INVESTIGATION INTO DIRECT ENERGY CONVERSION WITH MEDIUM ENERGY HELIUM-ION BEAMS

A Thesis

by

AVERY ALLAN GUILD-BINGHAM

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

December 2004

Major Subject: Nuclear Engineering

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Approved as to style and content by:

Ron R. Hart (Chair of Committee)	Francis J. Narcowich (Member)
Leslie A. Braby (Member)	William E. Burchill (Department Head)

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ABSTRACT

Investigation into Direct Energy Conversion with Medium Energy Helium-Ion Beams.

(December 2004)

Avery Guild-Bingham, B.S., Texas A&M University

Chair of Advisory Committee: Dr. Ron R. Hart

The Department of Energy (DOE) Nuclear Energy Research Initiative (NERI) Direct Energy Conversion project has identified the fission fragment magnetic collimator reactor (FFMCR) as a promising direct fission fragment conversion concept. The US DOE NERI Proof-of-Principle Project at Texas A&M is focused on experimental verification of FFMCR operation principles. The purpose of this experiment was to test design parameters of a scaled prototype of a direct energy collector chamber of the FFMCR. The charge collection efficiency was found using a He^+ ion beam to be approximately 88% for beam energies ranging from 20 to 80 keV. The 2.4 10^{12} ± 10% ohm resistor used in the experiment holds-up under the stress of high voltage to 40 kV. Electric current leakage tests of the charge collection device also indicate that Teflon® is quite sufficient as an insulator for potentials as high as 40 kV. It is suggested that the present work be extended to determine power efficiencies and to achieve results with higher beam energies.

ACKNOWLEDGEMENTS

I would like to thank Dr. Ron Hart for his patience and guidance and his strong insistence that I achieve my goals. I would also like to thank those who offered support and assistance in completion of this work. This includes my colleagues, Don Algama, Jason Harp, and Matt McCormick, for help in maintaining the accelerator system. I would additionally like to thank Matt McCormick, and Gokul Vasudevamurthy for their work in calibrating the high-ohmic resistor. I would like to thank Lucas Phinney for his instruction in the operation of the 150 keV accelerator. Additionally I want to thank Dr. Pavel Tsvetkov for his general assistance in this work. Finally, I thank my wife, Frances, who supported my choice to pursue a graduate degree.

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CHAPTER I

INTRODUCTION

Direct energy conversion (DEC), also referred to as direct collection, is the conversion of the kinetic energy of charged particles released in nuclear reactions to potential energy by decelerating and ultimately collecting the particles on high-voltage plates.[1] As early as 1944, E. P. Wigner proposed applying direct collection to fission fragments, and by 1957, G.M. Safonov performed the first theoretical studies of direct fission fragment energy conversion (DFFEC).[2] DFFEC is the direct collection of fission fragments which are the highly charged particles released as a result of nuclear fission. Prototypes based on some of those studies were constructed and irradiated in research reactors which experimentally confirmed the basic physics concepts of DEC. The results were limited by technological difficulties and poor efficiencies were achieved which resulted in much of the DFFEC work to terminate by the late 1960s.[3]

In 1959 G. I. Budker suggested the possibility of converting "thermonuclear energy directly into high-voltage electrical energy in an industrially economic manner".[1] In 1960 Samuel Glasstone also suggested that direct energy conversion from thermonuclear energy, the energy released from nuclear fusion, into electric energy was feasible.[1, 4] However, it was not until 1969 that R. F. Post analyzed a multiplate collector design which allowed for high conversion efficiencies on the order of 90%. Post showed the possibility of developing economic mirror reactors for which the collector was designed. Researchers at Lawrence Livermore Laboratory then contributed work to establish direct energy collection with fusion mirror reactors as scientifically feasible.[1] That work and other advancements in pulsed power, magnetic insulation, and nuclear

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This thesis follows the style of the *Journal of Nuclear Science and Technology*.

fusion have improved the achievability of DFFEC.[3] Generating electric power directly from charged fission fragments through direct energy conversion may now prove to be a more effective way of converting nuclear power into electricity than traditional thermodynamic power generation methods. The completed Department of Energy (DOE) Nuclear Energy Research Initiative (NERI) DEC project has identified the fission fragment magnetic collimator reactor (FFMCR) as a promising DFFEC concept.[5]

The US DOE NERI Proof-of-Principle Project at Texas A&M is focused on experimental verification of FFMCR operation principles.[5] The FFMCR system is different from other DEC systems in that it is based on an out-of-core approach. This system will use magnetic collimation to transport fission fragments from emission in the core to multistage direct energy collectors. One advantage of this feature is that it allows the electric components to be located away from the radiation produced by the nuclear reactor. The FFMCR DEC system also takes advantage of features originally formulated for application in mirror-based fusion systems.[1,3] The method for direct conversion of fission fragment kinetic energy to electricity considered to be the most efficient is a multi-stage Venetian Blind charged particle collector.

An FFMCR non-fissioning scaled prototype will be tested at the K500 Superconducting Cyclotron Facility at the Texas A&M University Cyclotron Institute. Fission fragments will be simulated using a high energy He-ion beam. The Cyclotron will generate 90-100 MeV He-ions. The beam will be attenuated through one millimeter of copper which will reduce the kinetic energy to the range of 4 MeV.[6] The yield of the transmitted beam will be an average voltage/charge ration of 1.5 MV/charge.[7] The prototype will be at ultra-high vacuum (UHV), and the He-ion beam will be guided by a magnetic field into a collector plate which will be charged to a voltage of 1.5 MV. The beam will also be scattered into Venetian Blind collectors. The final design of the prototype can be seen in Figure 1.

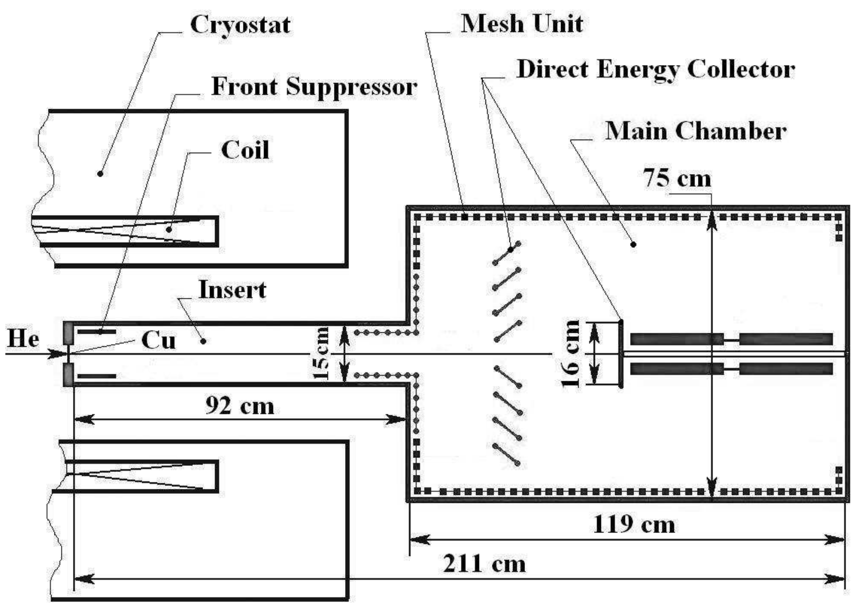

Figure 1. Non-Fission Prototype of FFMCR System[5]

In the present work, a geometrically scaled model (roughly 1:8) of the final stage of the FFMCR prototype was tested using a 150 kV accelerator in the Ion Beam Laboratory at Texas A&M University. The present work modeled the main chamber and main stage of charge collection of the prototype. The magnetic field and the Venetian blind multi-stage collectors were neglected from the scaled model of this experiment. The 150 kV accelerator produces a monoenergetic beam which eliminates the need for the Venetian Blind collectors to achieve high efficiencies. A monoenergetic beam should be able to charge the target to a potential equal to the beam energy.

The purpose of the present work was to test the high-ohmic-glass resistor and Teflon® insulation to be used in the main experiment under similar electric field conditions. Additionally, this work was intended to determine the target and ion behavior as the target is charged to high voltages. A potential problem with the prototype is electric breakdown as high voltages are achieved. The present experiment was designed with the hope of identifying any microdischarges that may lead to the possibility of a complete electrical discharge and determining if steps could be taken to prevent breakdown. The experiment was also intended to determine charge collection and power collection efficiencies. Previous work by Barr and Moir obtained a power efficiency of 47% while more recent work by Phinney achieved efficiencies around 85%.[6,9] Results from this work should contribute to the understanding of high-voltage charge collection and the materials to be used in the prototype.

