

**AN ELECTRON GUN CONTROLLER FOR A
SMALL ELECTROSTATIC ELECTRON
ACCELERATOR**

By

Stephen Thomson

A thesis submitted in partial fulfillment of the requirements for
the degree of

Bachelor of Science

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Abstract

The Houghton College electrostatic electron accelerator uses a small Van de Graaff generator and an accelerator column made from alternating high-density polyethylene and aluminum rings to create a uniform electric field. The accelerator column is evacuated to about 10^{-6} torr by a rotary forepump and a diffusion pump. To produce the electrons, an electron gun made from a 3RP1 CRT is located inside the high voltage terminal. The electrodes of the electron gun require user-controlled voltages for the anode, focus and intensity grids. Since the gun is located inside the HV terminal, a microcontroller/amplifier circuit was designed to produce the required voltages and communicate with the user via a non-conducting, fiber optic RS232 link. The remote control system has been tested with the electron gun attached to the vacuum system.

Thesis Supervisor: Dr. Mark Yuly
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INTRODUCTION

1.1 Electrostatic Accelerators

1.1.1 Purpose of Accelerators

The study of the structure and interactions of nuclei has become an increasingly important area in physics. In the late 1920's and early 1930's, physicists needed a probe to disrupt and interact with the particles that make up the nucleus in order to study the nucleus [1]. By 1933, physicists knew that the nucleus contained the positive charge and also most of the mass and energy of the atom, but little was known about the forces governing the nucleus. A technique used to discover more about the nature of the nucleus was the scattering of high speed particles from the nucleus [2].

One of the earliest experiments which used scattered particles as a probe was done by Geiger and Marsden who scattered α -particles from gold-foil [3]. Rutherford used this to demonstrate the existence of protons [4]. To do this, naturally emitted α -particles from Ra and Th were incident upon a gold-foil and the deflection of the α -particles was noted. At the time Geiger and Marsden were performing their experiments, the prevalent theory was that the nucleus contained negative particles and an equal positive charge distributed throughout the sphere that was believed to be the atom [5]. This theory led to the belief that deflections of a scattered α particle would be small, which contradicted the results of Geiger and Marsden. While performing their experiment, Geiger and Marsden noted that a more intense source of α -particles than is naturally available would be necessary to get good statistics [6]. Rutherford reiterated this sentiment as a challenge to the physics world, and so the quest to be able to produce an intense source of incident particles began [7].

1.1.2 History of the Electrostatic Accelerator

In hopes of creating a viable method for accelerating particles, in 1929 R.J. Van de Graaff constructed the first model of an electrostatic generator. The electrostatic generator was used to create a large potential difference to accelerate charged particles. For nuclear experiments, the charged particles were usually ions. Figure 1 shows a positive ion source which uses electrons to ionize a plasma and create an ion beam. Figure 2 shows the ion source placed in an evacuated tube with one end attached

to the high voltage terminal of the electrostatic generator and the other attached to ground. As the positive ions enter the tube they are repelled from the high voltage terminal and accelerated to ground. Thus a high-energy beam of charged particles suitable for conducting investigations of the nucleus is obtained.

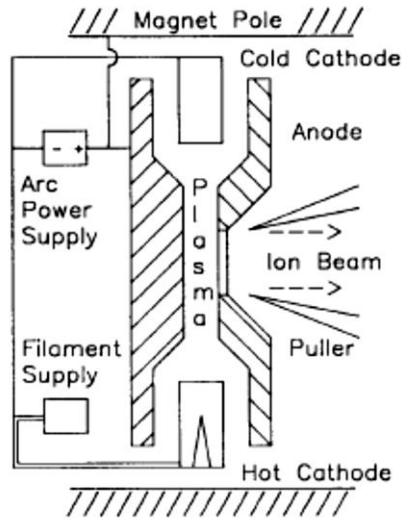


Figure 1. Positive ion source. Electrons are emitted from the filament and travel through the plasma in a cycloidal path ionizing the neutral atoms of the plasma. Positively charged ions are expelled from the plasma, creating the ion beam. Taken from Ref [8].

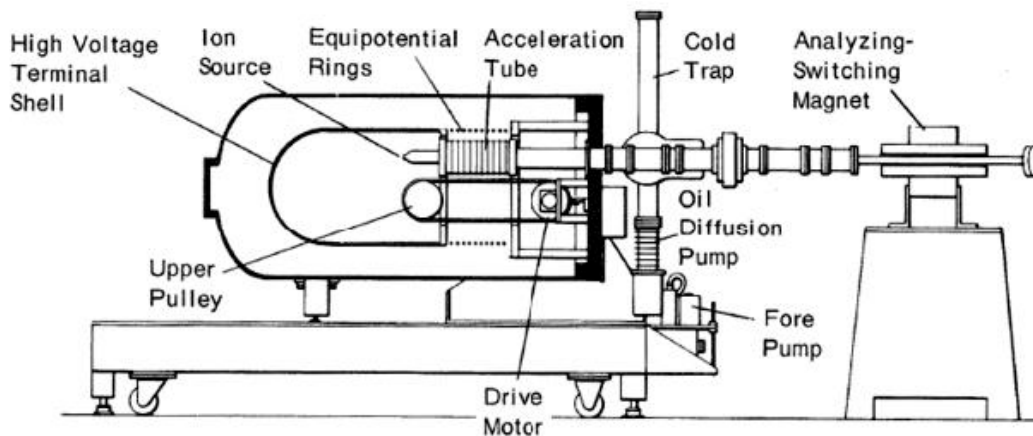


Figure 2. The operating principle of an electrostatic accelerator. Positive charges enter an evacuated tube at low energy and are repelled by the large negative potential to the other end of the tube. The Van de Graaff electrostatic generator shown on the left supplies the positive high voltage. Taken from Ref [9].

In order to create an electrostatic accelerator, Van de Graaff needed a method for creating a high voltage. The idea for his electrostatic generator which created the required high voltage came from Lord Kelvin's water drop apparatus [10]. Lord Kelvin's design utilized drops of water which were charged via a slight charge on a nozzle and collected in a conductive funnel [11]. The slight charge on the nozzle is created by putting the nozzle in contact with a different metal which naturally tends to give electrons to the metal of the nozzle. The water drops transfer their charge to the conductive funnel before dripping out of the funnel. The limit to the amount of charge that can be built up on the funnel is the breakdown voltage of the air between the nozzle and funnel, causing a discharge of the funnel.

Although the basic principle was old, it was Van de Graaff who first used it to construct an electrostatic generator capable of being used in a practical particle accelerator [2]. Figure 3 shows the original generator, consisting of two 24-inch hollow copper spheres as terminals, one positively charged and the other negatively charged. The generator could be powered by an ordinary wall socket and a potential of 1.5 MV could be reached between the two terminals [12]. The basic principles of operation are as follows: charge is attracted from ground to a high potential brush, but there is an insulating belt between the two. This causes the charge to be trapped on the belt. The belt on the pulley system is constantly moving, and so carries the charge up to the high voltage terminal. Once on the insulator, the charges are not free to move around, so even if they are repelled strongly by the charge on the hollow metal high voltage terminal, they are still carried by the belt into the sphere. Once inside the sphere, the charges are in a field free region inside a conductor and so, after they are collected by the brush inside the sphere, they spread to the surface of the sphere. Thus, large potentials can be built up on the metal sphere. The energy that the charges gain (eV) is provided by the motor powering the pulley.

In 1932, working with K.T. Compton and L.C. Van Atta, Van de Graaff began the construction of a 10 MV electrostatic generator for M.I.T. at Round Hill near South Dartmouth, MA. This time, the two spherical terminals which were 15 m in diameter were used with two 4 m wide belts each. The reason that the spherical terminals were so large is because the limiting factor on the high voltage was the breakdown voltage of air and, by spreading out the charges, a higher potential could be reached before reaching that critical point. An evacuated tube for accelerating ions was supported between the two terminals and a workplace for conducting nuclear scattering experiments was within one of the

terminals [13]. The highest potential difference between the two conducting shells was 5.1 MV with 1.1 mA of current available for accelerating ions [13]. The spherical terminals were so large that they needed to be enclosed inside a hangar. The hangar was located near the ocean, leading to humidity problems. High humidity caused the terminals to not reach their full potential because the breakdown voltage of air decreases as humidity increases. Thus, when the high voltage terminal reaches this lower breakdown voltage, any attempt to continue to increase the voltage will cause the terminal to ionize the air and discharge. Subsequently, in an experiment by R.G. Herb [14], it was found that a higher potential could be reached by operating an electrostatic generator inside a pressurized air tank because the breakdown voltage increased and, later, that by replacing the air with other gases having higher breakdown voltages, such as SF₆, even higher potentials could be maintained [15]. This innovation allowed for an spherical terminals to be smaller while still reaching the same high voltage as the older and much larger terminals.

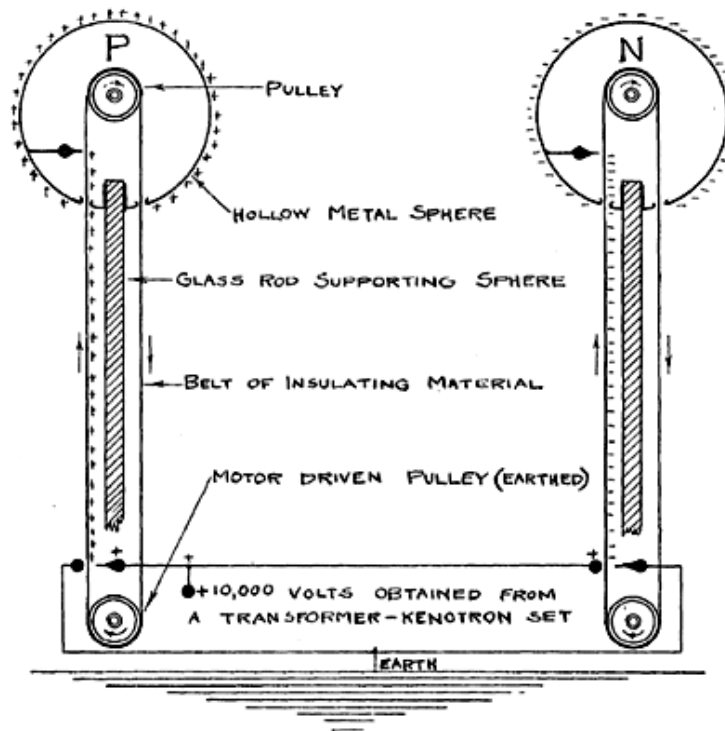


Figure 3. The original Van de Graaff generator. A high voltage supply sprays charge on a moving belt. The belt carrying the charge is rotated by the pulleys. Inside the hollow metal sphere the belt is discharged to the surface of the sphere, creating a potential on the spherical terminal. By charging one terminal negatively and the other positively, a large potential difference can be reached. Taken from Ref [2].

1.1.3 Advantages of the Electrostatic Generator

An advantage of the electrostatic generator is its voltage stability. In the 1930s, when the technology was new, the Round Hill generator already was able to obtain a voltage fluctuation of only 0.1% [13]. Since then, generators have become even more stable by using voltage regulation circuits. Figure 4 shows a beam of monoenergetic charged particles being deflected in a constant magnetic field. If all the particles have precisely the same velocity and charge, they will all be deflected by the same force

$$\vec{F} = q\vec{v} \times \vec{B} \quad 1.1$$

where q is the charge of the particles, \vec{v} is the velocity of the particles and \vec{B} is the magnetic field. Thus, the greater \vec{v} is, the smaller the deflection for a given magnetic field. Consider a beam of particles from an accelerator that pass through a uniform magnetic field, then strike a collimator slit, as shown in Figure 4. If the particles strike the upper edge of the slit, they have less kinetic energy than is desired so the voltage on the high voltage terminal must be increased. Conversely, if the particles strike the lower edge of the slit, they have more kinetic energy than is desired, so the voltage must be decreased. By measuring the current on each side of the slit, the accelerator can be told whether to raise or lower the voltage on the terminal to center the beam. Because modern electrostatic accelerators produce very stable, nearly monoenergetic beams, they are very suitable for conducting nuclear experiments which require precise energy control.

