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Undergraduate Research and Creative Opportunities
Final Report
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Faraday Cup Designs for High Efficiency Determination of Energy- and Angular-Resolved Charged Particle Fluxes

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Introduction

In order to build a spacecraft, we must understand how the construction materials will behave in the space environment (i.e. when subjected to the solar wind). The USU Materials Physics Group performs electron emission tests on spacecraft materials in an Ultra-high vacuum (UHV) test chamber (Fig.1). The chamber utilizes Faraday cups (Fig.2) in order to quantify electron flux at a location within the chamber. This measurement is important in characterizing beam profiles of electron guns used in UHV experiments. Perhaps more importantly, the Faraday cups are used to detect secondary electrons (SE) and back-scattered electrons (BSE) emitted from the surface of at test material. Faraday cups provide a means to quantify the SEs and BSEs emitted from a material by measuring the current resulting from these electrons striking the inside walls of the Faraday cup. The ability to quantify these SEs and BSEs emitted from a given material is an important application of this instrument. How a material behaves when charged particles strike it is an essential material property when dealing with spacecraft materials. Faraday cups facilitate the understanding of this behavior. The intent of this project is to characterize the performance of current Faraday Cup detectors (used by the Materials Physics Group), how we can optimize that performance in order to obtain more accurate measurements, and how we can alter the design to meet desired requirements such as energy and angular resolution.

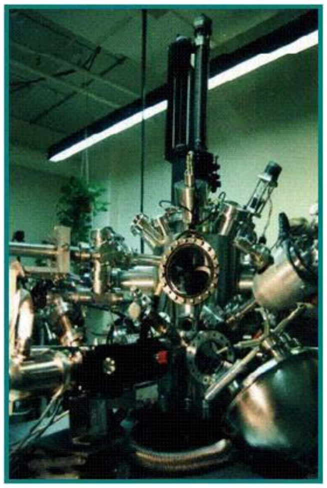


Fig. 1 USU Materials Physics Group UHV electron emission spectroscopy vacuum chamber.

Fig. 2 A Faraday cup currently in use inside the UHV chamber (pen shown for scale).

Project Progress

In order to improve Faraday cup designs, or tailor them to specific design requirements, we need to understand the current Faraday cup performance better. This was accomplished through the use of an electron optics ray tracing software called SimIon$^{\text{TM }1}$. The latest version of SimIon was purchased using the URCO grant funds and has been a vital tool in understanding the performance of the current Faraday cup. The new version has enabled a more accurate study of the current Faraday cup design largely due to the ability to import the exact geometries of the instrument from SolidWorks$^{\text{TM }2}$ and create and finer mesh to solve the Laplace equation (Eq. 1). The Laplace equation is used in SimIon to numerically approximate the potential (V) at each node of the mesh around the geometry. This method produces more accurate results as the distance between each node goes to zero. Thus, setting up a finer mesh has enabled more accurate simulations. Other important new features of this software will be discussed later.

$$\nabla^2 V = 0 \qquad \text{(Eq. 1)}$$

Fig. 1 shows the Faraday cup that we are interested in analyzing. This Faraday cup was designed and built by Kendall Ford and Dr. JR Dennison.[2] I have taken this design and created a 3D model using SolidWorks. This model served two functions. One was to generate drawings of the Faraday cup for documentation (Appendix A) and the second was to import the geometries into SimIon. This Faraday cup is capable of energy discrimination, where we can "filter" electrons that do not have enough kinetic energy to overcome the bias potential. This enables us to see the kinetic energies associated with an electron flux. From Fig. 3 we can see how this is accomplished. This figure shows the grid-free bias aperture in front of the Faraday cup used to "filter," or discriminate the kinetic energies of the incident electrons. In addition to the bias aperture, the Faraday cup is also held at a negative potential in order to reject incoming electrons that have a lower kinetic energy than that of the Faraday cup potential.