CHAPTER II

EXPERIMENTAL

ACCELERATOR SYSTEM

Overview

The linear accelerator used in this experiment is capable of producing 150 keV singly-charged ion beams. The accelerator consists of several main components. Atoms of gas are ionized in the ion source, which is a Physicon hot cathode ion source. The ions are accelerated and formed into a beam by the ion-extractor-electrode system. The ion beam leaves the extractor and passes the focusing lens electrodes.[10,11] The beam then reaches the glass cross region and then the mass separation magnet. From here the beam enters the beam line and then the target chamber.

The gas used to supply the source for this work was 99.9% pure Helium, and the ion source was used to produce a singly-charged He-ion beam. The source is operated under high vacuum however, other trace gasses such as nitrogen, oxygen, hydrogen, and water vapor are often present in the beam. The ions leaving the source are accelerated through a constant-gradient accelerating column and into the glass cross region.[11] A valve can control the gas supply to the source during operation.

The glass cross contains a shutter which can stop the beam before it reaches the mass separator. The shutter is preceded by vertical deflection plates which can be biased and are used to center the beam as it enters the mass separator. Connected to the deflection plates is a 1” aperture which prevents secondary electron backstreaming into the source.[11] Below the glass cross is a Varian diffusion pump. This pump helps maintain high vacuum pressure near the ion source. Operating pressures in the glass cross are on the order of 10-6 torr however base pressure is typically maintained at approximately 10-7 torr.

From the glass cross the beam enters a magnet mass separator. The magnetic field can be adjusted to allow for isotopic and charge separation. The magnetic field strength required is a function of beam energy and atomic mass. The magnetic field settings used in this experiment were compared to expected results based on mass spectra done with the accelerator at several different beam energies. Once the beam leaves the mass separator it enters the beam line. A valve can close off the beam line from the mass separator in or out of accelerator operation.

Once the beam enters the beam line there are several knife-edge collimators which can be adjusted for beam shaping. At the end of the beam line is a final collimator which has an adjustable setting of full collimation (no beam), no collimation, 1/4", 1/8", and 1/32" diameter collimation before the beam enters the target chamber. The collimators are all mounted on a linear motion vacuum feedthrough. A beam profiler precedes the collimator. The profiler provides information about beam shape. The beam line is kept under vacuum with an ion pump, and is typically maintained at 10-8 torr but increases to 10-7 torr during operation. The beam line can be isolated from the target chamber with a valve. The overview of the accelerator system from the source until the beam enters the target chamber is shown in Figure 2.

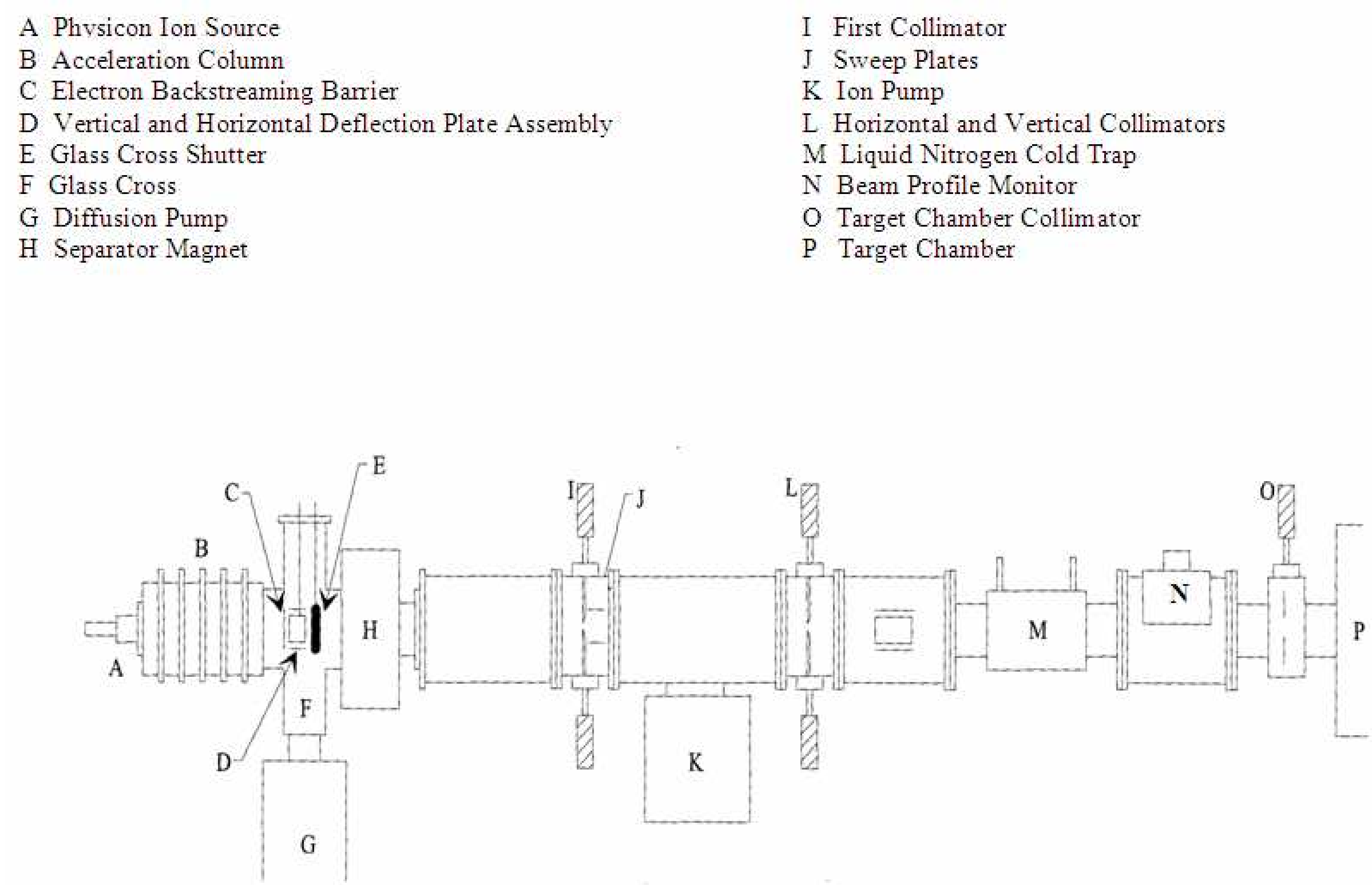

Figure 2. 150 keV Accelerator Source and Beam Line Components[11]

Target Chamber

The target chamber is maintained at ultra high vacuum (10^{-8} torr) by a diffusion pump coupled with a cryopump. A high vacuum can hold off approximately 100 kV per centimeter.[8] Upon entering the target chamber, the beam passes the shutter bias cup and is either stopped by the target chamber shutter or interacts with the target. A top down view of the target chamber is shown in

Figure **3**. A Rutherford Backscatter detector is also present in the target chamber but is not shown below.

A Charge Collection Target
B Target Bias Cup
C Goniometer / Target Holder
D Target Chamber Shutter
E Shutter Bias Cup
F Collimator

