Construction of Snap-Together Ion Source and Testing Facility

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ABSTRACT

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In an effort to answer some of the outstanding questions of the enhancement effects found in fusion in the low energy region a facility was needed. At Brigham Young University we have constructed a new snap-together ion source for use with a small, low-energy (0-20 keV) particle accelerator. Our source was modeled after the pocket Penning Ion Gauge source with the addition of a permanent magnet. We have also built a test facility to characterize this new source. To have a stable operation with helium, the internal pressure of the source must be about 0.5 Torr and a pressure difference across the exit port of three orders of magnitude in a vacuum and an anode-cathode voltage of approximately 450 V and a discharge current of 20 mA. The typical ion current, measured at an extraction point, at 10 kV was 5 μA. The design and construction of the ion source and test facility will be discussed here.

Keywords: ion source, PIG, permanent magnet, low energy spread

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Chapter 1

Introduction

1.1 Motivation

In the Laboratory Nuclear Astrophysics Research (LNAR) group we are interested in the study of fusion reactions in condensed matter. These reactions occur at very low energies, usually just a few electron volts (eV). Our interest lies in the investigation of properties which enhance fusion within materials. For this line of research we need a low energy particle accelerator of less than 10 keV energy, with low energy dispersion. A beam with good emittance is one with a low energy spread which is critical to eliminate uncertainty in our results. Our challenge consisted in creating a reliable ion source that would support a low energy accelerator, provide low energy spread and permit simple disassembly for quick cleaning and repair.

We looked into the option of buying an off-the-shelf accelerator source, but found that they did not meet our needs. We also inquired into having one built for us, but because of the large lead time we decided to build one ourselves.

We needed an ion source that could be adapted quickly to different ions and desired it be made from readily available parts. We also wanted it to be a simple enough design so that it could be

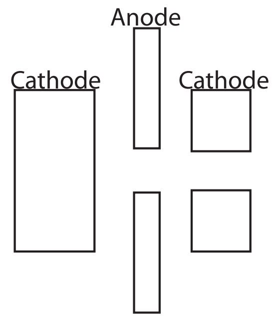

Figure 1.1 Cross section of cathode-anode arrangement in PIG ion source

customized for use with a variety of systems. Our first concern was how we were going to attach the source to an accelerator. Since it would be designed for quick adaptation, it needed to be on a common type of flange. We decided to build the ion source onto a standard 50 mm Klein Flange (KF 50) for use with elastomer seals or 3.38 inch Conflat for metal seals.With these specifications in mind, we began designs for an acceptable source.

A unique feature of our design is that the source is held together by magnets, allowing for tool-free assembly. Advantages of this strategy include: quick replacement of electrodes, ease of repairs and the use of the already present magnetic field to help direct the flow of ions. We have dubbed this source design a "snap-together ion source".

1.2 Penning Ion Gauge Ion Source

The Penning discharge was first discovered by L. R. Maxwell in 1931. Penning discharge occurs when ions are created by an electric current within a magnetic field. The magnetic field concentrates the ions in the center axis of exit hole. In 1937, F.M. Phillips invented the Phillips Ionization Vacuum Gauge from which the Penning Ion Source (PIG) was developed. This type of ion source consists of a cylindrical disk anode and two cathodes, one on each side of the anode (Figure 1.1).

The ions are then extracted from the source through a hole one of the cathode [1].

Many of these sources suffer from short lifetimes because they operate at high current. This operating range causes erosion to the electrodes due to sputtering, which leads to the need for frequent replacement. Baumann and Bethge presented a PIG type ion source with end extraction and an electromagnet which resulted in low power consumption and a compact size [2]. This type of source was later modified, further reducing the power consumption of the electromagnet [3]. With modification this source can be adapted to use solid source materials in place of gases. In efforts to make the PIG ion source smaller the electromagnet was replaced by a permanent magnet. This design became known as the pocket PIG [4]. Two novel characteristics of this source include a significant reduction in power consumption and an elimination of the need for external cooling.

This pocket PIG was further improved upon by Nouri, leading to a source with a very small energy spread of about three electron volts [5]. A small energy spread increases the efficeny of the beam on target and provides greater accuracy in the energy applied to the nuclear reaction. These characteristics are of interest for our design so we used Nouri's model for reference.

1.3 Accelerator

For a source to provide ions to an accelerator they are extracted from the plasma using an electrode. The potential on the electrode attracts the ions out of the source and into the accelerator tube. Once in the tube the ions are accelerated and focused by the electric field inside the evacuated accelerator tube. This tube is made of alternating metal plates and glass insulators with the metal plates acting as equipotential planes. These equipotential planes have a stepped potential applied to them that is maintained by a voltage divider network of resistors [6]. The extracted ions create an ion beam which is accelerated by the potential difference in the equipotential planes.

1.4 Objective

In an effort to study fusion in condensed matter we sought a particle accelerator that could be operated in the energy regime of 0-20 keV. This would allow us to study the enhancement effects to fusion in various materials to better understand the causes of these enhancements.

This low energy regime presented a variety of other challenges, the foremost being that we would need an ion source that had a very low energy spread (1-2 eV). Having a low energy spread would give us accuracy in our system and assist us in understanding of what was occurring within the nuclear reactions. After construction of an accelerator and an ion source that could fulfill these requirements we plan to perform a variety of fusion related experiments.

1.5 Significance

Electron screening for nuclear reactions in metals plays an important role in the low energy region, but there is still no theory that can describe these enhancements in fusion reactions [7]. In an effort to gain more experimental data in this low energy region we are constructing a facility in which to perform these experiments. Our ion source and accelerator could become valuable tools in learning what some of he causes of the enhancements might be.

1.6 Outline

This thesis includes a description of the construction and initial characterization of our snap-together PIG ion source and test facility. The first section covers the design and construction of the source. Comments are made on the stages of development with explanations of the design modifications and material choices. The next section includes a description of the experimental setup used to operate and test the ion source. Equipment and power supplies are documented along with setup specifications. The final section includes the initial characterization of the ion source.

Chapter 2

Methods

In this chapter I present the process of designing and the subsequent method used to characterize our ion source. I will go over the steps and the experimental setup used in this process. For illustrative purposes in this section, please refer to Figure 2.1.

2.1 Design

Once it was decided that we would construct our own source, we began to search the literature to find other sources that demonstrated the design and specifications we sought. The concept of the pocket PIG was used as the starting point for the project [5]. This pocket PIG source was chosen because of its low energy spread and the variety of ion species that it can be used with. The snap-together feature refers to the source being held together via magnetic force.

