Installation and Characterization of Charged Particle Sources for Space Environmental Effects Testing

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Charged particle sources are integral devices used by Marshall Space Flight Center's Environmental Effects Branch (EM50) in order to simulate space environments for accurate testing of materials and systems. By using these sources inside custom vacuum systems, materials can be tested to determine charging and discharging properties as well as resistance to sputter damage. This knowledge can enable scientists and engineers to choose proper materials that will not fail in harsh space environments. This paper combines the steps utilized to build a low energy electron gun (The "Skevington 3000") as well as the methods used to characterize the output of both the Skevington 3000 and a manufactured Xenon ion source. Such characterizations include beam flux, beam uniformity, and beam energy. Both sources were deemed suitable for simulating environments in future testing.

I. Introduction

The Space and Environmental Effects Branch (EM50) simulates two different categories of environments for all of their material testing. The first category of environments is the natural space environment which includes: high and low energy protons which range from 700 KeV to 1 KeV; high and low energy electrons which range from 2.5 MeV to 10 eV; Ultra Violet (UV) radiation which ranges from 125 nm to 400 nm, and lastly plasma environments including Low Earth Orbit and Geosynchronous Orbit. (Plasma is an ionized gas which contains both positively charged ions and negatively charged electrons). The second category is manmade environments and includes thruster plumes, orbital debris, and contamination. Thrusters are used to propel satellites and for attitude control. One type of thrusters, known as electric propulsion devices, generates a charged particle (ion) beam to create thrust. Orbital debris can be anything manmade that has been ejected into outer space. This debris can include, but is not limited to, space craft parts. Contamination comes from coatings and other ejected materials used on spacecraft.

A requirement for recreating any space environment is that all the tests must be done in a vacuum. A wide range of vacuum technology is applied by the EM50 Branch in order to accommodate a diverse set of requirements associated with each space mission. In order to maintain a proper vacuum system, many steps need to be taken. First, a chamber with enough flanges to allow sufficient access to test the sample is required. A typical high vacuum seal incorporates a copper gasket used between two adjoining stainless steel flanges in order to assure a proper seal. Once the chamber is assembled with the correct accessories (e.g. electrical and motion feed throughs) and testing materials, two different pumps can be used to pump down the chamber to the desired pressure. (Note: Atmospheric pressure is approximately 760 Torr.) Pressures between 1 and 1,000 Torr are considered to be rough vacuum. A medium vacuum is considered to be between 1 and 10^{-3} Torr. A high vacuum is one between 10^{-3} and 10^{-7} Torr, while an ultra high vacuum is one with pressures below 10^{-7} Torr. A roughing pump is used to pump down a chamber from atmospheric pressure to a medium vacuum. A thermocouple vacuum gauge is used to measure the pressure of the chamber while the roughing pump is in use. Once the chamber reaches a medium vacuum, a turbo pump is turned on so that the chamber can reach high vacuum pressures. In this case, the thermocouple gauge can no longer be used to measure the pressure. Instead, an ion-gauge is used to measure pressures below 10^{-3} Torr. An ion gauge works by ionizing neutral gas particles and measuring the ions as a current. Large ion currents imply a high neutral particle count, whereas low currents suggest a reduced number of neutral gas particles. All testing done by the Space and Environmental Effects Team is done in a vacuum setup comprised of the basic components just described.

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II. Background on charged particle sources

This report describes two main sources that have been tested in these vacuum chambers which span both the natural and man-made environments. The first source is a home-made, low energy, electron gun which is used to simulate the natural low energy electron environment. Because this gun is home-made and its capabilities were unknown, the electron gun, dubbed the "Skevington 3000", had to be installed in a vacuum system and characterized before it could be used in environmental effects tests. It will eventually be used for tests such as surface charging tests where only the lower energy electrons will collect on the surface. In the case of highly resistive coatings, excessive surface charging can lead to electrical breakdown of the surface in the form of an arc. The second source is a Xenon ion source which is used to simulate the man-made Hall Effect Thruster environment. Hall Effect thrusters propel satellites by accelerating positively charged ions through an electric field. Xenon is a popular choice of gas for Hall Effect Thrusters because it ionizes easily and can produce a lot of thrust due to its large atomic mass of 131.3 AMU. This Xenon ion source will eventually be used in ion-erosion tests. Because neither of these sources had been used previously, they both needed to be characterized before they could be used in an environment simulation.