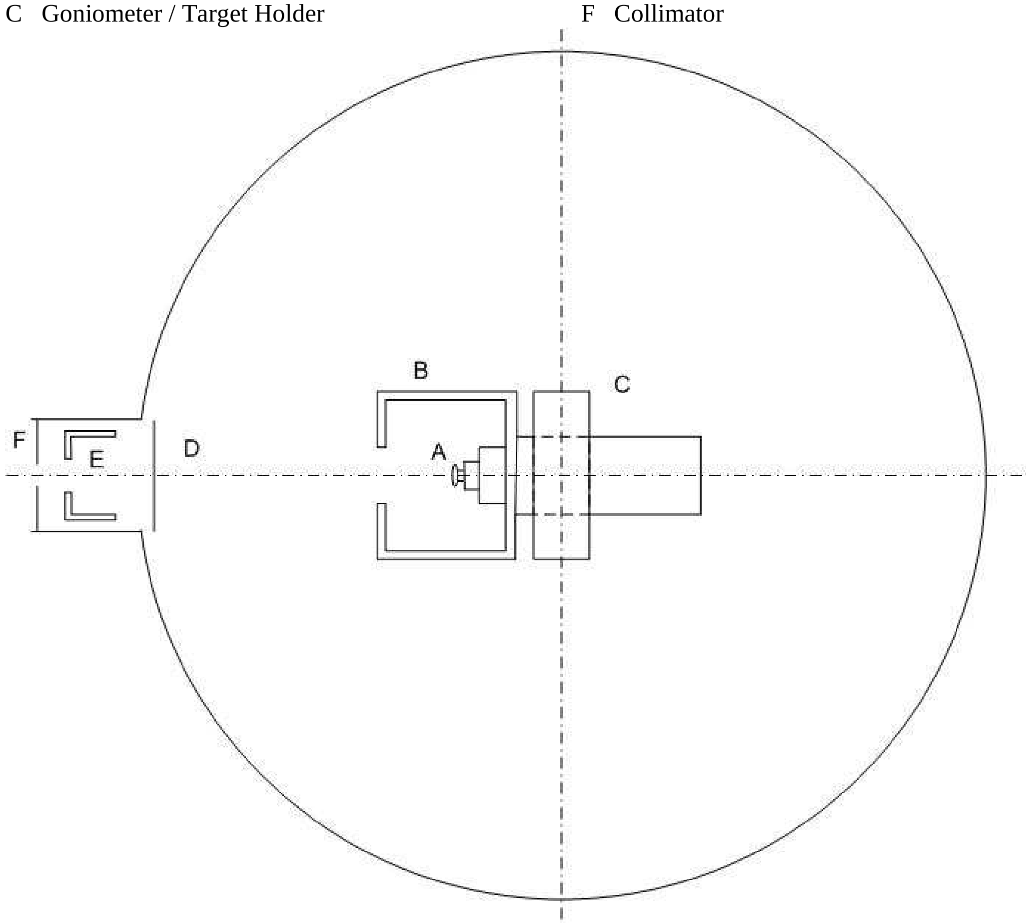

Figure 3. Target Chamber

CHARGE COLLECTION SYSTEM

Overview

The charge collection device used in this experiment consisted of an aluminum electron suppression cup, a stainless steel 304 target, a 2.4 ± 0.2 Teraohm glass resistor, a Teflon® insulating cylinder, and other aluminum pieces necessary for conduction within the Teflon®. Teflon® has a volume resistivity of $>10^{18}$ ohm-cm according to DuPont specifications. The stainless steel target used had a 0.75" diameter and a thickness of 0.135". The target had a mechanically polished mirror finish and the edge was rounded to reduce the electric field around the edge.

A cross-section of the charge collection device is depicted at roughly actual size in Figure 4. The stainless steel target is depicted as Component one. The target was connected through the Teflon® cylinder to an aluminum cylinder, Component 2, by a threaded rod. The target and the cylinder are both threaded to ensure the connection between the Components and to ensure the target is firmly in place. The glass resistor is represented by Component 3. Component 2 was held in contact to the glass resistor by a plate attached to a spring in compression. This plate is represented as Component 4 in Figure 4. The spring was held in compression by an aluminum plate external to the Teflon® cylinder which could be tightened into the Teflon® by three screws. This plate is represented as Component 5 in the figure.

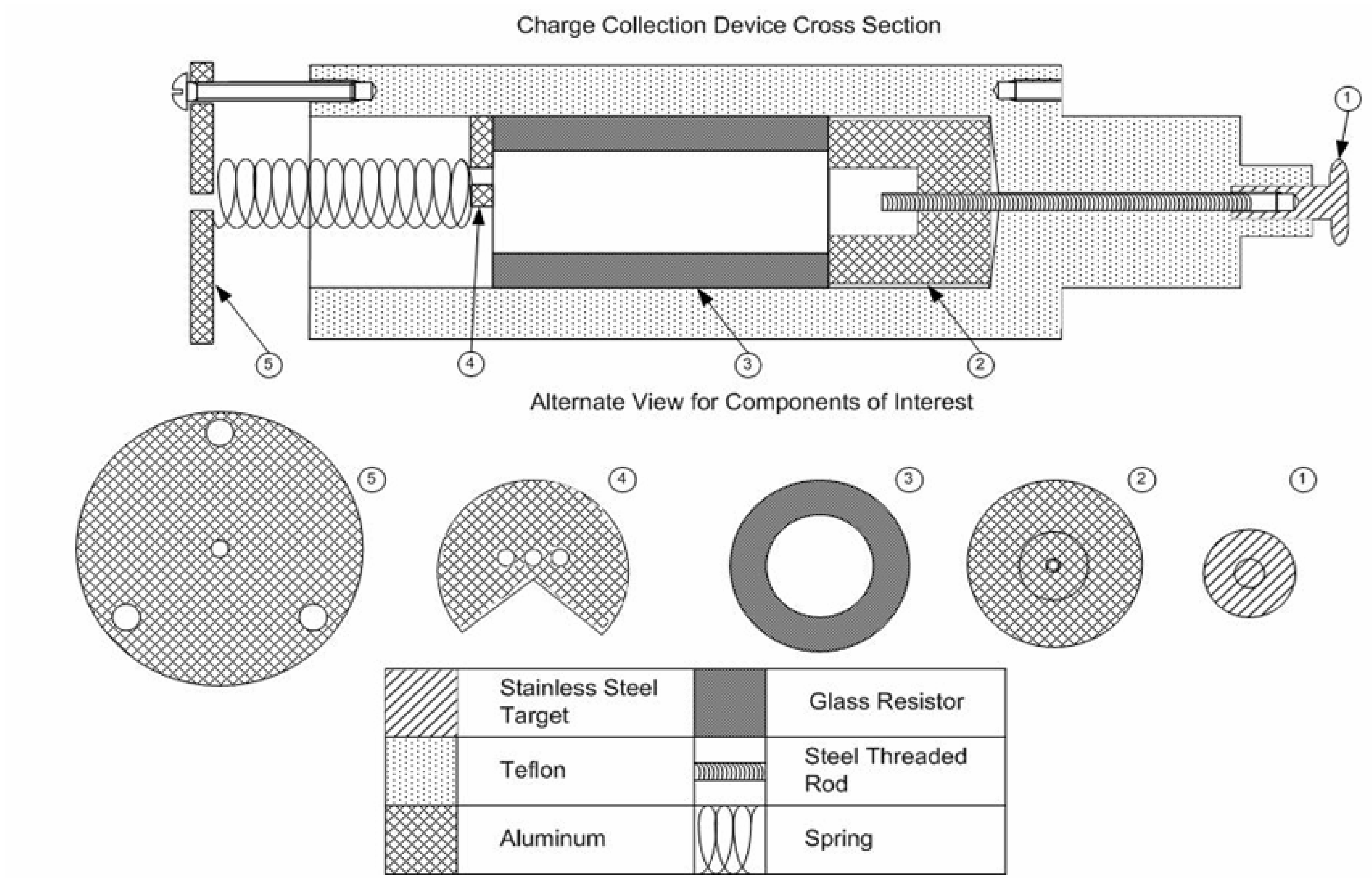

Figure 4. Charge Collection Device

The target functions as a direct converter in that as the positive ions in a beam hit the target the charge collects increasing the potential of the target to a maximum that approaches the kinetic energy of the beam which drives a current across the resistor. Beam energies ranging from 20 to 80 keV were used in this experiment. High resistance limited the beam current required to produce a potential on the charge collection plate which may have reached as high as 80 kV in this work. By keeping the beam current required to achieve the maximum potential low, the power applied to the target is kept low. For example, if the kinetic energy in the beam is 100 keV then the maximum potential on the target is 100 kV. Assuming the resistance through the charge collection device was 1 Teraohm, the beam current required to produce the maximum voltage on the target would be 100 nA, and the power through the device (100nA X 100 kV) would be 0.01 watts. The specific heat of glass is approximately 0.9 J/(g·K).[12] Assuming all the power is dissipated across the resistor the total temperature change while charging up the target with a 100 keV beam for 5 minutes at the conditions described above is approximately 0.2 C. If the resistance were on the order of 10^{10} ohm the power and consequently the temperature change would be 100 times greater. High resistance will be especially important for the FFMCR prototype where the beam energy is in the 4 MeV range.

The target bias cup was negatively biased by a battery from 0 to 350 V, and an electrometer was used to measure current on the cup. An additional electrometer was also connected to the target shutter to measure incident beam current. An electrometer connected to Component 5 in Figure 4 allowed current from the target to be measured directly. The basic electronic setup for the experiment is shown in Figure 5.

