Effects of dust on Argon Plasma in a GEC Reference Cell RF Discharge

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***Abstract*—Dust particles in plasma obtain a charge due to the continuous absorption of free electrons and ions from the surroundings. Depending on the dust size and number density, this can significantly alter the local plasma, as well as the global discharge characteristics. Here we present measurements of the changes in optical emission originating from argon plasma, as well as changes in the electrical properties of the discharge, as dust is introduced into the plasma with varying number densities and sizes. Measurement of the electronic signals of the discharge, including the electrode potential, current, and derivative signals allows determination of the complex impedance and with that, determination of changes in the equivalent circuit of the discharge.The experimental results are compared with numerical results from a two-dimensional dusty plasma fluid model.**

I. INTRODUCTION

Complex (dusty) plasmas are as old as plasmas and occur in a variety of places from laboratory experiments to interstellar clouds and planetary ring systems [1], [2]. Dusty plasmas are partially ionized gases containing small solid particles [3]. Dust grains are small particles that form within a plasma and normally obtain a negative charge causing the particles to levitate within the plasma [4]. Dusty plasmas can be found in Saturns rings, high energy fusion reactors, and in the surface processing industry [1], [5], [6].

In the surface processing industry, plasmas play an important part. They are used in all areas of surface processing from surface etching to hard coatings, and even in solar cells [2], [6], [7]. Dust can become an issue when dealing with plasma-assisted etching and microelectronics, but can be helpful when dealing with the fabrications of hard coatings [6], [7]. Plasma-surface interactions are influenced by the positive ion energy, which is affected by the presence of dust [7]. The presence of dust in high energy fusion reactors cause issues because dust breaks down the inner lining of the reactor and makes the plasma unstable [5].

Some past research done in plasma physics was to determine how the dust forms within the plasma, dust crystal formation, phase transitions, and wave activities [2], [8], [9]. Some research has been done studying the discharge properties of dusty plasma [9]. The purpose of this project is to determine how dust introduced from the exterior changes the plasma parameters locally and globally. The presence of dust changes plasma parameters but it is uncertain to what extent it changes them. We will be looking at the plasma glow to determine how the dust changes the plasma locally, and analyze the effective circuit to see how the dust affects the plasma globally. This paper will focus on the global effect of the dust by determining how dust changes the the effective circuit.

II. THEORY

In order to determine the global effects that dust has on the plasma we look at how the dust changes the effective plasma circuit. Figure1 shows the effective circuit before dust is added (Left) and after dust is added (Right). The sheaths act completely capacitive while the plasma acts completely resistive. The dust floats between the plasma and the sheaths, and is represented by a black box since its effect on the plasma circuit is unknown.

To study the plasma circuit it needs to be broken up into its different components. In order to determine the sheath capacitance and the plasma resistance, the total resistance (impedance) of the circuit needs to be calculated. The impedance (Z) is the total resistance of the circuit and is given by:

$$|Z| = |V|/|I|, \tag{1}$$

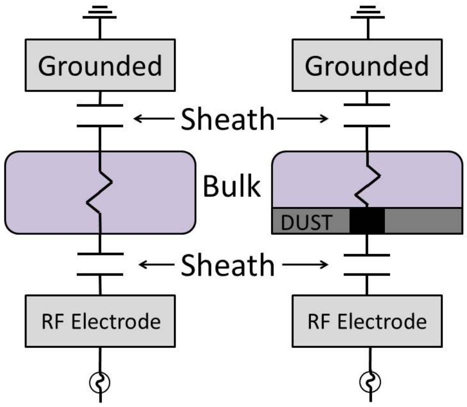

Fig. 1: **Left:** Schematic of the effective plasma circuit before dust is added. **Right:** Schematic of the plasma circuit after the dust is added. Since it is unknown how the dust affects the circuit it is shown by a black box. The bulk in the diagram is the central part of the plasma discharge.

where V is the potential and I is the current going through the circuit. The phase angle difference (Φ) is the difference in phase angles between the current and potential signals. A sinusoidal curve was fit to each signal, to determine that signals phase angle, and then the difference was found using $\Phi = \phi_I - \phi_V$. Once Z and Φ are determined, the plasma resistance can be calculated using the equation

$$|R| = |Z|/\sqrt{1 + tan(\Phi)^2}. \tag{2}$$

From the plasma resistance, the total sheath capacitance can then be calculated using the formula,

$$|C| = |R|tan(\Phi). \tag{3}$$

Once the capacitance and the resistance are calculated, the impedance can be recalculated using the original impedance formula,

$$Z = R_B + iC, \tag{4}$$

where C is the capacitance of both sheaths compbined. By taking the complex conjugate to get,

$$|Z|^2 = |R|^2 + |C|^2. \tag{5}$$

Calculating the impedance the second time allows for comparison between this equation and equation 1.