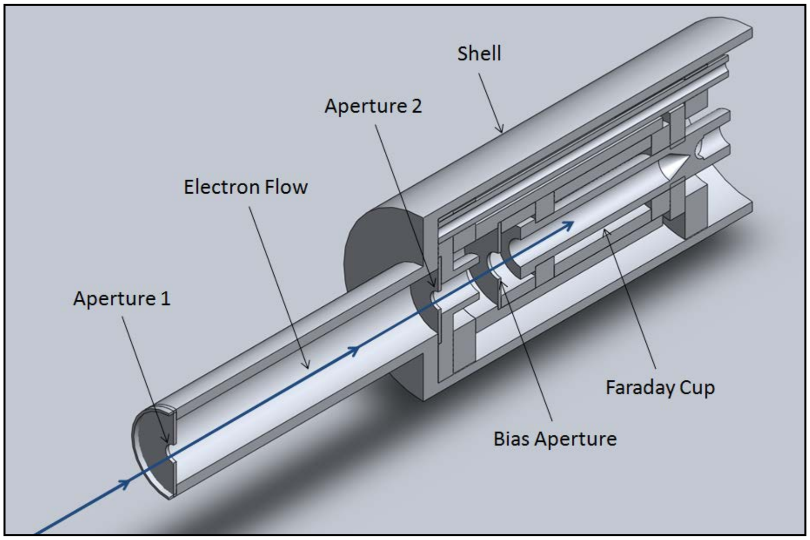


Fig. 3 3D cross-section of the Faraday cup Assembly with some major components labeled.

The Bias Aperture (Fig. 3) serves two functions. The first being energy discrimination and the second, is the capability to keep SEs from coming out of the Faraday cup itself. If the SEs and BSEs produced as a result of the primary electron (PE) collisions inside the cup were allowed to escape, the capture efficiency of the device would decrease. Thus, the measurement would not be as accurate as it could be. This is illustrated in Fig.4, where the bias aperture is at -100 V and the Faraday cup is at -95 V. A kinetic energy of 2 eV was used for the SEs in Fig. 4, since this is the energy that most SEs have when ejected from a material.[3] The difference of 5 V was chosen to capture the more energetic SEs that can also occur.[3] The internal geometry of the Faraday cup also plays a critical role in retaining the SEs and BSEs. From Fig. 4 we see that the spray of electrons will most likely collide with the inside wall again before it has a chance to escape. These additional collisions further reduce the chance of losing electrons.

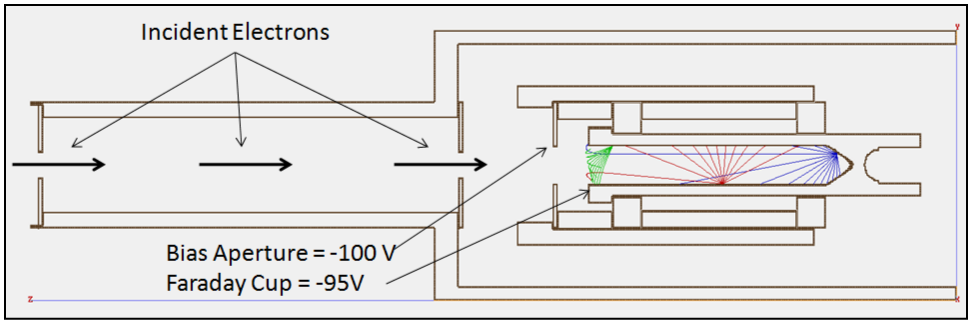


Fig. 4 Theoretical SEs (green, red, and blue groups), each electron in each group has a KE=2 eV. Each line represents the path line of an electron. The trajectory for each electron originates at the point source (where an incident PE might have impacted) and moves outward along its path line.

The reason we care about retaining these SEs and BSEs is because we want an accurate measurement. The amount of current that these instruments detect can be on the order of 10^{-14} A.[4] Hence, a handful of electrons missing can be significant depending on the desired accuracy. Another way in which we can reduce SEs is by coating the inside walls of the Faraday cup with a material that has a low SE yield. Fig. 5 and 6 show the emission yields of microcrystalline graphite and copper, respectively. From these figures we can see that, by coating the walls with microcrystalline graphite, or a similar material, we will have a lower emission yield per incident electron. This lowers the chances of SEs escaping at the source (*i.e.* where the incident PEs impact the Faraday cup). The BSEs will have nearly the same kinetic energy going out of the Faraday cup as they did when they entered. Little energy is lost if the electron “bounces” off the inside wall of the device. Therefore, we rely on geometry to stop them from exiting. This is the reason for the conical section at the bottom of the Faraday cup (Fig. 4).