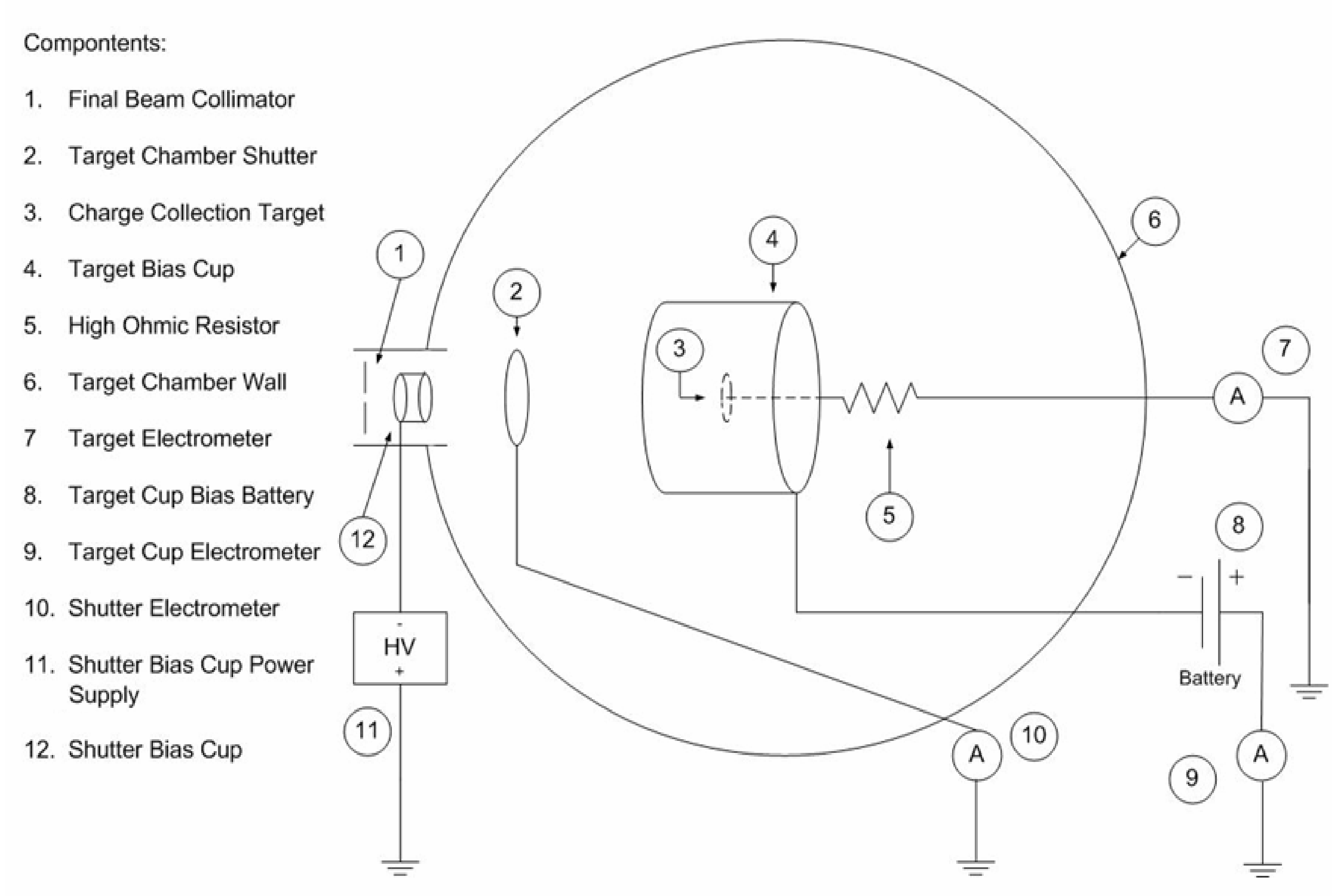

Figure 5. Basic Experiment Electric

Secondary Electron Suppression

The shutter bias cup and the target bias cup are both biased negatively to reduce the effects of secondary electrons. Secondary electrons are produced as ions transfer part of their kinetic energy to electrons within a medium of interaction such as a gas or more probably part of the accelerator system. The shutter bias cup served two functions which contributed to an accurate beam current reading from the shutter. First, the negative bias on the cup repelled secondary electrons from interacting with the shutter which would cancel positive current on the cup. Second, the negative bias also served to turn back any secondary electrons produced by ion interaction with the shutter. If these electrons were allowed to leave the shutter the shutter current would be as much as twice the actual beam current.

The target cup served a similar purpose. The target cup prevented any secondary electrons produced outside the cup from interacting with the target. A potential of -200 V is sufficient to repel most secondary electrons. For the primary experiment the target cup had a greater bias than the shutter cup so that electrons were not actually accelerated into the target. The expected ion beam interactions resulting in secondary electron production are shown in Figure 6.

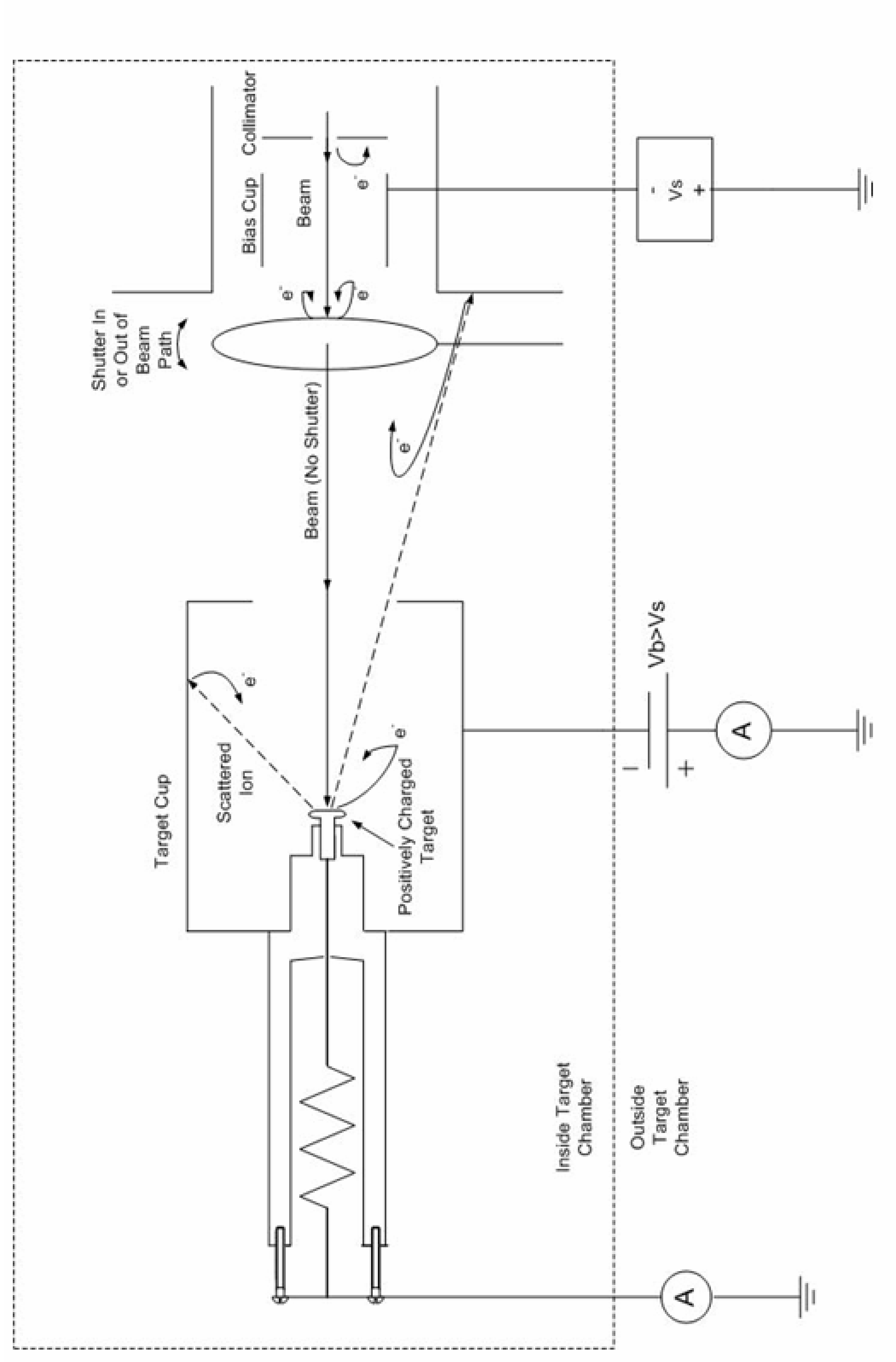

Figure 6. Secondary Electron Effects

PROCEDURE

Primary Measurements

The resistor used in the in the experiment was obtained from BURLE Electro-Optics. As mentioned previously the resistor used in the experiment needed to be high. The 10^{12} ohm range reduced the beam current required to achieve the theoretical maximum potential to the nA range in the present work. Since the current on the shutter and the target could be measured directly, the resistance needed to be known in order to determine the voltage obtained on the target and the power efficiency achieved by the charge collection device.

Before the charge collection device was configured the resistor was measured using a calibrated 10 kV power supply. An attempt was made to use the beam to confirm the resistance of the glass at higher voltages during the primary measurements. Using the beam to calibrate the resistor should be possible because current on the target is at a maximum when the current times the resistance is equal to the energy in the beam. This is true when the target is charged to a potential in kV equal to beam energy in keV. In other words a plateau in the target current should occur once the current is sufficient to achieve the maximum potential at a given beam energy. Adding any additional current to the beam should not change the potential reached by the target, since the additional ions will be reflected. The current which achieves the maximum potential on the target is the threshold current that corresponds to the kinetic energy of the beam. After measurements were taken from the charge collection device the resistor was recalibrated in air with a 150 kV power supply up to 20 kV. The resistor was found to be approximately 2.4 Teraohms both before and after the experiment was performed.

