

A Low-Cost Van de Graaff Accelerator

by

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Submitted to the Department of Physics
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Abstract

A small, low-cost Van de Graaff electrostatic accelerator capable of accelerating electrons and producing bremsstrahlung x-rays has been constructed using components commonly found in most undergraduate physics laboratories. The electrons originate within the negative high-voltage terminal and are accelerated by a uniform electric field through an evacuated glass tube. Electron currents of up to 6 μA were collected in a Faraday cup. The end-point of the bremsstrahlung x-ray energy spectrum has been measured to be between 300 and 400 keV.

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Introduction

1.1 A Low-Cost Van de Graaff Accelerator

The goal of this project was to design and construct a low-cost electrostatic accelerator, capable of producing electron or ion beams for scattering experiments. Using a Van de Graaff generator as a voltage source, the apparatus would be able to produce a stable electron or ion beam in the range of 400 keV. If heavy hydrogen is substituted for the electrons and use is made of the d-d neutron production reaction, the accelerator would be capable of producing neutrons of about 3 MeV [1].

To use this reaction, the deuterium gas would be ionized, then the deuterons would be accelerated to energies of the range of 150 keV to 450 keV. At the end of the chamber would be a target of copper. At first, the deuterons would impregnate the copper target. Then, as the density of deuterons in the target increased, accelerated deuterons would interact with those in the copper to produce either ^3He and a neutron or ^3H (Tritium) and a proton. If the beam is operated between the energies of 150 and 450 keV, the probability of producing a neutron is much greater than that of a proton [2].

1.2 History

In 1929 R. J. Van de Graaff constructed his first model of a belt-charged electrostatic generator at Princeton University [3]. The idea of a belt-charged electrostatic generator can be traced to earlier dates [4], but it was Van de Graaff who built the first functional model. The original device consisted of two 24-inch diameter charged terminals, one positive, the

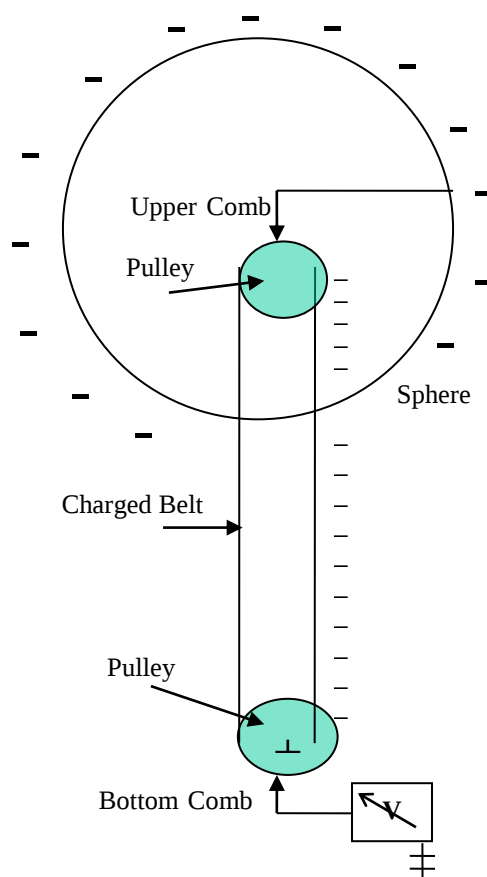


Figure 1: A simplified drawing of a Van de Graaff Generator. The important components are the two pulleys, the two combs, the charged belt, and the sphere.

other negative, and could produce a potential of 1.5 MV [5]. Three years later, the Massachusetts Institute of Technology (MIT) funded the construction of a Van de Graaff generator consisting of two 15-foot diameter spheres that could reach a potential of 5.1 MV [6]. The early models contained only two pulleys, two combs, a charged belt, and a charged sphere (Fig. 1).

These Van de Graaff generators were designed to be ion sources. The large MIT generator used one of the support columns to contain an evacuated acceleration tube, which could be used to accelerate electrons or positive ions to 2.75 MeV [7]. In 1937, researchers concluded that using a pressurized environment to control humidity and increase air pressure would increase the corona breakdown voltage (see Fig. 2) [8]. This allowed for smaller accelerators and increased operating voltages. Some studies concluded that pressure and maximum potential are linearly related; i.e. if the pressure of the air is doubled, the maximum potential of the sphere doubles [9].

Concentric potential surfaces surrounding the high voltage terminal were added to decrease the voltage difference between the sphere and the innermost shell (Fig. 2). Instead of the full potential between the sphere and ground, the concentric surfaces have voltage differences that divide the total potential of the sphere; i.e. if the terminal has a potential of 4 MeV and is surrounded by three evenly spaced concentric shells, the voltage drop between the sphere and the innermost shell, between shells one and two, two and three, and three and ground will be one MeV. Developments have continued during the past sixty years. Pressurized air

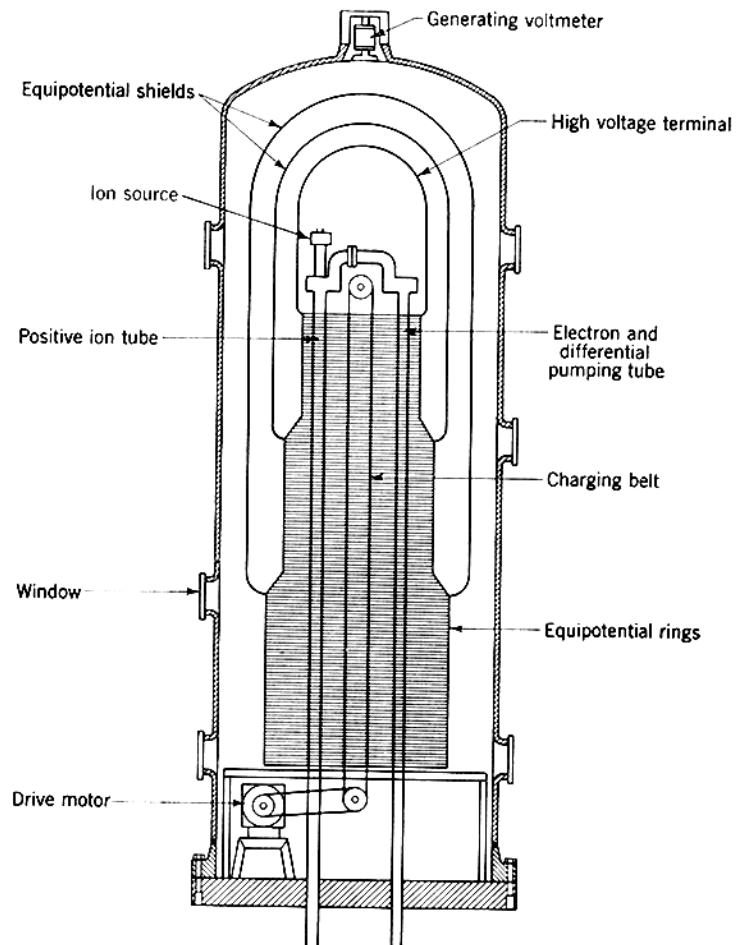


Figure 2: A drawing of the MIT 4 MV design with a pressurized container, equipotential rings, and equipotential surfaces. Two acceleration tubes are shown within the column, one for positive ions, the other for negative. (taken from [10])

has been replaced by nitrogen, freon, and sulfur hexafluoride, the last having the highest breakdown voltage [11], but little has changed with the general design.

Van de Graaff accelerators are used in a variety of ways. Nuclear experiments often require low energy (less than ten MeV) ions. Astrophysics experiments that investigate stellar nuclear reactions require low energy collisions. The low energy beams for these investigations can be efficiently supplied by Van de Graaff accelerators. Van de Graaff accelerators can produce nearly monoenergetic (all particles having the same energy) beams. The voltage of the terminal can be finely adjusted to the specific voltages needed for an experiment. The voltage can be regulated by a grounded probe that can be placed at various distances from the outer concentric surface. The maximum potential difference between the probe and the concentric surface is a function of the distance between the two and will determine the voltage of the terminal. Van de Graaff generators are also very reliable, having few moving parts that could break or malfunction.

Principle of Van de Graaff Operation

The original Van de Graaff design has changed little since R. J. Van de Graaff first published his idea in 1931 [12], which uses the principle that inside a conducting sphere, the electric field is zero. Therefore, if there is a supply of charges to the inside of the sphere, they will repel to the surface of the conducting sphere. The only limit to the charge on the sphere is the breakdown voltage of the surrounding medium. If the sphere was totally isolated in an infinite vacuum, the total charge capacity of the sphere would be infinity.