Three main criteria were looked at in order to characterize the Electron Gun and the Xenon ion source. The first criterion addressed was beam energy which is measured in electron volts (eV), and is the amount of energy obtained by a single electron when moved through a difference potential of one volt. The second criterion was flux. Flux is a measurement of current divided by area, and has units such as Amps per centimeter squared. In both the characterization of the Electron Gun and the Xenon ion source, the flux is the current measured by a Faraday Cup divided by the area of its aperture. A Faraday cup is a device used to measure charged particle beams in a vacuum system. Figure 1 is a picture of the Faraday cup used to measure the electron beam.

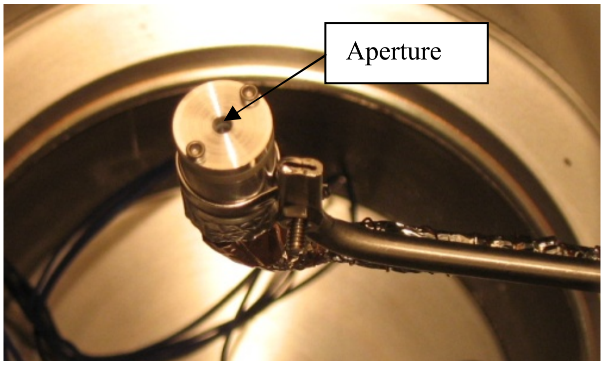

Fig 1: Picture of the Faraday cup used to measure the flux of the Skevington 3000 electron gun

The last criterion was beam uniformity, which is the amount of flux over a given range of positions. Beam uniformity was looked at by creating graphs of the flux at different positions along the vacuum chamber. For the Skevington 3000, all three of these criteria were necessary because none of these characteristics were previously known. However, because the Xenon ion source had been previously tested by the manufacturer, the flux capabilities were already known, and thus only the beam uniformity was important to measure for proper characterization.

A. The Skevington 3000

The Skevington 3000 low energy electron gun uses the same technology that has been used for decades for things such as cathode ray tube televisions. A model of the Skevington 300 was designed using ProE and is seen in fig 2. It employs two 0.1mm Tungsten cathodes. The cathode is wound into a filament in order to increase the emission area. The two cathode design was chosen so that when one cathode burns out, the circuit can be quickly switched to turn on the second cathode without breaking vacuum. As seen in fig 3, one power supply is connected to this filament and is used to heat it through Joule heating. A second, cathode bias supply, is connected in series with the heater supply and is the driving force behind propelling the electrons off of the filament. An electric field is actually created between the filament (cathode) and a grounded anode. The anode is made out of a nickel mesh grid anode that lies 10 mm above the cathode. Because this grid has a high transparency, most of the electrons will pass through the anode without being lost to ground. When a bias of 50 volts is applied to the filament (with respect to the anode) electrons of 50 eV energy are created. Once inside the chamber, a Faraday cup is used to measure the current produced by the electron source. Also in the circuit, as seen in fig 3, are meters used to measure the currents and voltages at certain locations. V2 corresponds to the voltage across the cathode bias supply or the beam energy, while V1 corresponds to the voltage across the heating supply. A2 refers to the emission current, or the current that is being emitted by the cathode. A1 corresponds to the heating current, while A3 corresponds to the current that is measured by the Faraday cup and is used in the measurement of flux.