The charge collection device was assembled after thorough cleaning of the Teflon® and other components. The cleaning procedure included washing the components with distilled water then rinsing with acetone and methanol. The Teflon® had to have an extremely clean surface. The Teflon® was soaked in an HCl bath for over an hour to ensure any aluminum on the surface would be completely dissolved. The Teflon® was then rinsed in acetone followed by methanol. All components were handled with latex gloves during and after cleaning.

Measurements were taken with beam energies form 40 to 80 keV. After some preliminary analysis, it was determined that the current readings from the target were insufficient to determine if the threshold current had been reached. Additional measurements were taken at 40 and 80 keV beam energies. Based on the initial resistance calibration the current greatly exceeded the maximum threshold for each beam energy level.

Several tests were setup to check for leakage current in the charge collection device. These tests include applying voltage from a battery to the target cup of the fully assembled-charge-collection-device and measuring current with an electrometer. The Teflon® should hold off any current effectively making the circuit open as shown as circuit 1 in Figure 7. An additional test was to apply a voltage (75 to 250 V) to the target with a battery and measuring the current through the resistor as seen by circuit 2 in Figure 7. A high voltage power supply was attached to the target and currents were measured through the cup and resistor as in circuit 3 of Figure 7. A test for leakage current through the Teflon® to the goniometer can be seen with the setup of circuit 4 in Figure 7. No significant leakage current was found in any of the tests.

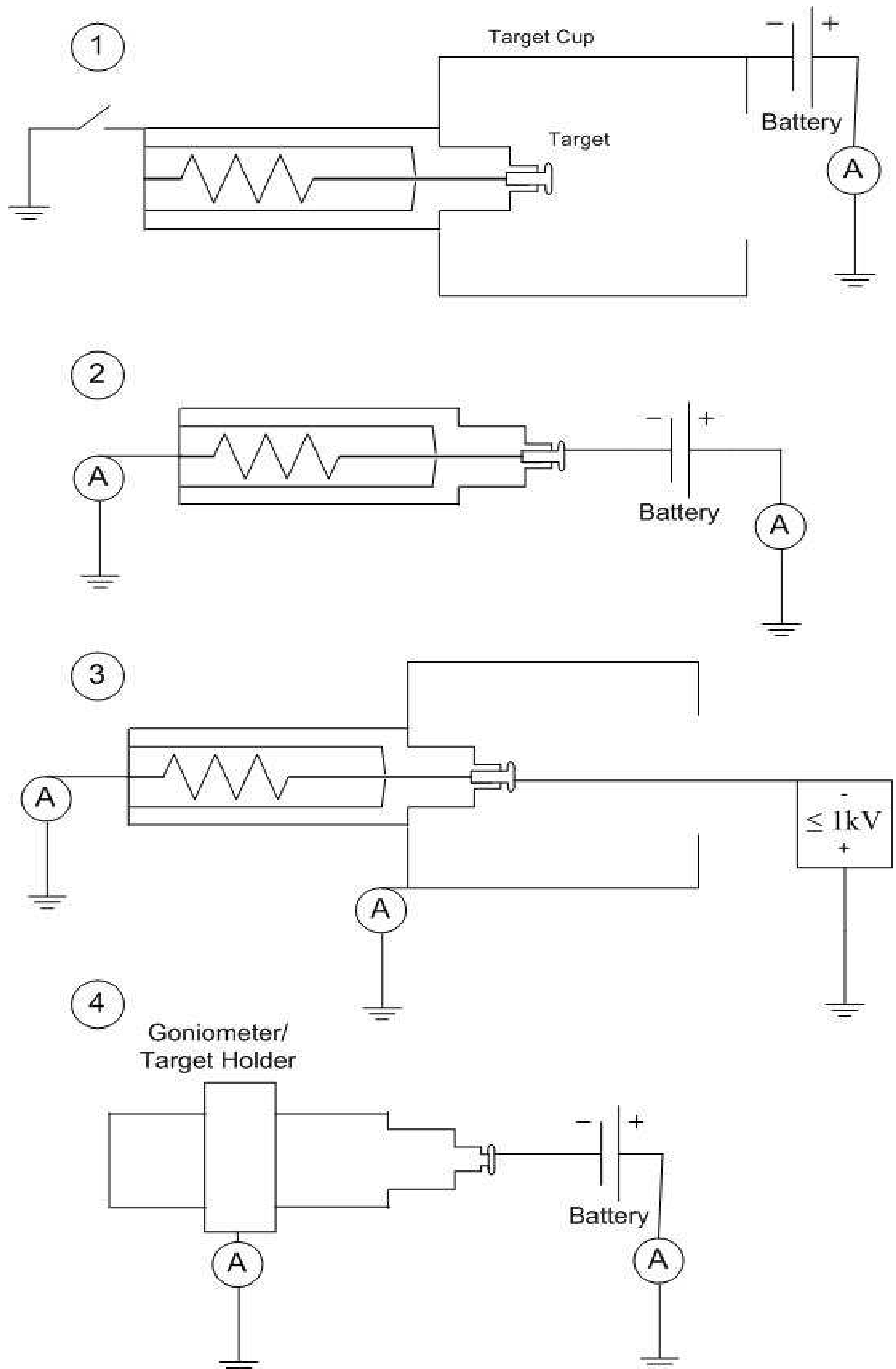

Figure 7. Leakage Current Tests

Problem Assessment

Due to problems in determining the threshold current a series of tests was devised to determine the cause of the problem. Three tests were devised. First, measurements were made varying the bias of both the target and shutter cups to determine the effects of secondary electrons. Second, the beam was used to test leakage current by removing the glass resistor and measuring currents on the target cup and from the back of the Teflon®. Finally, measurements were made with the cup completely removed. These additional tests did not indicate significant leakage current.

CHAPTER III

RESULTS AND DISCUSSION

The charge collection efficiencies for all energies measured are in Table 1 below. The power efficiency could not be calculated because a threshold current was never reached at any beam energy. Appendix I show the results of the primary measurements made with beam energies of 40 to 80 keV. Because a monoenergetic He^+ beam was used the current collection should have approached 100%.[1]

Table 1. Current Collection Efficiency

Beam Energy [keV]	Current Collection Efficiency
40	80.50%±10%
50	88.90%±10%
60	95.11%±10%
70	88.70%±10%
80	88.80%±10%

Ohms law was to be used to determine the voltage on the resistor. The threshold current was never reached which implied that the resistance through the charge collection device was much lower then expected. This reduced resistance could be a result of leakage current across the surface of the Teflon® or as a result of breakdown from the target to the cup or glass resistor. Leakage current could also explain the loss of charge collection efficiency.

The resistance of the glass resistor was measured to be 2.4±10% Teraohms up to 10 kV, and again was found to be the same up to 20 kV after the primary measurements with beam energies from 40 to 80 keV. The measurements taken to calibrate the resistor can be seen in Appendix II. BURLE Electro-Optics found the resistance to be 1.0 Teraohm. However, no information was given on the methods of calibrating the resistor. The resistor was recalibrated up to 20 kV after being exposed to high voltages, because it was necessary to ensure that breakdown hand not occurred across the resistor. Since the resistor was found to have the same resistance after the experiment breakdown across the surface of the resistor was unlikely.

Another factor that could have potentially reduced the resistance of the circuit was leakage current. It was observed during calibration of the resistor that leakage current was present across the Teflon® insulator used. This leakage current disappeared when the Teflon® was cleaned thoroughly. The results of the leakage current tests using the charge collection device can be seen in Appendix III. All four tests seem to be consistent in suggesting that leakage current was not a major factor. An additional leakage current test using the ion beam was completed with similar results. The resistor was removed from the charge collection device and the beam current was measured from the back of the Teflon®. The current measured on the target was in the pico-amp range close to the zero reading of the electrometer. This test demonstrated that leakage current across the Teflon® was in the negligible even up to 40 kV on the target. Additionally, the current on the cup was approximately equal to the current of the beam. This indicates that the target achieved the voltage of the beam. Thus the beam was turned back and interacted with the negatively-biased target cup. It is interesting to note that at currents around 10 nA and greater close to 100% of the beam currents were observed on the cup. The results can be seen in Table 2.

Table 2. Cup Current from Ions Repelled by a Charged Target and Leakage Current Measured Through The Teflon

(keV) V_{beam}	(nA) Shutter Avg	(nA) Cup	Cup I / Shutter I (%)	(nA) Target
20	1.1	0.3	27	~10^-3
20	1.8	0.8	44	~10^-3
20	11	11	110	~10^-3
20	11	11	110	~10^-3
20	3	3	110	~10^-3
20	10.4	11.2	98	~10^-3
40	14	12.6	90	~10^-3
40	12	12	100	~10^-3
40	20	19.7	98	~10^-3
40	29	28	96	~10^-3

During the primary measurements spikes were observed in the current readings on the target. These spikes were originally thought to be microdischarges between the charge collection plate (target) and the target cup. However, measurements were made with the cup removed and similar current spikes where observed on the target current. The effects of secondary electrons were also considered. However the results from varying the target and shutter cup bias had negligible effects on the target current. The results from this test can be seen in Appendix IV.