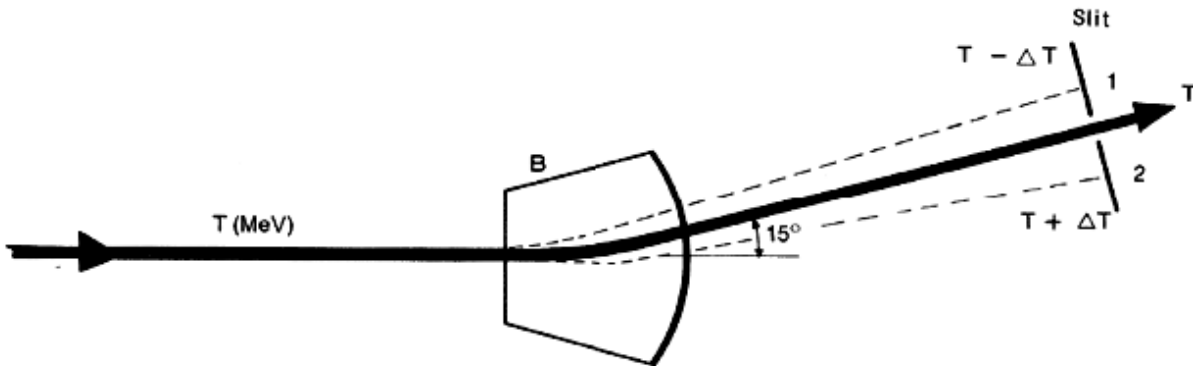


Figure 4. Particle trajectory deflected by a magnetic field. The solid black line represents the trajectory of particles with the desired energy. The beam passes through a collimator slit. If the beam strikes the collimator, then the voltage on the high voltage terminal is adjusted so as to center the beam. Taken from Ref [9].

There are multiple ways to control the voltage on the terminal. The most common way is to adjust the rate charge is “sprayed” on the belt, which in Figure 3 would be done by changing the voltage obtained from the transformer-kenotron set which was a series of vacuum tubes designed to generate up to +10 000V. Another common method of controlling the high voltage is to place a grounded metal needle at a distance from the generator. By placing ground closer to the terminal, corona discharge occurs and so the maximum voltage is lowered. This can also be used for regulation. If the voltage on the terminal rises, so does the corona discharge. If the voltage on the terminal decreases, so does the corona discharge. A less precise method to lower the voltage on the electrostatic generator is to change the speed of the belt on the pulleys.

Another advantage of the electrostatic accelerator is that it is flexible. Either positively or negatively charged particles can be accelerated by changing the charge on the belts of each generator. Thus, many different nuclear experiments can be performed with varying incident particles, without requiring much change in the electrostatic accelerator.

1.2 The Houghton College Electrostatic Accelerator

1.1.4 History for the Houghton College Electrostatic Accelerator

Small electrostatic accelerators have been constructed by undergraduate students at other colleges [16], which suggested that building an accelerator would be a good project for students at Houghton College. The idea for the design of Houghton College Electrostatic Accelerator was prompted by Frank B. Lee’s article “A Homemade Atom Smasher” [17]. Figure 5 shows his design. Lee accelerated electrons from ground potential toward a positively charged high voltage terminal. A glass accelerator tube was used with evenly spaced wire rings on the outside of the glass tube to maintain a constant electric field inside the tube. Because one end of the accelerator tube is at ground and the other at high voltage, corona current flowing down the column from ring to ring causes the voltage difference between each electrode ring to be constant, as if the air between the rings formed a resistor chain.

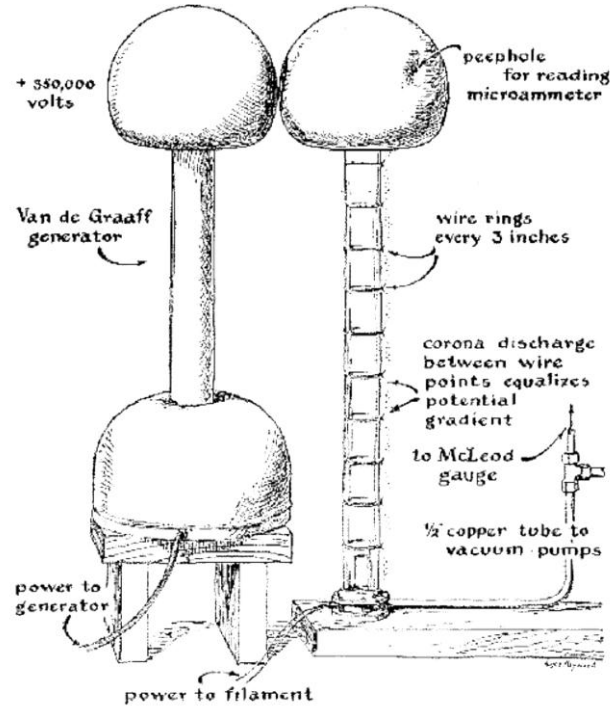


Figure 5. Lee's design for the electrostatic accelerator. The Van de Graaff generator operated at high positive potential relative to ground. Electrons produced by the filament at the bottom of the accelerator tube were accelerated to the high voltage terminal. The evenly spaced wire rings on the accelerator tube create a constant electric field. Taken from Ref [17].

This means that

$$\frac{dV}{dx} \approx \frac{\Delta V}{\Delta x} = C \quad 1.2$$

where C is a constant. As there is no voltage change in the y or z-directions,

$$\frac{dV}{dz} = \frac{dV}{dy} = 0 \quad 1.3$$

The electric field is given by

$$\vec{E} = -\vec{\nabla}V. \quad 1.4$$

Since the gradient of V is zero in the y and z directions,

$$\vec{E} = -C\hat{i} \quad 1.5$$

Therefore there is a uniform acceleration in the \hat{i} direction and the charged particles are accelerated only in the direction along the tube.

Figure 6 shows the original design for the Houghton College electron accelerator. This design is described in greater detail in Ref [18]. It altered Lee's original idea by placing the electron gun inside the high voltage terminal and by charging the high voltage terminal negatively to repel electrons. This meant that the beam would be at ground when it reached the target, which allowed detectors to be placed near the target without fear of the high voltage terminal discharging to the detectors. Since the electron gun was inside the high voltage terminal, the filament needed to be powered by a battery. Although with this method a beam spot of sorts was observed, because the ring electrodes were on the outside of the tube, stray electrons striking the insulating glass of the accelerator tube caused charge to build up and the electron beam to be deflected. To solve this problem, a new design for the accelerator tube was necessary.

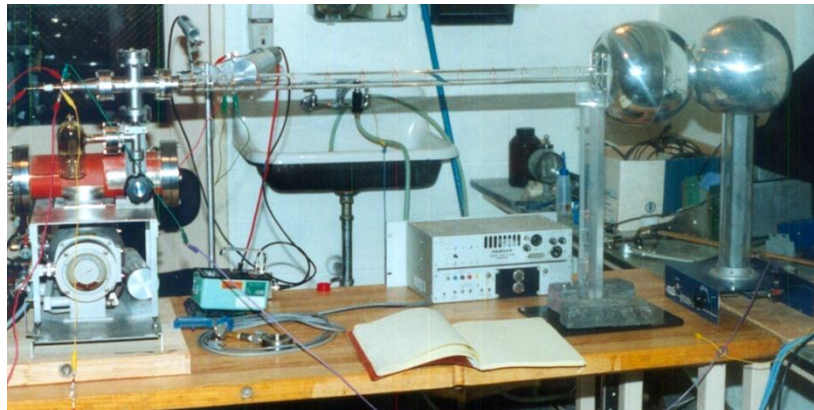


Figure 6. The initial Houghton College electrostatic accelerator design. The Van de Graaff generator is located on the right, and is electrically connected to the high voltage terminal which houses the electron gun. A glass accelerator tube with evenly spaced copper rings produced a uniform electric field inside the tube. To the left the vacuum system can be seen [18].

Figure 7 shows the redesigned column made from alternating high-density polyethylene and aluminum rings which were glued together to solve the problem of charge building up on the glass wall. The conductive rings had smaller inner radius, which made it impossible for stray electrons to build up on the plastic insulator. The design is described in detail in Ref [19].



Figure 7. The improved accelerator tube. For this tube, the conductive rings were of inner diameter 3.81 cm and the insulator rings were made with inner diameter of 5.08 cm so as to not allow charge to build up on the walls of the accelerator tube [19].

Although this design solved the problem, it was very delicate and kept leaking. The next design used alternating Teflon and stainless steel washers sealed with o-rings and compressed by 6 threaded nylon rods. This too leaked as the nylon rods stretched under the pressure and allowed the o-rings to stop being compressed. The nylon rods were replaced with acrylic rods, which have a higher tensile strength and did not stretch. Instead they shattered because they were too brittle. These problems have been solved by using pre-stretched nylon rods to compress the o-rings [20].

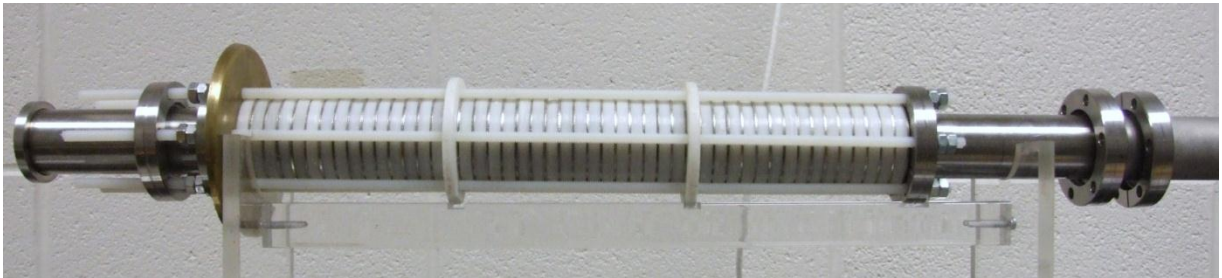


Figure 8. The current accelerator tube. Pre-stretched nylon rods are used to compress the o-rings.

1.1.5 Motivation of the Houghton College Electrostatic Accelerator

Once the Houghton College electrostatic accelerator is operational, it will hopefully be used for a variety of experiments. For example, a deuteron ion source can replace the electron gun. A deuteron is composed of a proton and a neutron. Incident deuterons may be allowed to strike a deuterium target, allowing the d-d reaction investigated. This reaction can also be used to create a neutron source for other scattering experiments.

Another application for the accelerator would be x-ray fluorescence. X-ray fluorescence occurs when x-rays cause the emission of a tightly held inner electron of a material. With this electron gone, the other electrons move to lower energies to fill the vacancy left by the emitted electron. During the process in which outer electrons are moving to lower ‘orbitals’, radiation characteristic of specific atoms is emitted. Thus, the material the x-rays are incident upon can be identified. This technique can be used, for example, in geochemistry, which is the study of the chemical composition of the earth.

Another possible interesting application of the accelerator might be to accelerate positrons. Positron beams are being produced at Lawrence Livermore National Laboratory [21]. Figure 9 shows a possible method for accelerating positrons at a low current using a positron source in place of the electron gun. Positrons are emitted from a positron source, such as the decay ^{22}Na . Some emitted positrons are collected on an aluminum foil held at high positive voltage, while the rest of the emitted positrons are blocked [22]. The electric potential then causes the stopped positrons in the foil to be accelerated. This method would create a beam of monoenergetic positrons.

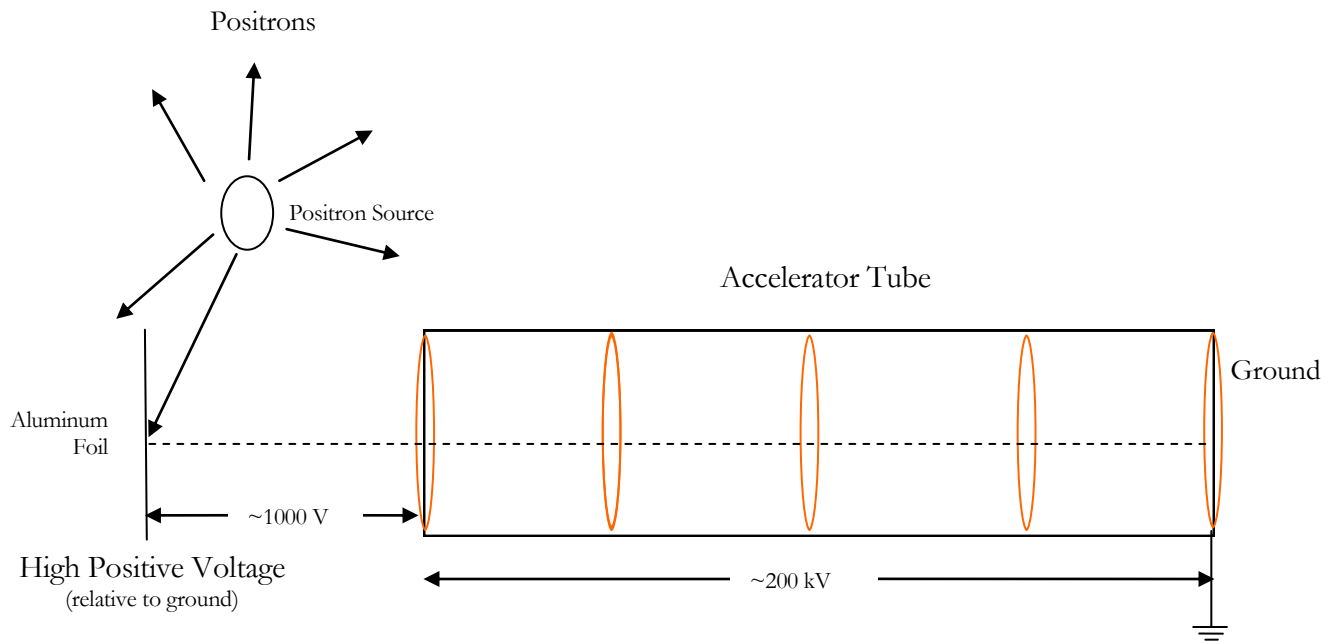


Figure 9. A method for accelerating positrons. Positrons are stopped by the aluminum foil. The electric potential then accelerates them toward ground.

