Effects of dust on the optical emission of rf discharges: Experiment and simulation

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***Abstract*—Dust particles obtain a charge due to the absorption of free electrons and ions from their surroundings. When immersed in a radio frequency discharge, these dust agglomerates may cause changes to the local plasma. In this experiment the optical emission of the discharge was analyzed. Since emission is due to relaxation of atoms in excited states caused by electron impact excitation, the altered emission of the plasma traces changes in the electron density and temperature within the plasma. These results are compared with a two dimensional fluid model to determine accuracy within the experiment.**

***Index Terms*—radio frequency discharge, GEC reference cell, dusty plasma, fluid model simulation.**

I. INTRODUCTION

Dust particles are common contaminants in plasma ranging in size from 10nm to 1mm. They can be found in plasmas contained in technological equipment and have been found to be potentially harmful as in the case of beryllium/carbon plasma facing components (PFC's) [1]. Not only have these particles been observed within the laboratory, but they have also been analyzed within astrophysical and atmospheric conditions [2, 3], and have the potential to be important components within these systems. Thus several experiments have been carried out to study the characteristics of these dust particles and their effects on plasma more carefully. Procedures such as thermophoresis involving electrode heating on a radio frequency discharge [4], studying dust agglomerates on the rings of Saturn [2], and studying the formation of dust within an rf discharge [5] have all been carried out to analyze the properties of such dust agglomerates.

Plasmas are becoming more and more essential components within technology. Studying the effects of dust on plasmas, therefore, has become necessary. Studies such as analyzing the formation of dust particles within certain radio frequencies [6], and simulations such as particle-particle particle-mesh simulations [7] and two-dimensional fluid models [8] have been used to learn more about these complex plasmas.

In this experiment the effects of dust particles on radio frequency discharges was focused on by observing changes within emission for different amounts of particles introduced into the plasma. Although electronic data measuring the electric potential, current, and derivative signals were measured also, this paper will focus on results from images taken with the charge-coupled device (CCD) camera. A two-dimensional fluid model was employed to compare with experimental results.

II. THEORY

What distinguishes plasma from other states of matter is the ionization of particles due to a high amount of energy given to the system. This energy knocks electrons off neutral atoms, creating an environment containing neutral atoms, electrons, and ions [9]. When the electrons collide with neutral atoms, the atom enters an excited state. When the atom de-excites, a photon is released creating emission. From a previous experiment

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utilizing argon plasma [10], the emission intensity of the plasma can be described as

$$I_\lambda = n_e n_{AR} \int_0^\infty 4\pi v^3 \sigma_\lambda(v) f_e(v) dv, \quad (1)$$

where $n_{e,}$ $n_{Ar,}$ σ, $\lambda_,$ and f_e, are the electron and argon atom density, the cross section of the photon emission due to electron excitation, the wavelength of the photon emitted, and the electron velocity distribution function. This equation signifies the dependence the emission of the plasma has on electron density and the distribution of electrons.

When dust particles enter the process, plasma is then referred to as complex plasma. Dust particles become charged due to freely moving negative electrons and positive ions within the system. As the less massive electrons move considerably faster than the ions within the plasma, collisions involving electrons with particles occur more often than collisions involving ions with particles. Thus, the dust becomes negatively charged. One can say the dust particles absorb a number of electrons in the plasma, changing the dynamics within the system. This could result in a decrease of the amount of free electrons that collide with neutral atoms within the plasma.

By taking exposures of the plasma, the local distribution of the emission intensity from the plasma can be observed. Since emission within the process is the result of electrons colliding with neutral atoms, one can determine changes in the amount of free electrons within the plasma. Since dust particles are expected to absorb free electrons, the intensity within the plasma should, by theory, decrease somewhat due to the reduced amount of free electrons colliding with neutral atoms to release a photon.

III. Experiment

A diagram of the Gaseous Electronics Reference Cell at CASPER is shown in figure 1. The stainless-steel chamber is made of two electrodes. The top electrode is a grounded cylinder that is hollowed out to allow exposures to be taken of the top view of the chamber. The images were taken with a CCD camera located at the top of the GEC reference Cell. Side-view images were also taken through another CCD camera at the side of the chamber. To illuminate any dust particles involved in the experiment, two diode lasers with cylindrical lenses were used to create laser sheets that helped to enlighten the dust clouds.