CHAPTER IV

CONCLUSIONS

This work indicates that the resistor used in the experiment holds-up under the stress of high voltage to 40 kV. Though it cannot be determined from the available data, it is thought that higher voltages where achieved on the target and consequently the resistor. However, higher voltages need to be confirmed before it is conclusive that the resistor is sufficient for the FFMCR prototype.

The leakage tests also indicate that Teflon® is quite sufficient as an insulator for potentials as high as 40 kV. It was apparent that the surface of the Teflon® must be kept very clean to ensure that leakage current across the surface is not a problem.

The possibilities of breakdown from the target to the cup and across the surface of the resistor seem very unlikely based on the results of this experiment. However, it is very possible that the vacuum inside the Teflon® cylinder was inadequate, which could contribute to microdischarges from the threaded rod to some point on the resistor. Steps to take in the future would be to modify the insulating cylinder to allow for better vacuum conditions inside the cylinder.

Future steps to be taken may include Rutherford backscattering or some other measurements to determine the voltage achieved by the target. This information would be useful in conjunction with the direct current measurement to determine the power efficiency achieved as well as information about the threshold current.

More work needs to be done to determine why charge collection efficiency was approximately 88% rather a possible 100%. It is possible that the target achieved 98%

due to the estimated error in the electrometer readings. It may be helpful to recalibrate the electrometers used in this experiment. A voltage reading of the target could also serve as an additional means to calculate current and check the charge collection efficiency.

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APPENDIX I

CHARGE COLLECTION MEASUREMENTS

The charge collection results presented here are a compiled result of several days of measurements at each energy level. After analysis revealed that the estimated threshold current had been exceeded at several energy levels. The measurements were primarily focused in the 20 to 40 keV beam energy range. The base pressure in the target chamber was estimate to be about 10^{-8} torr with an upper operating pressure of approximately $2x10^{-7}$ torr. No significant differences were found within this variation of pressure. Figure 8 - Figure 12 show the results for measurements at 10 keV increments from 40 to 80 keV beam energies.