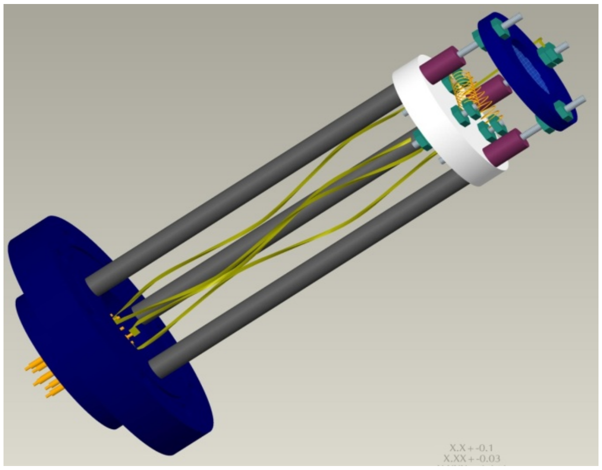

Fig 2: 3D model of low energy electron gun designed using ProE

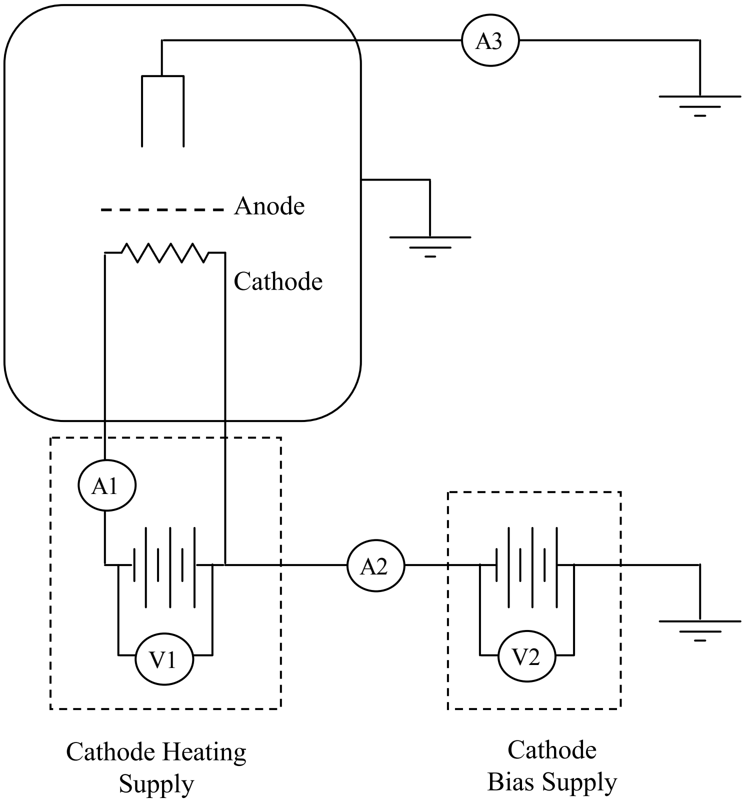

Fig 3: Electron gun circuit schematic

B. The Xenon Ion Source

The Xenon ion source was professionally manufactured by the Kaufman and Robinson, Inc. EM50 purchased the source to simulate effects caused by Hall Effect Thrusters. The disadvantage of a Hall Effect Thruster is that the energetic ions produced by the thruster can actually deteriorate the surrounding satellite material in a process called sputtering. This specific source is a Kaufman and Robinson KDC 160 16cm ion source and is ideal for use for sputtering, or ion-erosion testing. It is made primarily out of stainless steel, molybdenum, and alumina parts. The parts schematic can be seen in fig 4 and is similar to the electron gun in the sense that it too employs both a cathode and anode. However, in this case, the cathode is used to ionize the Xenon gas that is injected into the source. Once the gas is ionized into positively charged ions, the ions are accelerated by an accelerator grid on the front of the source. A neutralizer cathode is placed on the front of the source to produce electrons to neutralize the charge of the ion beam as seen in fig 5. If the electrons were not added to the ion beam, at high enough flux, the ions would being to reach space-charge limits and would create a less uniform beam. Also as seen from fig 4, this source requires five power supplies to operate correctly.