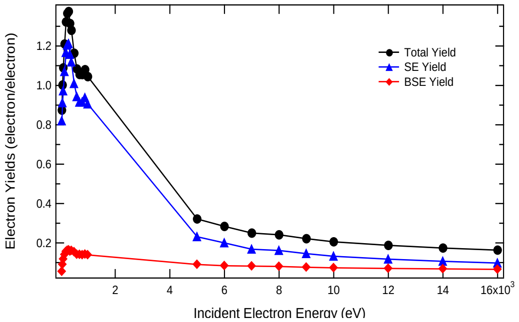


Fig. 5 - Total SE and BSE yields as a function of incident electron energy for microcrystalline graphite.

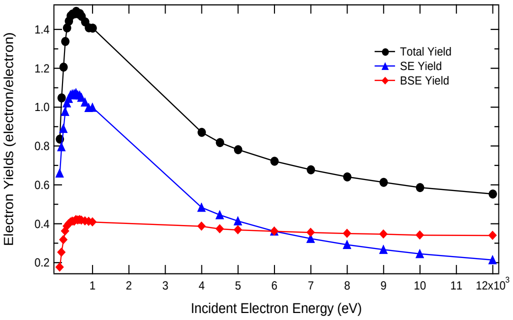


Fig. 6 - Total SE and BSE yields as a function of incident electron energy for Cu.

The energy resolution of the Faraday cup was determined from the electron capture efficiency (Fig. B1 - B2 in Appendix B). From Eq. 2, the capture efficiency (ϵ) is defined as the ratio of the number of electrons captured by the Faraday cup (N_c), to the number of incident PEs that entered (N_{PE}). The energy resolution of the Faraday cup is defined as the smallest change in kinetic energy (ΔKE) we can detect, while maintaining 100% capture efficiency. The efficiency is calculated by executing simulations with SimIon and then importing that information into a MatLab program that I have written to determine how many electrons were captured. The simple efficiency calculation can then be carried out since the number of PEs (N_{PE} = 250) is defined in

SimIon. A new feature of SimIon allows for 3D Gaussian distributed electron beams. This feature was implemented in these simulations in order to better model an actual electron beam. This calculation assumes that there are zero SEs and BSEs, since SimIon does not model this phenomenon.

$$\epsilon \equiv \frac{N_C}{N_{PE}} \tag{Eq. 2}$$

Referring to Fig. 7, the Bias potential is set to -100 V, meaning that we wish to collect only those electrons with a kinetic energy greater than 100 eV. Fig. 7 shows the Faraday cup capture efficiency as a function of beam kinetic energy. We can see that the original configuration, where the bias aperture is at a greater potential than that of the Faraday cup (Fig. 7), cannot discriminate (reject) electrons close to the bias potential. The best this configuration can do according to the simulation is ~ 98 eV. Even then, it takes about another 2 eV, for the capture efficiency to reach 100%. Fig. 7 is clearly not the ideal configuration for energy discrimination. With SimIon we were able to try a number of different configurations in order to find the best set-up for energy discrimination (Fig. B4 is an example of another configuration attempted). Fig. 8 shows the best configuration found. Where, the bias is -90 V and the Faraday cup is -100 V. Comparing Fig. 8 to Fig. 7, there is a dramatic improvement in energy discrimination and energy resolution (*i.e.* the ΔKE required to reach 100% capture efficiency has shrunk, considerably). Fig. B5 in Appendix B shows the capture efficiency as a function of energy resolution, for the configuration in Fig. 8. From this plot, we can see that the energy resolution is about 0.05%.