Chapter 2

THEORY

Originally, Van de Graaff generators were created to supply steady high voltage to electrostatic particle accelerators. The maximum energy the charged particles attain is directly proportional to the maximum voltage difference that can be provided.

As seen in Figure 10, a Van de Graaff generator consists of a hollow conductive high voltage terminal mounted upon an insulating column. The charge on the high voltage terminal needs to be constant to provide a constant accelerating voltage for an accelerator. To charge the sphere, an insulating moving belt carries the charge to the conducting sphere. Charge is ‘sprayed’ on the belt, and there are a variety of methods to accomplish this. One method sometimes used for charging the belt is called frictional charging.

In the method of frictional charging, or triboelectricity, the molecules on the belt have a low work function and the molecules on the pulley have a higher work function [23]. This means that as the belt makes contact with the pulley, covalent bonds are formed in which the shared electrons are more tightly held by the belt. Thus, as the belt peels away from the pulley, most of the electrons from the bonds with the pulley stick to the belt, creating a positively charged pulley. This positively charged pulley in turn attracts more electrons from the grounded comb. The electrons attracted from the comb are intercepted by the pulley which is an insulator. This means that the electrons are securely lodged on the belt. The now negatively charged belt rotates so that the electrons from the comb approach the high voltage terminal; if the terminal is charged, the electrons will be repelled. However, because the electrons are firmly lodged in the insulator material of the belt, they are carried into the terminal regardless of this repulsion requiring the motor rotating the pulley to do work. Inside the conductor there is no electric field, so the collecting of charge can continue regardless of the potential on the sphere and the charges are spread out on the surface of the sphere storing the energy equivalent to the work done by the motor [2].

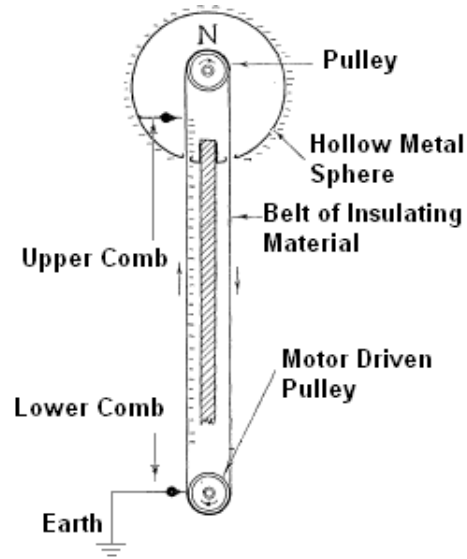


Figure 10. Schematic diagram of a Van de Graaff generator. The motor driven pulley becomes positively charged, which attracts electrons from the grounded lower comb. These electrons are intercepted by the insulating belt before they can reach the pulley. The charges are unable to move in the insulated belt, and are trapped there until they reach the corona point collector inside the terminal where the electrons are discharged to the surface of the terminal. Adapted from Ref. [2].

Once the lower pulley has been charged, the up-current collected by the upper comb in the terminal is constant. However, not all of this current goes to increasing the potential on the sphere. Some current is lost to the corona discharge, or ionization of the surrounding air [24]. When this ionized air mixture allows electrons to travel to ground, loss of potential occurs. Coronal discharge occurs only when the voltage on the terminal is above a certain threshold, so usually electrostatic generators are operated with voltages below this threshold value. Also, some current is directed down the accelerator tube, which is called the resistive current. This current is linearly proportional to the voltage on the high voltage terminal. Another loss of current, called the beam current, occurs when electrons are accelerated down the accelerator tube, which is constant.

There are several factors limiting the maximum potential on the sphere. When charge builds up on the terminal it acts like a capacitor. The voltage (V) on the capacitor is given by

$$V = \frac{Q}{C} \tag{2.1}$$

where Q is the charge on the terminal and C is the capacitance of the terminal. The net current flowing to the terminal is given by

$$i = \frac{dQ}{dt}, \quad 2.2$$

so, taking the derivative of Equation 2.1 we find that

$$i = \frac{dQ}{dt} = C \frac{dV}{dt}. \quad 2.3$$

The current (i_{up}) up to the high voltage terminal of our Van de Graaff accelerator is constant, but some of this current is lost as the beam current, resistive current and as corona discharge. The total current charging the high voltage terminal is therefore

$$i = i_{up} - i_{beam} - i_{resistive} - i_{corona} = C \frac{dV}{dt} \quad 2.4$$

where i_{beam} is the beam current, $i_{resistive}$ is the resistive current which is directly proportional to the terminal's potential, and i_{corona} is the corona discharge current. The current lost to corona discharge increases rapidly when the voltage of the high voltage terminal is above a certain threshold. Initially, when the terminal is uncharged, $V=0$ and $\frac{dV}{dt}$ is large.

The time-dependence of the voltage on the terminal can be calculated using Equation 2.4. Both i_{up} and i_{beam} are constant. As the electrostatic accelerator will be operated below the corona discharge levels, i_{corona} will be considered zero. The resistive current, which is proportional to the voltage on the terminal, is given by $\frac{V}{R}$.

$$i = i_{up} - i_{beam} - \frac{V}{R} = C \frac{dV}{dt}. \quad 2.5$$

This is a differential equation which can be solved. The time-dependent solution to this equation is

$$V = R(i_{up} - i_{beam})(1 - e^{-\frac{t}{RC}}). \quad 2.6$$

A method for estimating the maximum voltage is to use the breakdown voltage of air as the limiting factor for the voltage on the generator. The breakdown voltage of dry air at standard temperature and pressure is $3 \times 10^6 \text{ V} \cdot \text{m}^{-1}$ [25]. This means that the maximum electric field at the surface of the terminal can be $3 \times 10^6 \text{ V} \cdot \text{m}^{-1}$. The electric field at the surface of a sphere is

$$\vec{E} = \frac{kQ}{r^2} \hat{r} = \frac{V}{r} \hat{r} \quad 2.7$$

where r is the radius of the terminal. Since the radius of the spherical caps of the terminal are 12.5 cm, an estimate for the maximum voltage on the terminal is 375 kV.

A method for increasing the maximum voltage of the generator is to surround the terminal with an insulating gas such as SF_4 or pressurized N_2 which will increase the minimum ionization potential of the gas surrounding the terminal. By increasing the ionization potential, a higher voltage can be reached before ionization of the gas will occur.

The maximum charge on the terminal can be found if the capacitance of the terminal is known. The capacitance of a sphere is

$$C = 4\pi\epsilon_0 r \quad 2.8$$

where r is the radius of the sphere. Thus, the capacitance is about 14 pF. By combining this value with the maximum voltage on the terminal, the charge on the terminal is approximated to be

$$Q = CV = 4\pi\epsilon_0 rV. \quad 2.9$$

Thus, the maximum charge on the terminal is about $5 \mu\text{C}$.

This information can be used to find the time required to charge the terminal after it is completely discharge. First, the value of $R(i_{up} - i_{beam})$ must be found. Assuming that the terminal has been charging for a long time Equation 2.6 becomes

$$V = R(i_{up} - i_{beam})(1 - 0). \quad 2.10$$

As the maximum charge on the terminal is 375 kV,

$$375 \text{ kV} = R(i_{up} - i_{beam}). \quad 2.11$$

The up current for the generator is approximately 7 μA and the beam current is expected to be 0.1 μA . Thus, R is approximately 54 $\text{G}\Omega$. Assuming that 250 kV is the desired voltage, the time taken to charge the terminal then is found by

$$250 \text{ kV} = 375 \text{ kV}(1 - e^{-\frac{t}{RC}}). \quad 2.12$$

Thus, the time required to charge the terminal is about 0.8 s.

The energy stored in the terminal can be found. The energy E_{cap} stored in a capacitor is given by

$$E_{cap} = \frac{1}{2}CV^2 = \frac{1}{2}QV. \quad 2.13$$

Thus, approximately 1 J of energy can be stored in the terminal.

APPARATUS

The design for the electrostatic accelerator makes use of a Van de Graaff generator. The high voltage terminal is held at a large negative voltage relative to Earth ground. Inside the negative terminal is an electron gun, emitting electrons from the cathode at a negative potential relative to the negative high voltage terminal. These electrons then travel down the accelerator column, which has multiple alternating conductive rings and plastic spacers. The conductive rings increase in potential as their distance from the negative high voltage terminal increases until they reach the end of the accelerator column at Earth ground potential. Once at the end of the accelerator column, the electrons drift through the evacuated beam pipe until reaching a target or screen. The path from electron gun to the phosphor screen or target is held at vacuum. The pressure is on the order of 10^{-6} torr.

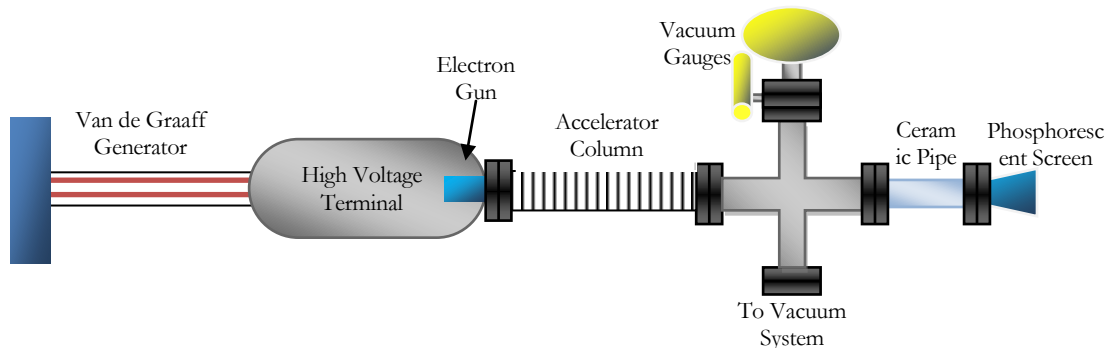


Figure 11. Schematic diagram of the accelerator. The Van de Graaff generator is horizontal, with the electron gun and electrical control circuit inside the high voltage terminal. Electrons are accelerated through the accelerator column. At the end of the accelerator column, the electrons have reached their peak energy and will continue to drift until incident upon the fluorescent screen.

3.1 Van de Graaff Generator

The Van de Graaff generator used to produce the necessary high voltage is a Winsco N-100V. The terminal is composed of a cylindrical section of length 42.5 cm with spherical caps at each end of 25 cm diameter. The entire length of the generator, when on its side as in Figure 11, is 118 cm. The maximum voltage of the generator was previously calculated using the X-ray Bremsstrahlung spectrum to be $200 \text{ kV} \pm 50 \text{ kV}$ [19], which is approximately 50% of the theoretical maximum. Humidity is one

cause for this shortfall [13]. Another reason is the unavoidable irregularities on the surface of the high voltage terminal [2]. Furthermore, the theoretical predictions approximate the high voltage terminal as spherical with the earth being infinitely far away. Thus, the calculated value is expected to be much greater than the actual voltage maximum.

3.2 Electron Gun

Figure 12 is a schematic of an electron gun, which is the source of electrons for the accelerator. It contains a filament, and only functions under vacuum. The filament heats the cathode, which is coated with a metal with a low work function. This then emits electrons by thermionic emission [26]. The average energy of the electrons leaving the cathode by thermionic emission will be approximately $3.2kT$ where k is Boltzman's constant and T is the temperature of the cathode [27]. Thus, energies of electrons emitted from the cathode will most likely be between 0.1 eV and 0.5 eV. However, even though the emitted electrons have varying energies, since electrons will be accelerated to 200 keV a variation of 0.5 eV will have little effect on the total energy of each electron.

