Potential Mapping of an Indium-Tin-Oxide Glass Box in a GEC Reference Cell

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Abstract— **The use of indium-tin-oxide (ITO) coated boxes, as well as boxes coated with other substances, placed on or floating above the lower electrode in studies using Gaseous Electronics Conference Radio Frequency Reference Cells have increased in interest, as have the use of plain glass boxes. This increase in interest is due to the greater ability to control the confinement forces and in effect create dust chain structures which aid in studies within other areas of physics such as; entropy, kinetic dust temperature, plasma balls and coulomb explosions. Further analysis of the data obtained using these boxes shows what appear to be at least two different regions of confinement inside the boxes as well as some unexpected phenomena related to anomalous values and behavior of the electric field. These areas affect the dust to dust and dust to plasma interactions independently in the separate regions and are therefore of great interest. In this study electric potential and electric field maps created in MatLab with data obtained using two probes mounted on CASPER's S-100 nano-manipulator will be presented, connecting the information obtained from these maps to the behavior of the dust observed for different experimental conditions.**

Index Terms—**Complex Plasma, Indium-Tin-Oxide, ITO box, S-100, GEC Cell**

I. Introduction

PLASMA is a quasi-neutral ionized gas (consisting of positive ions and free electrons), often occurring at low pressures (as in the Earth's upper atmosphere and in fluorescent lamps) or at very high temperatures (as in stars or in nuclear fusion reactors) [1]. Plasma has a very high kinetic energy, an indefinite shape, an indefinite volume, extremely low density, is compressible, and has the ability to flow. Dusty (or complex) plasma is plasma containing mm to µm sized particles suspended in it [1]. Dusty plasmas are found naturally occurring in nature; repetitive examples include fire, the auroras (northern and southern lights), the solar wind, interstellar space, the sun, nebulae, the ionosphere, lightning, pulsars and much more [1]. Plasmas in general are electromagnetic (Maxwell-Boltzmann) systems [2]. GEC RF Reference Cells are used for experimental dusty plasma research.

Recently indium-tin-oxide coated glass boxes, as well as plain glass boxes, have been placed on the lower powered electrode in a Gaseous Electronics Conference Radio-Frequency Reference Cells to provide confinement. Using these boxes provides researchers an increased ability to control the confinement forces which, in effect, create the dust chain structures. Acting as probes, the dust in these structures aid with fundamental studies in other areas of physics such as entropy, kinetic dust temperature, plasma balls and coulomb explosions.

In this case, the dust particles used are comprised of melamine-formaldehyde (MF) and dropped into an argon plasma. The MF dust particles are synthetically manufactured (by MicroParticles DE), come in a variety of sizes, and are therefore uniform in shape, size, density, and mass (depending on the particle size). Once dropped into the plasma these particles are bombarded mainly by the electrons within the plasma and gain a negative charge [3]. Dust levitates in the sheath region and is used in this case as probes to allow comparison to the electric potential and the electric field maps of the inside of the box. We are interested specifically in looking at the electric potential and the electric field at the rf system power values at which the dust, due to a host of forces, is able to levitate in the box and at those which it is no longer able to.

The electrostatic force, the gravitational force, the ion drag force, and the neutral drag forces act on the particles while they are in the plasma [4][5]. In the ion rich plasma sheath region, particles are acted on by gravity, the ion drag force, the neutral drag force, the electric field, the magnetic field (though negligibly small), and a host of other forces (also negligibly small) both pulling them downward and pushing them upward. The main force pulling down is gravity while the main force pushing up is the electrostatic force. The state of equilibrium reached at certain points between these forces is what allows the particles to levitate.

A comprehensive analysis of the electric potential inside the box is needed before any proper analysis of the system can be accomplished. From the electric potential the electric field inside the box can be calculated by taking the negative gradient of the potential.

We present in this study, an analysis of the experimentally determined electric potential and electric field maps of the inside of an ITO box in a GEC reference cell. These maps were created using data obtained by two probes mounted on CASPER's S-100 nano-manipulator. The Zyvex S-100 nano-manipulator is a tool typically used for positioning and testing of micro- and nano-scale research and development applications [6]. The probes used included both a reference and measurement probe. The reference probe was kept in the plasma at all times in order to produce a baseline, this baseline is the plasma potential being read by the reference probe. The measurement probe was used to collect data of the electric potential inside the ITO box at different points within the box. The information from these maps is connected to the behavior of the dust observed for different experimental conditions. To determine the reliability of the technique used to produce these maps, they will be compared, along with continued research throughout the coming year, to other independently produced maps.