An obvious problem is how to supply a conducting sphere with charged particles from the inside. As a solution, Van de Graaff suggested the use of an insulating charged belt that runs between two pulleys (see Fig. 1). Once an insulator receives charges, they are not free to move around on the surface. Therefore, as the charges approach the conducting sphere, they can not migrate down the belt, repelled by the electric field. Instead, they continue to the inside of the sphere. If a conductor was used, the electric potential at the base of the Van de Graaff would always need to be greater than that of the conducting sphere in order to force the charged particles into the sphere.

But how can charges be “attached” to the insulating belt? Van de Graaff proposed the following method. Ground the bottom pulley and place a charged metal screen near the moving belt. Raise the potential of the screen until the electrons on the screen move to the pulley, because of the corona effect. As electrons move to the lower potential pulley, they will pass onto the moving belt, becoming embedded in the insulator. Van de Graaff proposed a similar process within the high voltage terminal, requiring that the top pulley be neutral and the charges be repelled from the insulating material onto a metal screen near the belt. The charges would be repelled by the pulley but encounter no field due to the charges on the sphere. Hence, they would migrate to the surface of the sphere.

Van de Graaff generators require an insulating column, which contains the insulating belt that supplies charge to the sphere, and are surrounded by air or a pressurized gas that serves as an insulator. Good insulating media will have a high breakdown voltage (the potential when the medium begins to conduct allowing charge to escape from the sphere). The Corona effect happens when the ionization potential of the air is reached on a charged surface and the electrons

can migrate through the gaseous mixture of ionized air molecules to ground [13]. This surface discharge will limit the maximum voltage and charge for a given radius sphere.

Spheres are used because charges on a smooth surface spread out as much as possible, until the electrical forces are in equilibrium. A sphere is continuous surface, having no edges or points. If the surface is uneven, charges will concentrate on a sharp edge, creating a larger electric field. This stronger field will cause the surface to obtain the breakdown field sooner at some points on the surface, resulting in a discharge with a lower total charge on the sphere.

Since the sphere is surrounded by an insulator, it acts as a capacitor, for which

$$Q = CV \quad (1)$$

where V is the voltage across the capacitor plates and Q is the charge on the plates. The capacitance, C , for a sphere is

$$C = 4\pi\epsilon_0 r \quad (2)$$

where r is the radius of the sphere. Taking the derivative of Eq. 1 we get

$$\frac{dQ}{dt} = C \frac{dV}{dt} \quad (3)$$

and,

$$i = C \frac{dV}{dt} \quad (4)$$

For our Van de Graaff generator, the up current is constant, while the current down the equipotential rings and support column is proportional to V . Therefore,

$$i = i_u - \frac{V}{R} = C \frac{dV}{dt} \quad (5)$$

where i_u is the up current from the belt, R is the resistance of the high voltage terminal, and $\frac{V}{R}$ is the current that is lost to the corona effect and down the equipotential rings and support column. When the Van de Graaff generator is first turned on ($t = 0$), the potential is zero and $\frac{dV}{dt}$

(the rate the potential of the sphere is changing) is large. After a period of time, $\frac{V}{R} \approx i_u$ and

$\frac{dV}{dt} = 0$, which means that the voltage remains constant.

Reorganizing Eq. 5 we get the differential equation:

$$\frac{dV}{dt} + \frac{V}{RC} = \frac{i_u}{C} \quad (6)$$

Eq. 6 provides the time dependent voltage equation for a Van de Graaff generator:

$$V = i_u R(1 - e^{-t/RC}) \quad (7)$$

Now, since the breakdown field of air is approximately 30,000V/cm [14] we find that the maximum attainable voltage on a spherical high voltage terminal is given by

$$E_{sphere} = \frac{kQ}{r^2} = \frac{V}{r} \quad \text{because } V = \frac{kQ}{r},$$

where E_{sphere} is the electric field of a sphere, Q is the charge on the sphere, r is distance from the center of the sphere to a point outside of the sphere (in this case r is the radius of the sphere because we want to find the voltage on the surface of the sphere), and V is the voltage of the sphere. Therefore, given the maximum electric field of a sphere surrounded by air,

$$V = E_{sphere} r = 30000 \frac{V}{cm} \cdot r \quad (8)$$

Our Van de Graaff generator has a radius of 13 cm and, using Eq. 8, a maximum attainable voltage of 410,000V and a maximum charge on the sphere of 5.92μC.

The original design was altered to accommodate an acceleration chamber in the same glass cylinder surrounding the charged belt. Therefore, if a cathode is attached to the end of the acceleration chamber in the sphere and a grounded anode is located at the other end the electrons will be accelerated toward the anode.

If the electric field in the acceleration tube is not uniform electrons may be deflected. Equipotential rings were added to provide a constant electric field. Equipotential rings are placed at equal distances along the acceleration tube. If the acceleration tube is in the Van de Graaff support column, then the column is surrounded with the rings (see Fig. 2). Since the rings are placed at equal distances apart, there is equal resistance between each ring. The resistance in this case causes an equal voltage drop between each ring because of the “corona discharge which equalizes potential gradient” [15]. The equal voltage drops create a constant electric field, accelerating the electrons along the axis of the tube.

The electrons, after being accelerated down the evacuated tube, strike the anode or target being held at ground. When electrons strike the target, they decelerate, releasing energy in the

form of bremsstrahlung x-rays energy. The endpoint of the bremsstrahlung spectrum can be measured at 0° to find the energy of the electrons.

Accelerator Design Considerations

3.1 Apparatus

The idea for the apparatus came from Frank B. Lee's article, "A Homemade Atom Smasher." [16] This article describes a Van de Graaff generator in contact with a spherical high voltage terminal. The high voltage terminal is attached to one end of an evacuated tube that is surrounded by equipotential rings of wire and a cathode is located at the other end of the tube. The voltage generator produces a positive potential, which attracts electrons from the cathode. The target is enclosed in the high voltage terminal (see Fig. 3).

In our apparatus the cathode was placed in the high voltage terminal and the Van de Graaff produced a negative potential. Copper wire was used for equipotential rings, a cathode from a cathode ray tube was the source of electrons, and a Faraday Cup, held at ground, was used to "collect" the accelerated electrons. A drawing of our apparatus can be found in Fig. 7 and a scale drawing is provided in Fig. 9. The vacuum pump used to evacuate the chamber is discussed in Appendix A.

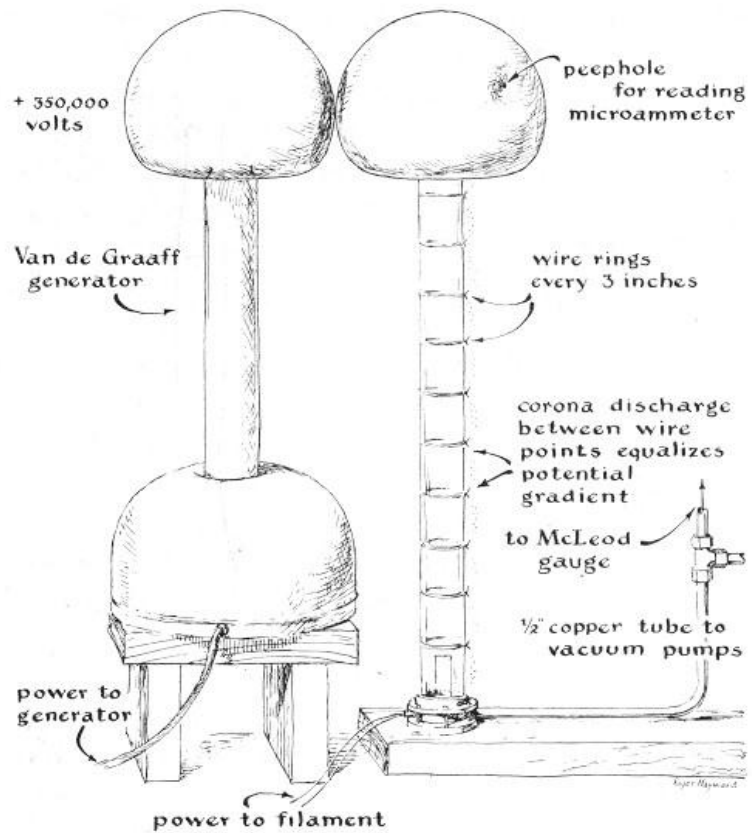


Figure 3: A sketch of Frank B. Lee's accelerator design. The VDG would provide the high voltage. Inside the high voltage terminal would be the target and ammeter. The filament would be at the base of the acceleration tube. (taken from [17])

The changes made in the design allowed the beam spot on the target to be observed, since the target Faraday cup is at ground potential. The current was measured by attaching an ammeter

between the target and ground instead of placing the ammeter inside the terminal. The bremsstrahlung x-ray energy was measured to find the energy of the electrons.