III. EXPERIMENT

A. GEC RF reference cell

The experiments were performed using a Gaseous Electronics Conference (GEC) radio-frequency reference cell. The GEC cell is an experimental enviornment used to run a variety of plasma experiments. The cell is designed to allow for fair comparison of results between different laboratories and has been modified to run dusty plasma experiments [10].

The top electrode as seen in Figure 2, is hollow and grounded. Dust shakers are placed just above the upper electrode and dust is inserted into the cell through the top electrode. Two cameras are placed around the cell, one above to take top images of the plasma and one to the side to take side images of the plasma. There are two diode lasers placed around the cell; One is a horizontal laser and is used with the top camera and the other is a vertical laser and is used with the side camera. The lasers illuminate the dust by scattering the light off the particles which is then picked up by the cameras. This allows for images of the dust to be taken. Figure 2 also shows the bottom electrode which is powered using an RF amplifier. Cutouts are placed on the lower electrode and are used to create potential wells. Potential wells contain the particles and prevents them from falling off the edge of the electrode.

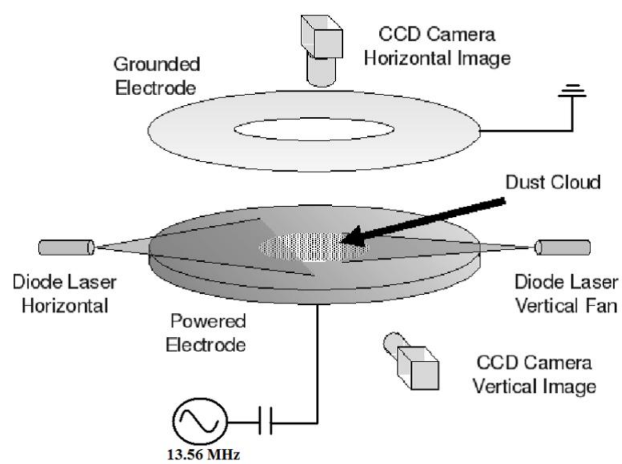

Fig. 2: Schematic of the modified GEC RF reference cell.

B. DATA COLLECTION

The GEC Reference cell was set up with an electrode spacing of 1.99 centimeters and a 2.0

inch diameter cutout . Baseline images and data were taken at three different pressures, 200 millitorr, 400 millitorr, and 600 millitorr, and three different powers, 3, 4, and 5 watts. Once the baseline images were taken, they were repeated using the 1.5 inch diameter cuout and adding dust.

In order to determine how dust affects the plasma, baseline images and electronic data were taken without the dust. Once the baseline images were taken dust was added and more images and electronic was taken. After all the dust runs for one setting was complete, process was repeated for different settings. The experiment was run for the settings listed in figure 3.

Experiments performed

Power	Pressure	#particles		electrode spacing	
3W	400mTorr	0	10000	2.0cm	3.3cm
4W	400mTorr	0	10000	2.0cm	3.3cm
5W	400mTorr	0	10000	2.0cm	3.3cm

Fig. 3: List of settings used for the experiment.

C. FLUID MODEL

The fluid model is a two dimensional model used to solve the equations for the electrons, ions, and dust within an argon plasma [10], [11]. It uses a variety of equations to solve for different plasma parameters that are difficult to measure in the lab such as electron, ion and dust densities, ion and electron temperatures, and plasma potential. The fluid model geometry is very similar to the cell geometry in the lab and allows for comparison between experiments and fluid model runs. the settings used in the fluid model were the same as in the lab except only the 3.3 centimeter electrode spacing ws used.