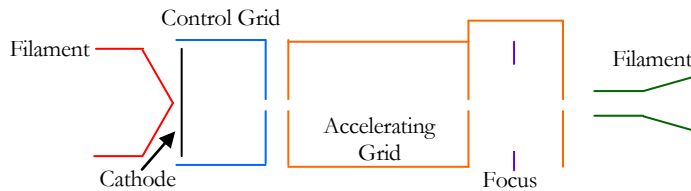


Figure 12. Schematic of the electron gun. The filament is shown in red, the cathode is next to the filament in black, the control grid is shown in blue, the accelerating grid is orange and the focusing grid is in purple. Deflection plates are shown in green.

Once the electrons are emitted from the cathode, they are repelled by the control grid. The control grid is a few volts negative relative to the cathode. This allows only the emitted electrons with initial energy above a certain threshold to pass. The electrons which make it past the control grid are then accelerated by the positive potential difference between the control grid and the accelerating grid. The electrons then pass through the focusing grid, which is held at a slightly negative potential relative to the accelerating grid, and allows the beam to be focused.

Throughout the process of building an electrostatic accelerator, many different models of electron guns were used. Figure 13 shows the original homemade electron gun. Its design included a filament, cathode and accelerating grid. This electron gun functioned, although it was inadequate because the

beam spot was could not be focused. Figure 14 shows the next electron gun, which was an attempt to solve this problem. An RCA 3RP1 cathode ray tube (CRT) was dismantled by first drilling a small hole in its side with a diamond-tipped drill bit to break the vacuum without harming the tube. A continuous ring around the neck of the CRT was scored, and molten glass was touched to the score. This caused the CRT to break along the score, and the base of the tube to be separated from the screen. The RCA 3RP1's filament, cathode and accelerating grid were kept and mounted on a flange with epoxy [28]. Again, the electron gun worked, but it too failed in that it could not be focused. The gun was mounted crookedly on the flange, so the benefit of being able to deflect the beam was desired as the beam was off-centered and it appeared that the electron beam would not make it all the way down the long accelerator tube. Figure 15 shows the current electron gun, designed to solve these problems. It was constructed in the same manner as the second gun and contains a filament, cathode, accelerating grid, focusing grid and deflection plates, which were all taken from an RCA 3RP1. A current of $0.4 \mu\text{A}$ was produced by the original electron gun, while currents between 0.1 and $0.5 \mu\text{A}$ are expected for the current electron gun.

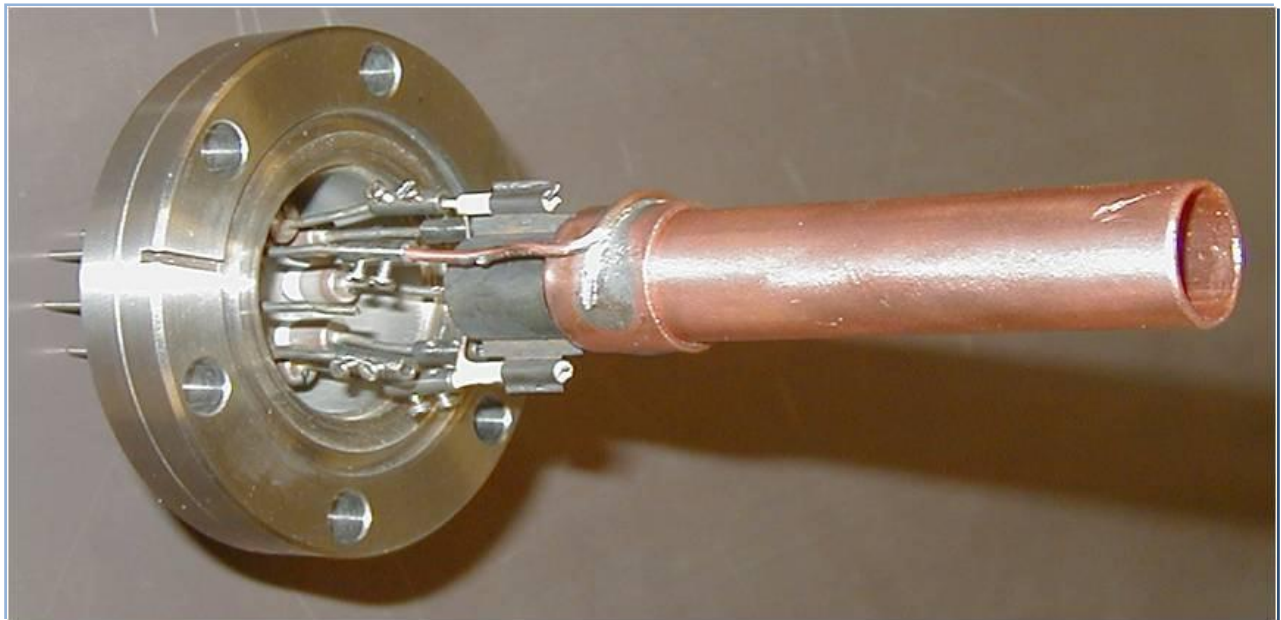


Figure 13. The homemade electron gun. The filament, cathode can and accelerating grid can be seen. The system has been mounted on a flange.



Figure 14. A past design of an electron gun. The filament, cathode can and accelerating grid from a 3RP1 CRT are mounted on a flange with vacuum epoxy so that it can be sealed to the evacuated accelerating tube. Behind the accelerating grid is the cathode can, into which the filament is inserted to heat.



Figure 15. Current electron gun. The last two deflection plates can be seen protruding from the flange. The vacuum epoxy is visible where the flange and electron gun are connected. This electron gun includes the filament, cathode, accelerating grid, focusing grid and deflection plates.

Figure 16 shows a screen from the CRT's which was attached to a flange and used as the target for the electron accelerator. To measure the current, a ceramic tube was attached to the flange with the screen attached. This electrically separated the screen and its flange from the grounded end of the accelerator tube and beam pipe. There is a conductive layer on the phosphor coating of the screen which has two

purposes. The first is so that the light from the fluorescence, which occurs when electrons collide with the phosphor, is all directed forward. The second is so that the electrons incident upon the screen can be carried away. A stiff wire was soldered to the flange at the base of the screen and was bent to be touching the coating on the screen, which allowed the current incident upon the screen to be measured by attaching the flange to ground through an ammeter. This also removed the possibility of charge building up on the screen.

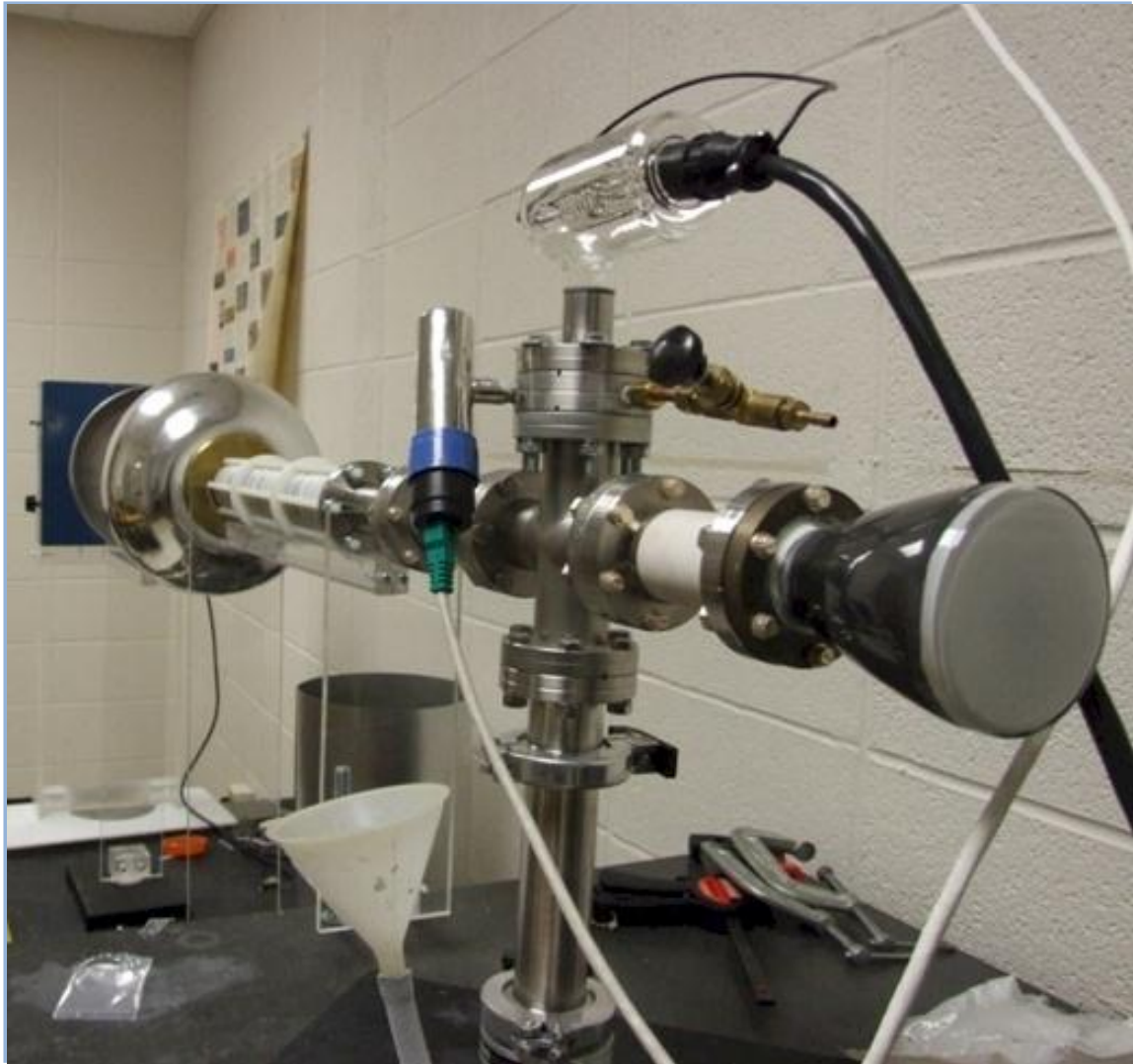


Figure 16. Photograph of the electrostatic accelerator. In the foreground is the phosphorescent screen attached to a ceramic pipe to electrically insulate the screen. At the top of the apparatus is the ion gauge. The Van de Graaff generator is visible at the far left of the photo attached to the accelerator tube, and both are supported by acrylic stands. Nylon rods compressing the accelerator tube are visible.

3.3 Vacuum System

In order to turn on the filament and accelerate electrons, the system needs to be evacuated. Figure 17 shows the series of vacuum pumps used to accomplish this. To evacuate the accelerator tube, initially an Alcatel M2008A rotary forepump is used. This pump can evacuate the system to pressures on the order of 10^{-3} torr. Once the pressure reached the lower limits of this range, liquid nitrogen was added to the cold trap and the air-cooled Varian HSH2 diffusion pump was allowed to begin evacuating the system. The diffusion pump sprays oil in a downward direction, giving particles which the oil contacts a preferred downward direction, toward the forepump, which removes them. This causes the pressure below the diffusion pump to increase to a level where the forepump can operate.