3.1.1 Principles of Our Van de Graaff Generator

The Van de Graaff generator used in this experiment used no external voltage source to supply current to the sphere. Instead, it used a principle called “Continuously Charging Electrophorous” in which the chemical properties of two substances result in a charge build up. In this case, the molecules of the insulating belt have a positive ionization number and the molecules of the pulley have a negative ionization number. When they come into contact, they form “superficial” covalent bonds, chemical bonds only on the surface where electrons are shared. Electrons migrate from the pulley to the belt, creating a positively charged pulley. When the belt separates from the pulley, most of the electrons return to the pulley [18]. The result is a positively charged pulley. After a short time the pulley builds up a substantial charge. The bottom comb then becomes negatively charged due to the positive potential of the pulley. Once the potential difference between the comb and the pulley becomes large enough, the air between the two breaks down and electrons migrate toward the pulley and stick to belt that is traveling through the space between the comb and pulley. Therefore, no external voltage source is needed to supply charge to the insulating belt. A similar process is used at the top, except the pulley is a neutral substance. Electrons repel from the pulley, off of the belt and to the surface of the sphere.

The maximum voltage of our 13 cm radius Van de Graaff generator was calculated to be approximately 410 kV, using the phenomenological estimate of Eq. 8 [19]. Because of several factors, the actual voltage of the generator was probably closer to 50% of the maximum [20]. The potential of the Van de Graaff generator when it was in contact with the high voltage terminal of the accelerator may have been higher because the surface area was basically doubled, allowing more charge to be stored. The capacitance of the Van de Graaff high voltage terminal, using Eq. 2, was approximately 14.5 pF, and, using Eq. 1, the charge on the sphere was approximately 5.92 μC .

The charge supplied to the sphere, I_c , was measured to be around 8 μA . Tests of the apparatus revealed a beam current in the range of 4-6 μA . This suggests that the charge supplied to the sphere leaves the sphere in ways other than the beam. The “missing charges” are lost to the corona effect and migration down the support column.

3.1.2 Electron Gun and Faraday Cup

The electron gun has a filament, a cathode, and an acceleration grid (see Fig. 4). The filament heats the cathode, which is coated with a substance that releases electrons when it is heated. The acceleration grid is at a small positive potential relative to the cathode and accelerates the electrons away from the cathode, toward the acceleration tube. A six-volt battery supplied the voltage difference between the acceleration grid and the cathode, as well as the power needed to heat the filament. A battery was used because it is a floating voltage source and could therefore be placed inside the high voltage terminal. The whole cathode floated at the high voltage so the electrons produced by the electron gun were at the negative potential of the sphere. A schematic of the cathode biasing used can be seen in Fig. 4, with feed-through pin numbers and dimensions shown in Fig. 5.

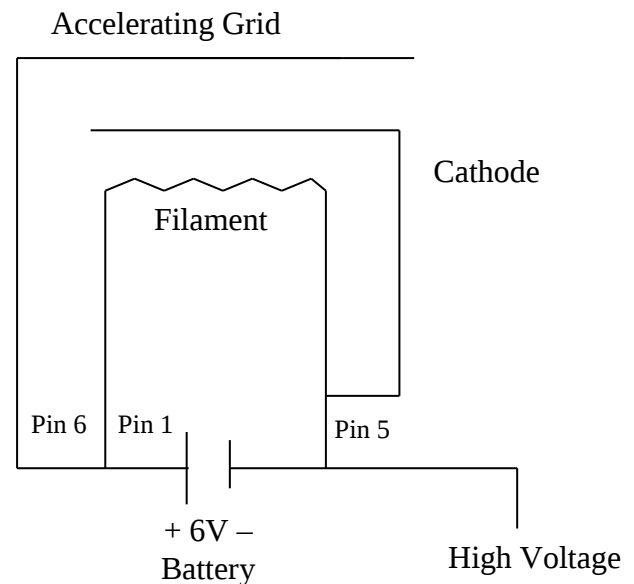


Figure 4: A schematic of the electron gun (filament, cathode, accelerating grid) and the battery that provided the biasing.

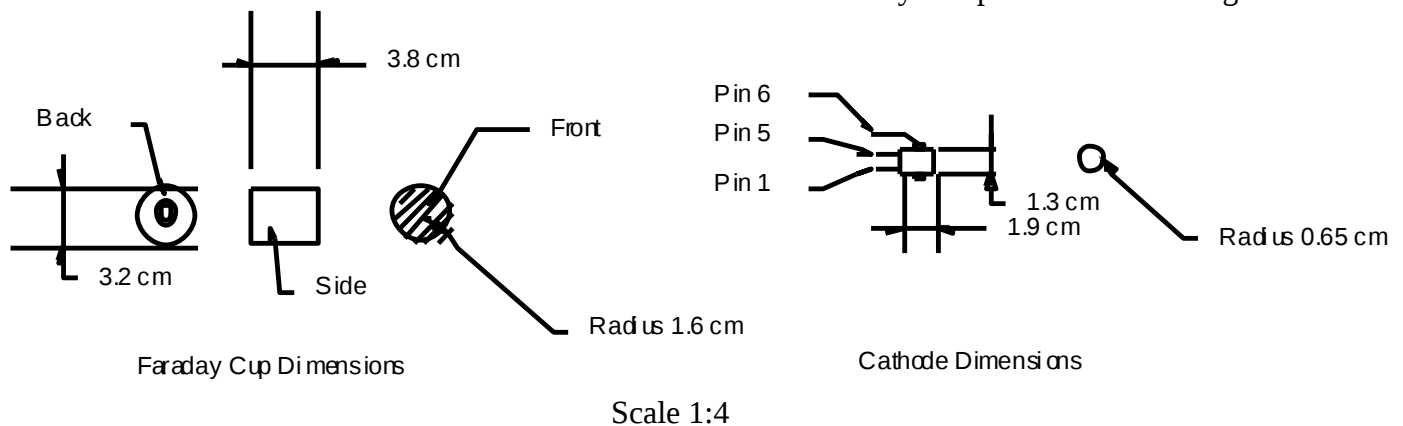


Figure 5: The dimensions of the Faraday cup, used to collect the accelerated electrons, and the cathode, the electron gun. The feed-through pin numbers correspond to those given in Fig. 4.

The Faraday cup, which was placed at the other end of evacuated tube, was an aluminum cylinder filled with a material that glowed when struck by electrons. This was used so the electron beam could be monitored visually. The Faraday cup was connected to ground, through an ammeter to measure the beam current. The dimensions of the Faraday cup are shown in Fig 5.

3.2 Operation of the Apparatus

The apparatus was first tested by substituting a 4000 V power supply for the Van de Graaff generator. The negative high voltage was attached to the sphere of the high voltage terminal, the negative contact of the six-volt battery, and pin 6 of the feed-through (see Fig. 6). The Faraday cup was grounded and placed about 20 cm from the cathode. A beam spot and between 1 and 2 μA were recorded from the Faraday cup. The beam spot gradually shifted off center, possibly because electrons accumulated on the glass and deflected the beam.

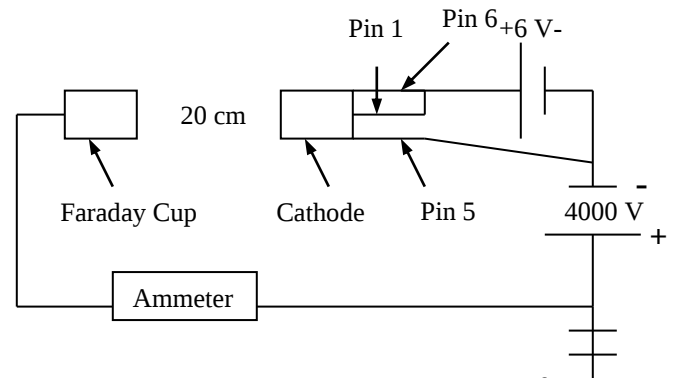


Figure 6: Schematic Diagram of the test circuit, using a 4000 V power supply and a six volt battery.

After testing the apparatus at -4000 V, the apparatus was moved to a smaller room that would provide shielding from the bremsstrahlung x-rays. The Faraday cup was placed at the end of the evacuated tube, about 90 cm from the cathode, and the Van de Graaff generator was placed in contact with the high voltage terminal (as in Figs. 7, 8 and 9).