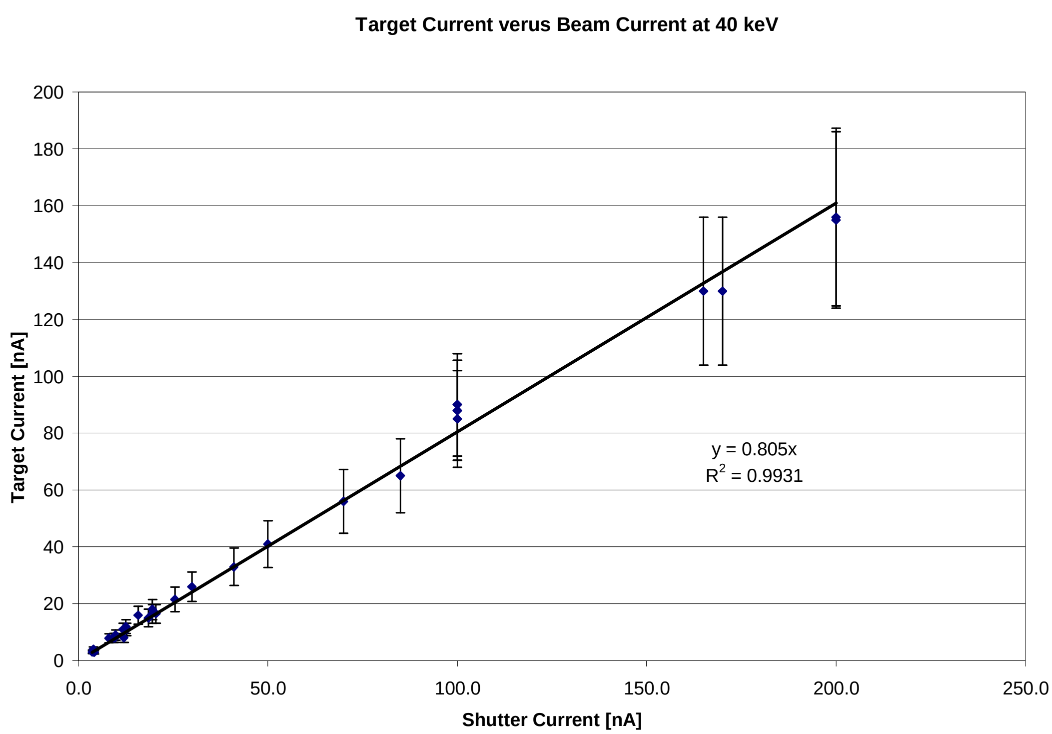

Figure 8. Charge Collection at 40 keV

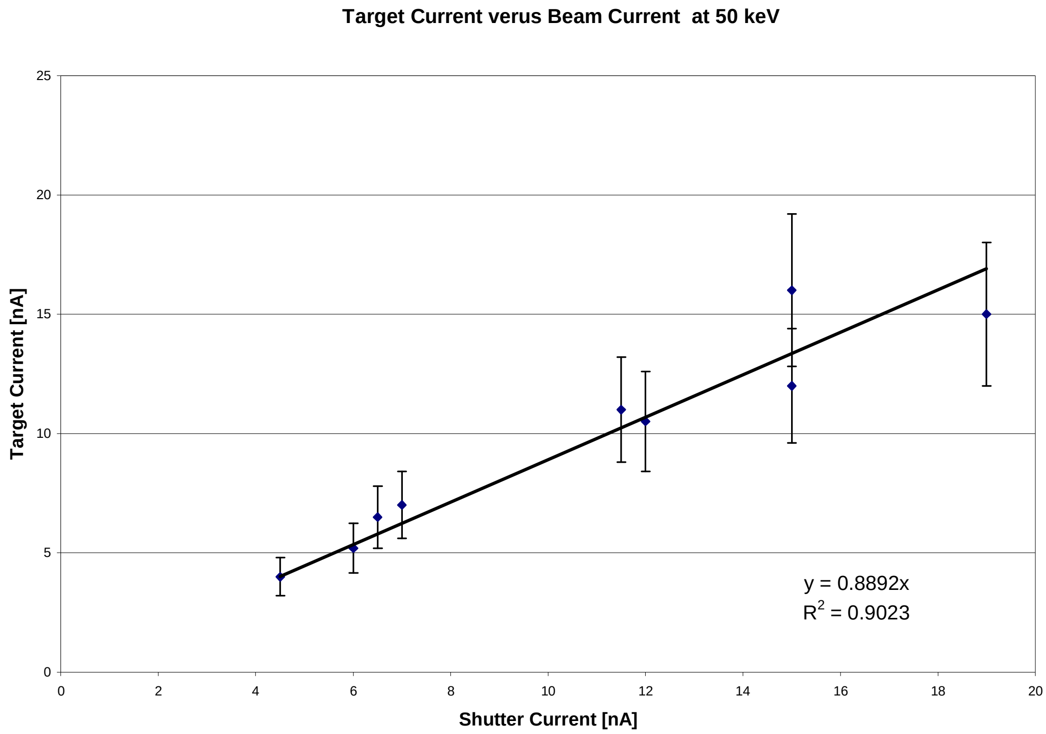

Figure 9. Charge Collection at 50 keV

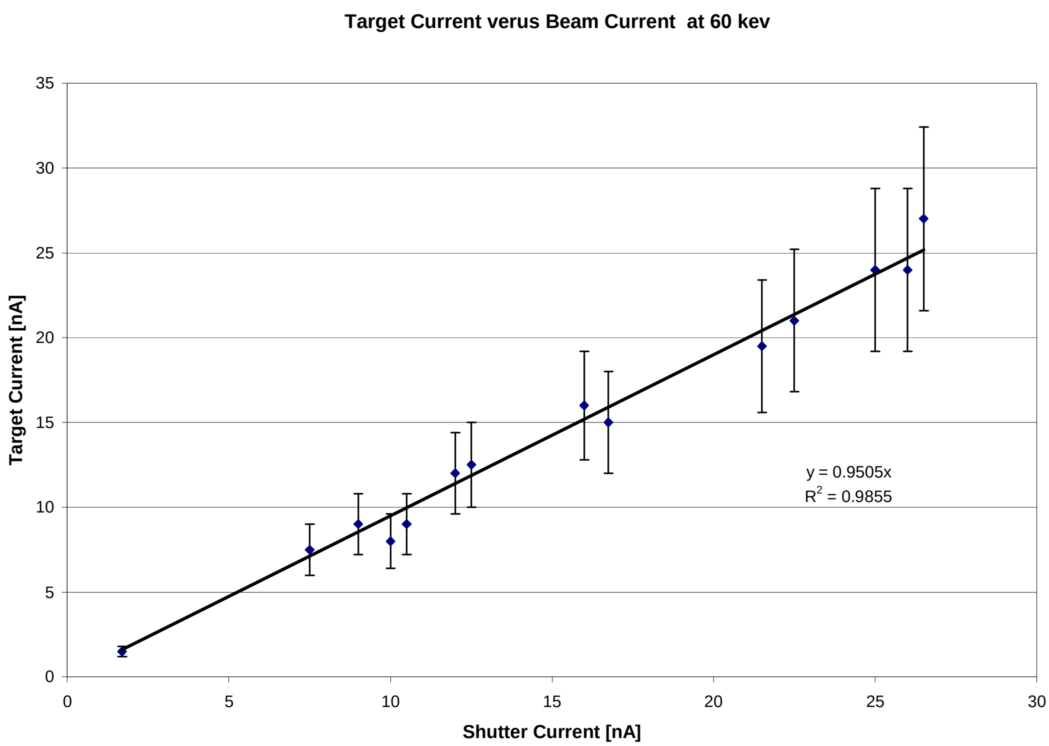

Figure 10. Charge Collection at 60 keV

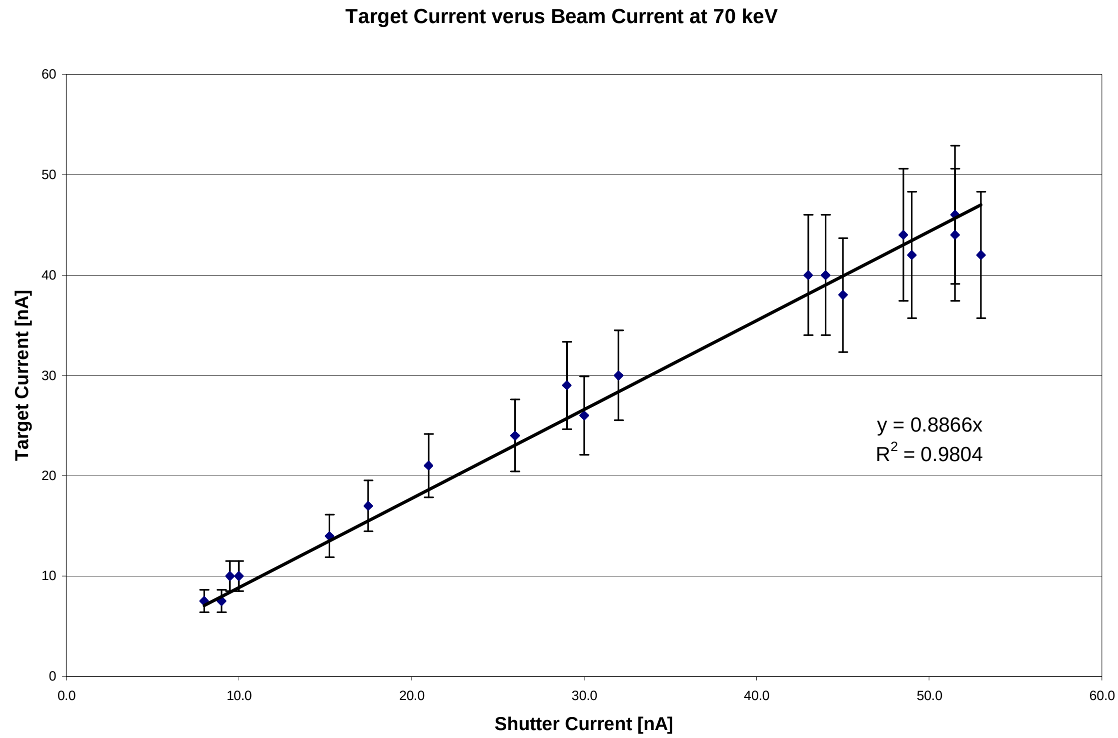

Figure 11. Charge Collection at 70 keV

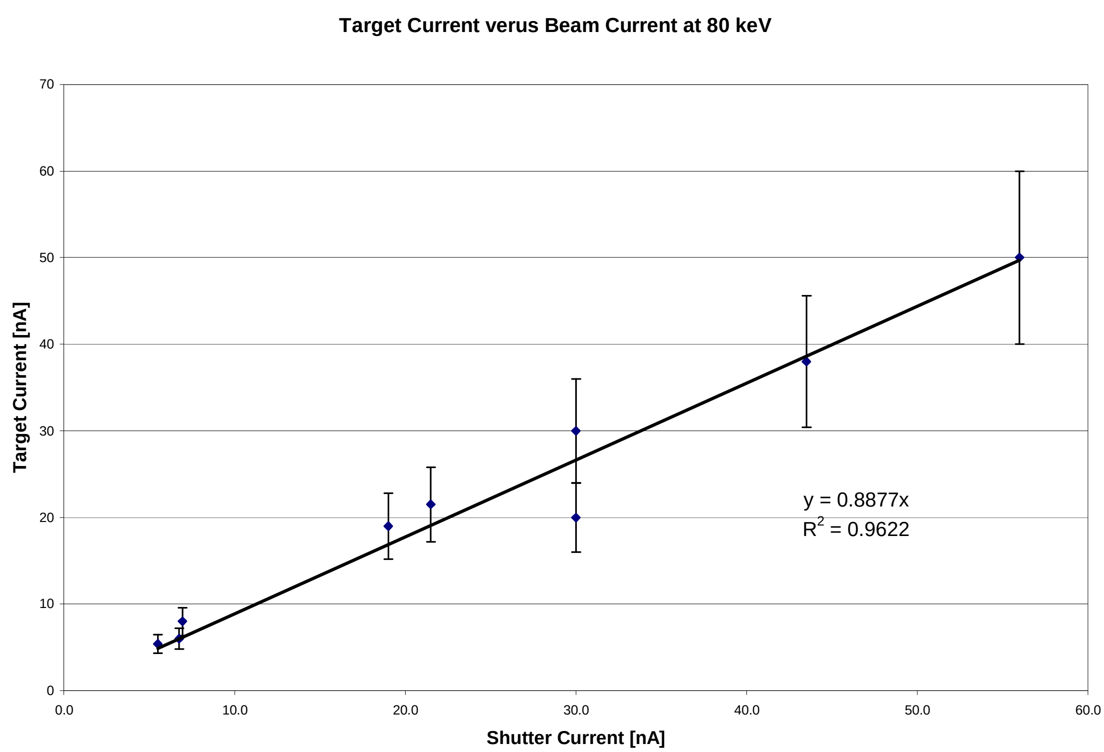

Figure 12. Charge Collection at 80 keV

Table 1 through Table 5 provides the raw data for Figure 8 though Figure 12.

Table 3. Data from 40 keV Measurement

V_{beam}	Shutter Avg	Target	% efficiency
40	3.7	3.1	84
40	4.0	4	100
40	4.2	2.9	70
40	8.0	7.9	99
40	9.3	8	86
40	11.8	11	94
40	12.0	8	67
40	12.5	12	96
40	12.8	11	86
40	15.8	16	102
40	18.5	15	81
40	20.5	16.5	80
40	9.6	8	83
40	9.8	9	92
40	19.5	16.5	85
40	25.5	21.5	84
40	19.5	18	92
40	30.0	26	87
40	41.0	33	80
40	50.0	41	82
40	85.0	65	76
40	165.0	130	79
40	70.0	56	80
40	200.0	155	78
40	100.0	88	88
40	100.0	85	85
40	100.0	90	90
40	200.0	156	78
40	100.0	88	88
40	100.0	90	90
40	170.0	130	76

Table 4. Data from 50 and 60 keV Measurement

V_{beam}	Shutter Avg	Target	% efficiency
50	4.5	4	89
50	6.0	5.2	87
50	6.5	6.5	100
50	7.0	7	100
50	11.5	11	96
50	12.0	10.5	88
50	15.0	16	107
50	15.0	12	80
50	19.0	15	79
60	1.7	1.5	88
60	7.5	7.5	100
60	9.0	9	100
60	10.0	8	80
60	10.5	9	86
60	12.0	12	100
60	12.5	12.5	100
60	16.0	16	100
60	16.8	15	90
60	21.5	19.5	91
60	22.5	21	93
60	25.0	24	96
60	26.0	24	92
60	26.5	27	102

Table 5. Data from 70 and 80 keV Measurement

V_{beam}	Shutter Avg	Target	% efficiency
70	8.0	7.5	94
70	9.0	7.5	83
70	9.5	10	105
70	10.0	10	100
70	15.3	14	92
70	17.5	17	97
70	21.0	21	100
70	26.0	24	92
70	29.0	29	100
70	30.0	26	87
70	32.0	30	94
70	32.0	30	94
70	43.0	40	93
70	44.0	40	91
70	45.0	38	84
70	48.5	44	91
70	49.0	42	86
70	51.5	44	85
70	51.5	46	89
70	53.0	42	79
80	4.5	6	133
80	5.0	4.5	90
80	5.5	5.4	98
80	6.8	6	89
80	7.0	8	115
80	19.0	19	100
80	21.5	21.5	100
80	30.0	30	100
80	30.0	20	67
80	43.5	38	87
80	56.0	50	89

APPENDIX II

RESISTOR CALIBRATION

The resistance was calibrated by making several current measurements at different applied voltages. A high voltage power supply source applied a known voltage and a current was read on the electrometer. The result was plotted and the resistance was determined using the inverse slope of the line of best fit using $I=(1/R)V$. Figure 13 shows the results from the calibration with a 10 kV power supply before the resistor was used in the charge collection device. Figure 14 shows the results of the resistor calibration up to 20 kV after the resistor had been exposed to at least 40 kV. The resistance was found to be 2.4±10% Teraohms.