IV. RESULTS

A. Experiment

After collecting the electronic data, matlab was used to calculate the different elements of the circuit and plot them verse the recorded power. Figure 4 shows the potential and current signals of the plasma circuit. From these signals ϕ_I and ϕ_V were obtained, which then allowed for Φ to be calculated. Once Z and Φ were obtained, equation 2 and then equation 3 were used to calculate the resistance and capacitance

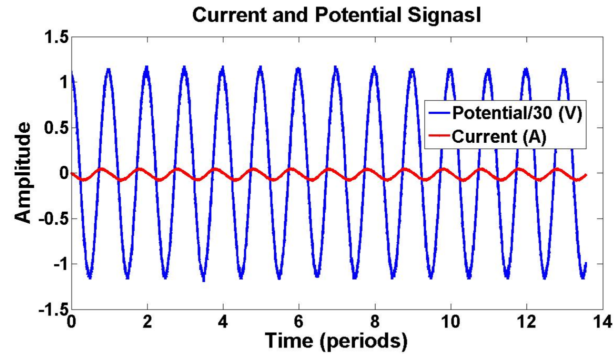

Fig. 4: Current and potential signals of the plasma circuit obtained from the electronic data.

for the runs with and without dust. Figure 5 shows the baseline data for impedance, capacitance, and resistance.

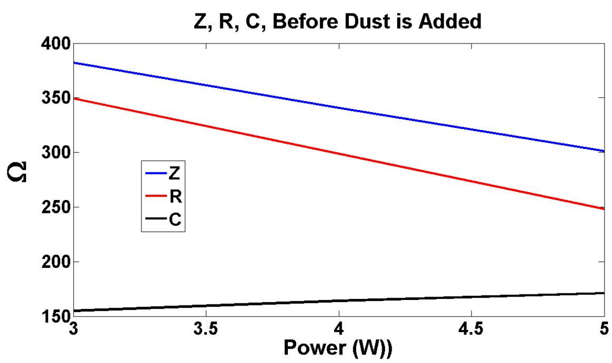

Fig. 5: Baseline data before dust was added.

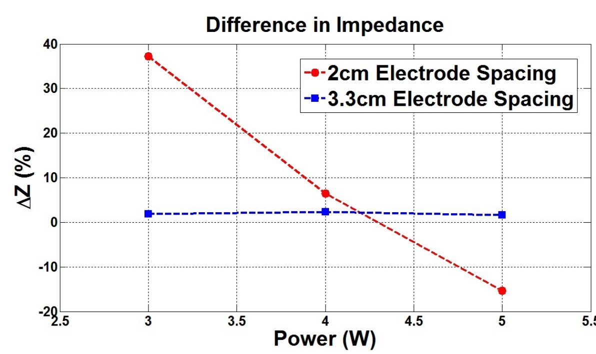

Fig. 6: Difference in Impedance the dust run and the no dust run. Taken at 400mTorr pressure, 1.5in diameter cutout, 6.5μm dust.

Figure 6 shows the difference in impedance between the dust and no dust cases. As figure 6 shows there is a large difference in impedance due to the dust with the small electrode spacing, but a small difference with the large electrode spacing.

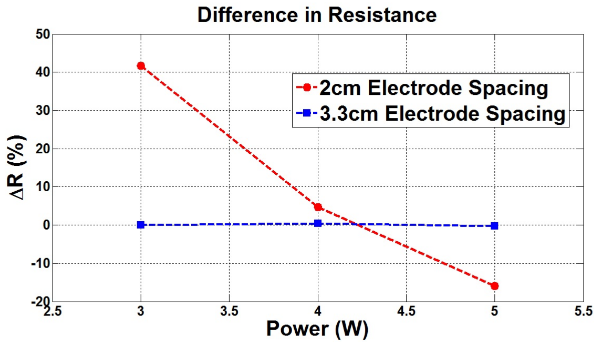

Fig. 7: Difference in Resistance between the dust run and the no dust run. Taken at 400mTorr pressure, 1.5in diameter cutout, 6.5μm dust.

Since figure 6 shows a change in impedance based on the dust it is important to look at the resistance of the system with and without the dust. Figure 7 shows the percent difference in the resistance of the plasma between the experiment with dust and without dust. From the image there is very little change in resistance with the large electrode spacing, but the dust causes a large change in resistance, around 40%, with the small electrode spacing.