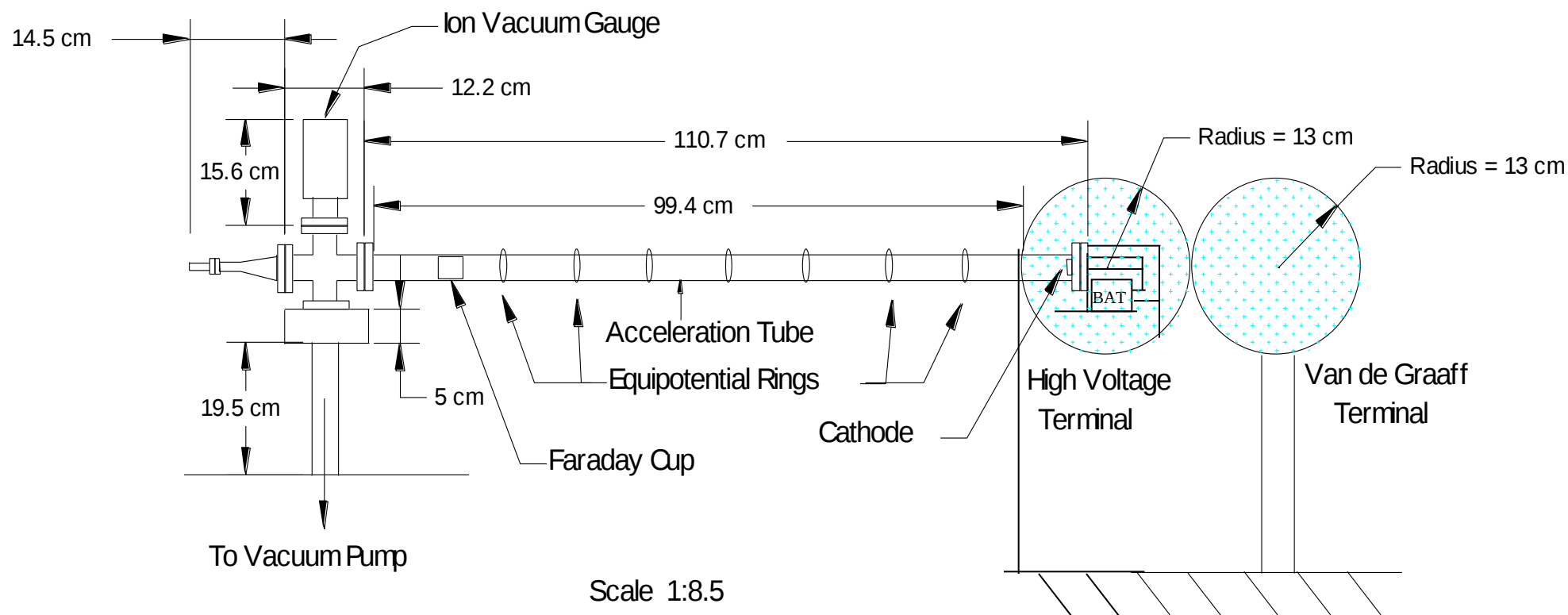


Figure 7: A scale drawing of the apparatus. The Van de Graaff terminal provided the high voltage. The cathode inside the high voltage terminal was the electron source. The equipotential rings provided a constant electric field in the evacuated tube and the Faraday cup collected the accelerated electrons.

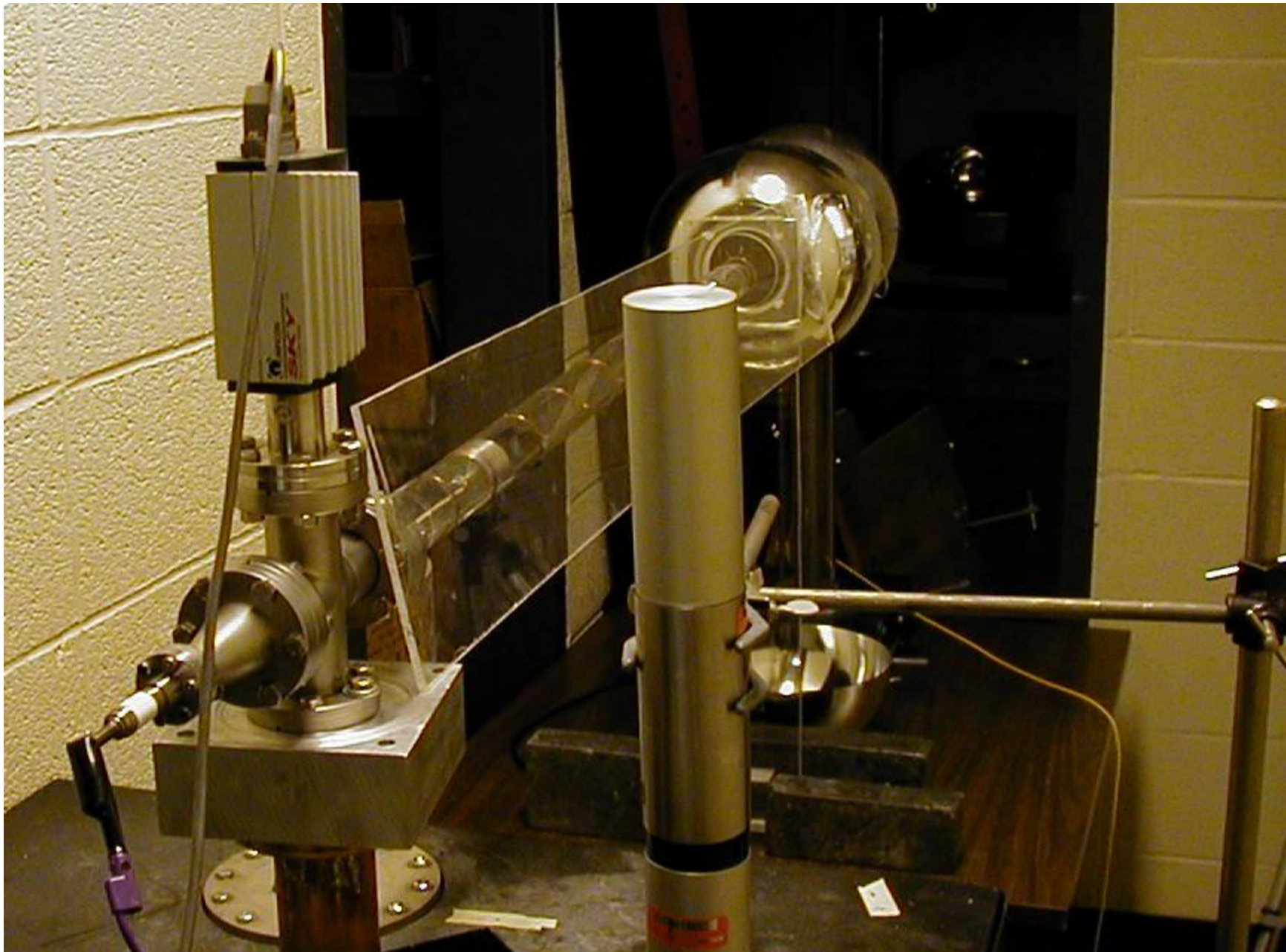


Figure 8: A picture of the apparatus with the Van de Graaff generator in the background, the high voltage terminal, the evacuated tube with copper equipotential rings, the Faraday cup and the plastic scintillator.

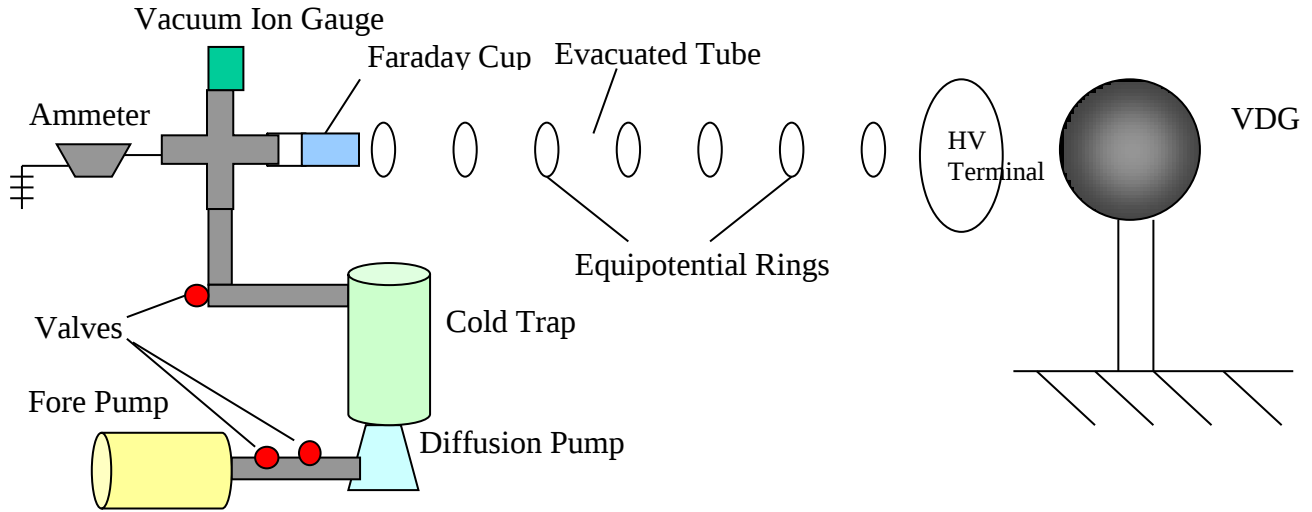


Figure 9: A simplified drawing of the entire apparatus, including the Van de Graaff generator (VDG), the high voltage terminal, the equipotential rings, the evacuated chamber and the vacuum pump.