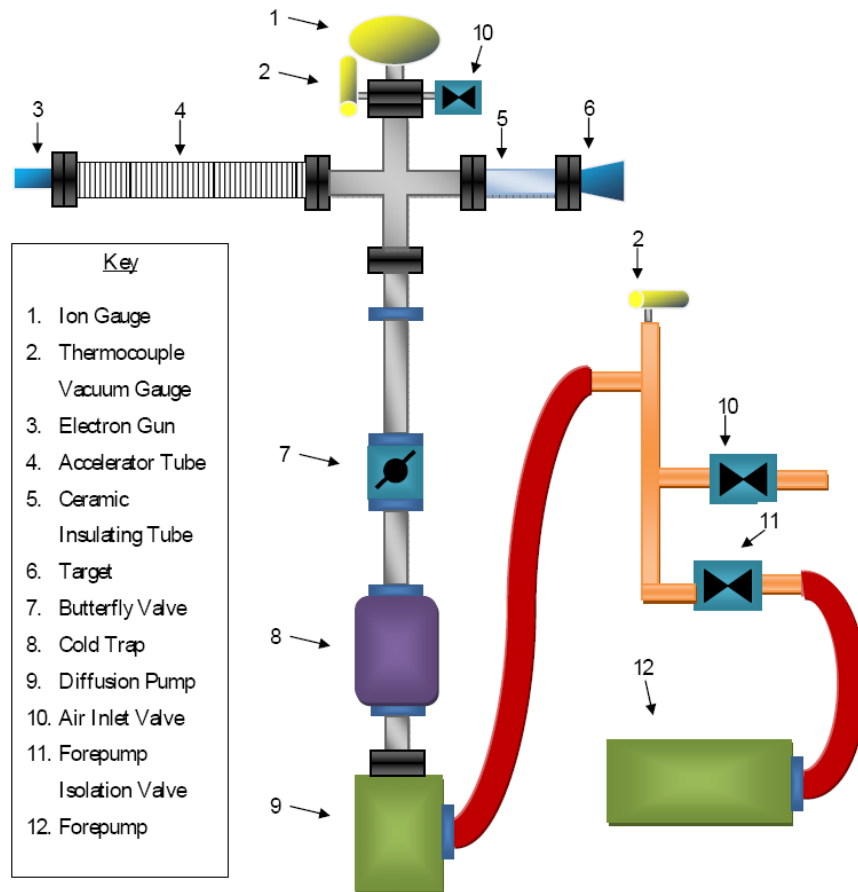


Figure 17. A schematic of the vacuum system of the electrostatic accelerator. The forepump is used to pump down the apparatus to pressure on the order of 10^{-3} torr. At this point, liquid nitrogen is added to the cold trap and the diffusion pump is turned on. Pressures of order 10^{-7} torr can be reached. Valves allow sections of the system to be isolated.

Two thermocouple gauges are used to measure the pressure, and are accurate when the pressure is above 10^{-4} torr. An ion gauge is used to monitor the pressure once it is below 10^{-4} torr. The pressure in the foreline is low enough for the lower thermocouple gauge to continuously monitor the pressure.

In order to vent the system up to air, valves have been installed at two positions of the accelerator, one above and one below the diffusion pump. Above the diffusion pump is a butterfly valve, which is designed to separate the upper part of the accelerator from the lower. When this valve is closed, the vacuum can be broken above the valve while the lower vacuum system is still held at vacuum. This allows work to be done above the valve and to then to quickly get back to vacuum. Similarly, when the forepump isolation valve is closed, the forepump can continue operating while vacuum is broken above the valve. However, the liquid nitrogen must be allowed to evaporate and the diffusion pump cool before letting air into the region below the butterfly valve.

3.4 Accelerator Tube

Figure 16 shows the accelerator tube which is made of alternating high-density polyethylene discs and stainless steel washers. The polyethylene discs have an inner radius of 0.9525 cm and outer radius of 1.905 cm while the stainless steel washers have a smaller inner radius of 0.68 cm and outer radius of 2.54 cm. Stray electrons travelling down the accelerator tube will be forced to collide with the steel washers that “hide” the polyethylene. This design keeps stray electrons from the electron beam from building up on the polyethylene discs and deflecting the beam. As the steel washers are conductors, the electrons will be repelled to the outer edge of the washers uniformly. Once these stray electrons have reached the outer edge of the washers, they are in the open air and can be carried away by corona discharge and thus not deflect the beam. The washers were chosen to be stainless steel because they are smooth and seal well with an o-ring.

Viton o-rings are between each polyethylene disc and stainless steel washer. This system of washers, o-rings and polyethylene discs is compressed by pre-stretched threaded nylon rods. The length of the accelerator tube is 0.38 m, and is composed of 49 stainless steel washers. One end of the accelerating column is connected to the high voltage terminal while the other is attached to ground. The stainless steel washers act as electrodes and the distance between each electrode in the accelerator tube is 0.6 cm. The air between each pair of washers acts as a large resistor. The potential difference between

successive pairs of electrodes is constant, and a constant accelerating electric field is produced inside the accelerator tube.

3.5 Electronics for Controlling the Electron Gun

The electron gun is located inside the high voltage terminal. Electrical signals cannot be sent into the terminal, because it is at such a high potential. A method for controlling the electron gun which avoids sending electrical signals into the high voltage terminal has been implemented. Figure 19 shows the circuit for a BASIC Stamp 2 microcontroller and a four-transistor amplifier located inside the high voltage terminal, which receives signals from the user via fiber optic. The signals are sent via Ethernet from a computer running LabView. The fiber optic cable is an insulator and avoids sending an electrical signal into the terminal. A serial signal from the BASIC Stamp 2 is sent to two MAX525 Digital to Analog Converters (DACs). The DACs can output a voltage between 0 V and 2.5 V, which is too small to control the electron gun, so the DAC outputs are input to the four-transistor amplifying circuit. Figure 24 (Section 3.5.4) shows the amplifying circuit which amplifies the voltage to a maximum of 12 V while also supplementing the current capability. EMCO DC to HV DC chips amplify the voltage up to 2000 V, enough to control the electron gun. The EMCO DC to HV DC chips can supply up to 5 mA.

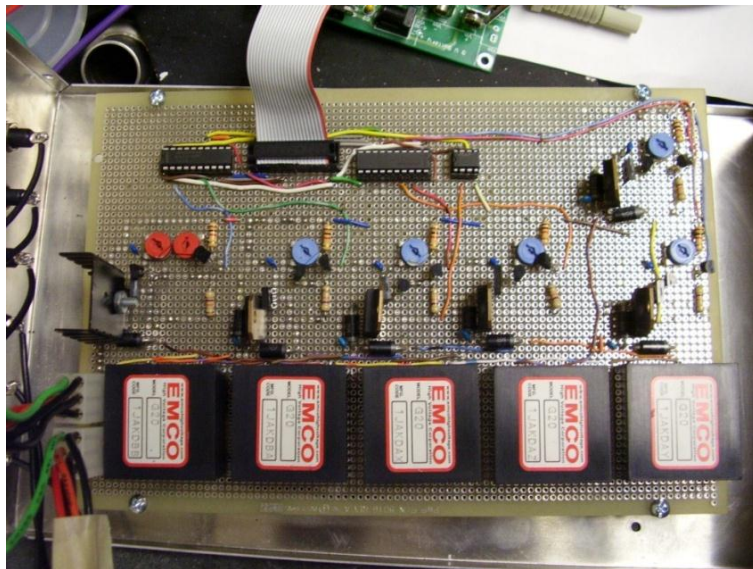


Figure 18. Top view of the control circuit board. Six amplifier circuits are shown. The ribbon cable from the Basic Stamp 2 is shown connecting to the circuit board with a DAC on each side and the high voltage output is located at the bottom left.

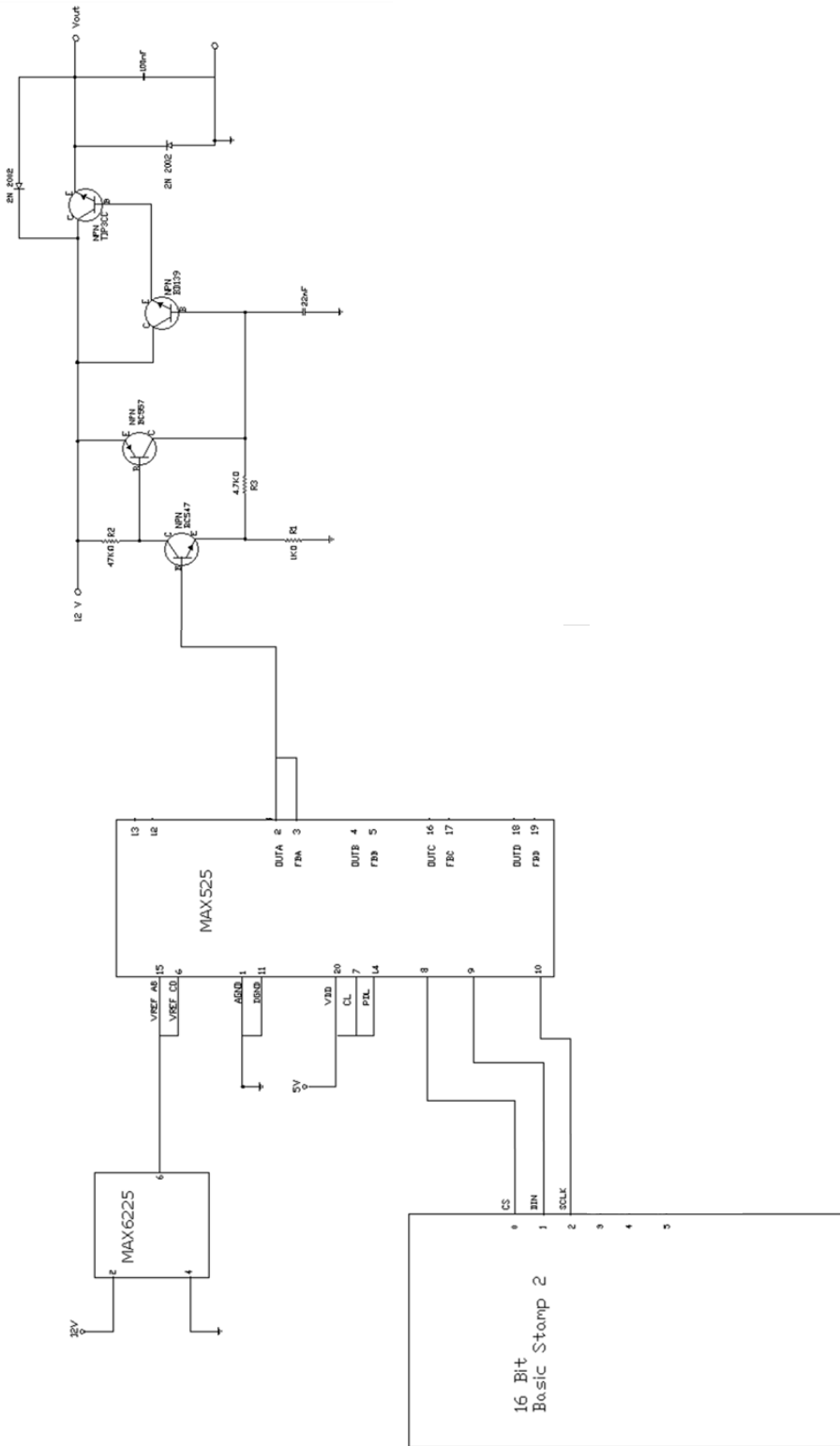


Figure 19. Schematic of one branch of the control circuit. Digital signals from the Basic Stamp 2 are sent in series to the MAX525 Digital to Analog Converter, which outputs corresponding analog voltages to the four-transistor amplifying circuit.

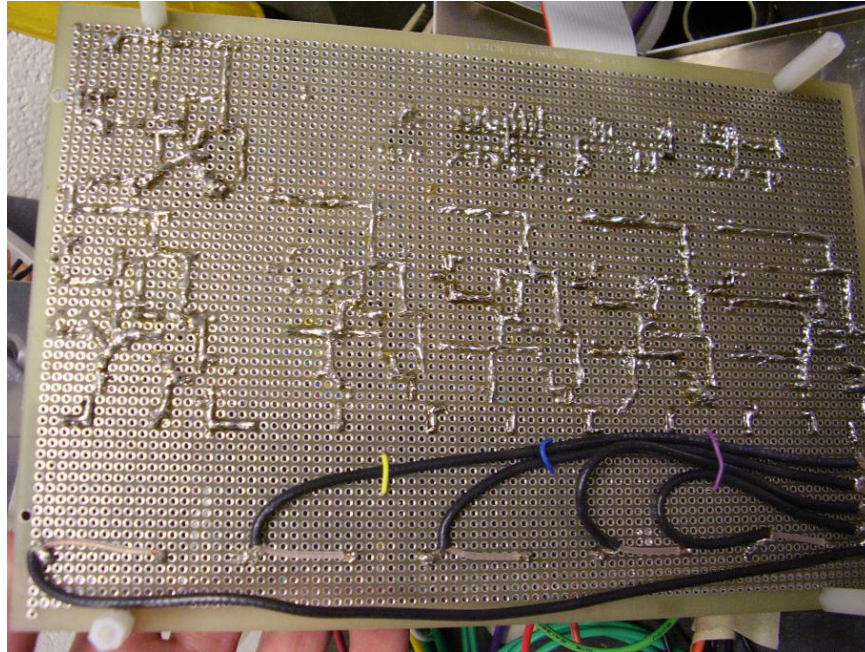


Figure 20. Bottom view of the control circuit board. The solder joints for the circuits are shown.

3.5.1 Basic Stamp 2

The Basic Stamp 2 (BS2) is a microcontroller. In this circuit, it is used to send signals to the DACs. A computer can communicate with the BS2 via 9600 baud RS232, telling it what signals to send to the DAC. The BS2 has a processor speed of 20MHz. It can be powered by any voltage between 5 and 15 V DC, and at most it draws 25 mA [29].