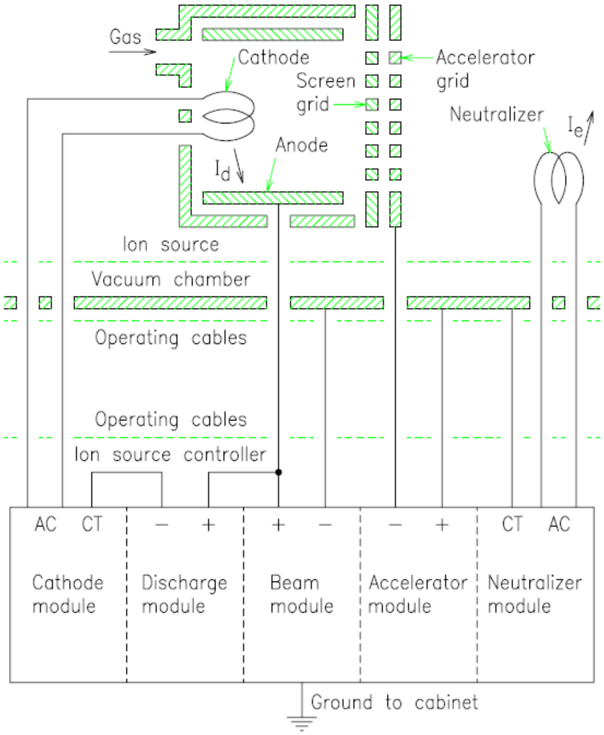

Fig 4: Schematic of Xenon Ion Source taken from the Kaufman and Robinson, Inc. Ion Source Controller operating manual

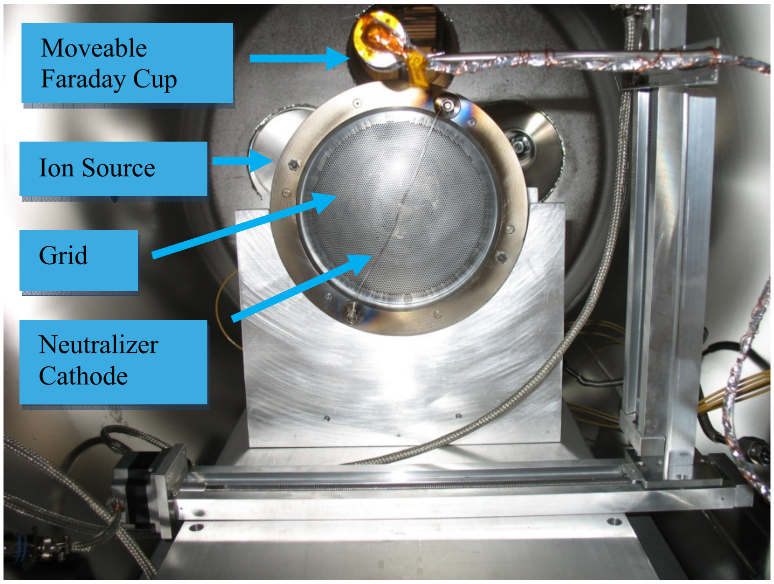

Fig 5: Picture of the Xenon Ion Source installed inside a vacuum chamber

In the case of the Xenon ion source, a specially fabricated Faraday cup was used to measure the current of the ions. Because the source is used to test sputtering on materials, a regular Faraday cup, made from aluminum will not survive. Therefore, a material had to be chosen with a low enough sputter yield so that it could hold up against the high energy ions given off by the Xenon source. For this reason, the Faraday cup was machined out of a carbon graphite material. Also, because only the ions should be measured as current by the Faraday cup, a negatively biased grid must be placed inside of the Faraday cup to repel the electrons from reaching the back of the cup and being measured as part of the total current.