The use of magnets brought with it the question of magnetic placement and the influence of the magnetic field on the ion beam. The magnetic field used for the penning effect needs to be confined to the plasma and should not interfere with the particles exiting the source. Stray magnetic field could deflect or defocus the ion beam. We needed magnets with sufficiently high Curie temperature as to not be damaged by the heat radiated from the formation of a plasma. Using a program called

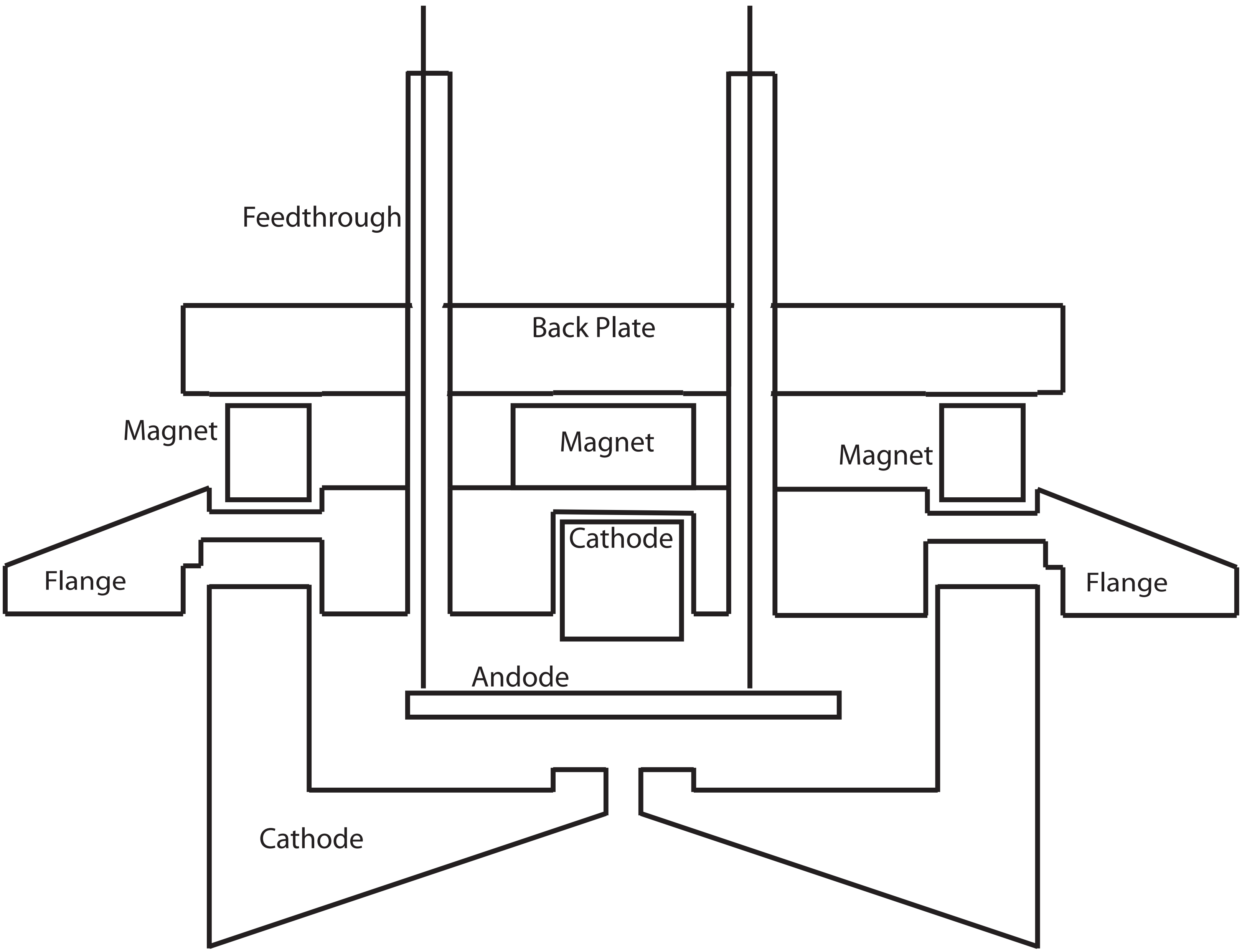

Figure 2.1 Cross sectional exploded view of ion source

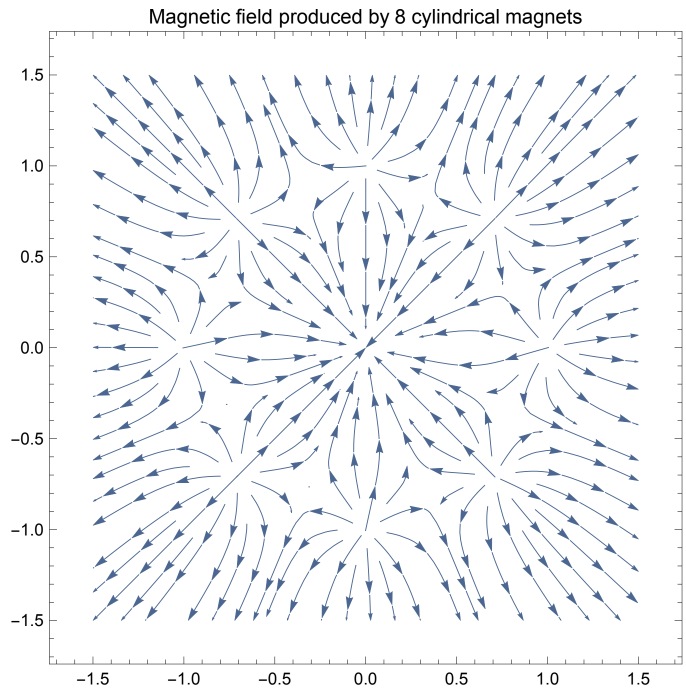

Figure 2.2 Mathematica plot of magnetic field produced by the eight SmCo magnets when placed on flange

Quickfield, I was able to get a rough idea of how the magnetic field would behave with different configurations of the magnets and with different materials. In order to shape the magnetic field as desired we made the source out of a combination of iron and high quality stainless steel.

Upon investigation, the most common type of magnet was Neodymium6, but these would not fit our application because their Curie point is only 310 degrees Celsius. We found that the best magnets were samarium cobalt (SmCo) because of their high Curie point of 750-800 degrees Celsius. We found that the best way to design the magnetic field would be to use eight weaker magnets equally spaced along the perimeter of the cathode with one stronger magnet at the center. We then ordered eight 1/4 inch diameter by 1/4 inch long cylindrical SmCo magnets. We had a 1/2 inch by 1/8 inch disk magnet for the center.

First, we needed a KF- 50 flange which we made out of stainless steel and the cathode which we made out of iron. A cross sectional view of the cylindrical cathode is shown in Figure 2.3.

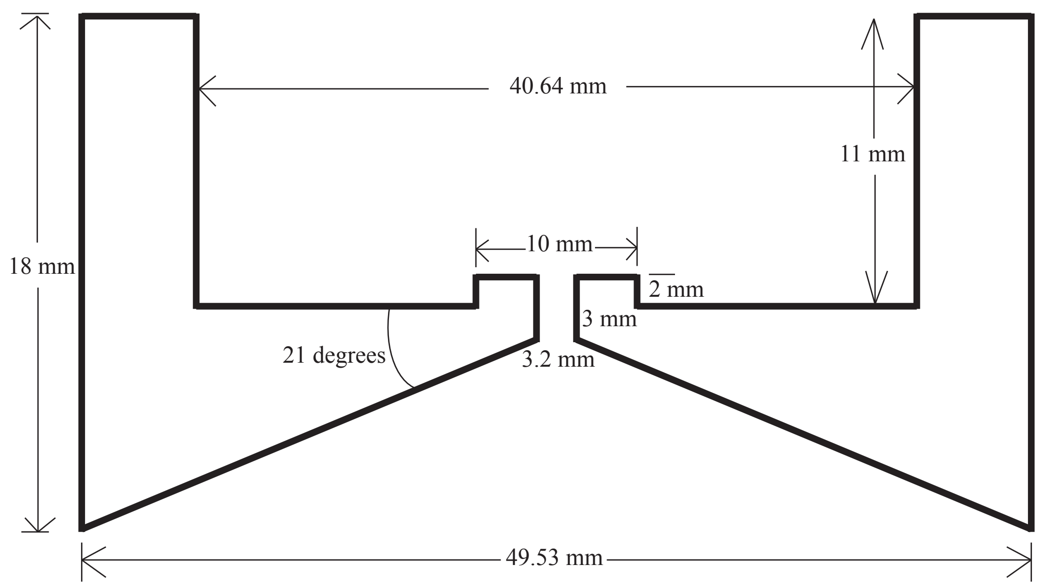

Figure 2.3 Cross sectional view of ion source cathode

This cathode design is important because it also provides a cavity in which to make the plasma. The cavity is formed by a two millimeter protrusion in cathode and the anti-cathode. The anti-cathode is a cylinder that fits into the center of the modified KF 50 (Fig. 2.4). Following Nouri, the outside 21 degree angle was specifically designed to help with ion extraction [5].