The BS2 is programmed in PBasic 2.5 and can be programmed to transmit data to the DACs in serial or in parallel. This means that either DACs which receive data in series or parallel can be used. Figure 21 shows the Basic Stamp 2 chip and circuit board. Data is output from the circuit board using a ribbon cable.

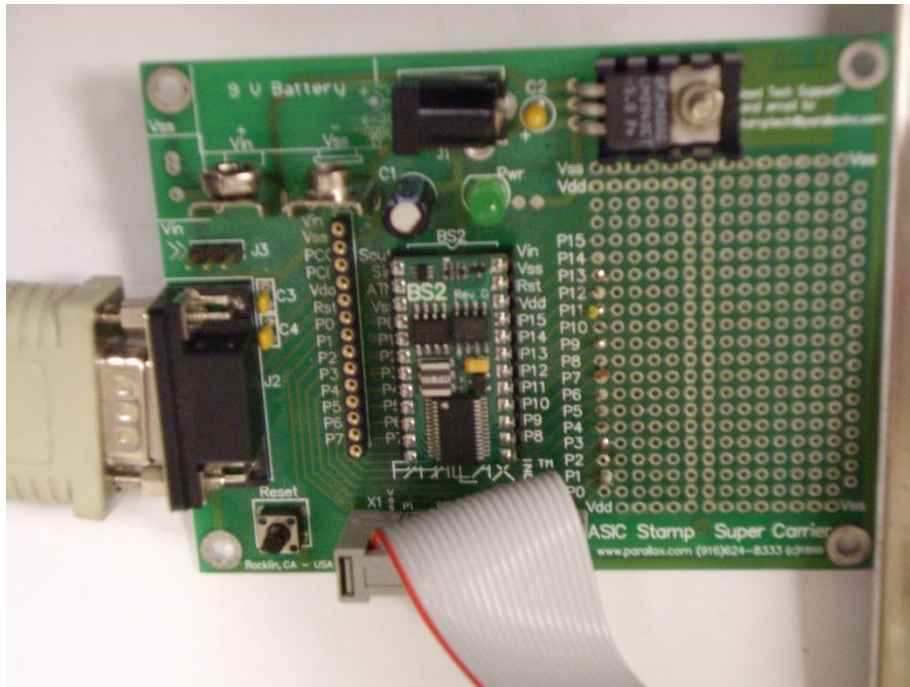


Figure 21. The Basic Stamp 2 circuit board. An RS232 cable is shown connecting on the left. Data is output from the BS2 via ribbon cable, shown at the bottom.

3.5.2 Digital to Analog Converters

Digital to analog converters receive digital signals and output a voltage that corresponds to the digital value. Digital values are encoded in binary, and as the value of the binary number increases, so does the analog voltage output by the DAC. Originally the DAC 7625P was used to control the transistor circuits. The DAC7625P receives 12-bit data sent in parallel and has four analog outputs. To control the filament, deflection plates, intensity grid, accelerating grid and the focus six outputs are required. This meant that two DAC7625P chips were required. However, the DAC7625P is out of production and if the DAC7625P chips ever stopped working, the ability to replace these chips without having to construct a new circuit was desired. To solve these problems, the MAX525 was chosen to be the replacement. The MAX525 requires data to be sent to it in serial format, rather than parallel. It too is a 12-bit chip, so there are 2^{12} , or 4096, channels. With this information, the expected output voltage from the MAX525 can be calculated. The output from the MAX525 DACs is given by

$$V_{out} = V_{ref} \times \frac{NB}{4096} \quad 3.1$$

where V_{out} is the voltage output by the DAC, V_{ref} is the reference voltage, NB is the numeric value of the DAC's binary input code and 4096 is the number of channels [30].

3.5.3 MAX6225

A method was needed to supply the MAX525 DACs with a consistent 2.5 V reference voltage. As the DACs require 5 V to operate, the plan was to obtain the reference voltage by connecting the 5 V through a 500 k Ω resistor to ground, as shown in Figure 22. The 500 k Ω resistor was chosen assuming that the current drawn by V_{ref} was constant. Recall from Equation 3.1 that V_{out} is directly proportional to V_{ref} . In order to have a reliable consistent output from the DACs to the amplifying circuits, V_{ref} needs to be constant. Running 5V through a resistor to ground in order to obtain 2.5 V was problematic because the resistance changes as the temperature of the resistor changes. Also, the power supply voltage itself could change, or the current drawn by the DACs (I_1) could change which would alter the amount of current (I_2) going through the 500 k Ω resistor to ground, thus changing V_{ref} . An obvious solution to this problem was the low-noise, precision 2.5 V MAX6225 chip designed for being a voltage reference. This chip had the added advantage that in can output 2.5 V while receiving any input voltage between 8 V and 36 V. Figure 23 shows the schematic for the MAX6225. At room temperature the voltage output should be accurate to $\pm 0.02\%$ [30].

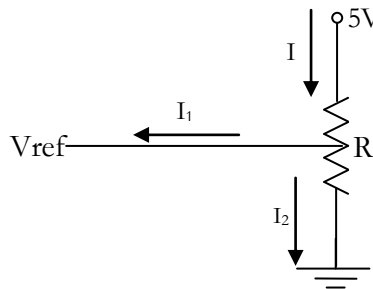


Figure 22. Original method to supply reference voltage. The 5V, which is necessary to power the DACs, is connected through a 500 k Ω potentiometer to ground.

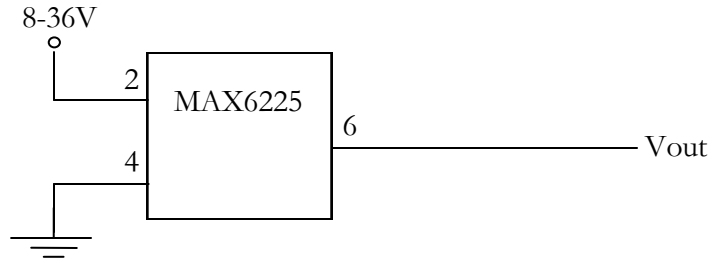


Figure 23. Schematic for the MAX6225. Input voltages between 8 and 36V allow the output voltage of the MAX6225 to be 2.5V.

In order for the MAX6225 to be useful, a voltage between 8V and 36V needs to be readily accessible inside the HV terminal. The BASIC Stamp 2 chip runs at 9V, so it was natural to also use that power supply to power the MAX6225 as well.

3.5.4 Four-transistor Amplifying Circuit

The four-transistor amplifying circuit, shown in Figure 1, receives an input voltage between 0 and 2.5V and amplifies both the voltage and the current. BC547, BC557, BD139 and TIP33C transistors are used. The TIP33C is the power transistor of the circuit.

The theoretical voltage amplification of the transistor circuit is given by [31]

$$\text{Amplification} \cong \frac{R_3 + R_1}{R_1} \quad 3.2$$

where R_1 is $1\text{k}\Omega$ and R_3 is $4.7\text{k}\Omega$. Thus, the voltage amplification is

$$\text{Amplification} \cong \frac{4.7\text{ k}\Omega + 1\text{ k}\Omega}{1\text{ k}\Omega} \approx 5.7. \quad 3.3$$

However, when measured, the voltage into the four-transistor circuit is amplified approximately 3.3 times to a maximum of 7.7 V when powered by 9V. Using the actual measured amplification, we can see that the input voltage which will obtain the maximum 7.7 V from the transistor circuit is

$$\frac{7.7\text{ V}}{3.3} \cong 2.3\text{ V} \quad 3.4$$

Combining this input voltage for the transistor circuit with Equation 3.1, we can see that the input code NB which will give the maximum output is given by

$$2.5V \times \frac{NB}{4096} \cong 2.3V. \quad 3.5$$

Thus, we can see that NB will approximately be 3768 or, in hexadecimal, EB8.

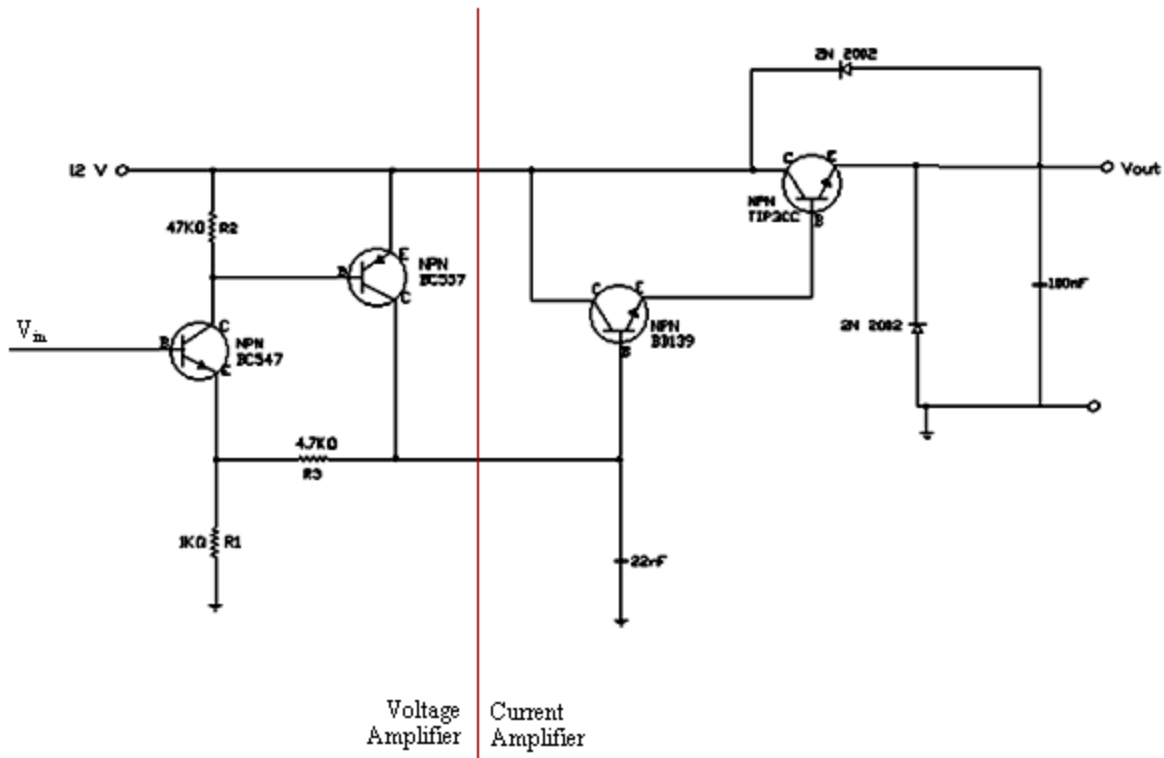


Figure 24. Schematic of the four-transistor amplifying circuit. Voltage is input to the NPN BC547 transistor. Both the current and voltage are amplified in this circuit.

3.5.5 EMCO Converters

To obtain the high voltage necessary to power the electron gun, EMCO G20 DC to HV DC converters are used. They provide a maximum output voltage of ± 2000 V and a maximum output current of 0.75mA. When off, they draw less than 165 mA and when on at full load, they draw less than 275 mA. The output voltage from the EMCO is approximately linearly proportional to the input

voltage after 0.7 V, which means that all input voltages below the threshold of 0.7 V result in an output voltage of zero. Thus, the EMCO converters scale the voltage by $\frac{2000}{12}$.

$$V_{out\ EMCO} = \frac{V_{out\ transistor}}{12V} \times 2000V \quad 3.6$$

where $V_{out\ EMCO}$ is the voltage output from the EMCO chips and $V_{out\ transistor}$ is the voltage input into the EMCO converters from the transistor circuits. To operate the electron gun inside the high voltage terminal, at least 200 V is required, but preferably closer to 1000 V. These factors make the EMCO G20s well-suited for our circuit. From the four-transistor amplifying circuit, which can be run off batteries, we can obtain the current and voltage necessary to output 0.75 mA at ± 2000 V, which should be enough to control the electron gun. The current circuit is powered by a 9V battery, which means that we are unable to reach the maximum voltage of the EMCO chips. Using Equation 3.7 and our 7.7 V maximum input voltage for $V_{out\ transistor}$ we can see that the $V_{out\ EMCO}$ will be approximately 1283 V. This maximum voltage is adequate for controlling the electrodes of the electron gun.

A down side to these converters is that they require approximately 30 minutes to warm up [32]. This means that the behavior of the EMCO chips will be irregular until the chips reach thermal equilibrium. Thus, once the accelerator is turned on, there may be a down time of 30 minutes before the electron gun may be controlled.