Unlike the grounded top electrode within the chamber, the bottom electrode is charged by a frequency signal generator at 13.56 MHz. On top of the lower electrode lies a circular plate with a cutout. The cutout helped confine the dust clouds by creating a potential well. For this experiment, 1.5 and 2 inch cutouts were used. 6.5 and 12 μm-sized Melamine-formaldehyde dust particles were introduced into the cell through dust shakers at the top of chamber.

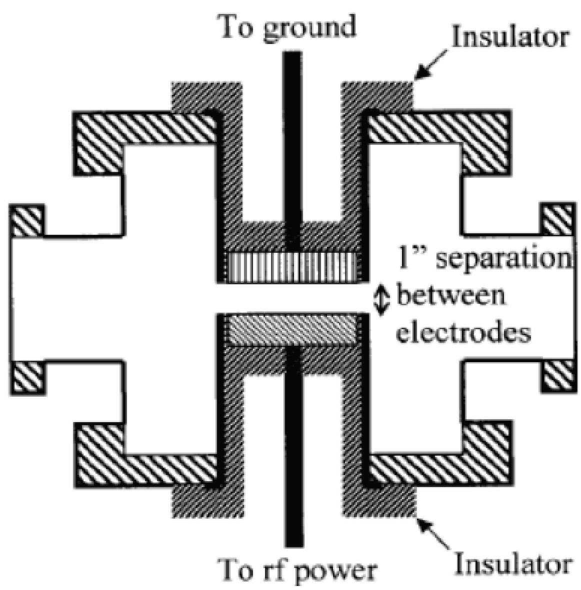


Figure 1: A schematic side-view of the GEC reference Cell at CASPER. Within our experiment, there was a 2 cm rather than a 1 inch difference between the electrodes.

The experiment was constructed into three parts. The first part of the experiment changed parameters of power, pressure, and amount of dust particles while using 6.5μm sized dust and keeping the electrode spacing at 1.99 cm. Powers of 3, 4, and 5 W were used and 200, 400, and 600 mT pressures were utilized. In the second part, the parameters and electrode spacing were not altered, but the size of melamine-formaldehyde dust was changed to 12 μm. The last section of the experiment consisted of an electrode spacing of 3.3 cm and 6.5 μm-sized dust particles. The same pressures and powers were again used. Images of the plasma without dust were first taken. Exposures including 100, 1000, and 10000 particles were then obtained. While both side and top-view exposures were taken of the chamber, electronic data through an oscilloscope was being taken. The data consisted of the potential, the current, and the two derivatives of these signals. The derivative channels were used in order to find the phase angle between the potential and current [4].

IV. THE FLUID MODEL

A two-dimensional model of the experiment was simulated to compare with the data from the lab and is described more thoroughly in previous papers [11, 12]. The theoretical model assumes the characteristics of ions, electrons, and neutral atoms within argon plasma at an experimental lab setting. The model accounts for plasma by creating a balance between ionized argon atoms and electrons. The electric field is modeled by Poisson's equation in where the dust particle charge is included. The movement of energy concerning electrons is accounted for through the excitation of argon atoms, ionization within the cell, and the absorption of electrons by dust particles. Ions are assumed to lose their energy through inelastic collisions with argon atoms.

When the plasma within the model reaches a periodic RF-cycle, dust can be added into the model. These dust particles are designed to obtain ions and electrons, therefore gaining a negative charge. The fluid model simulates several characteristics of the dusty plasma, including the electron density, the ionization of the plasma, the number of electrons, the heating of the electrons, and the amount of electrons lost in the plasma. The parameters set for the fluid model for this experiment include 3, 4, and 5 wattage powers and pressures of 200, 400, and 600 mT. Electrode distances of 1.99 and 3.3 cm were utilized in the simulations. Simulations with no dust particles and 10000 dust particles were performed.

V. DATA/RESULTS

a. The Images

After exposures were taken with the top view camera, the images were averaged and intensity profiles were constructed. Figure 2 shows a two-dimensional plot of the percent difference of intensity between the plasma containing no dust particles and 10000 particles was made. The plot illustrates a 4 percent decrease in intensity when 10000 dust particles are contained within the plasma. One can also observe the whole cell decreases in intensity overall as well. Figure 3 is an intensity plot of an exposure with 10000 particles contained in the plasma. The diode lasers illuminate the dust particles in the image order for their location to be known. The position of largest decrease in emission seems to coincide with the position of highest dust density."