The KF 50 flange was adapted to house the anti-cathode by boring a well with a 10 mm diameter in the center of the flange. The well was designed to leave a 1/8 inch gap of material between the anti-cathode and the center magnet. We then needed to have connections to the power source, the gas source and a vacuum gauge to monitor the source pressure. Three 1/4 inch stainless steel feedthrough tubes were welded 120 degrees apart on the KF 50 flange. Ultra-Torr fittings were used to secure and seal the tubes at a radius of 1/2 inches from the center of the flange (Fig. 2.6).

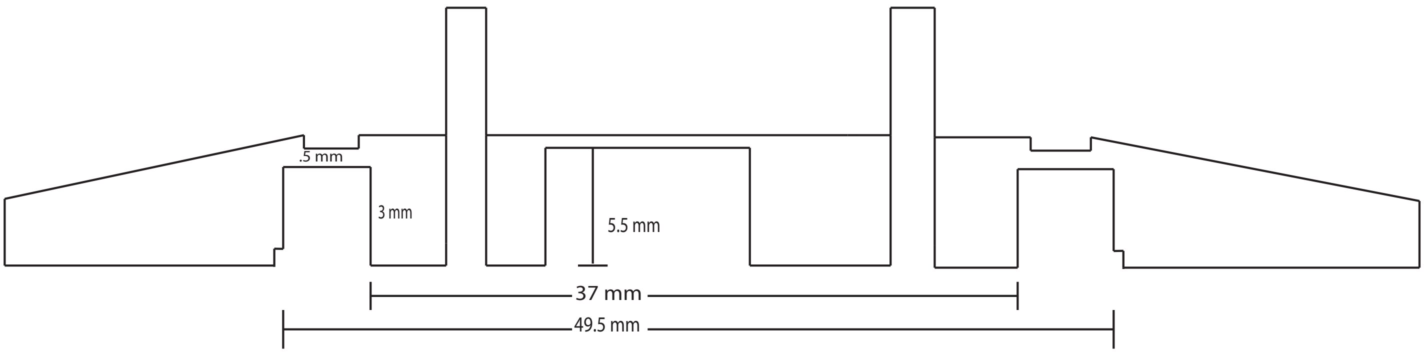

Figure 2.4 Mechanical drawing of the modifications made to a standard KF 50 flange

To completely enclose the magnetic field, we also needed another piece of iron on the outside of the magnets. We used a thick disk with holes to allow the tubes we attached to the flange to pass through. With that last piece, the skeleton for our ion source was completed (Fig. 2.7).

2.2 Connections

The next step was finding a way to take advantage of our feedthrough to get the current into the source while keeping it electrically isolated. To do this we first lined the feedthrough with a glass sleeve. Glass was chosen to provide electrical isolation. We made our anode out of a stainless steel disk with a hole in the middle, then welded three rods on it's edges 120 degrees apart to allow them to pass through the feedthrough.

The idea was that we would use the rods connected to the anode as a way to control the position of the anode and simultaneously give it the power it needed. We used Ultra-Torr fittings and the glass tubes to seal the system off from atmosphere. We threaded one of the rods attached to the anode and made a mate for use as a vernier, allowing us to position the anode in the source as needed. The second feedthrough connected to an Ultra-Torr tee that fed to a vacuum gauge and allowed proper positioning of the gauge. The other end was sealed with a support rod. The third

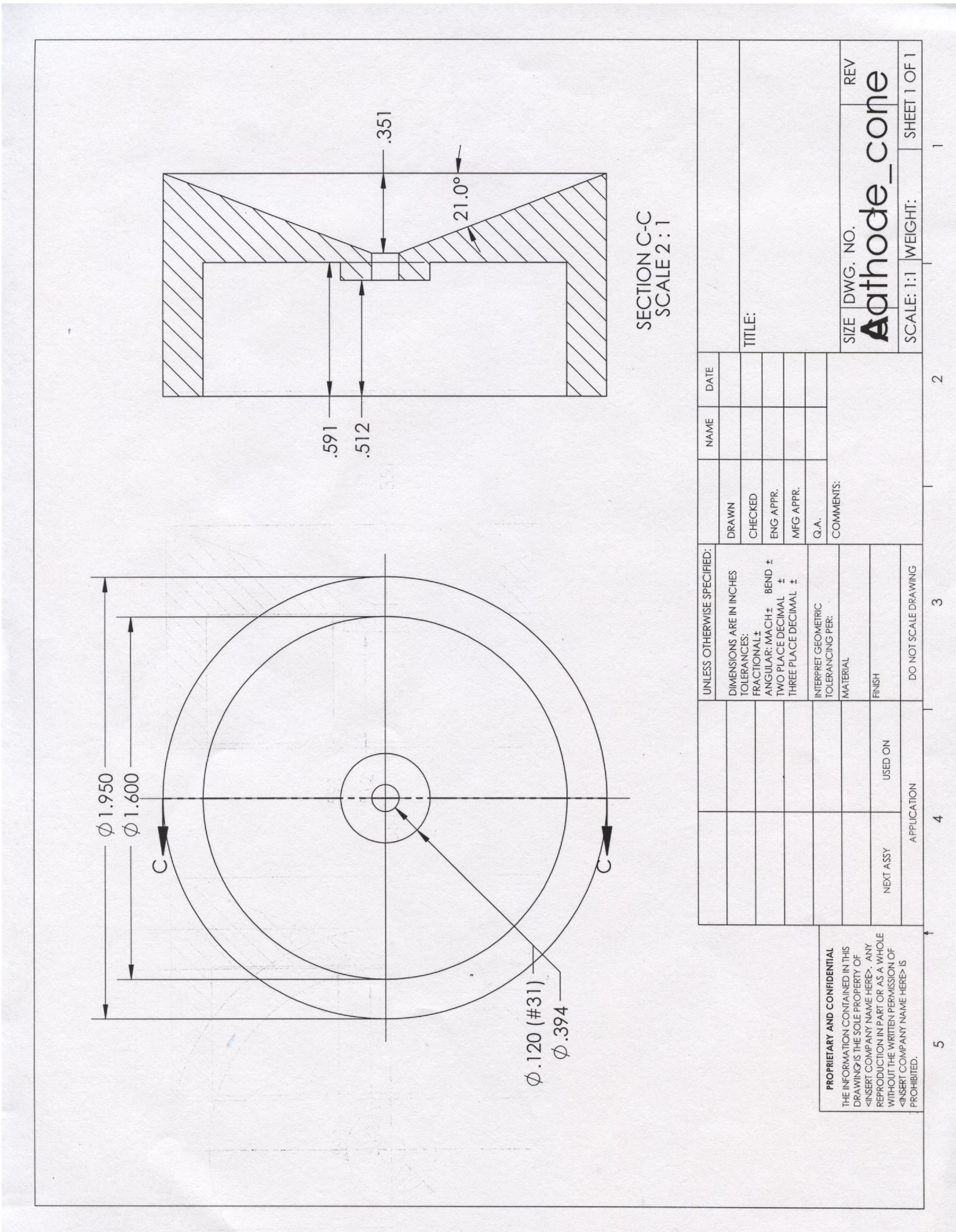

Figure 2.5 CAD drawing of ion source cathode.