III. Procedure

A. The Skevington 3000

The setup for the Skevington 3000 was done in order to measure the flux over a range of positions so that the maximum flux could be measured and the beam uniformity could be determined. The electron gun was mounted on a flange at the top of the vacuum chamber pointing down towards the center of the chamber. A Faraday cup was installed on a linear motion feed through vacuum flange perpendicular to the emitted electron beam. This is done so that the Faraday cup could be translated across it manually from outside the vacuum. Next, a heating current had to be chosen and kept constant so that only the beam energies could be altered. The heating current was first determined by keeping the Faraday cup at the center of the chamber and the beam energy constant at 100 eV. The heating current was then increased from 600 mA to 1750 mA at equal intervals to determine the saturation emission current without burning out the filament. The maximum emission current occurred when the heating current was about 1500 mA. However, at this high heating current, there was off-gassing of water molecules from the boron nitride which was used in the structure of the gun. This off-gassing created too high of a pressure for testing conditions. Therefore a heating current of 1200 mA was used for the next test in order to limit the amount of off-gassing of the boron nitride.

While keeping the heating current at 1200 mA and the position of the Faraday cup in the center of the chamber, changing the beam energy gave an approximation of what the emission current should be held at. Two distinct emission current levels were observed based on energy. Therefore, one emission current was used for the range from 10-50 eV and another for 100-1000 eV. An emission current of 0.1 mA was used in the next test for energies between 10-50 eV, while an emission current of 2.3 mA was used for energies between 100-1000 eV.

The final trial was run in order to measure the flux of the electron gun over a range of energies and a range of positions. The heating currents were kept constant and the flux was measured at each energy level and each position. Energies were increased from 10 eV to 50 eV in intervals of 10 eV each time while keeping the emission constant at

0.1 mA. Then, the energies were increased from 100 eV to 1000 eV in intervals of 100 eV each time while keeping the emission current at 2.3 mA. At each energy level, the Faraday cup was translated across the beam at an interval of 1.3 cm for a total of 15.2 cm. The center of the vacuum chamber, and therefore beam, was at a position of 11.4 cm with respect to the linear motion feed through. Once the measurements of flux were taken at each energy and position, the values were graphed in order to assess the uniformity of the beam.

B. The Xenon Ion Source

The Xenon ion source was slightly different than the electron source because it had been purchased and the capabilities were already known upon installation. Therefore, the flux and energies were set at whatever characterization had been given by the manufacturer and only the beam uniformity was measured. To do this, the source was set up free-standing on a stainless steel base inside the vacuum chamber. On that same base, a 2D motorized linear motion stage was also set up to mount the specially designed Faraday cup. This stage can be used to translate the cup both horizontally and vertically across the center of the source. It was also automatically translated by a computer so that the exact positions were known. In order to validate the beam uniformity, the Faraday cup was placed on the center of the source and then only moved up and down along the vertical axis taking measurements of flux at each position. The Faraday cup moved one centimeter every five seconds along the ion beam. Again, the flux versus position was graphed in order to see the uniformity of the beam.

IV. Data and Analysis

A. The Skevington 3000

Graphs of the flux versus position of the low energy electron source were split up into three charts. The first chart, as seen in fig 6, shows the lowest energies that range from 10 eV to 50 eV. The vertical line represents the position of the cup centered in the middle of the chamber, and thus in the middle of the beam. As expected, there is a peak flux at this point and a parabolic curve to either side which shows that the beam is uniform at these energies. At energies as low as 10 and 20 eV, only Pico Amps (10^{-12} Amps) of current were measured.