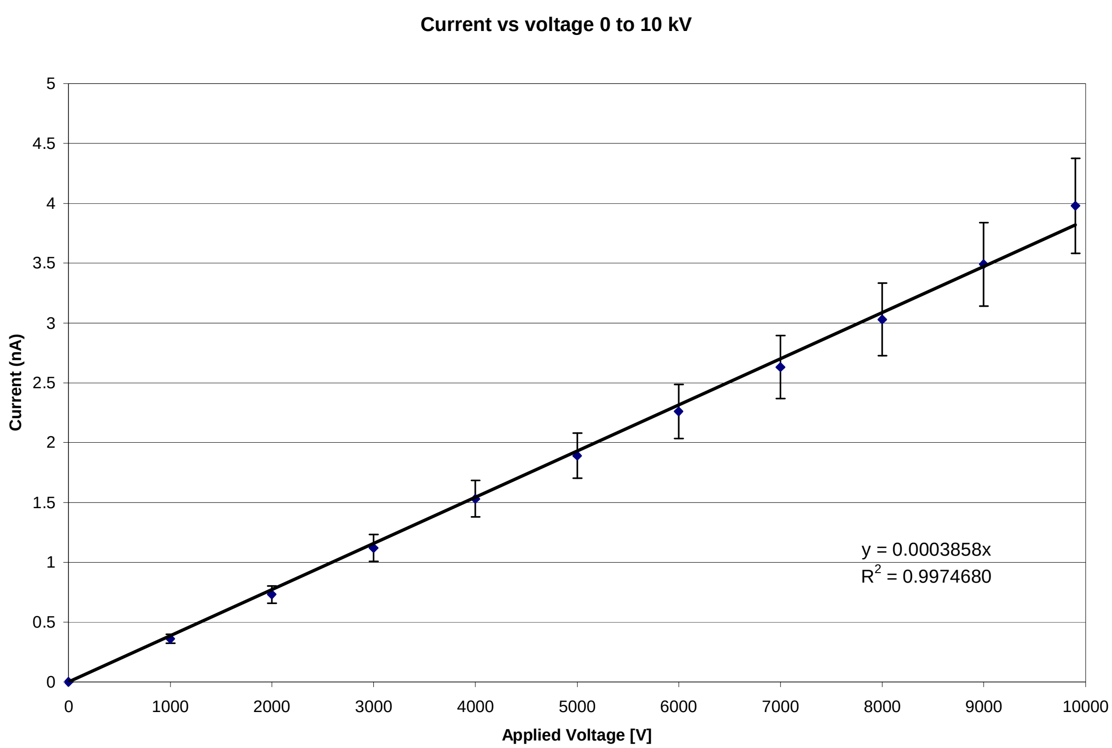

Figure 13. Resistor Calibration up to 10 kV

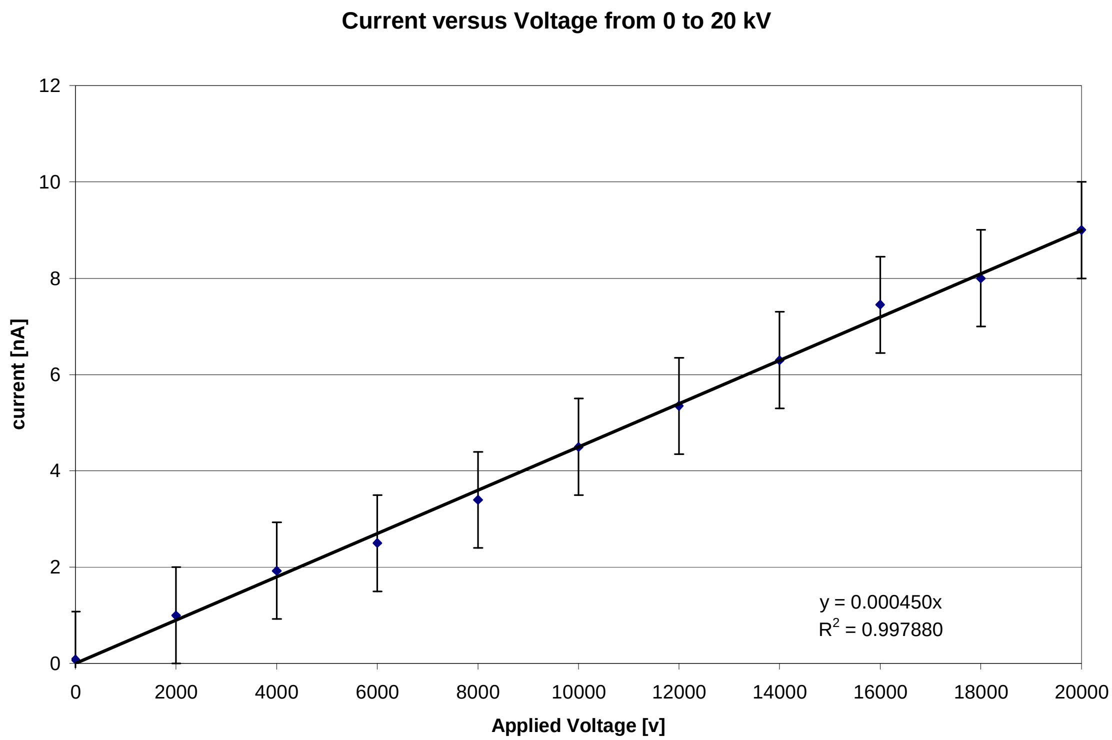

Figure 14. Resistor Calibration to 20 kV

APPENDIX III

LEAKAGE CURRENT MEASUREMENTS

The date in the following tables corresponds to the leakage current measurement described in Figure 7. The results of all four tests show negligible leakage current for the applied voltages. These tests do not rule out leakage current as a problem for much higher voltages which will be present in the prototype.

Table 6. Target Cup Leakage Current Test up to 360 V

Circuit one	
Applied Voltage [V]	Cup Current [pA]
0	0.3
90	2.3
180	4.0
270	3.5
360	5.0

Table 7. Target Leakage Current up to 270 V

Circuit two		
Applied Voltage [V]	Target Current [pA]	Resistor Current [pA]
70	36.0	27
70	33.0	27
70	32.0	26
180	62.0	55
270	90.0	83

Table 8. High Voltage Leakage Current Test up to 1000 V

Circuit three		
Applied Voltage [V]	Cup Current [pA]	Resistor Current [pA]
100	0.0	31.0
200	0.0	63.0
200	0.0	68.0
500	0.0	172.0
1000	0.0	350.0

Table 9. Leakage Current Test for Goniometer.

Circuit four	
Applied Voltage [V]	Cup Current [pA]
90	22.0
180	22.0
270	60.0

APPENDIX IV

TARGET/SHUTTER CUP BIAS

The following measurements were used to gauge the effect of secondary electrons on the collection efficiency. The results seem to indicate that the effects of secondary electrons on the target were negligible. The data was collected by varying the bias on both the shutter and target bias cups allowing a 40 keV beam to hit the target and taking a reading of the current on the target. The results are show in Table 10 below.

Table 10. Varied Bias Voltages

Shutter Cup Bias [V]	Target Cup Bias [V]	Beam I [nA]	Target I [nA]	Collection Efficiency (%)
0	350	9.0	6.3	70
0	350	9.2	6.5	71
250	360	4.0	3.5	86
250	360	4.0	3.0	75
350	180	4.2	3.5	83
350	180	4.1	3.6	88
350	0	3.7	2.7	73
350	0	3.9	3.2	82
350	270	9.0	7.0	78
350	270	9.2	6.4	70

VITA

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