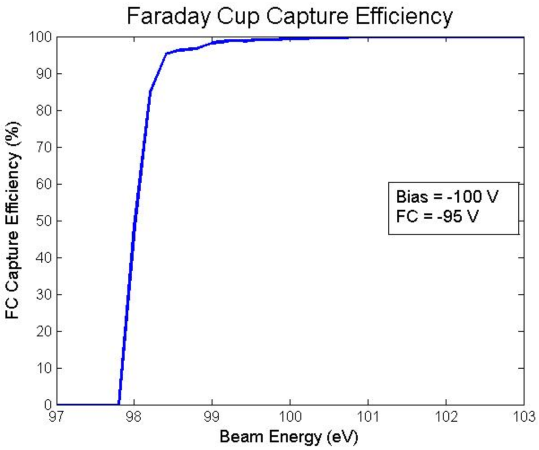


Fig. 7

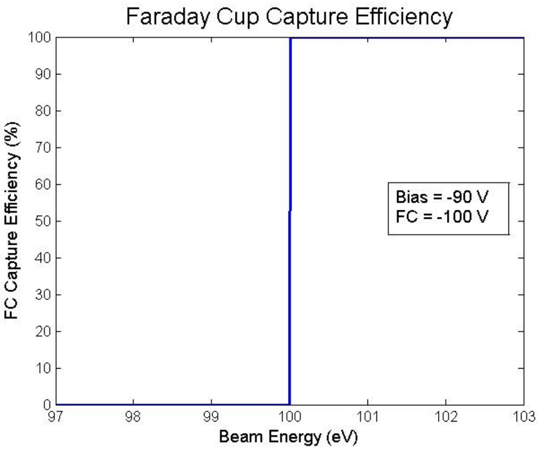
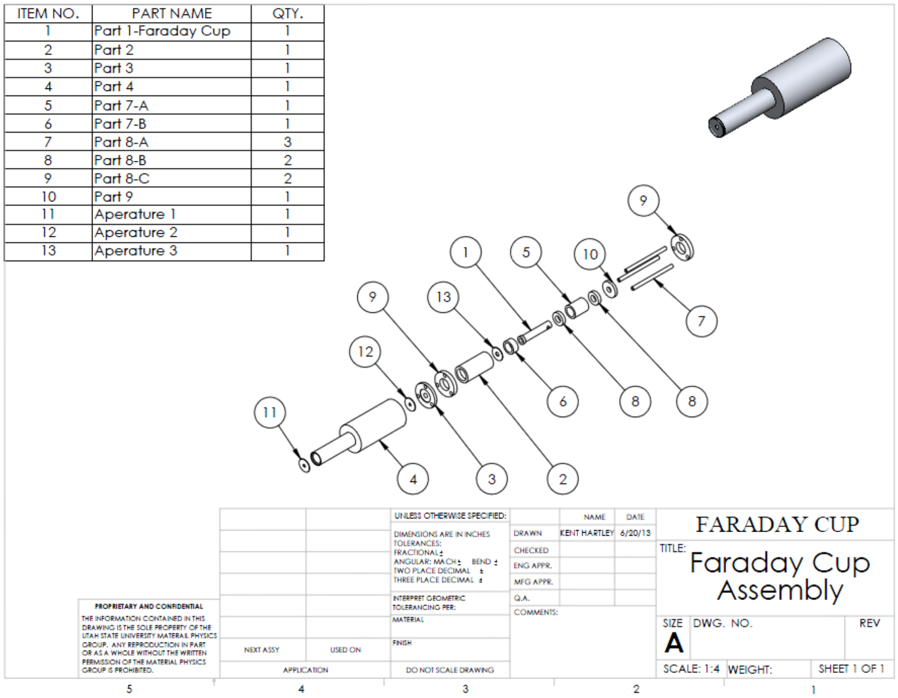


Fig. 8

Conclusion

The energy resolution of 0.05% is exceptional. However, this is the ideal case, since we have neglected any SEs and BSEs. The new configuration, where the bias potential is lower that the Faraday cup potential indicates that the bias cannot serve as a stop for SEs that might escape. Thus, material selection and possibly further geometry consideration should be made carefully in order to minimize SEs and prevent their escape. Previous analysis indicates that an energy resolution of 0.12% was possible by the geometry of the apertures alone.[2] With this analysis we now have an upper and lower bound for the energy resolution. This is a great project and the URCO grant has given me the opportunity to move it forward in addition to learning valuable engineering skills. Thank you for the opportunity.

<u>Appendix A</u>



ITEM NO.	PART NAME	QTY.
1	Part 1-Faraday Cup	1
2	Part 2	1
3	Part 3	1
4	Part 4	1
5	Part 7-A	1
6	Part 7-B	1
7	Part 8-A	3
8	Part 8-B	2
9	Part 8-C	2
10	Part 9	1
11	Aperature 1	1
12	Aperature 2	1
13	Aperature 3	1

Fig. A1 Sample of the drawings created for the current Faraday cup. This drawing shows an exploded view of the Faraday cup assembly.