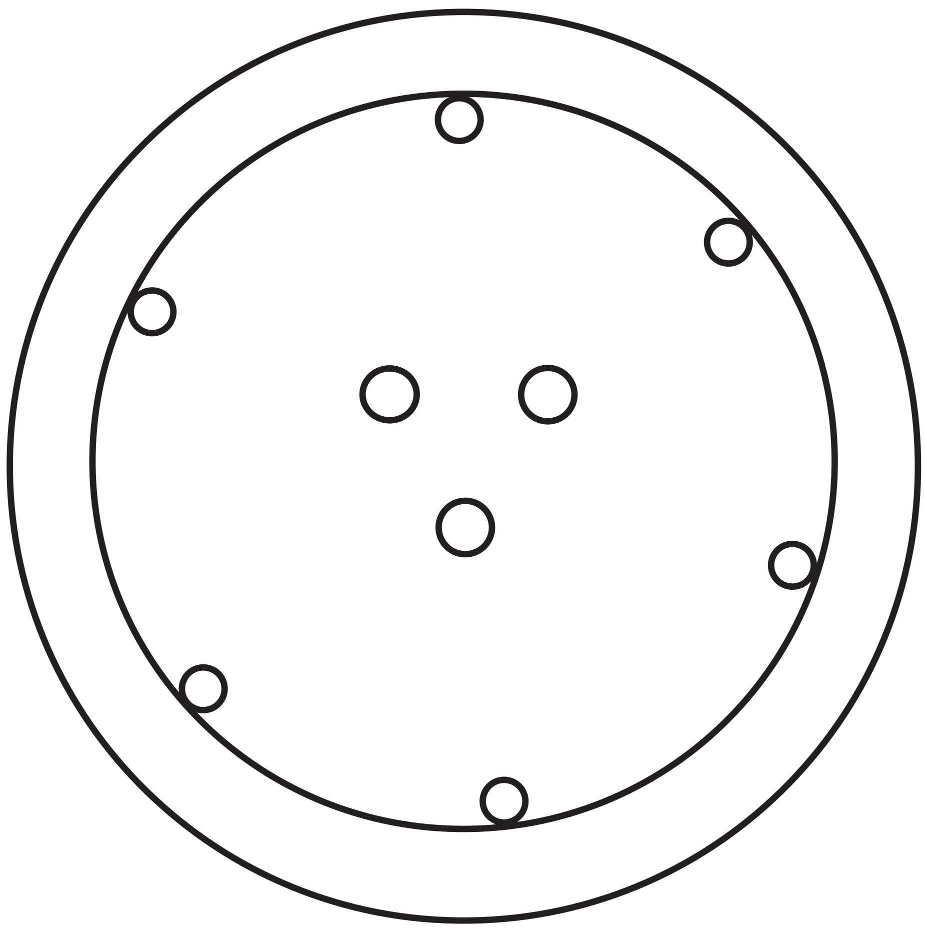

Figure 2.6 A mechanical drawing of the modifications made to a standard KF 50 flange

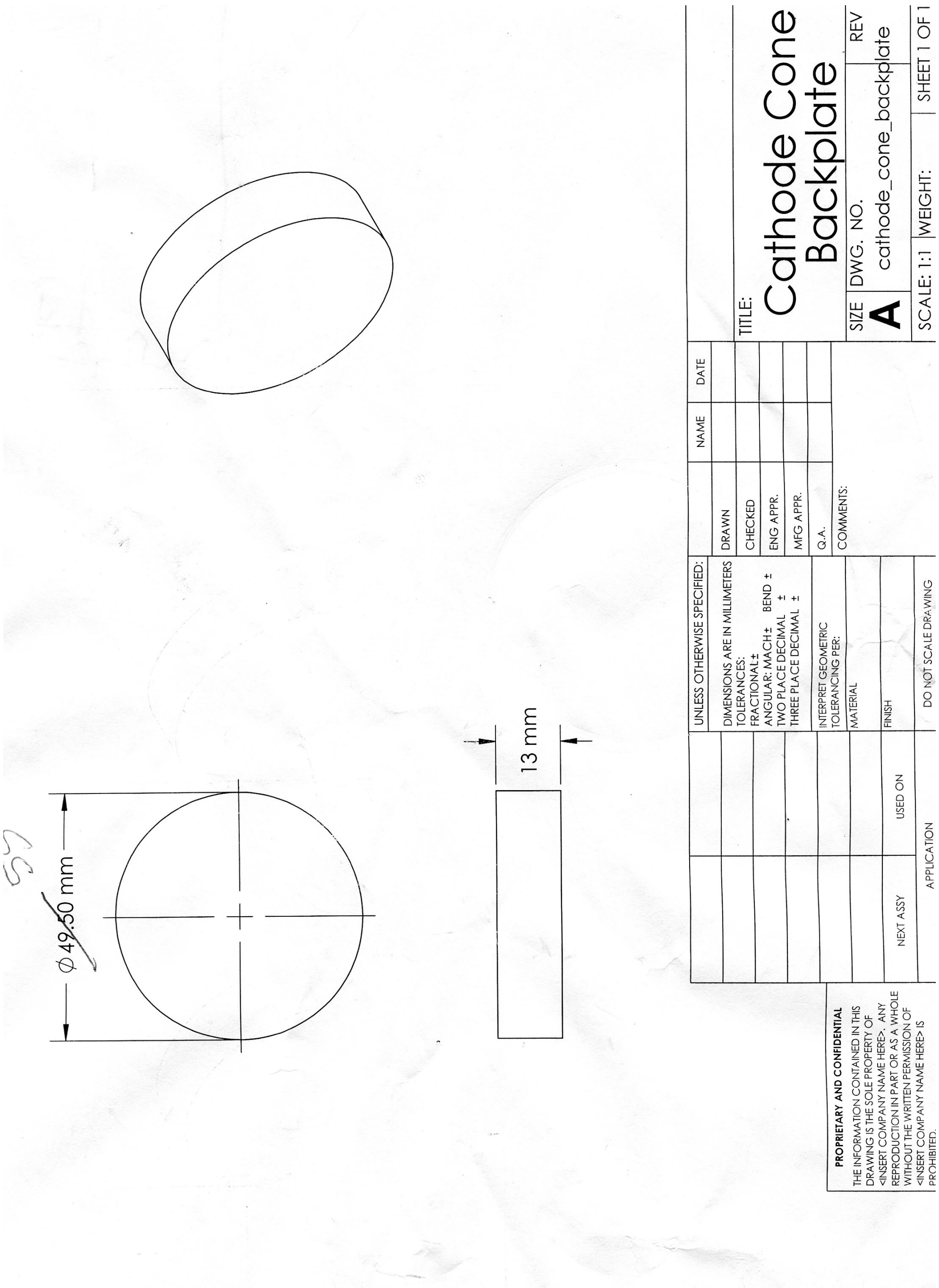

Figure 2.7 CAD drawing of back plate.

feedthrough was connected to a needle valve followed by a bellows valve that connected to our gas supply line.

A Helium leak detector was used to ensure a vacuum-tight seal on all connections.

2.3 Setup

A turbo pump with a pumping rate of 240 cubic feet per minute (CFM) was used. It had a six inch conflat connection to make sure that all of the connections from the vacuum pump were as large as possible to increase conduction and the pumping speed for the system as a whole. This required an adapter from a six inch conflat to a KF 50. It was attached directly to the chamber and backed by a roughing pump with a pumping speed of 12.1 CFM with a sieve to keep any oil from getting into the chamber.