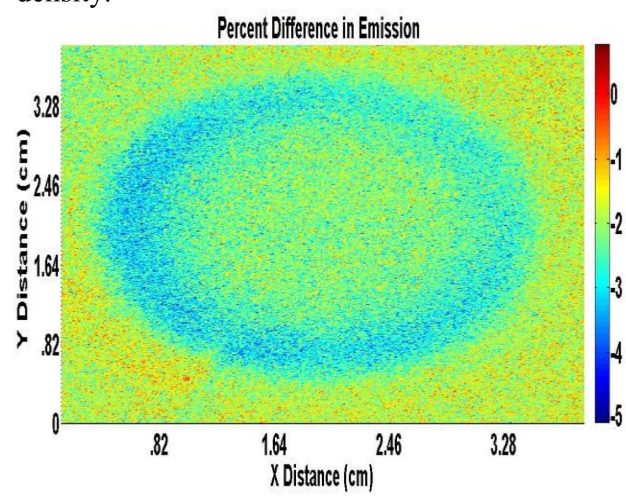


Figure 2: Percent Difference of Intensity between approx. 10000 particles and no particles within the plasma at a pressure of 400 mT and 4 W.

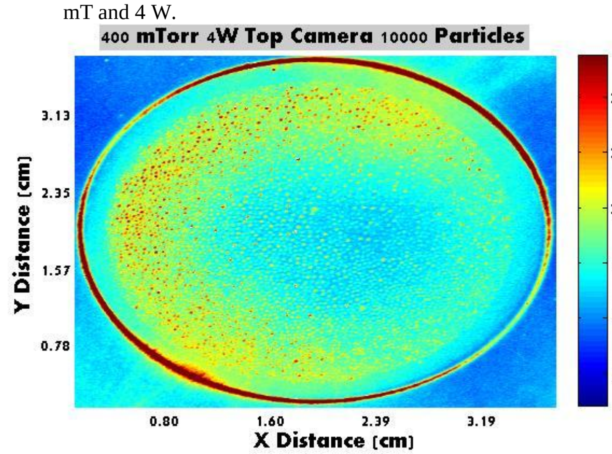


Figure 3: Intensity plot of exposure containing 10000 dust particles. The dust particles are illuminated by the diode lasers within the lab.

b. Plotting Differences between Intensities

After finding the percent difference between the intensity of the plasma with dust particles and the plasma containing no dust particles, the middle horizontal line of pixels in each image was taken and the difference of these lines was analyzed. A line plot illustrating the percent difference was constructed. In figure four, the percent difference of intensity between approximately 100 dust particles and no dust particles within the plasma, and the percent difference between approximately 10000 dust particles and no dust particles, were plotted. There is a clear decrease in intensity throughout the cell when dust particles are added. A significant decrease in intensity can also be seen at distances .82 cm and 3.29 cm. There is a larger decrease in intensity overall for approximately 10000 dust particles being added to the plasma compared to approximately 100 dust particles.

To illustrate the relationship of the location of the dust particles and the decrease in intensity within the plasma more clearly, line plots of the percent difference of intensity at 400mT 4 W and of the intensity of the exposure with approximately 10000 particles illumintated are shown in figure 5. At a distance of 0.82 and 3.29 cm there is a dramatic increase in intensity within the line plot. This is assumed to be where the dust particles lie. Within the percent difference line plot of intensity at 400mT 4 W there is also a decrease of intensity located at these distances, illustrating a correlation between the distribution of dust particles within the cell and the local distribution of intensity within the plasma.