When using the Van de Graaff generator as the potential source, the apparatus produced bursts of electrons from sparking in the region of the cathode. Still, energy spectra of the bremsstrahlung x-rays, count rates, and beam current were recorded, as will be described in the next section.

3.3 Preliminary Results

The beam current was in the range of 4 to 6 μA . The energy spectra and counts rates were measured using a Bicron BC400 plastic scintillator and an Amtek 8000A 512-channel multi-channel analyzer (MCA). Figure 10 is a schematic of the analysis circuit.

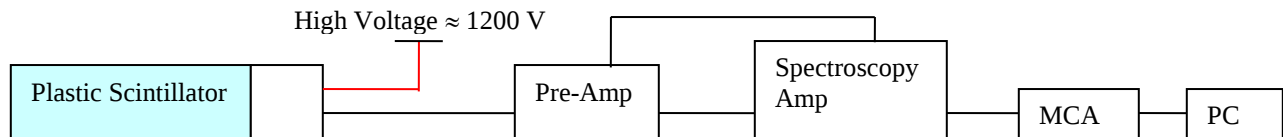


Figure 10: Schematic of the x-ray spectroscopy circuit. The plastic scintillator sent an electric pulse to the pre-amp whenever an x-ray was stopped in the detector. The spectroscopy amplifier amplified the pulse, which is proportional to the x-ray energy. The energy spectrum was recorded in the 512 channel MCA which periodically transferred the stored spectrum onto a PC.

The course gain on the spectroscopy amplifier was set to 5.8. The high voltage power supply was set to 1200 V and the recording time was 100 seconds. The energy spectrum was calibrated using ^{137}Cs and ^{133}Ba , which emit gamma rays at 662 keV and 356 keV respectively. Background was measured for 100 seconds with the Van de Graaff generator turned off. Measurements of bremsstrahlung x-rays were taken at varying angles from the beam line, at 25° , 43° , 66° , 86° and 111° . Fig. 11 shows the positioning of the plastic scintillator. Figures 12-17 show the energy spectra and count rates as a function of angle.

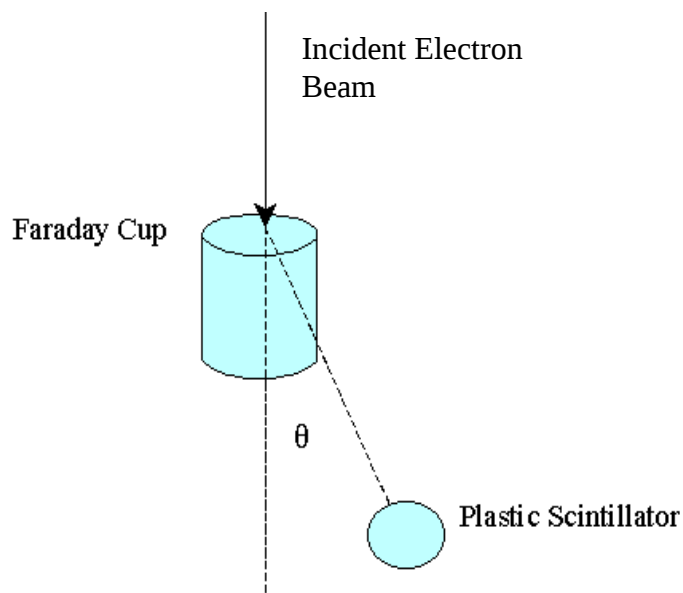


Figure 11: Detector placement for angular measurements
Theta (θ) is the angle from the beam line. The plastic scintillator was placed at various angles and energy spectra and count rates were measured.

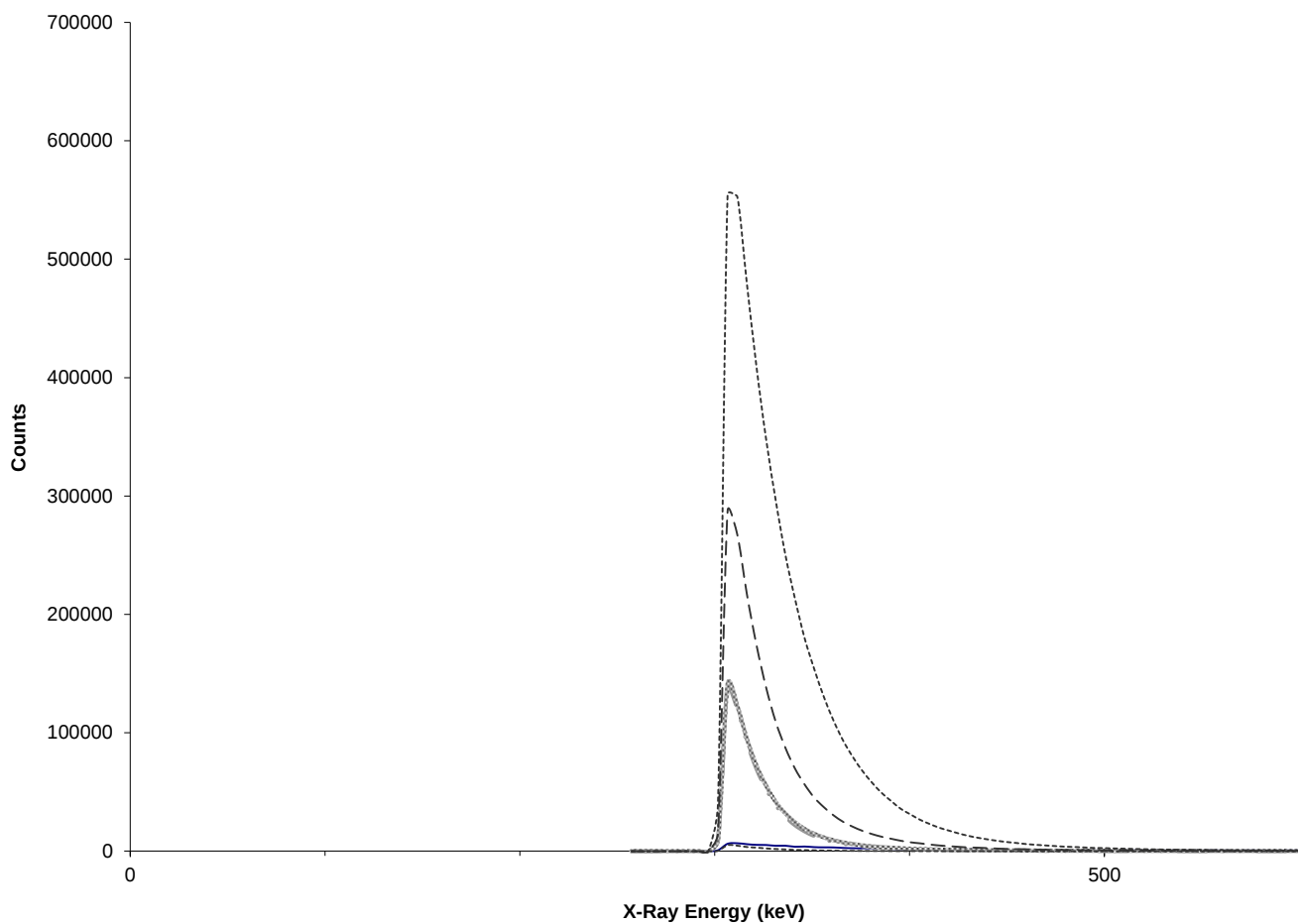


Figure 12: Energy spectra at 25° (thick), 43° (dark thick), 66° (top dashed), 86° (bottom dashed), 111° (dotted) and background (solid) for 100 seconds collection period, displaying the relative intensities of the bremsstrahlung x-rays at each position. The 25° and 43° energy spectra overlap.