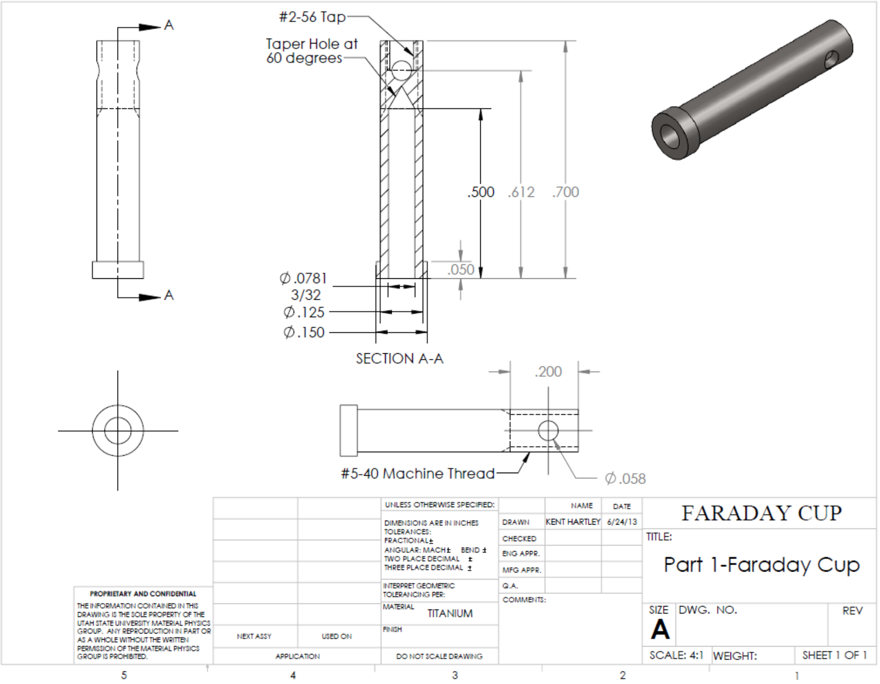


Fig. A2 Sample of the drawings created for the current Faraday cup. This drawing shows the actual Faraday cup.

Appendix B

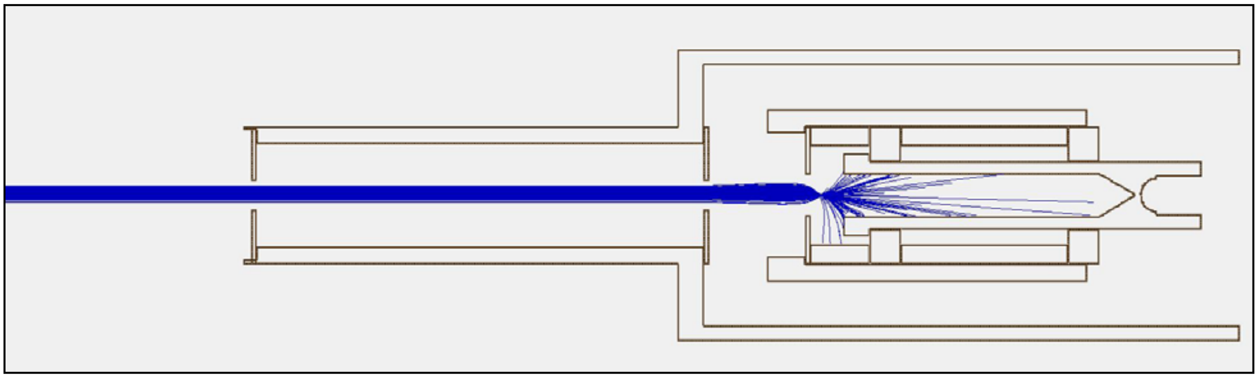


Fig. B1 Electron capture visualization – electrons (blue) move from left to right. Faraday cup = -100 V, Bias Aperture = -100 V, E-Beam = 100.1 eV