3.5.6 Powering the Circuit

A 9V battery is used to power the circuit. When powered by 9 V the Basic Stamp 2 and MAX525 can operate. When operating, the entire control circuit draws about 0.7 A of current. The four-transistor circuit is designed to receive 12V, but it has been demonstrated that both a CRT and the electron gun can be operated while the transistor circuits are receiving down to 8.4V. Thus, both the Basic Stamp 2 and the transistor circuit can be powered by the battery. At this time, the battery life while operating this circuit is unknown.

The MAX525 DACs require 5V to operate. This is supplied by the BASIC Stamp 2 circuit board which has an LM2940 5V regulation chip. This regulation chip requires an input voltage V_{in} such that

$6.25V \leq V_{in} \leq 26V$ and will output 5V with a maximum current of 1A. The uncertainty in the output voltage of the regulation chip is $\pm 3\%$ [33]. As the supply voltage for the MAX525 is required to be between 4.5V and 5.5V and the maximum supply current required is 0.98 mA [34], the Basic Stamp 2 circuit board's LM2940 is a convenient power supply for the MAX525 chips.

3.5.7 Transmitting Signals into the High Voltage Terminal

To communicate with the microcontroller inside the high voltage terminal, fiber optic cable is used. This avoids sending electrical signals into the high voltage terminal. The process for converting a digital electrical signal to a digital optical signal and then back is shown in Figure 25.

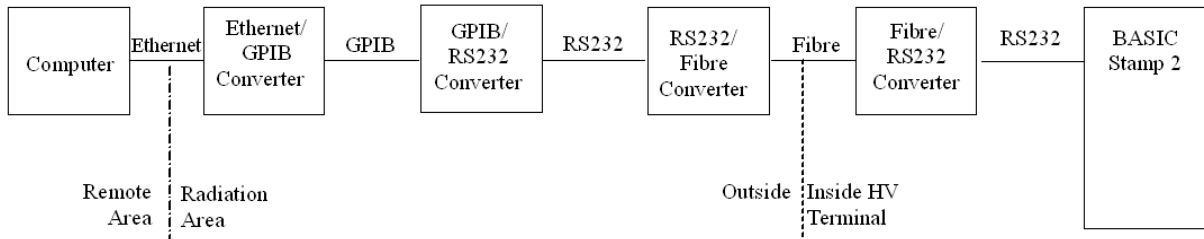


Figure 25. Conversions necessary to communicate with the Basic Stamp 2 microcontroller while inside the high voltage terminal. Note that the conversion to fiber optic disables the ability to reprogram the microcontroller.

This setup uses signals being sent via the Ethernet network to the GPIB-ENET converter. The Ethernet/GPIB converter is used because in addition to the Basic Stamp 2, various GPIB devices such as pressure sensors and pico-ammeters need to be controlled via Labview. Also, by using the Ethernet, the control computer can be in a remote area controlling the circuit over the network. The Ethernet signal is converted to GPIB (IEEE-422), which is then converted to RS232 by a GPIB-232CV-A. The RS232 data is converted to an optical signal by a FIB-232 Ip/ST converter and sent into the high voltage terminal via fiber optic, where it is converted back to RS232 by another FIB-232 converter. This method allows communication with the Basic Stamp 2, but lacks the ability to program the Basic Stamp 2. When a program is being altered on the Basic Stamp 2, the Basic Stamp Editor directly controls the output of the PC serial port, using a proprietary standard for communications that is not understood by the FIB-232. When trying to change the program through the setup in Figure 25, the converters cannot convert the non-standard signals, and thus the Basic

Stamp 2 program cannot be altered. Instead, to program the Basic Stamp 2, the BS2 must be electrically connected directly to the computer serial port.

3.5.8 Grounding

The entire control circuit will be located inside an aluminum box inside the high voltage terminal. The “ground” for the circuit will be the negative high voltage on the terminal. When conducting tests on the control circuit, problems were found when controlling the filament at the same time as the rest of the electron gun. This is because the filament is controlled by a four-transistor circuit directly, and not by the floating voltage output of an EMCO chip. This meant that the “ground” for the filament output was the same as the ground for the digital control circuits, and that it could not easily be floated to negative potentials as was desired. To solve this problem, the power for the control circuit can be provided by batteries, and the RS232 connection, which is grounded through the computer when connected to the computer directly, can be disconnected.

RESULTS

4.1 Output Voltages

A variety of tests have been performed on the control circuit for the electron gun. In order for the circuit to function properly, the voltage fluctuations and the linearity of the circuit needed to be measured.

1.1.6 EMCO Output Stability

The stability of the high voltage output of one EMCO chip has been monitored over time. This is especially important for the deflection plates of the electron gun, as fluctuations could cause the beam to wander off target. It is also important for maintaining monoenergetic beams, because voltage fluctuations on the accelerating grid will affect the energies of the accelerated particles. In fact, if there is too much fluctuation on either the control grid or the cathode, the control grid could stop the entire electron beam by repelling all the electrons or cause the beam spot to become unfocused. The input into the EMCO chip came from the four-transistor amplifier circuit via a DAC and the BS2. Figure 26 shows the divide-by-12.5 resistor chain used to make the measurements of the stability of the high voltage output of the EMCO chip.

The total voltage drop across the 1 M Ω resistor can be found. The resistance of the RSR MS8264 voltmeter used is about 10 M Ω , the equivalent resistance between 1000 V and ground is approximately 10.9 M Ω . With this information, the current flowing through the resistor chain can be found,

$$I = \frac{1000 \text{ V}}{10.9 \text{ M}\Omega} \approx 92 \text{ }\mu\text{A}. \quad 4.1$$

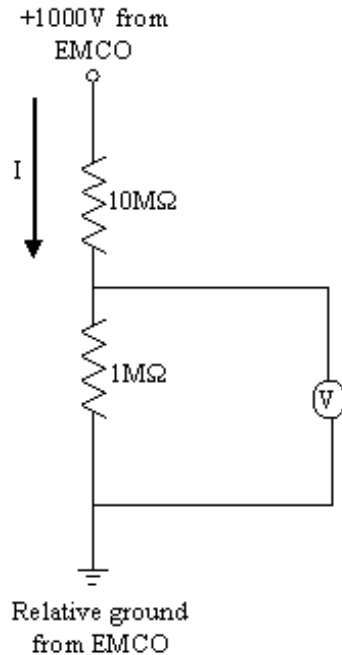


Figure 26. The divide-by-12.5 resistor chain used to measure EMCO output voltages. The positive floating output of the EMCO chip supplies the +1000 V while the negative output of the EMCO chip is relative ground.

This current can be used to find the voltage drop across the 1 MΩ resistor,

$$\Delta V \approx 1000 \text{ V} - (10 \text{ M}\Omega)(92 \mu\text{A}) = 80 \text{ V} \quad 4.2$$

Thus, as the voltage measured is approximately 80 V, and the actual voltage is 1000 V, the resistor chain approximately divides the voltage by 12.5.

With this divide-by-12.5 resistor chain in place, measurements were taken across the 1 MΩ resistor every second for 9 hours using a Protek B4100 Programmable Digital Multimeter reading out data to the computer via an RS232 connection. The computer was running Protek B4100 Programmable Digital Multimeter V.702. Figure 27 shows the results of these measurements.

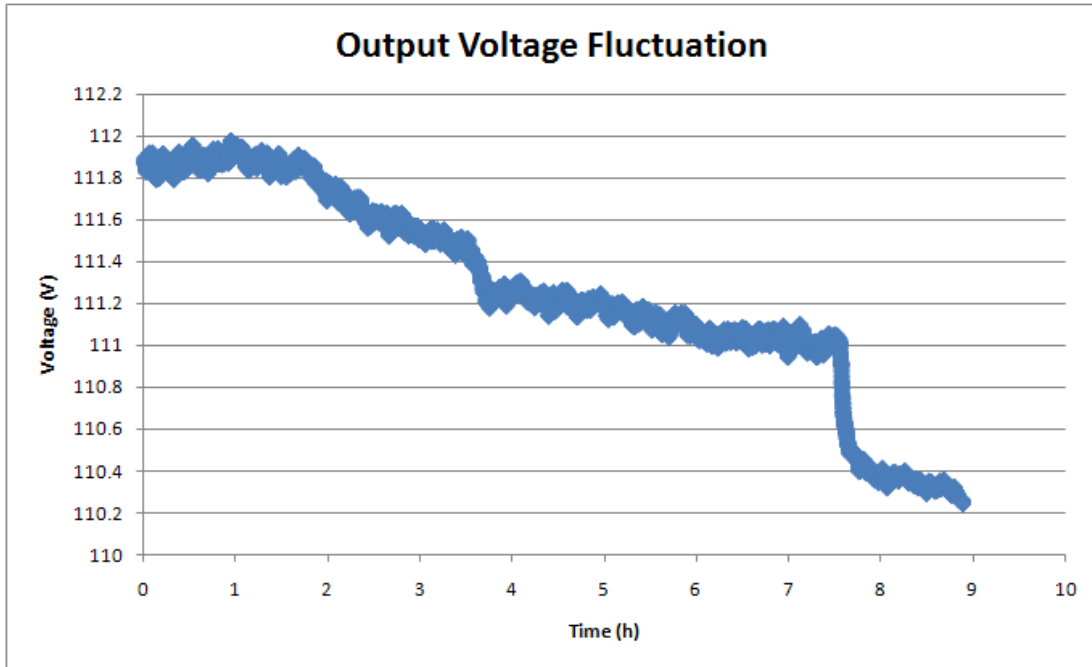


Figure 27. The output voltage of the EMCO chip over a period of 9 hours. The trend for the first 7.5 hours appears consistent with reaching thermal equilibrium.

It appears that during the first 7.5 hours the circuit approached thermal equilibrium. The voltage approaches equilibrium exponentially with time, which signifies that the control circuit itself is approaching thermal equilibrium. By examining the maximum and minimum voltages during the seventh hour of measurement, where the control circuit appears to be nearing equilibrium, it was found that the output voltage fluctuates by 0.1%. The reason for the sudden drop in voltage near the 7.5 hour mark is unknown, but it could be because of a change in the temperature of the surroundings.

1.1.7 Transistor-Amplifier Circuit Output

The linearity of the relationship between the input into the four-transistor amplifying circuit and the output of the transistor circuit has been measured. The signal sent from the BS2 to the DAC was increased by 100 (in hexadecimal) for each consecutive measurement, starting at 000 and with the last measurement at F00. The DAC output a corresponding voltage between 0 and 2.5 V, which are the minimum and maximum voltages the DAC can output. The output of the DAC was the input voltage for the transistor-amplifier circuit. The amplifying circuit was being powered by 8.8 V from a Protek 3032B power supply. Figure 28 and Figure 29 show the results.

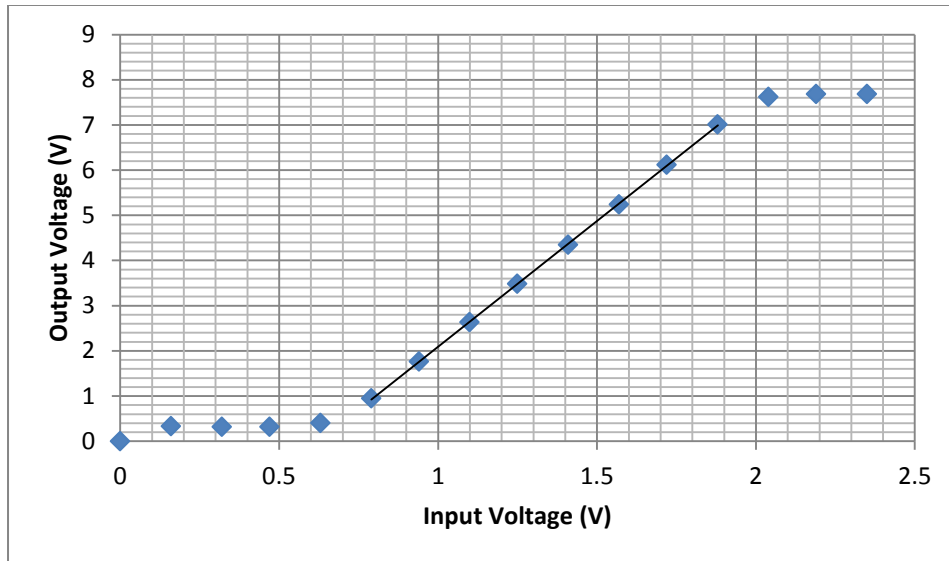


Figure 28. Output of the amplifying circuit. The relationship between the input voltage for a four-transistor amplifying circuit and the output voltage is plotted. The diamonds are the voltage output of the amplifier circuit. The black line is a linear fit.

