon_0^{1/2}V_{DC}^{3/4}}{3(eM)^{1/4}(n_0u_0)^{1/2}}. \qquad (7)$$

Utilizing typical plasma values to approximate the parameters of (7), the coefficients for the $V_{DC}^{1/2}$ and $V_{DC}^{3/4}$ terms differ by about five orders of magnitude, allowing the $V_{DC}^{3/4}$ term to be discarded. This equation then predicts a system in which

$$h \propto V_{DC}^{1/2}. \qquad (8)$$

B. Experimental Results

When plotting the data of position vs. applied DC bias, the data follow nearly a perfect parabola (as shown in Fig. 1) in which

$$h \propto V_{DC}^2$$

where h is the relative levitation height of the particles and b is the applied DC bias.

These data were consistent across all examined particle sizes from 4.5 to 12µm diameter particles with dust cloud sizes from five particles to more than 500 in a single layer.

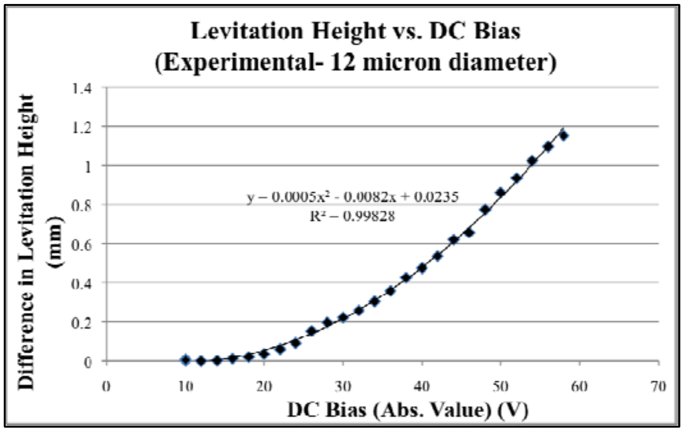

Fig. 1: The experimentally determined positioning of the dust particles fits a parabola as DC bias varies.

C. Numerical Analysis Results

Using a self- consistent dusty plasma fluid model, the plasma parameters were defined in such a way as to display the equilibrium height for dust particles in a plasma system identical to the experimental setup of the GEC cell. As evidenced by Fig. 2, a parabolic variation in levitation height was observed, similar to that seen in the experimental data.

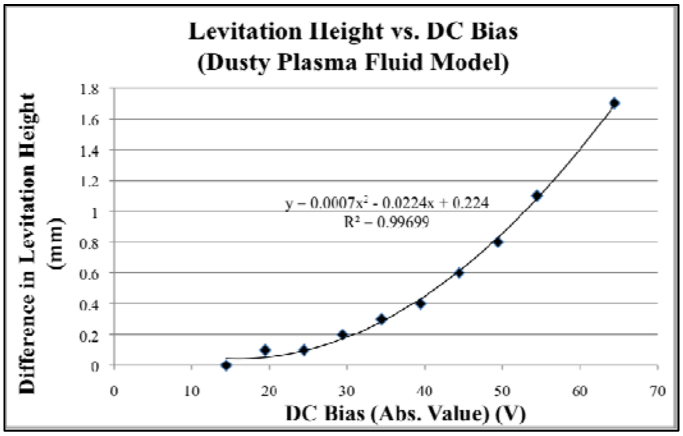

Fig. 2: The numerically determined levitation positions assume a quadratic fit as a function of applied DC bias.

IV. DISCUSSION

As indicated above, the theoretical results disagree with both the numerical and experimental predictions for levitation height within the system. Though the reasons for this are still unknown, two suggestions have been posed regarding how to reconcile the opposing results. First, it is possible that there exists a relationship between dust particle charge, Q, and DC bias. Since eq. (7) is a charge dependent height equation, this could alter the relationship between levitation height and applied potential. Second, the assumptions made within the mathematical progression (such as those necessary for the parabolic potential well or use of the Child-Langmuir Law) could be flawed. For example, the dust particles may not be sitting purely in the sheath, as assumed, but rather closer to the presheath, between the sheath and the plasma, in which case the properties of the potential well and electric field may differ greatly from those originally posed.

V. FUTURE WORK

The clear future path of this work is in reconciling the theoretical predictions with the numerical and experimental results. This will involve pursuit of a concrete relationship between particle charge and system potential. There exists an equation to relate particle oscillation frequency to potential and dust particle charge. Determining the oscillation frequency of the particles at different potentials may provide a way to relate charge to potential and, ultimately, to levitation height. This may provide the missing factors in eq. (7) that cause it to differ from the patterns observed in the data.

ACKNOWLEDGMENTS

Thanks to Mr. Jorge Carmona-Reyes for helpful discussions. Thank you to Dr. Victor Land for helpful discussions and the numerical analysis results. The authors would also like to acknowledge the work of Mike Cook and Jimmy Schmoke on the apparatuses associated with the experimentation detailed here. Thanks also to Baylor University graduate students James Creel, Angela Douglass, and Brandon Harris and NSF REU fellows Michael Pope and Pasha Tabatabai.

REFERENCES

[1] G. S. Selwyn, J. Singh, R.S. Bennett, “*In situ* laser diagnostic studies of plasma-generated particulate contamination,” *J. Vac. Sci. Technol. A*, Vol. 7, No. 4, pp 2758-2765, July 1989

[2] C. K. Goertz, “Dusty Plasmas in the Solar System,” Reviews of Geophysics, Vol. 27, No. 2, pp 271-292, 1989

[3] L. S. Matthews, R. L. Hayes, M. S. Freed, T. W. Hyde, “Formation of Cosmic Dust Bunnies,*” IEEE Transactions on Plasma Science*, Vol. 35, No. 2, pp 260-264, April 2007

[4] P. J. Hargis, et. al. “The Gaseous Electronics Conference radio-frequency reference cell: A defined parallel-plate radio-frequency system for experimental and theoretical studies of plasma-processing discharges,” *Rev. Sci. Instrum.*, Vol 65, No. 1, pp 140-154, January 1994

[5] T. Nitter, “Levitation of dust in rf and dc glow discharges,” *Plasmas Sources Sci. Technol.*, Vol. 5, pp 93-111, 1996

[6] E. B. Tomme, D. A. Law, B. M. Annaratone, J. E. Allen, “Parabolic Plasma Sheath Potentials and their Implications for the Charge on Levitated Dust Particles,” *Physical Review Letters*, Vol. 85, No. 12, pp 2518-2521, September 2000

[7] J. B. Pieper, “Three-Dimensional Structure in a Crystallized Dusty Plasma,” *Physical Review E*, Vol. 54, No. 5, pp 5636-5640, November 1996

[8] M. Zuzic, et. al., “Three-Dimensional Strongly Coupled Plasma Crystal under Gravity Conditions,” *Physical Review Letters*, Vol. 85, No. 19, pp 4064-4067, November 2000

[9] H. Thomas, et. al., “Plasma Crystal: Coulomb Crystallization in a Dusty Plasma,” *Physical Review Letters*, Vol. 73, No. 5, pp. 652-657, Aug. 1994