An electrical feedthrough opposite the ion source had a copper rod which was used for extraction of the ions from the source. We applied a negative voltage of 1 kV to it which would attract the positive ions and had a nano-ammeter attached to monitor when ions reached it. The system was evacuated before feeding in the helium and turning on the voltage (Figure 2.9). We determined the presence of a plasma by measuring the current in the source after ignition. These currents were found to be in the milliAmpere range.

After consulting the table for PIG ion sources [1], we began taking data by powering our source with a 1 kV, 10mA power supply. We connected the ion source to the 0-500 Volt power supply and begin making ions to determine the needed voltages at various pressures. We measured the current in the source while varying the voltage to get the curves in Figure 2.8. It was found that there was a decreasing resistance after the source pressure was raised above two Torr. This is explained by the introduction of more charge carriers as the pressure is increased, leading to a decreased resistance.

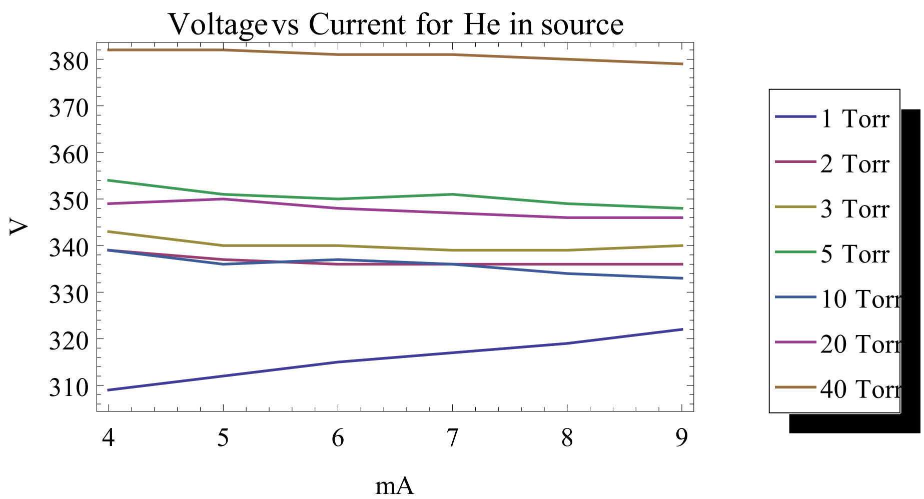

Figure 2.8 The voltages and corresponding currents at varying pressures inside the ion source

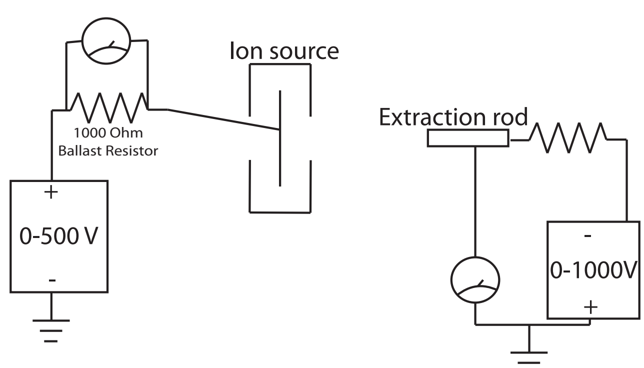

Figure 2.9 Wiring schematic for ion source and extraction rod

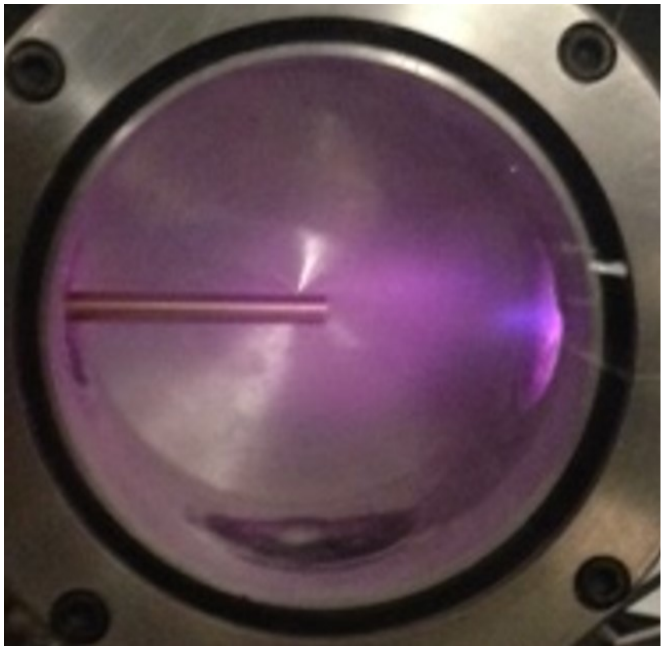

Figure 2.10 A visible ion beam is formed while running the system at high pressures.

2.4 Beam Current

To characterize the source, we installed it on one side of the chamber, and we metered the extraction rod installed on the opposite side. The source was being charged to have positive ions, while negative charge was placed on the extraction rod to attract ions from the plasma in the source. This allowed for the formation of a beam.

A voltmeter was placed in series with the extraction point to use it as a microammeter. Since it had an internal resistance of one megaohm, what we read in volts translated to microamps. With the ability to detect currents in the micoamp range we could accurately determine what was happening in the system. While performing this test, the turbo pump was run while leaking in helium at different rates to vary the plasma current. Once we established the plasma current we set the pressure and recorded the data. The voltage being applied to the extraction electrode was varied and the results can be found in the conclusions.

By running the system at a higher chamber pressure we were able to see the ionized gas to ensure that the beam was being extracted. In Figure 2.10 an ion beam can clearly be seen leaving the source (on the right) and flowing to the extraction electrode. This is identified by the purple line running right to left.

2.5 Extraction Electrode

Computer simulations have found that the ideal shape of an extraction electrode consists of a spherical exterior and a pierce interior [8]. This shape produces a beam with minimal diameter and emittance. With this in mind we designed our extraction electrode. It was found that the best results were achieved using a 1000 V extraction potential. Upon completion of the extraction electrode we needed a way to position it a few millimeters away from the cathode of the ion source and connect it to the first equipotential plane of the accelerator tube to give it the proper potential (Figure 2.12). For this we created a cylinder that the extraction electrode could be press-fit into the first equipotential plane. To improve the conduction, of the vacuum, we placed three equally spaced 1/4 inch holes around the cylinder.

2.6 Modified Setup

We adapted the experimental setup to incorporate a larger high vacuum pump so that we could achieve greater pumping speeds. We found a large diffusion pump that was rated at 3000 L/s for helium. To use this pump we added a liquid nitrogen cold trap and a pneumatic gate valve to protect the chamber from oil contamination. To handle all the extra weight and to position the equipment we used a t-slotted aluminum rack as a frame and bolted the gate valve to a steel plate with a hole for the adapter to the chamber. We replaced the oil mechanical roughing pump with a larger belt driven roughing pump (see Figure 2.14).