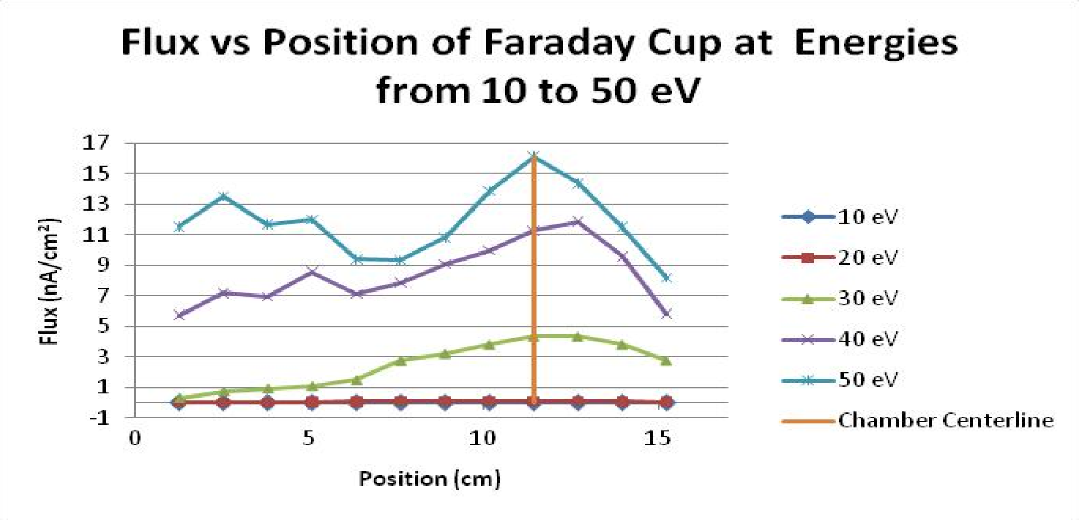

Fig 6: Electron Beam uniformity and range of flux at energies from 10 eV to 50 eV

In fig 7, the vertical line still corresponds to the center of the beam. Here, there is still a peak in the flux at this point. However, another peak starts to show up near one end of the beam. Although that means that this beam is not entirely uniform, it does not mean that the gun is not suitable for future testing. The outlying peak should only be noted and taken into account when reading data in future tests. Also, it is possible that the uniformity of the flux may change when the gun is used in chambers with different geometries.

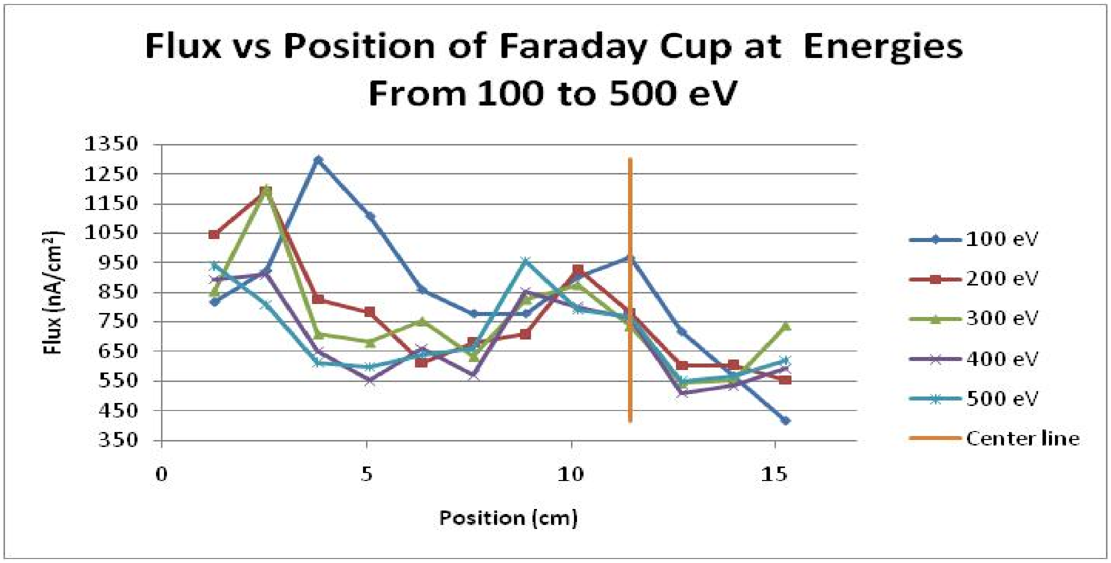

Fig 7: Electron Beam uniformity and range of flux at energies from 100 to 500 eV

The beam uniformity for the higher energies of 600 eV to 1000 eV is shown in fig 8. Here, the peaks are becoming steeper and the flux is at its highest overall level. One important note is that the highest flux was obtained at 600 eV and decreased as the energies approached 1000 eV. Also, at 800, 900, and 1000 eV, the flux trends are almost identical, which illustrates a saturation point was reached for the gun output around 600 eV. The beam also continues to become less uniform at the highest energy levels.