II. Experimental method and experiment

A. General Setup

In order to study the effect of confinement on the dust in a dusty plasma and to map the electric potential inside the ITO box, a Gaseous Electronics Conference Radio Frequency Reference Cell (GEC RF Reference Cell) [7], containing a dish placed on the lower electrode was used.

To allow greater control of the dust particles via the confinement forces, dust was introduced into a one-half-inch indium-tin-oxide (ITO) [8] coated glass box which was free floating with respect to the plasma. The box was placed on the lower electrode with a 2mm gap (see figure 1). Indium-tin-oxide is a clear conductive material (liquid or film) which acts as a transparent electrical conductor.

A radio frequency signal generator and amplifier supplied a frequency of 13.56MHz to the lower electrode; the upper electrode and cell walls were grounded. A matching network was used to maintain the system at an impedance of 50 Ω and argon gas was supplied to the system to create an argon plasma. The GEC reference cell system was initially assumed to be at room temperature, with the parameters varied inside the cell by changing the power being supplied to the system, the vacuum pressure inside the cell, and the amount of dust introduced to the system.

In the experiments performed, the forces involved were the ion drag force, neutral drag force, gravity, and electrostatic potential (producing an upward force). Changes to the rf power supplied to the lower electrode and the system as a whole, resulted in a change in the voltage being supplied to the box. Dust used were 8.89µm & 6.50µm Melamine-Formaldehyde (MF) particles. A side mounted StingRay 100mW (red) laser was used for illumination of the particles and two cameras (a Photron FASTCAM PC 1024 and a Sony XC-HR50), one above and one on the side of the GEC reference cell, were used to view and record the particles while they were inside the ITO box. The main camera used was the Photron FASTCAM PC 1024 with a CMOS sensor chip, K-2 infinity lens with a CF-1 objective (providing a focal length of about 30cm) and a frame rate of up to 1,000 fps at full resolution [9]. The other camera, mounted above the cell, was the Sony XC-HR50 with a CCD sensor chip [10].

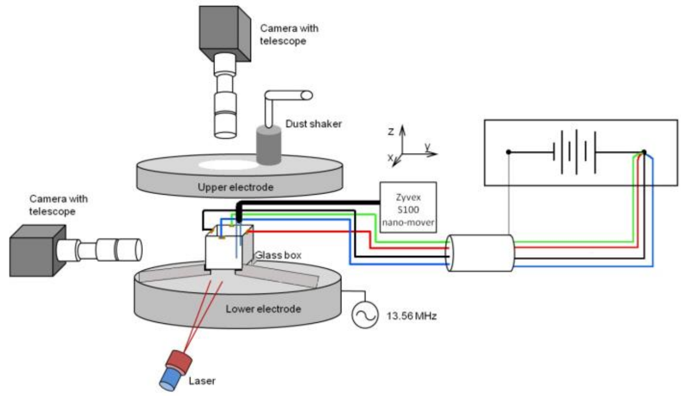


Fig. 1: Schematic of the experimental setup in the GEC Reference Cell.

In order to collect the data needed to create the maps of the electric potential and electric field inside the ITO box we used an S-100 nano-manipulator (Zyvex). Mounted on the S-100 were a reference probe (which was kept in the plasma at all times), and a measuring probe (which was kept in the sheath) to allow mapping the potential inside the ITO box. Data for two separate maps, one at 8 W (650mV) and one at 6 W (550mV), were collected. These values were chosen based on previous experiments in which the dust was dropped into the box and plasma; these are the values at which the dust was able to levitate and when it was no longer able to do so.