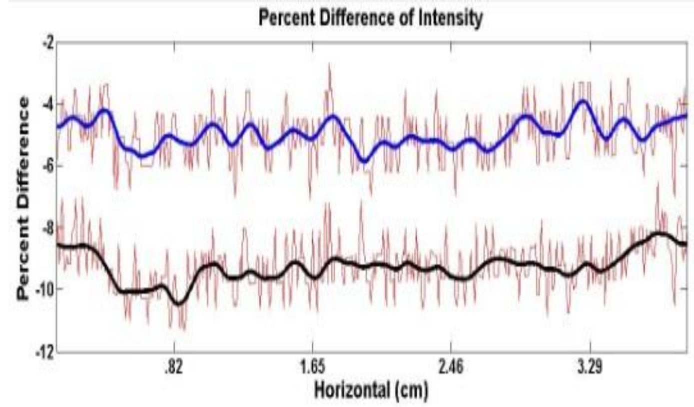
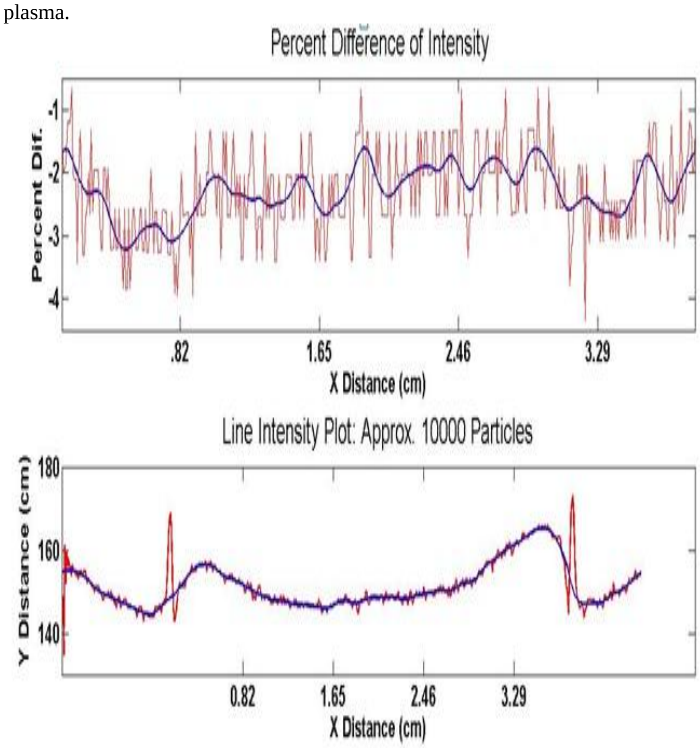


Figure 4: Percent Difference of Intensity between 100,10000 and no dust particles. The blue line shows results for 100 dust particles and the black line is for results containing 10000 dust particles within the plasma.



Figures 5: (Top) Percent Difference between 100, 10000, and no dust particles at 400mT, 4 W. (Bottom) Line Intensity plot where the dust within the plasma is illuminated

C. *Fluid Model Results*

Results are shown for the two-dimensional fluid model with parameters of 400mT pressure at 5W in figure 6. The fluid model only simulates half of the reference cell, from the center of the cell where the bulk of the plasma lies to the walls of the cell (see figure 1). The middle horizontal line of the simulation was compared with the change in electron heat by plotting a line graph. The heat from electrons was found to decrease around a distance of .02 m when 100000 particles were added to the fluidmodel. This distance is where the dust particles are located within the simulation.

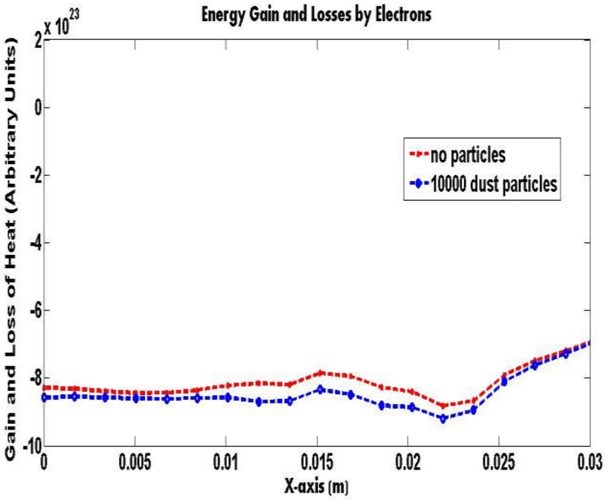


Figure 6: Results considering the electron heat within the two-dimensional fluid model.

VI. Discussion

Within the data, there is a correlation between where the dust particles are located within the cell and where the largest decreases in intensity occur within the plasma. The decrease in intensity of the dusty plasma becomes greater as more dust particles are contained within the reference cell. This is due to the dust particles absorbing electrons, causing fewer collisions with neutral atoms to release photons and emit light. This observation is confirmed through the two-dimensional fluid model. Runs at a pressure of 400mT and an input power of 5 W were analyzed. The electron heat seems to decrease within the cell at a distance of .02 meters. This distance is where dust particles exist within the simulation. When dust particles absorb free electrons, there are fewer electrons to collide with neutral atoms. This would mean a decrease in heat would exist where dust particles are located within the plasma. The fluid model results, therefore, validate the experimental results.

VII. Future Works

Analyzing the side-view exposures of the reference cell and the fluid model simulations is still in process. After this data has been fully examined, more parameters are to be tested to further inspect the effects of dust particles on plasma at different powers and pressures. Different types of dust particles, such as gold-coated Melamine-formaldehyde, can be observed within the GEC reference cell. Lastly, to confirm observations made within the lab, simulations of the fluid model will be run at the parameters paralleling the new parameters that will be tested within the reference cell.

VIII. Acknowledgements

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