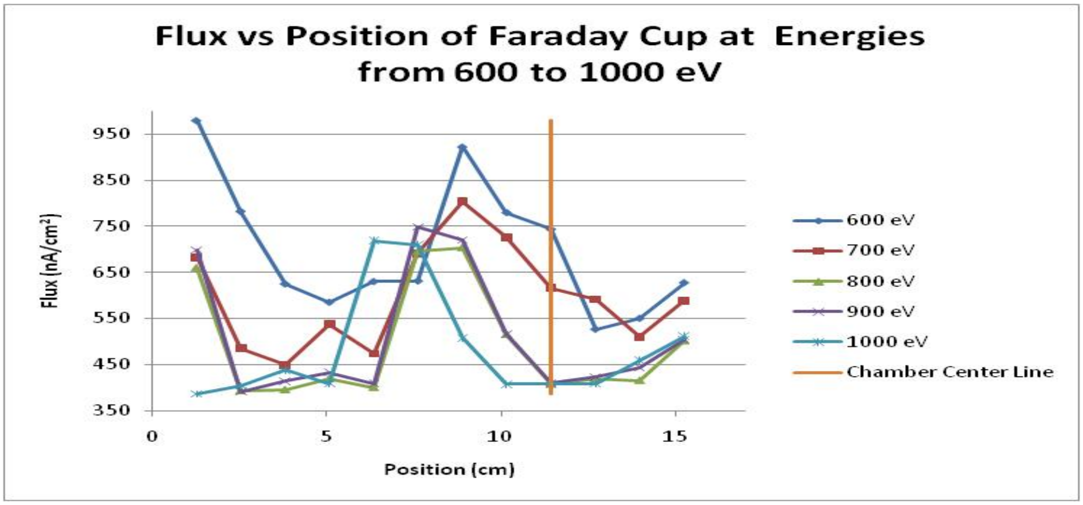

Fig 8: Electron Beam uniformity and range of flux from 600 eV to 1000 eV

B. The Xenon Ion Source

The Xenon ion source, as seen in fig 9, produced a very uniform beam. The vertical line represents the time at which the Faraday cup passes through the center of the source. In this graph, the flattened plateau to either side of the center of the source marks the very uniform beam. The parabolic shape on either side of the plateau represents the decrease in flux as the edges of the beam are reached. The sharp linear lines from 0 to 25 s and again from 180 to 225 s are formed from rapid movement of the Faraday cup across the source. The cup's starting location was in the center of the source and quickly drops to the bottom of the source to start taking measurements. Likewise, at the end of the trial, the Faraday cup moves from its last measurement at the top of the chamber back down to its centered home position.