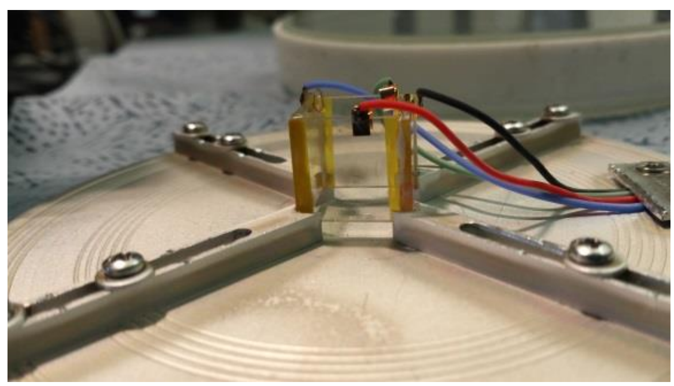


Fig. 2. Image of the ITO Box placed 2mm above the lower electrode in the GEC Cell.

B. The Dust

In the first few experiments performed the main objective was to determine the appropriate parameters at which to map the electric potential inside the ITO box. The parameters used were; 19.6 SCCM, a natural bias of -156V, a system power of 26 W [11] which was decreased throughout the course of the experiments, a pressure of 315mTorr, a driving frequency of 13.56MHz, and both 8.89µm & 6.50µm dust particles. The rf power supplied to the system, and in effect the voltage being supplied to the box, was varied to see at what rf power the dust would levitate in the box and where, how they moved and in what shape, and at what rf power they would drop.

The data collected was analyzed using ImageJ and the plugin MTrack2, in order to track the positions and trajectories of the particles. A movie editing program, Kinovea [12], was used to determine at exactly what point in the image sequence (and indirectly at what power) the particles dropped. It was observed that the particles rose in height in the box and became more compact, being pushed together and up by a very strong force, immediately before dropping. This can occur in a matter of milliseconds. The force(s), electrostatic repulsion, pushing the particles up and together seems to completely disappear, causing them to drop. The exact time of this occurrence in the image sequences was determined with the use of Kinovea. This is important to know because it tells us at exactly what power the particles become discharged and are no longer able to levitate in the plasma.

C. *The Maps*

The remainder of the experiments performed were conducted using the S-100 nano-manipulator, the reference probe, and the measuring probe to map the potential inside the ITO box. The reference probe was mounted approximately an inch above the measuring probe to ensure it would be in the plasma throughout the experiments. Data for three separate sets of maps were collected, two at 8 W (650mV; one with the box inside the GEC cell and one without the box inside the GEC cell) and one (with the box inside the GEC cell) at 6 W (550mV).

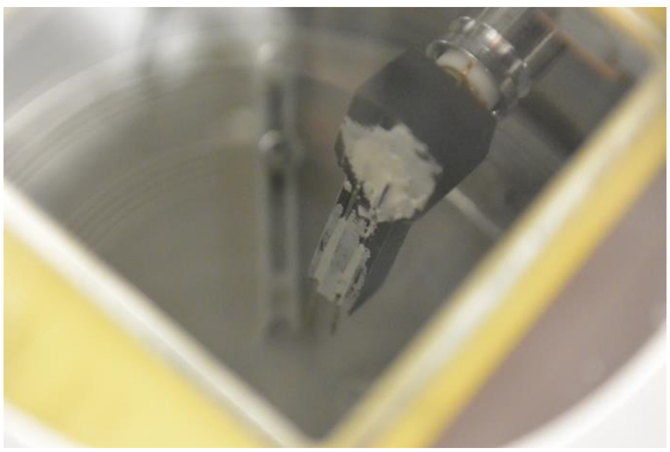


Fig. 3. Image (top-view) of the S-100 with the reference probe mounted 1 inch vertically above the measuring probe.

The data collected was analyzed, initially in Microsoft Excel and then imported into MatLab. MatLab was used to create a matrix map of the electric potential data to be plotted as a surface figure. Using a MatLab file exchange program [13] a new matrix map of the electric field was created and then converted from units of volts per pixel to volts per meter.

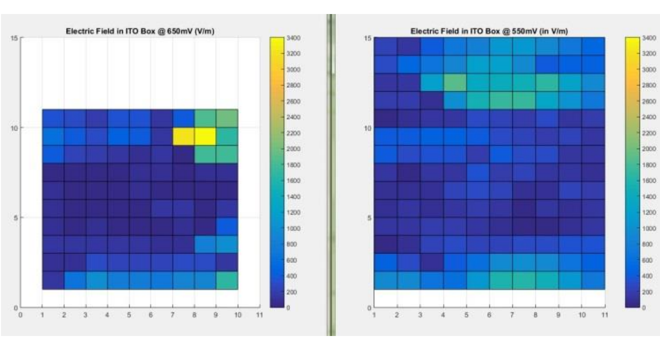


Fig. 4. Maps of the electric field inside the ITO box at 650mV (left) and 550mV (right).