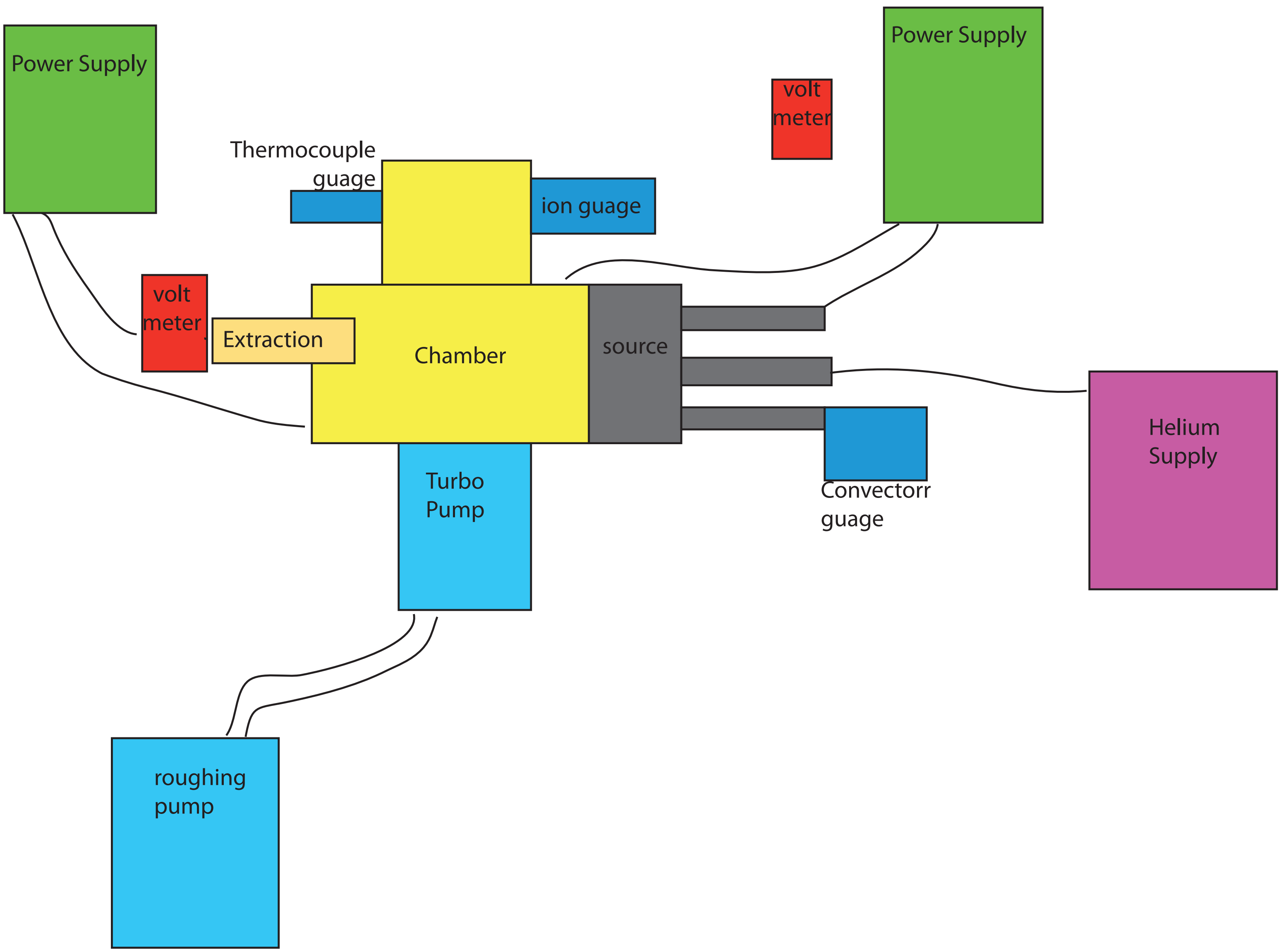

Figure 2.11 Block diagram of set up used to acquire beam current data

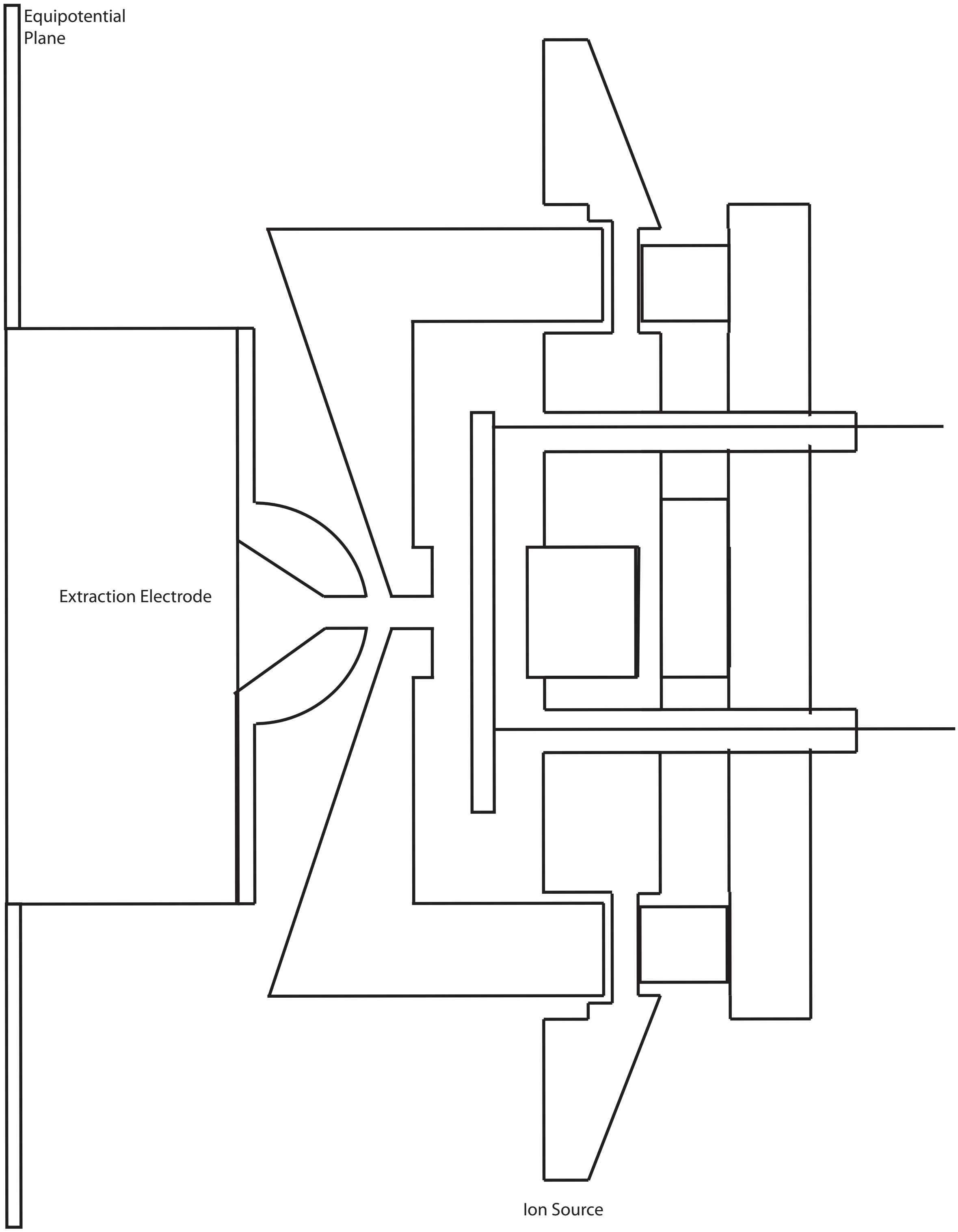

Figure 2.12 Extraction electrode and ion source cross sectional view

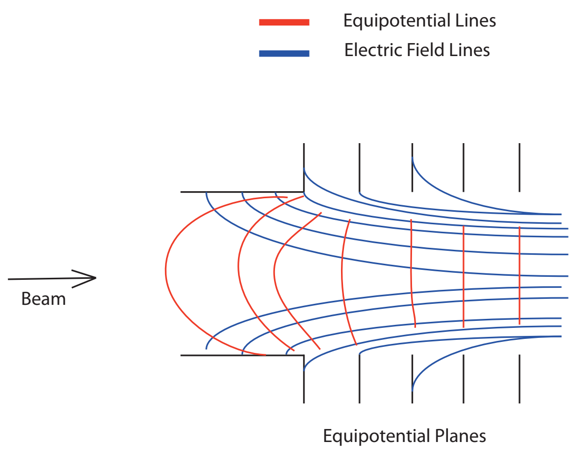

Figure 2.13 Diagram of accelerator electric field and equipotential lines

2.7 Accelerator Setup

We built a frame to hold the table and installed a 1/4 inch thick piece of plexiglass to protect the user from the high voltage. Then an aluminum plate with rounded edges was placed at high voltage and rested on the rack. The voltage on the aluminum plate was raised to match the voltage on the first equipotential plane of the