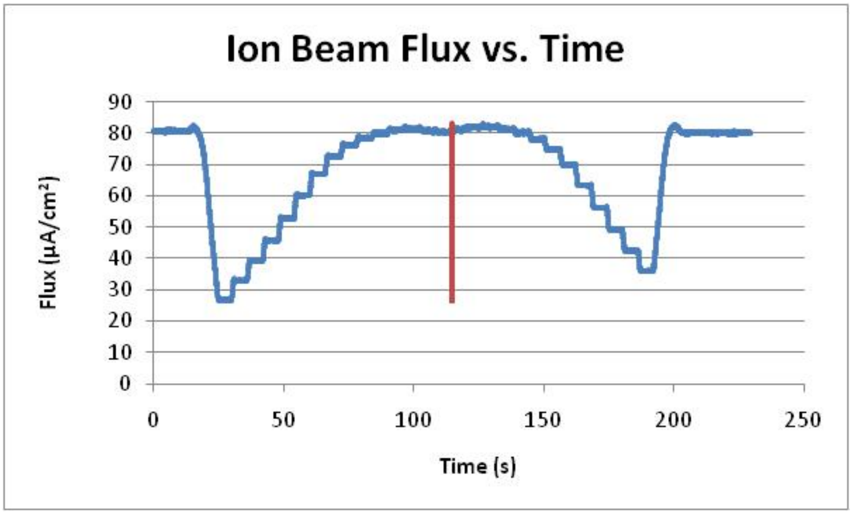

Fig 9: Ion beam uniformity and range of flux of Xenon ion beam

However, the fig 9 data must be analyzed to account the detector angle. As the Faraday cup moves further away from the center of the source, an angle of incidence is created between the aperture of the cup and the ion beam. At a large enough angle, the ions will no longer be able to make it into the aperture. That angle was determined by doing an analysis of the thickness of the materials in the Faraday cup and then was accounted for in fig 10. By accounting for this angle discrepancy, the flux curve plateau at the center of the beam is extended. Figure 10 shows a trial different than in fig 9, but still illustrates the increased beam uniformity.

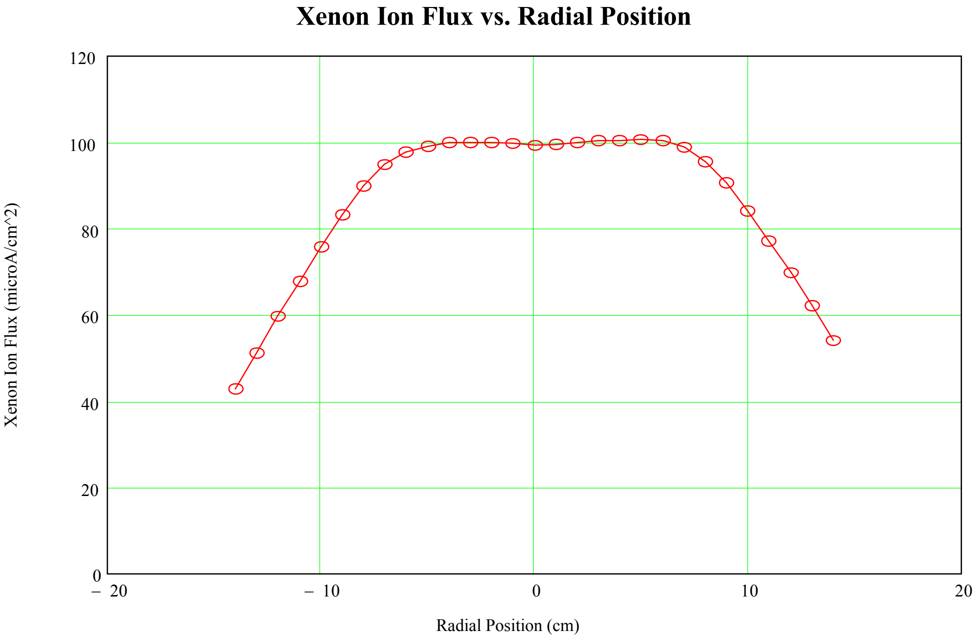

Fig 10: Beam uniformity of the Xenon ion source after accounting for the angle of the Faraday cup with respect to the ion beam.

V. Conclusion

In conclusion, both of the charged particle sources described in this paper will be valuable for future testing work in EM50. The Skevington 3000, although not perfectly uniform at all energy levels, produced enough flux at low energies to be useful in the next phase of primary mirror surface charging tests on the James Webb Space Telescope. Likewise, with the Xenon ion source's high flux capabilities and uniform beam profile, it will be an ideal source for use in ion erosion testing on materials such as solar arrays. By testing materials in both of these natural and manmade environments, many pitfalls can be avoided in the manufacturing of hardware systems that will be flown in space. Proper materials can be chosen that will not break down due to arcing from low energy electron charging or from high energy ion erosion. A lot of resources can also be saved by testing materials in these environments early in the spacecraft development process. Therefore, expensive systems like satellites and telescopes will meet their mission lifetimes without experiencing failures brought on by interactions with the space environment.

VI. Acknowledgements

The author would like to thank the members of the EM50 Branch for sharing their expertise in the area of space environmental effects testing.