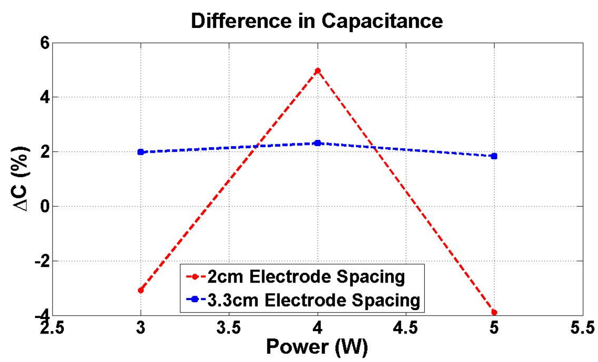

Fig. 8: Difference in Capacitance between the dust run and the no dust run. Taken at 400mTorr pressure, 1.5in diameter cutout, 6.5μm dust.

The percent difference between the case with dust and without dust was then found and plotted in figure 8. Here it shows that there is very little change in the sheath capacitance during the 3.3 centimeter experiment, and a large change in capacitance for the 2 centimeter experiment.

B. Fluid Model

After the fluid model finished running the data was analyzed and graphed using a matlab code. The code took the data at the center point x=0 and graphed the parameters verse the height. Figure 9 shows different combinations of charge densities. The red line is the total charge density, ion charge density plus electron charge density, for the case without dust. The blue line is the same calculation but for the case with dust, while the pink dotted line is the total charge density, electron density plus ion density plus dust charge density. The blue line shows where the dust is sitting by the large jump in charge density between 10 centimeters and 10.5 centimeters.

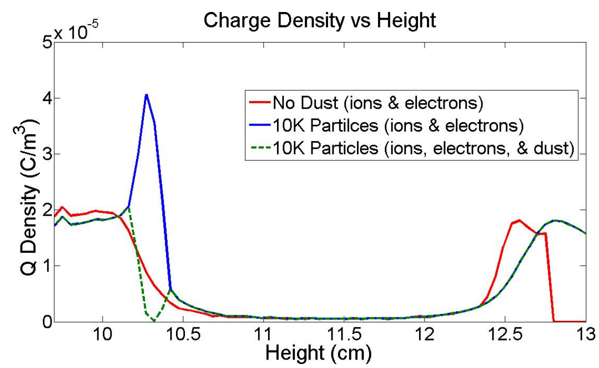

Fig. 9: Total Charge Densities for the no dust and dust runs in the fluid model. The setting for this run were, 4W, 400mTorr, 1.5 inch cutout, 6.5μm MF Dust, 3.3cm Electrode spacing.

V. DISCUSSION

Figures 6 through 8 show that the presence of dust has a greater impact on the plasma circuit when the electrodes are closer together and a very minimal impact when the electrodes are far apart. For the small electrode spacing the impedance and the resistance follow the same trend, dust increases them the most at 3 watts and then decreases it at 5 watts. Figure 7 shows that at 3 watts the dust causes around a 40% increase in the impedance and resistance. Figure 8 shows the capacitance has a small change due to the dust. This could be due to due to error within the system. For the large electrode spacing the dust does not have a large impact on the system. The increase in resistance at 3 and 4 watts of the small electrode spacing could be due to the dust acting as a resistor, since resistors applied in a series circuit increase the total resistance of the system. The decrease in the resistance at the 5 watts could be due to the dust changing the shape of the plasma by either increasing or decreasing the size of the bulk. Since the dust changes the different circuit components less with the larger separation could be due to the dust changing the plasma less.

Figure 9 shows the total charge densities with and without dust. The blue line is the charge density of the dust run without the charge of the dust added in. The large increase between 10 centimeters and 10.5 centimeters shows where the ions are located. Since the charge density with the dust added in follows the no dust very closely it is determined that the dust is sitting where the blue line spikes up. From the figure there is a slight change in both the plasma size and capacitance size. The small change in size would correlate with a small change in resistance and cacitance. Using,

$$R_b = 10^{-7}(n_{gas}/n_e)\sqrt{T_e} \tag{6}$$

The resistance for the plasma before dust and after dust was calculated, where T_e is the electron temp, n_e is the electron density, and n_{gas} is the atom density calculated using $n_{gas} = P/(k_B T)$. Using the numbers given in the fluid model the percent change in the resistance came out to be around 7% for the 3.3 centimeter spacing. This is around the same increase as found in the experimental results.

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