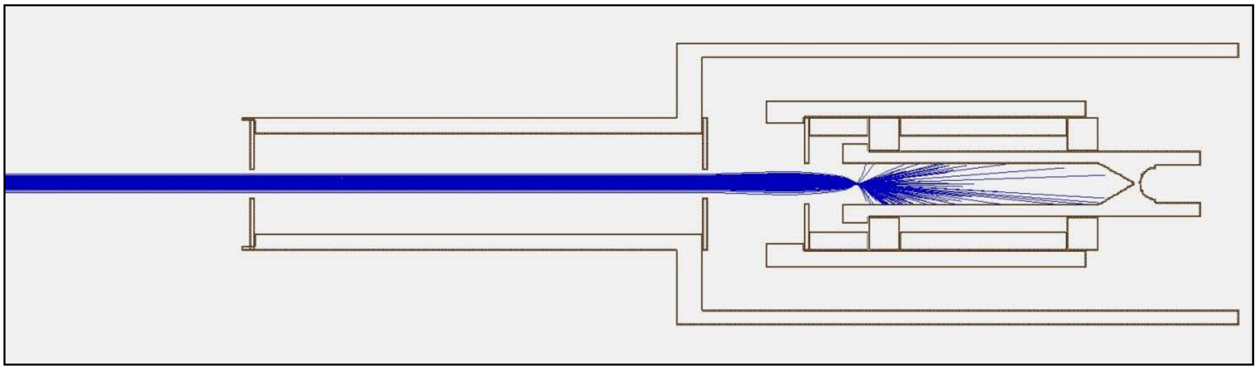


Fig. B2 Electron capture visualization – electrons (blue) move from left to right. Faraday cup = -100 V, Bias Aperture = -90 V, E-Beam = 100.1 eV

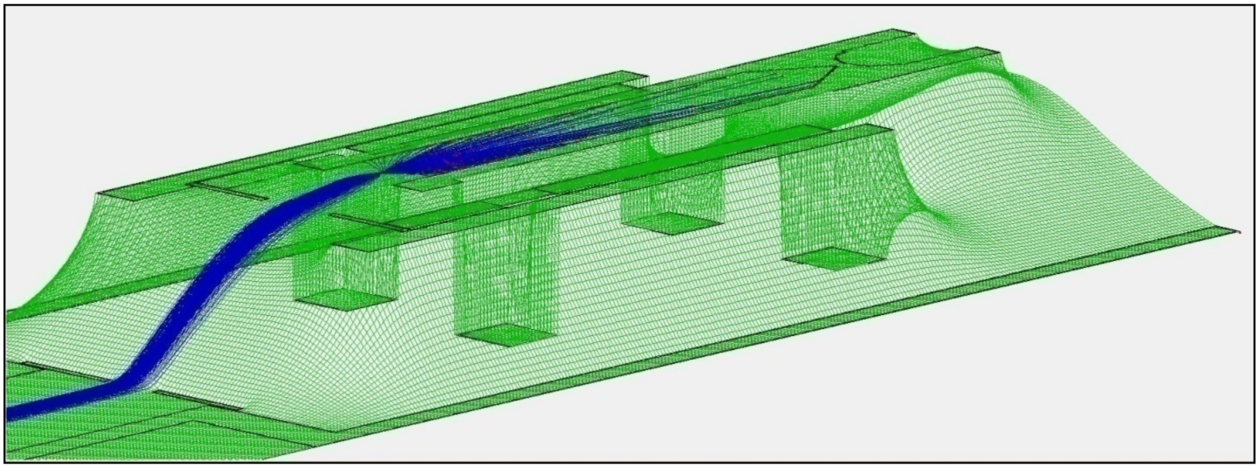


Fig. B3 Electron capture visualization – electrons (blue) move from left to right. Potential energy contours (green) graphically show how much energy the incident electrons need to make it into the Faraday cup. Faraday cup = -100 V, Bias Aperture = -90 V, E-Beam = 100.1 eV

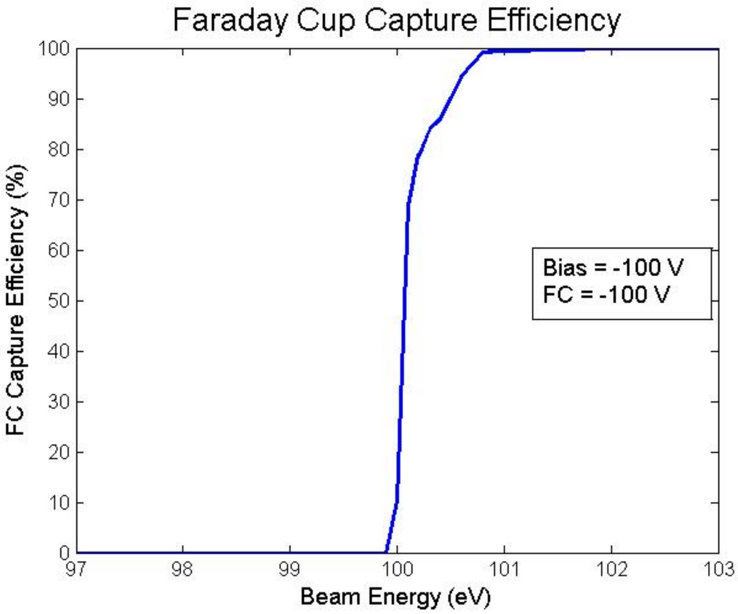

Faraday Cup Capture Efficiency
FC Capture Efficiency (%)
Beam Energy (eV)
0
10
20
30
40
50
60
70
80
90
100
97
98
99
100
101
102
103
Bias = -100 V
FC = -100 V