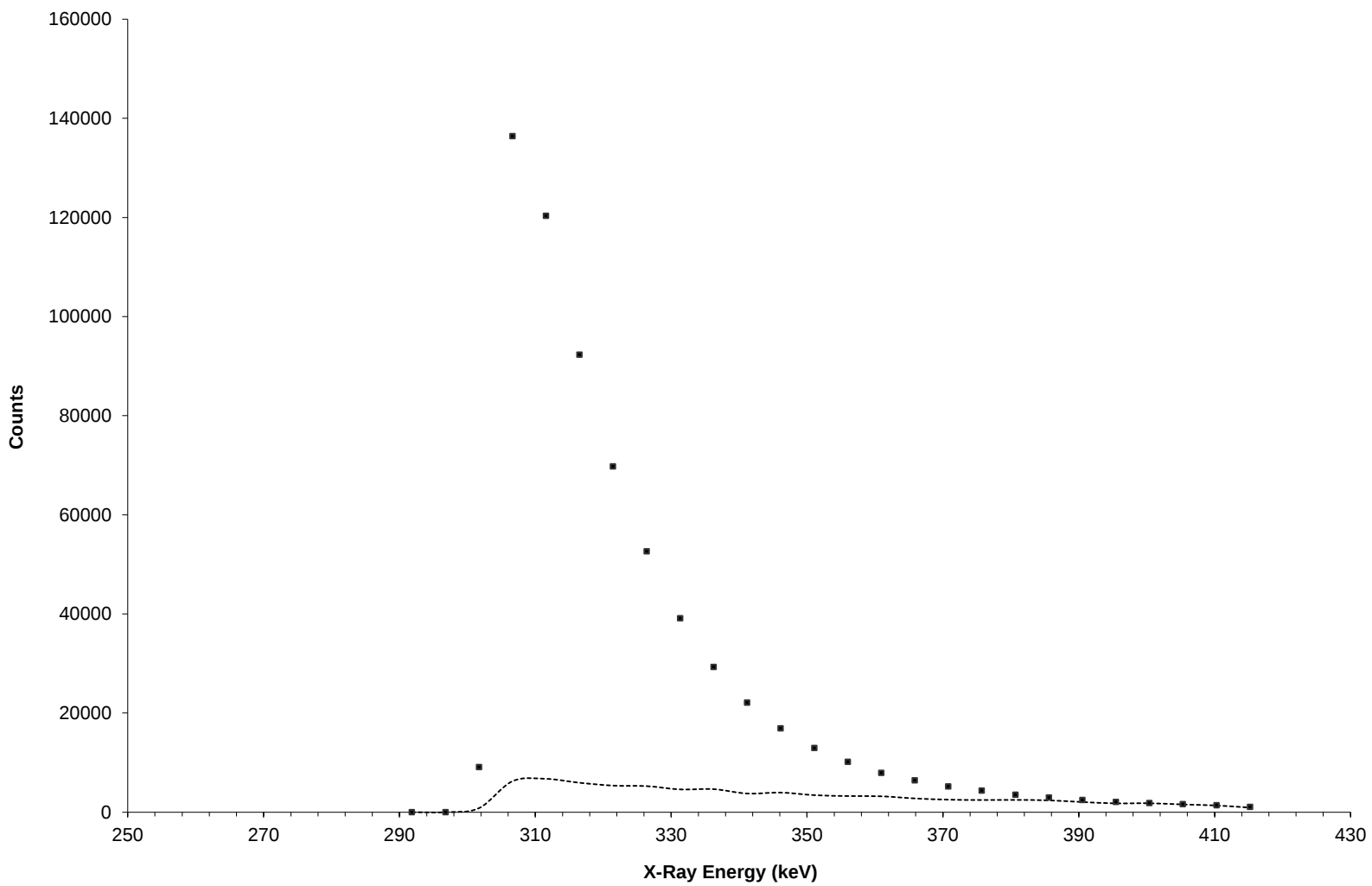


Figure 13: Energy distribution at 25°. The background is the dotted line. Error bars are smaller than the symbols.

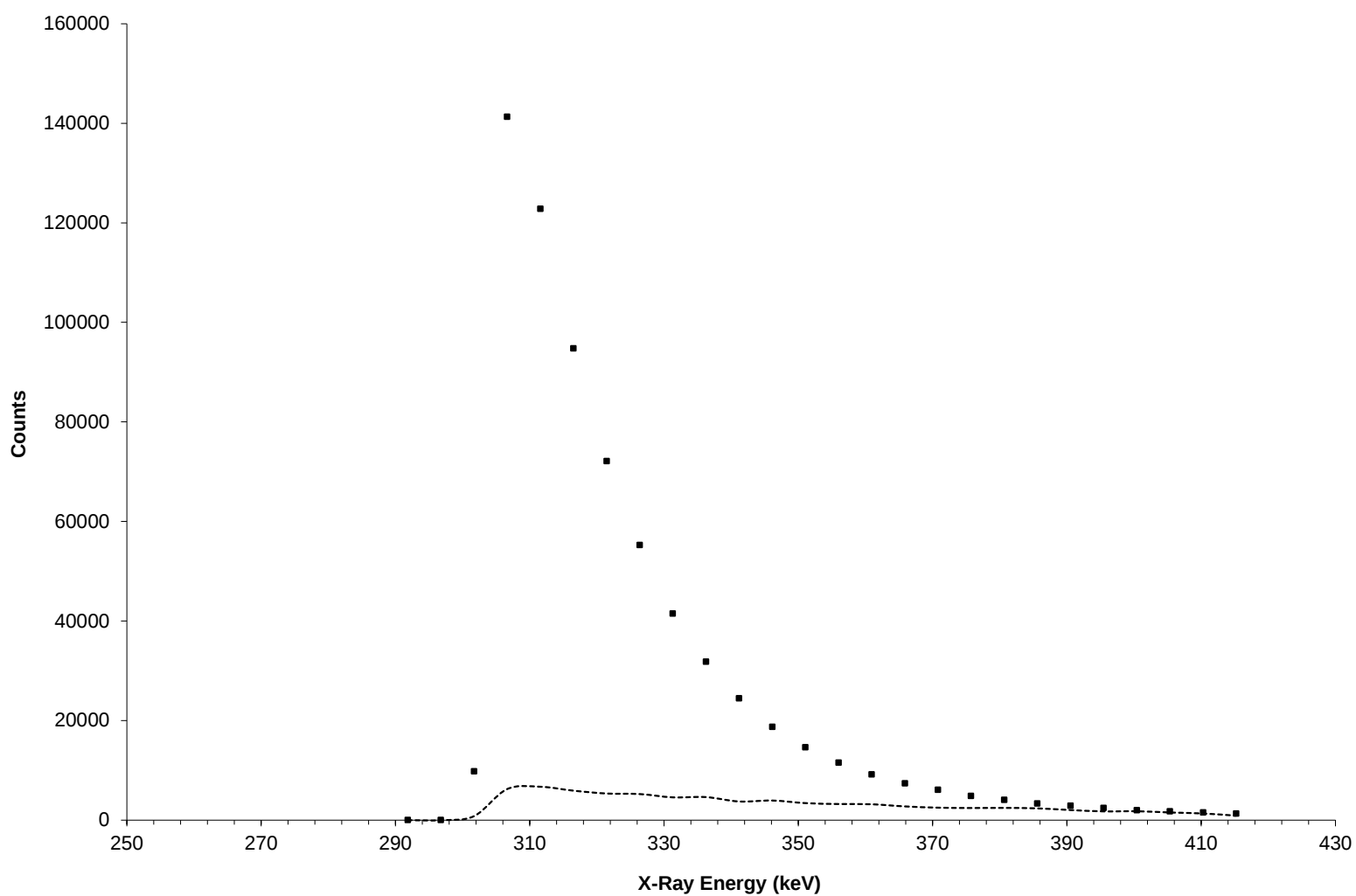


Figure 14: Energy distribution at 43°. The background is the dotted line. Error bars are smaller than the symbols.