III. DATA

All potential and electric field maps inside the ITO box and without the ITO box were obtained using data collected from the same 2D "slice"/plane within the GEC cell. The ITO box was removed from the cell before the data used to create the third map was collected for three reasons; 1) to map the same slice of space in the box and compare the electric potential and electric field to the inside ITO box's potential and electric field, 2) to determine if there was any erosion of the ITO on the surface of the box from it being used and 3) to explore the black marks located at specific spots on the inside surface of the ITO box, after the conclusion of the ITO box mapping experiments (see figure 4).

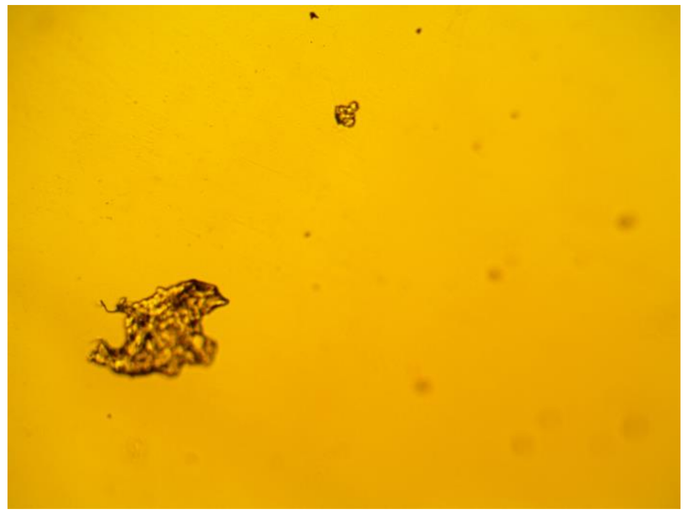


Fig. 5. Image of black marks on inside surface of the box, taken using a mircroscope.

All data was collected using the reference probe and the measuring probe, which were separated vertically by a one inch. The reference probe collected data which acted as a baseline which we would later subtract from the corresponding measuring probe data, ensuring that what we have mapped was purely measured data.

The change in the natural bias for each of the mappings (below) was most likely caused by the electrically conductive properties of the indium-tin-oxide.

A. *First Mapping*

The first set of data was performed at a system rf power of 8 W, system pressure of 315mTorr, a gas flow rate of 20 SCCMS, with a natural bias of -63V to -65V.

B. *Second Mapping*

For the second set of data obtained, the system rf power was changed to 6 W, the pressure was held at 315mTorr, the gas flow rate kept constant at 20 SCCMS, with a natural bias ranging from -45V to -47.5V.

C. *Third Mapping*

To create the third set of maps, the ITO box was removed from the GEC cell and the same region inside the GEC cell was mapped again without the box. The rf power was set to 8

W, system pressure was held at 315mTorr, gas flow rate was 20 SCCMS, and the natural bias was -44V to -47V.

IV. Results and Analysis

The data required to create each map was obtained independently of all others. Each data set obtained was collected using two probes, a reference probe and a measuring probe separated by a one inch distance (see figure 2). The reference probe was placed one inch above the measuring probe to ensure that at all times the reference probe was collecting data from the plasma bulk only; therefore, each mapping had two sets of data for each point on the map, the reference data and the measured data. In order to analyze the resulting data, the difference between the measuring probe and reference probe data at each point was determined to ensure we were only mapping measured data. The result of this was a matrix of measured data.