accelerator. With the same voltage the plate could be used as a ground reference for the ion source power supplies. Since the power supplies were to be isolated from the rest of the system we needed a battery to power them. We used a lead-acid battery and a power inverter, both of which were placed on the plate. To control these power supplies we attached a lexan rod to each power supply which extended through the plastic plate and replaced the knobs to control the voltages.

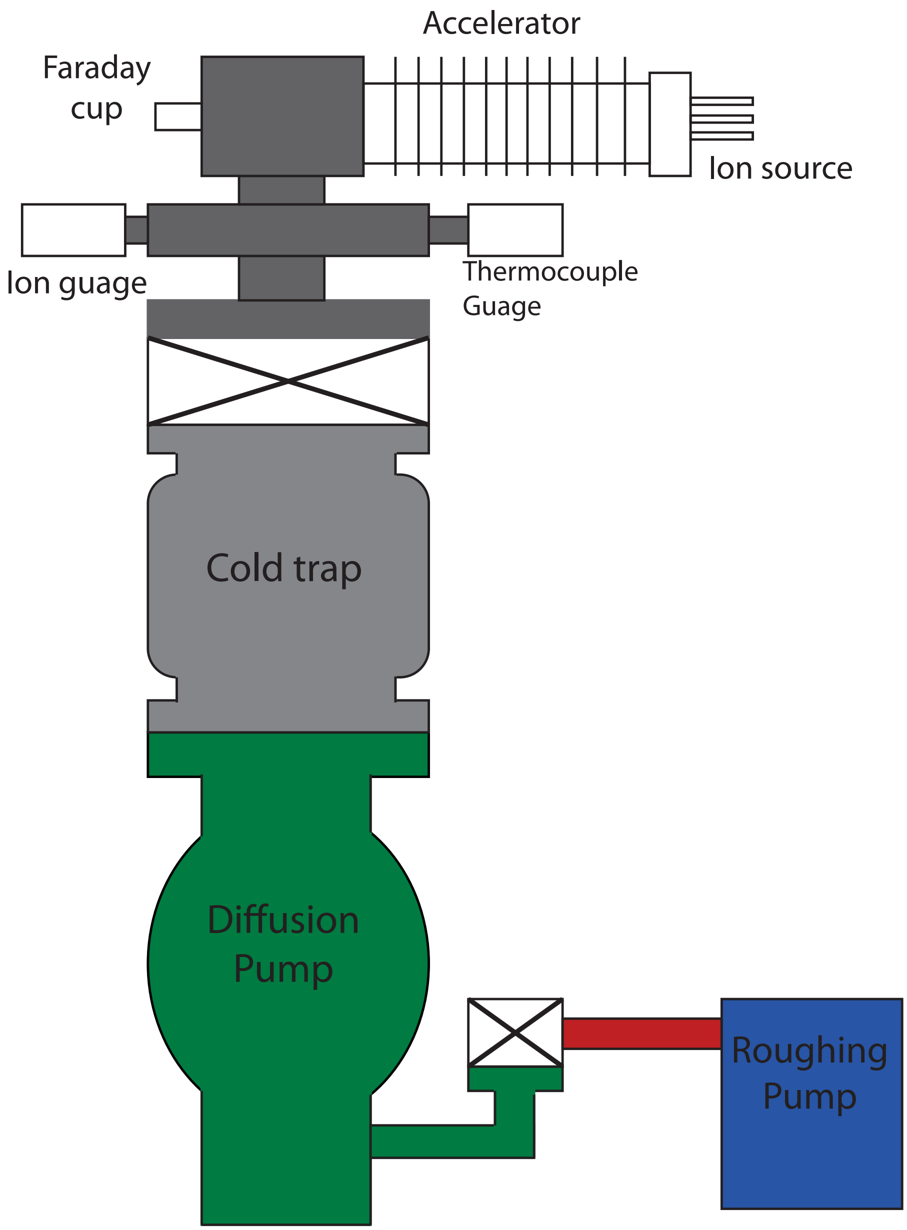

Figure 2.14 Block diagram of modified vacuum set up using a diffusion pump and cold trap

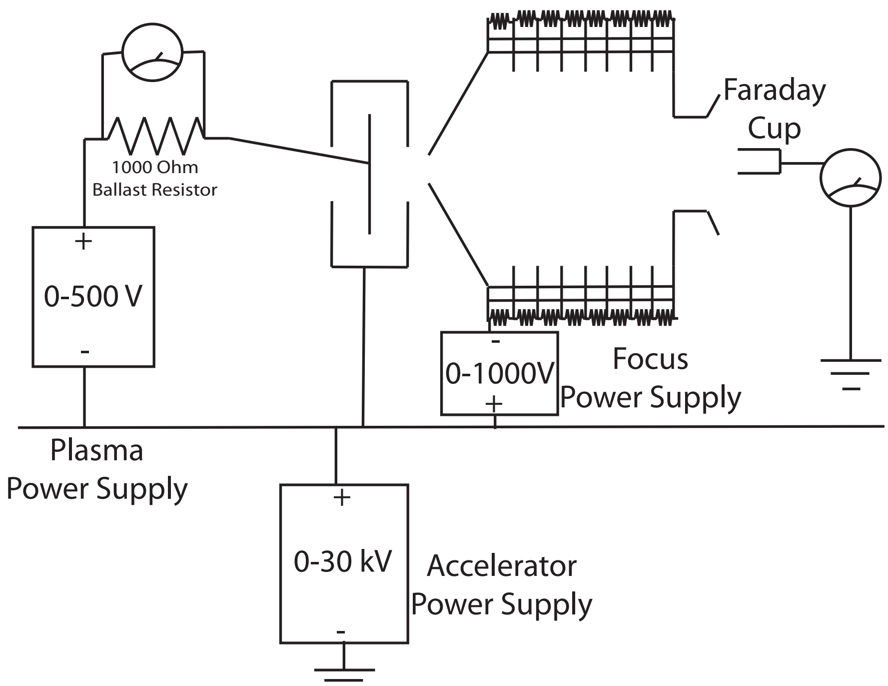

Figure 2.15 Wiring diagram for the accelerator setup.