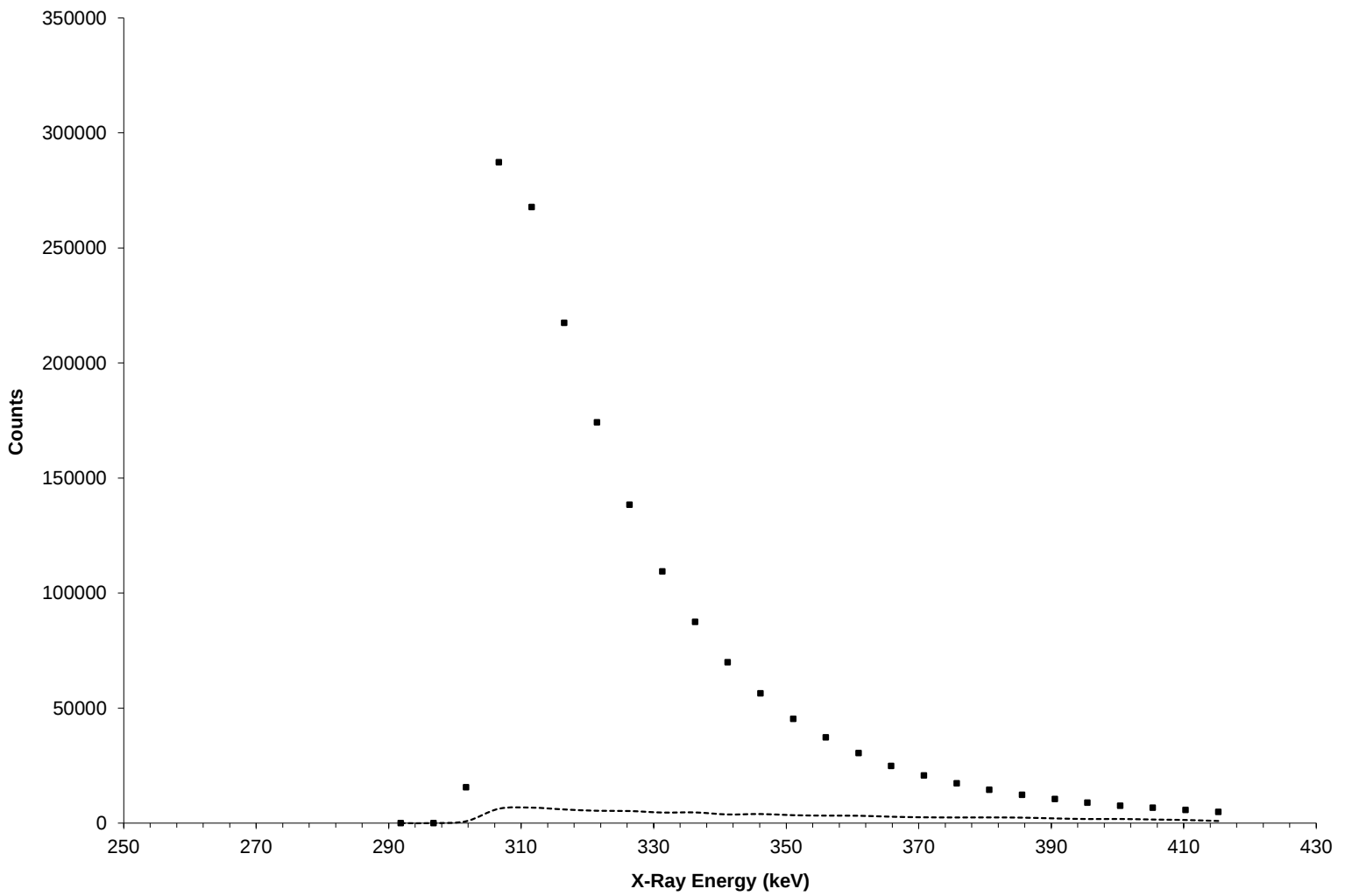


Figure 15: Energy distribution at 66° . The background is the dotted line. Error bars are smaller than the symbols.

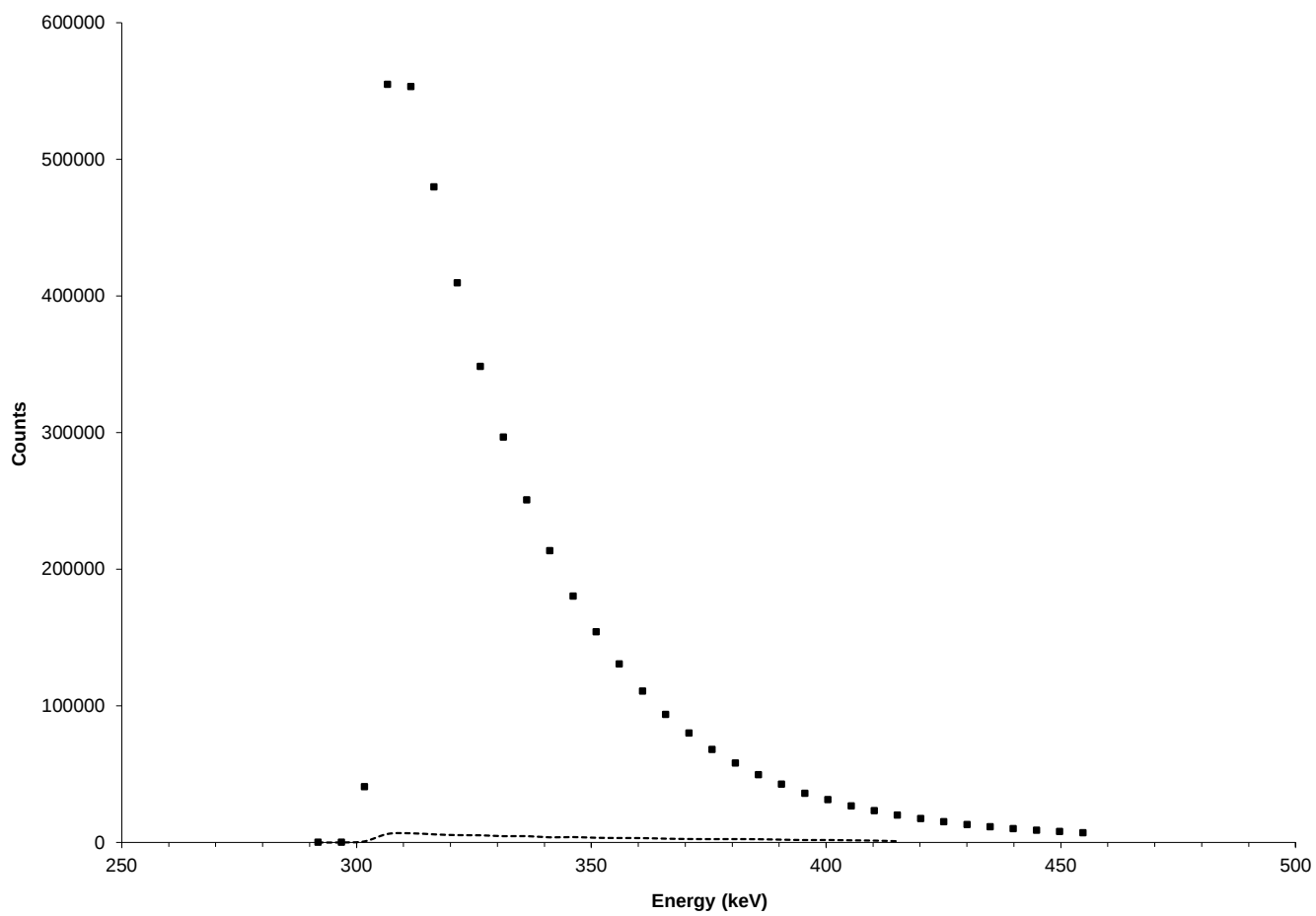


Figure 16: Energy distribution at 111°. The background is the dotted line. Error bars are smaller than the symbols.

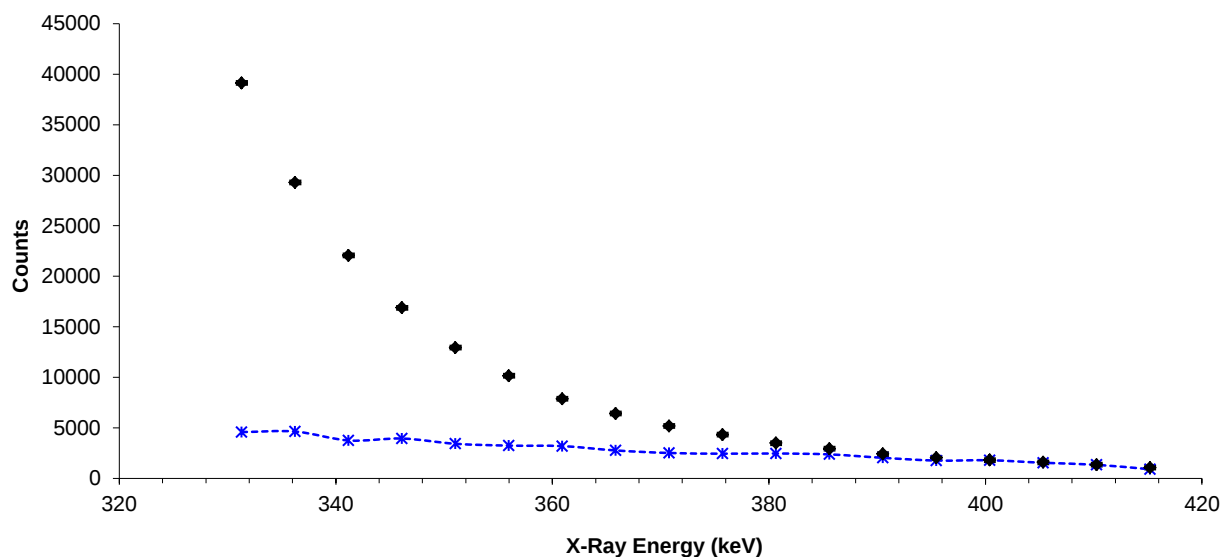


Figure 17: Energy spectrum near the bremsstrahlung endpoint energy for 25°. The background is the dotted line. Error bars are smaller than the symbols.