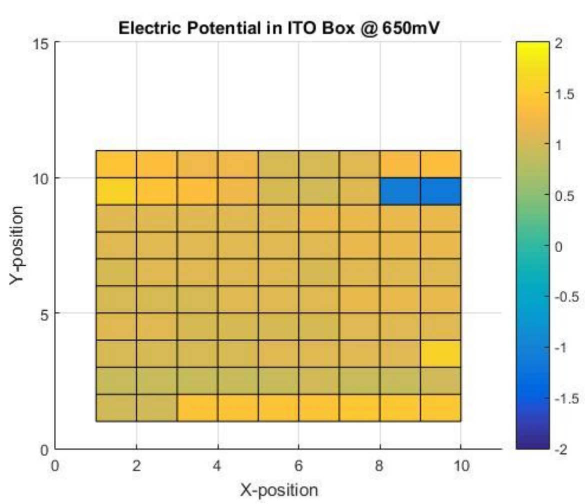
The S-100 range of motion is limited and smaller than the total width of the ITO box. Due to this we were only able to map about 6 mm horizontally and about 6 mm to 9 mm vertically of the box.

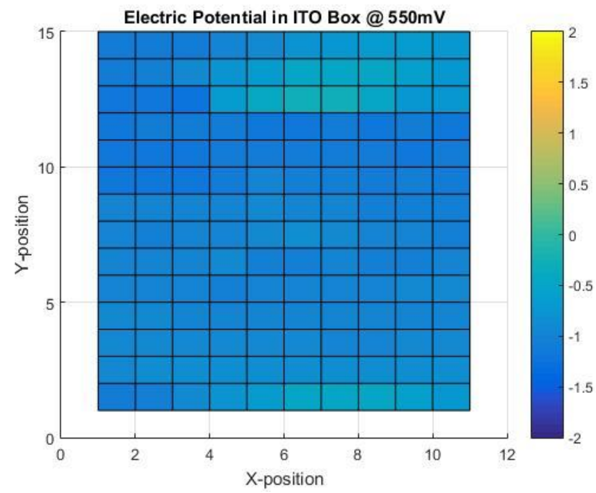
Once this data matrix was calculated it was imported into MatLab and to ensure that the program plotted the data points in their proper order. From this matrix of electric potential values, the electric field values within the box at each point were obtained by taking the gradient of the matrix in MatLab.

A new matrix, consisting of the electric field values, was then created and mapped as a surface plot and as a quiver plot.

This analysis shows two separate regions of confinement within these boxes as evidenced by two or more separate regions exhibiting large changes in the electric field and the electric potential in different and very specific places within the box (see figure 3). These different areas, or regions, in the box seem to affect the dust to dust and dust to plasma interactions independently of each other and therefore are of great interest (see circled areas in figures 6 and 8).

A. *Electric Potential Maps*





Figs. 6. Maps of the electric potential inside the ITO box at 650mV (top) (a) and 550mV (bottom) (b). (Potential In Units of Volts)

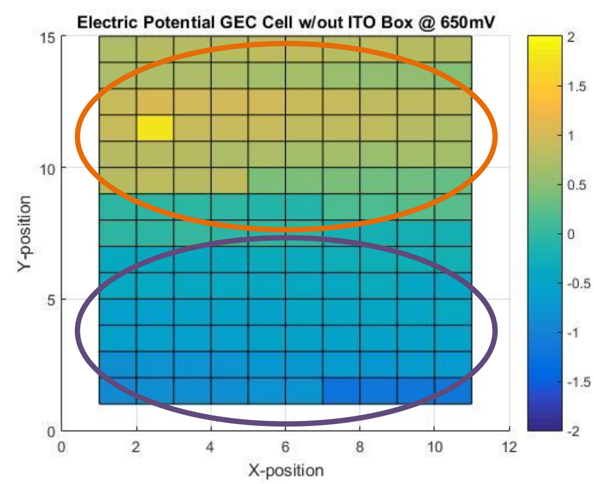


Fig. 7. Map of the electric potential inside the GEC Cell without the ITO box at 650mV. (Potential In Units of Volts)

These maps represent the electric potential; the first two figures are of the potential inside the ITO box while the last figure is the potential inside the GEC cell without the box. The x- and y- positions on the figures represent the arbitrary position of the probes being moved within the box, with x representing the horizontal motion and y representing the vertical motion. It total the probes were moved horizontally about 6 mm and vertically about 6 mm to 9 mm.

In relation to these maps, specifically in relation to figure 6a, the dust was observed levitating in the middle section of the map slightly below the top of the map, as shown below (see figure 8).