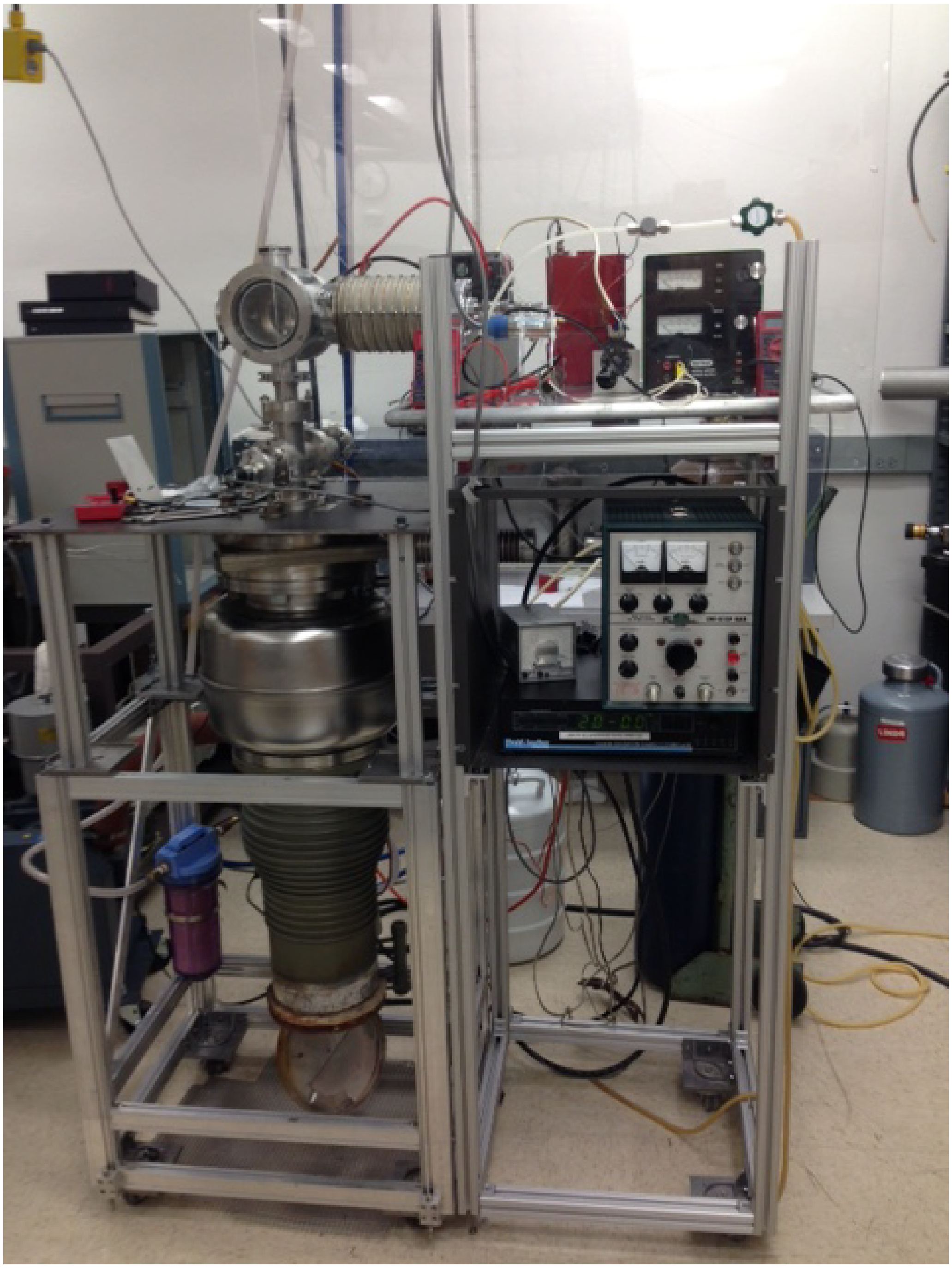

Figure 2.16 The full setup of the vacuum system, accelerator and high voltage controls.

Chapter 3

Results and Conclusions

In this chapter I present the data taken from the source which gives an initial characterization of the source, along with an analysis of these results.

3.1 Operating Requirements

Two of the most important specifications for a source to function properly are the operative voltage and current.

Pressure (Torr)	Ignition Voltage (Volts)
1	325
2	323
5	340
10	360
20	400
50	440

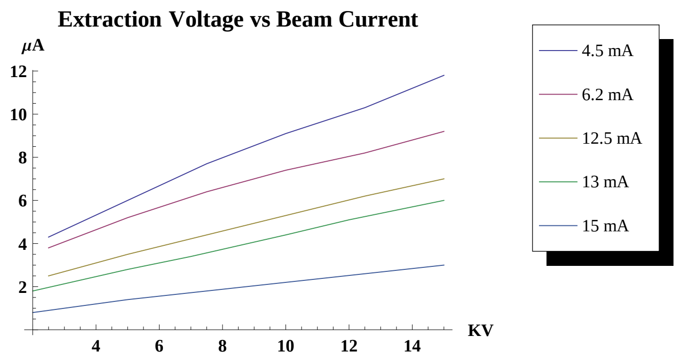

Figure 3.1 Beam current at extraction site with constant plasma current and varying extraction voltage.

In the table the required voltage for plasma ignition is given according to helium pressure inside the ion source. This set of data was a starting point for ion source characterization.

To have a stable operation with helium, the internal pressure of the source must be about 0.5 Torr and a pressure difference across the exit port of three orders of magnitude and an anode-cathode voltage of approximately 450 V and a discharge current of 20 mA. The typical ion current, measured at the extraction point, at 10 kV was 5 μA.

3.2 Specifications for Ion Source

We found the beam currents as shown in Figure 3.1. This set of data presented an unexpected negative correlation between the plasma current and the beam current. It appears that there is not a high enough high vacuum pumping speed to maintain a sufficient mean free path between source and extraction site. We expected to see the positive correlation between beam current and extraction voltage. We saw that as the pressure in the source is increased the plasma current also increased. This caused a reduction in mean free path within the chamber resulting in a negative correlation.

3.3 Future Work

With the completion of the new test facility which has a significantly higher pumping speed, we can now progress forward and obtain more data. With these higher pumping speeds we hope to get a difference of four to five orders of magnitude across the exit port. The next step is to run the same tests as before with this new setup in order to confirm the results. We will then maximize the aperture size of the cathode to allow the greatest flow of ions, while still maintaining the necessary mean free path. We will then be able to take measurements to determine the beam width and energy spread of the extracted ions.

3.4 Final Conclusions

Having collected data we have determined some aspects of the characterization of the source. However, due to the lack of pumping speed provided by the turbo pump, no other relevant data was taken. To increase the pumping speed a oil diffusion pump was chosen to act as the high vacuum pump for the new facility. The results taken with the turbo pump thus far look promising as we have created an ion source and successfully extracted ions from it. Thanks to the new setup with increased pumping speed further analysis can now be made.

Bibliography

[1] B. Wolf, *Handbook of ion sources* (CRC Press, 1995).

[2] H.Baumann and K.Bethge, “Pig ion source with end extraction for multiply charged ions,” Nuclear Instruments and Methods **122,** 517–525 (1974).

[3] H.Baumann and K.Bethge, “The Frankfurt PIG ion source,” Nuclear Instruments and Methods **189,** 107–110 (1981).

[4] J. Yu, X. Ren, and Z. Song, “A universal pocket PIG ion source with a permanent magnet,” Review of scientific instruments **67,** 1375–1377 (1996).

[5] Z. Nouri, R. Li, R. Holt, and S. Rosner, “A penning sputter ion source with very low energy spread,” Nuclear Instruments and Methods in Physics Research **614,** 174–178 (2010).

[6] P. W.Bygrave and J. Lambert, *Accelerator Nuclear Physics* (High Voltage Engineering, Burlington, Massachusetts, 1970).

[7] M. F. J Cruz, H Luis and A. P. Jesus, “Electron screening effects in nuclear reactions: still an unsolved problem,” Nucelar Physics in Astrophysics V 337 (2012).

[8] M. Abdelrahman and S. Zakhary, “Simulation studies for ion beam extraction systems,” Brazilian Journal of Physics **39,** 275–279 (2009).

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