Fig. B4

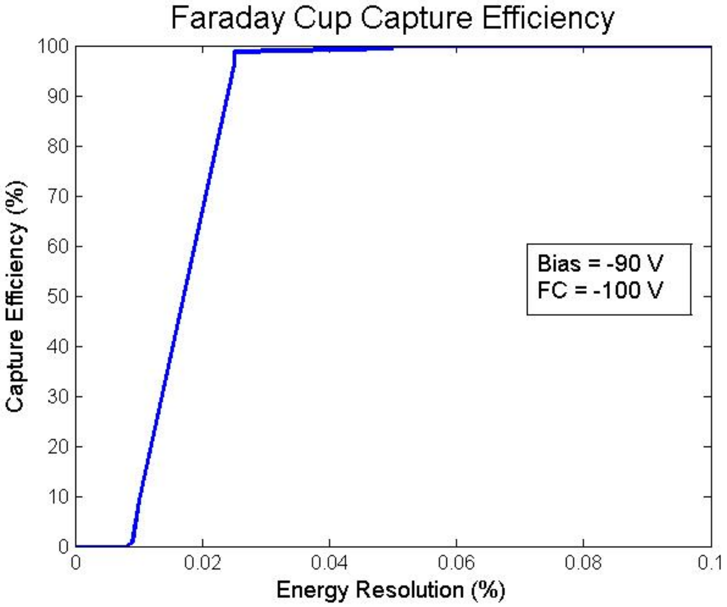

Faraday Cup Capture Efficiency
Capture Efficiency (%)
Energy Resolution (%)
0
10
20
30
40
50
60
70
80
90
100
0
0.02
0.04
0.06
0.08
0.1
Bias = -90 V
FC = -100 V

Fig. B5

References

1 SIMION^{TM} Version 8.1. Scientific Instrument Services, Inc. Ringoes, NJ. http://simion.com/.

2 Kendall Ford with JR Dennison, “Development of Improved Faraday Cup for Measurements of Charged Particle Energy and Angle-Resolved Cross Sections,” Utah State University Student Showcase, Logan, UT, April 18, 2000.

3 Jason T. Kite. 2007. “Secondary Electron Production and Transport Mechanisms By Measurement of Angle-Energy Resolved Cross Sections of Secondary and Backscattered Electron Emission From Gold.” PhD Dissertation, Utah State University, Logan, UT. Pg. 30-33

4 John H. Moore, Christopher C. Davis, Michael A Coplan. 1983. “Building Scientific Apparatus.” Addison-Wesley Publishing Company. London. Pg. 320.

5 Robert E. Davies. 1996. “An Instrument for Experimental Secondary Electron Emission Investigations, With Application to the Spacecraft Charging Problem.” MS Thesis, Utah State University, Logan, UT. Pg. 87-94

6 Kent Hartley and JR Dennison, “Faraday Cup Designs for High Efficiency Determination of Energy- and Angular-Resolved Charged Particle Fluxes,” Utah Undergraduate Research on Capitol Hill Salt Lake City, UT, January 31, 2013.

7 Kent Hartley and JR Dennison, “Faraday Cup Designs for High Efficiency Determination of Energy- and Angular-Resolved Charged Particle Fluxes,” Utah Council on Undergraduate Research, Logan City, UT, February 22, 2013.

8 JR Dennison, Jason Kite, C.D. Thomson, Jodie Corbridge, Robert Berry, and Carl Ellsworth, *Final Report Part IV: Additional Materials Reports*, NASA Space Environments and Effects Program Grant, “Electronic Properties of Materials with Application to Spacecraft Charging,” May 2003. Published by NASA electronically at http://see.msfc.nasa.gov/ee/db_chargecollector.htm, the work is comprised of 6 individual *Materials Reports* with a combined length of ~250 pages.