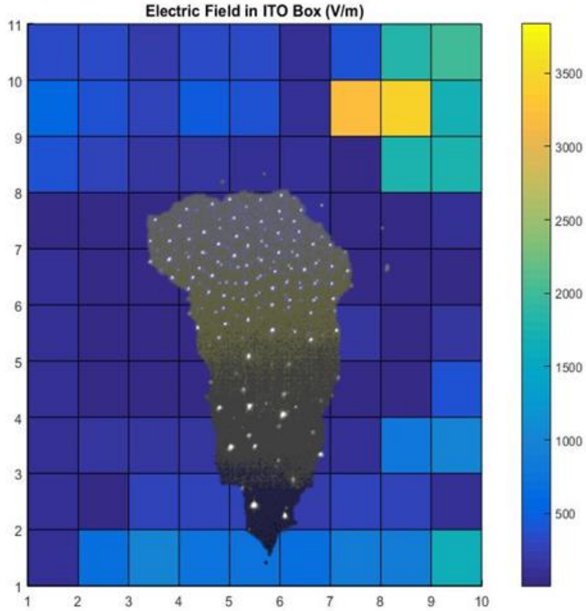
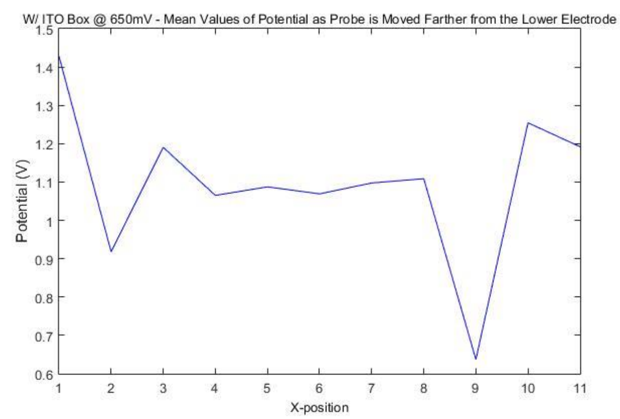
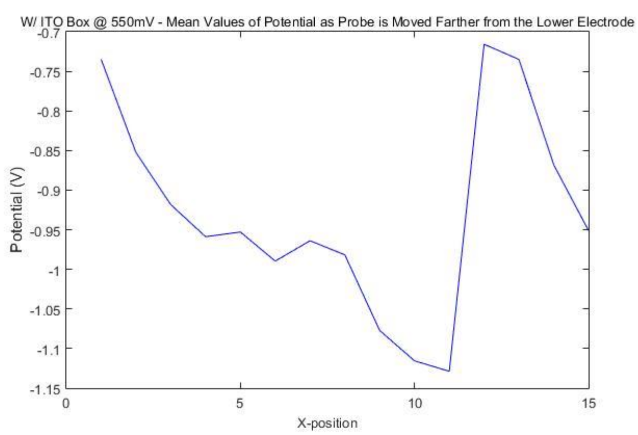


Fig. 8. Electic Field map of the box at 8 W (650 mV) with an image of the particles levitating transposed on top of it to show where they were located.

a



b



c

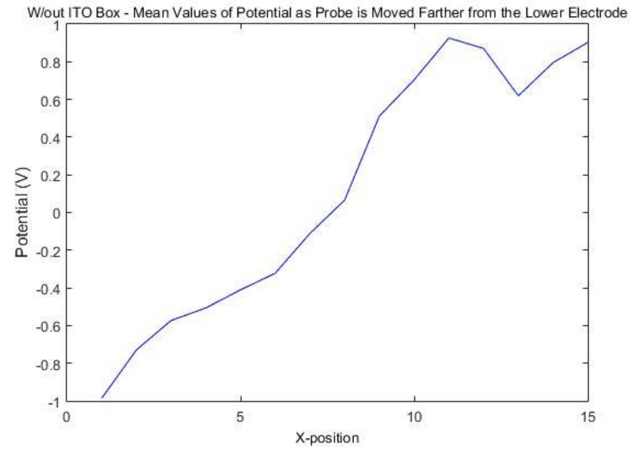
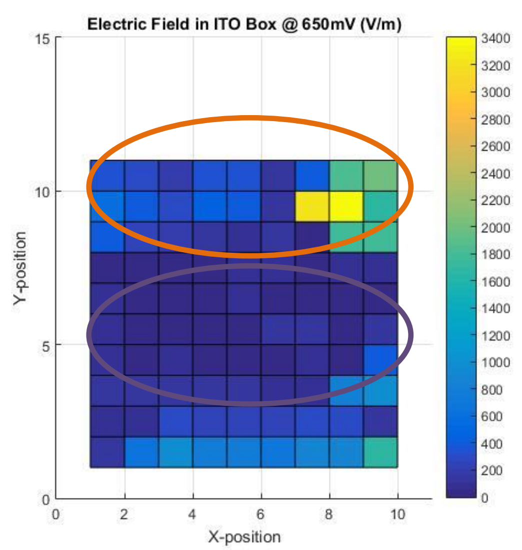