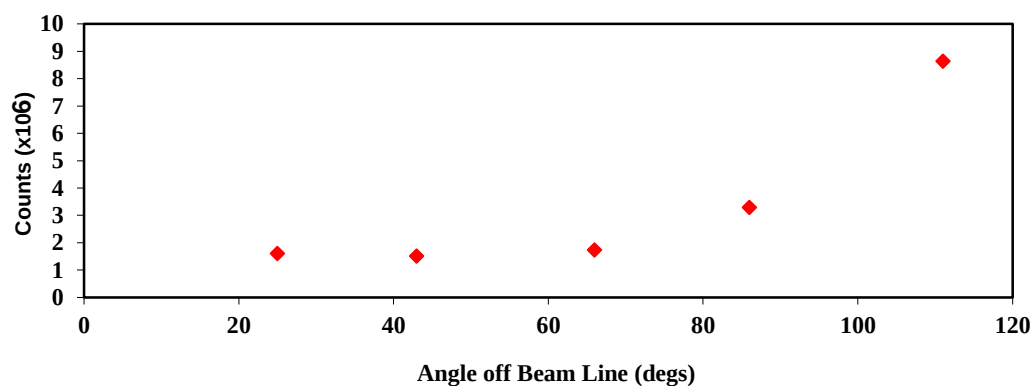


Figure 18: Angle distribution of bremsstrahlung x-rays. The counts at lower angles would be expected to be greater than counts at high angles. The counts were lower at the low angles because of the attenuation of the bremsstrahlung x-rays in the Faraday cup and other materials of the apparatus.

Fig. 17 shows the region of greatest interest, the region of the bremsstrahlung x-ray energy endpoint. As can be seen from this plot of energy versus counts, the spectrum lacks an easily defined endpoint because the sparking created a non-monoenergetic beam of electrons. The energy spectra of the bremsstrahlung x-rays appear to merge with the background x-rays near 400 keV. During the experiment, the amplifier gain was too low, causing the area near the endpoint to fall into a few bins at the low energy end of the spectrum. In future measurements, the gain on the spectroscopy amplifier should be raised to at least 20x to increase the number of channels devoted to the region of interest, 300-400 keV.

Conclusion

The next step for this project is the construction of an aluminum/plastic ring acceleration chamber, replacing the glass tube (see Fig. 20). The aluminum and plastic rings are currently being milled. The rings will be glued together with vacuum epoxy, and plastic dowels will be used to ensure the rings are aligned. The advantage of using aluminum and plastic rings is that any charge that “sticks” to the chamber walls will not create a disturbance in the electric field. Instead, the charge will be transferred to the outside of the ring and will join with the other charges that are descending the voltage ladder of the equipotential aluminum rings. Also, the sparking that occurred in the region of the cathode needs to be corrected. Possible remedies include moving the cathode farther into the high voltage terminal to a region with smaller fields and removing sharp edges from the terminal and cathode.

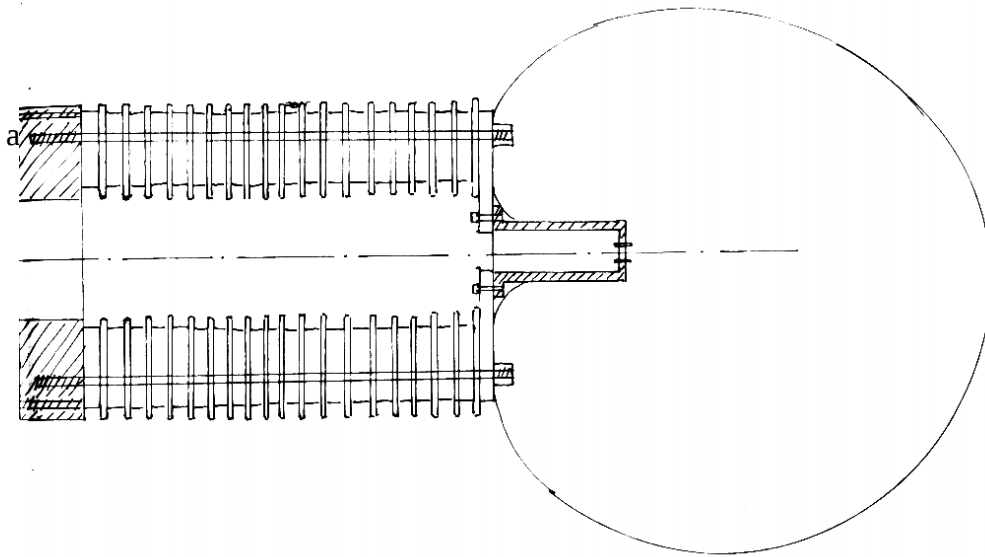


Figure 19: A sketch of the proposed accelerator tube constructed of alternating aluminum and plastic rings connected to the high voltage terminal. (taken from [21])

Appendix A

The Vacuum System

Charged particle acceleration requires a long mean free path, since charged particles interacting with the air lose energy by ionizing the atoms in the air. Also, a filament will burn out if it is not in a low pressure environment. In order to reduce the pressure and increase the mean free path, the apparatus employed a three stage vacuum pump system: a cold trap, a diffusion pump and a rotary fore pump. (See Fig. 21).

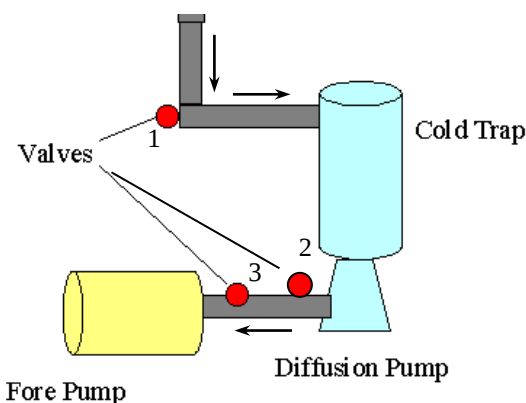


Figure 20: A drawing of the vacuum pump apparatus. First, the fore pump was used to reduce the pressure to 10^{-4} Torr. Then, the diffusion pump was turned on and the cold trap was filled with liquid nitrogen.

First, the apparatus was pumped down to a pressure of 10^{-4} Torr with the fore pump. The fore pump is a mechanical (rotary) vacuum pump. It operates with an off-center piston and moveable vane. The vane maintains a seal between the piston and the chamber edge to ensure that no air can pass between them. As the piston rotates, it creates an increasing size cavity on the right side where the intake from the vacuum chamber is located. This creates a low pressure region into which air molecules flow from the higher pressure in the vacuum chamber. The piston continues to rotate and the vane seals this pocket of air molecules. As the piston rotates, it confines the air to a smaller volume on the exhaust side of the chamber. As the piston compresses the air molecules in the cavity, it forces a valve open on the exhaust and the air exits the chamber (see Fig 22).

Next, the cold trap is filled with liquid nitrogen. The cold trap is made of two cylinders, the inner holds liquid nitrogen and the outer one is connected to the vacuum chamber. The inner cylinder becomes so cold that it lowers the thermal energy of the air

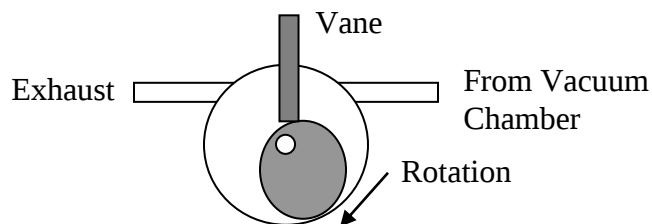


Figure 21:
A rotary pump with an off-center piston

molecules in the outer cylinder. As the molecules cool, they sink to the bottom of the cold trap where they are removed by the diffusion pump.

The diffusion pump creates jets of oil that are directed downwards by nozzles. The high velocity oil vapor creates a downward current in which air molecules become trapped, flowing down to exhaust to the fore pump, where the air molecules are removed. The oil condenses against the cool walls of the diffusion pump chamber (the walls are cooled by a fan and cooling fins) and sinks back to the oil reservoir at the bottom of the pump. Any oil that rises near the cold trap condenses against cooler baffles, and then returns to the reservoir [22]. A diffusion pump must not be operated until the pressure is below 10^{-3} Torr or the oil will oxidize and become useless for the diffusion pumping process [23].

Directions for Operation

To turn on the vacuum pump:

- 1) Make sure valves 1 and 3 are open and 2 is closed. (valve 2 is a pressure release that allows air into the chamber).
- 2) Turn on the Fore Pump.
- 3) Wait until the pressure is at least of the order of 10^{-4} Torr.
- 4) Fill the cold trap with liquid nitrogen.
- 5) Turn on the Diffusion Pump, using 75 Volts.
- 6) Continue to check and fill the cold trap as needed.

To shut down the vacuum pump:

- 1) Turn off the diffusion pump.
- 2) Close valve 1.
- 3) Open Valve 2
- 4) Turn off the fore pump
- 5) Close valves 2 and 3.

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