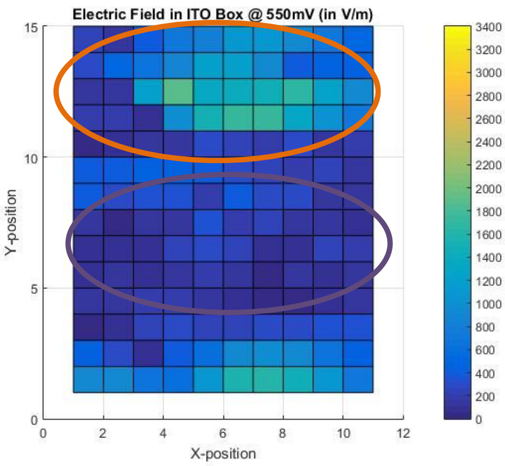
Fig. 9. The above graphs represent the change in the electric potential as the probes are moved vertically from the lower electrode, where the x-axis represents the vertical motion of the probes. From top to bottom: potential inside the ITO box at 650mV (top) (a), potential inside the ITO box at 550mV (middle) (b), and potential inside the GEC cell at 650mV (bottom) (c).

Figure 6 shows the change in the mean of the potential values as the probes are moved vertically away from the lower electrode. The ITO box clearly has an effect on the potential. Without the box (at 650mV; bottom figure) the potential in the GEC cell gradually rises as the probes are moved farther vertically from the lower electrode.

With the box (at 650mV; top figure) the potential is always positive, and is fairly constant. In the box (at 550mV; middle figure) the potential is always negative and appears to increase negatively as the probes are moved farther vertically away from the lower electrode.

B. Electric Field Maps





Figs. 10. Maps of the electric field inside the ITO box at 650mV (top) (a) and 550mV (bottom) (b).

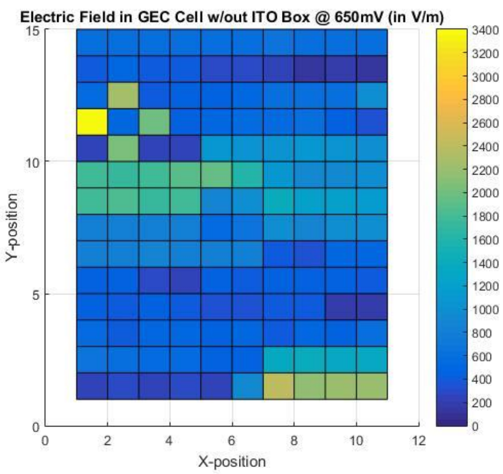
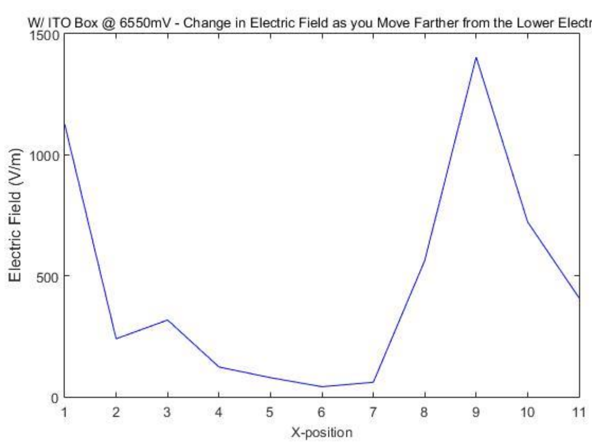


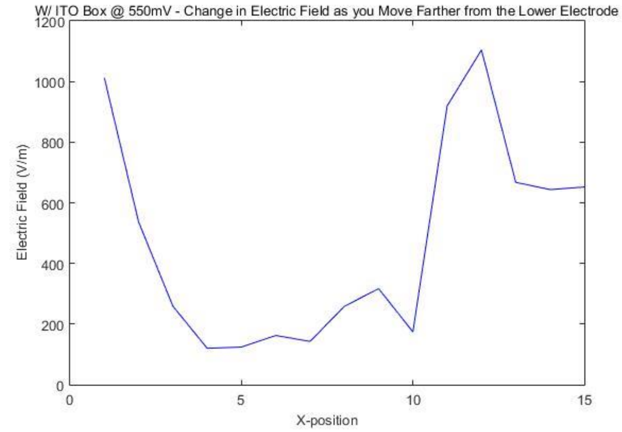
Fig. 11. Map of the electric potential inside the GEC Cell without the ITO box at 650mV.

The maps above represent the electric field; the top two figures are of the electric field inside the ITO box and the bottom is the electric field inside the GEC cell without the box. The x- and y- positions on the figures represent the arbitrary position of the probes being moved within the box, with x representing horizontal motion and y representing vertical motion.

a



b



c

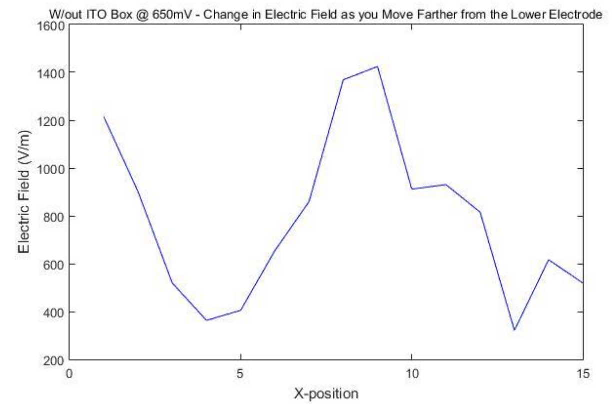


Fig. 12. The above graphs represent the change in the electric field as the probes are moved- vertically away from the lower electrode, where the x-axis represents the vertical motion of the probes. From top to bottom: the electric field inside the ITO box at 650mV, the electric field inside the ITO box at 550mV, and the electric field inside the GEC cell at 650mV.

The x, y plots show the change in the mean of the electric field values as the probes are moved vertically away from the lower electrode. It is quite clear that the ITO box affects the electric field within the GEC cell while changes in the rf power only minimally affects the electric field within the ITO box. Despite the rf power change the trend in the change of the electric field mapped inside the ITO box remains the same. Another thing to note is the amount which the electric field drops when in the ITO box in comparison to without the ITO box. Also, when dropped into the ITO box at an rf power of 8 W (650 mV) the dust could be seen levitating the region of very minimal electric field. However, when turned down to an rf power of 6 W (550 mV) the dust would no longer be able to levitate and would simply drop despite the very minimal change in the electric field.

V. Conclusion

There is still much work and research that needs to be conducted. Throughout the next year we will continue to conduct research and collect data on these ITO boxes and how their confinement force affects the electric potential and electric field within an argon plasma in a GEC rf cell, and dust when dropped into the plasma in the box.

VI. Appendix

A. Script Used to find the Electric Field from the Electric Potential

```
Nx = 165;  %Number of X-grids
Ny = 165;  %Number of Y-grids
mpx = ceil(Nx/2);  %Mid-point of x
mpy = ceil(Ny/2);  %Mid point of y
V = matrixmap3
[Ex,Ey]=gradient(V);
Ex = -Ex;
Ey = -Ey;
% Electric field Magnitude
E = sqrt(Ex.^2+Ey.^2);
x4 = (1:Nx)-mpx;
y4 = (1:Ny)-mpy;
% to get proper units (Voltss/meter) divide Ex and Ey by 38pixels times the
% distance 1 pixel is equal to (in meters).
E2 = sqrt(Ex2.^2+Ey2.^2);
```

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