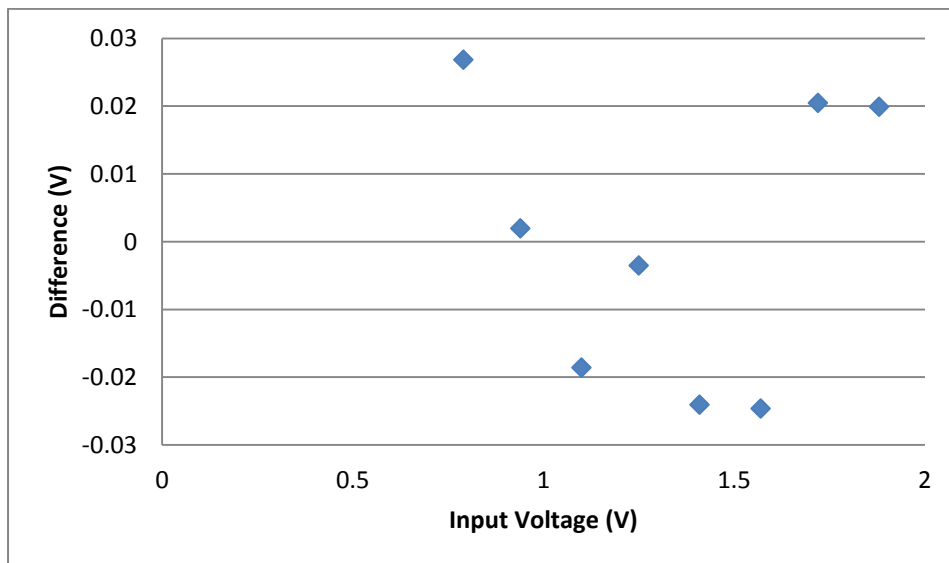


Figure 29. Linearity of the amplifying circuit. The difference between output voltage of the amplifier circuit and the linear fit is plotted.

The threshold input voltage near 0.7 V must be reached before the output voltage begins to increase with the input voltage. This is because the transistors of the amplifying circuit turn on at about 0.7 V. Also, there is a maximum output voltage for this circuit of about 7.7 V due to the 8.8 V supply.

4.2 Controlling the Electron Gun

The linearity of the amplifying circuit is helpful for controlling the electron gun, but the control code can correct for any non-linearities in order to control the electron gun. The fluctuations in the output voltage of the EMCO chips are small enough for controlling the deflection plates because a change of 1 V will only deflect the beam a few millimeters, even when the accelerating potential is just 300 V. However, fluctuations of even 1 V on either the control grid or cathode are enough to significantly reduce the beam current. Using this circuit, tests were made to control, initially, a cathode ray tube and later the electron gun.

1.1.8 Operating a CRT

Tests were performed on an RCA 3RP1 cathode ray tube. Initially, a GW Instek GPS-3030DD power supply was used to power the filament at 6 V. The control circuit was used to control the accelerating voltage, the cathode, the focus and the horizontal and vertical deflection voltages on the CRT. Figure 30 shows the voltages on each of the electrodes of the electron gun. The power supply for the filament was made to float at -320 V by connecting one side of the filament to the cathode. This was done so as to avoid sparking between the filament and cathode. If the potential between the filament and cathode is large, because of their close proximity, sparking may occur. The control circuit was powered by 8.9 V from a Protek 3032B power supply.

Figure 31 is a picture showing the circuit connected to the CRT. Figure 32 shows the circuit connecting the circuit board to the CRT. The floating outputs from the EMCO converters allowed the positive outputs of the focusing grid, control grid and cathode to be connected to earth ground.

Figure 33 shows the beam spot which was obtained using this method, focused to a sharp small circular point.

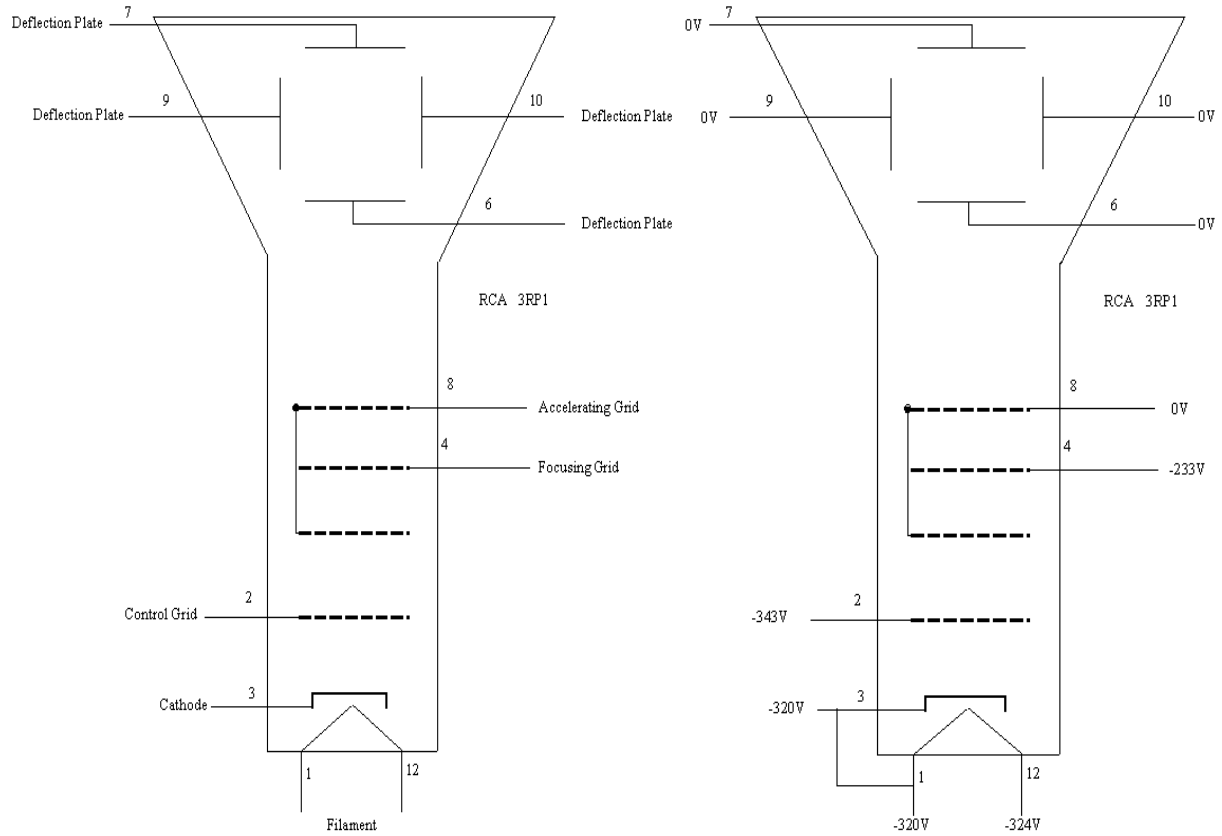


Figure 30. Schematic of the cathode ray tube bias circuit. The schematic on the left shows the electrode connections on the CRT. On the right, the voltages applied to each electrode are shown.

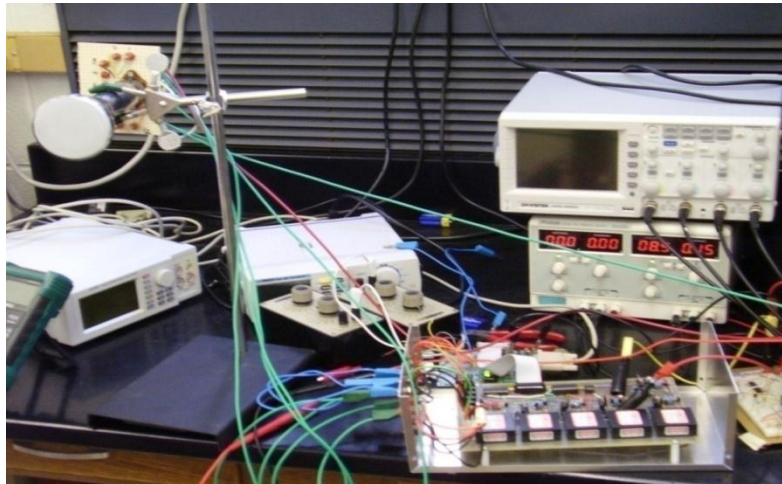


Figure 31. A photograph of the test setup. A CRT is being controlled by the control circuit.

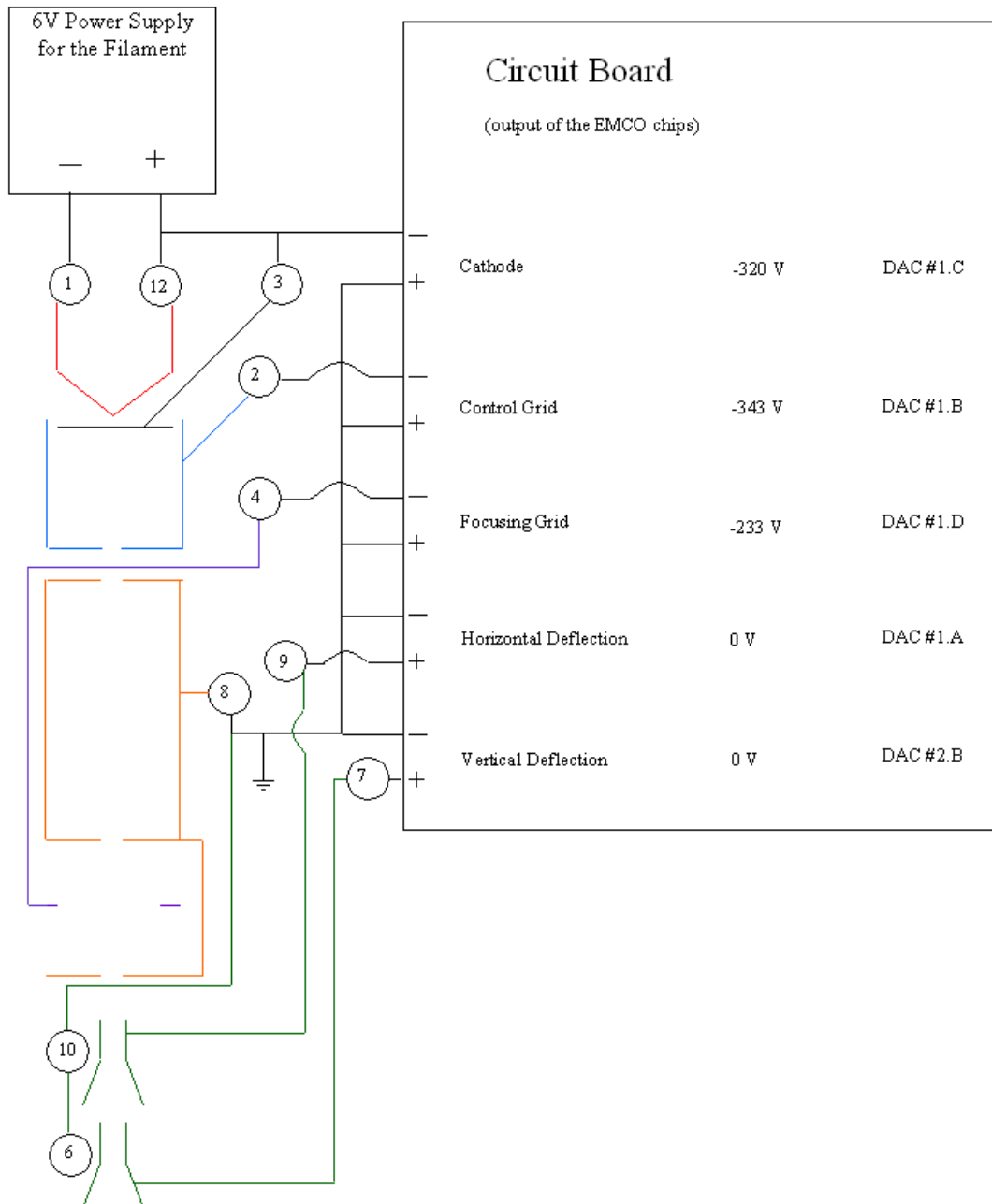


Figure 32. Connections between the outputs of the EMCO chips and CRT electrodes. The accelerating grid (pin 8) is at ground. The voltages listed on the circuit board are the voltages of the corresponding pin which allow the CRT to operate. The DAC # shows which individual circuit controls which electrode.

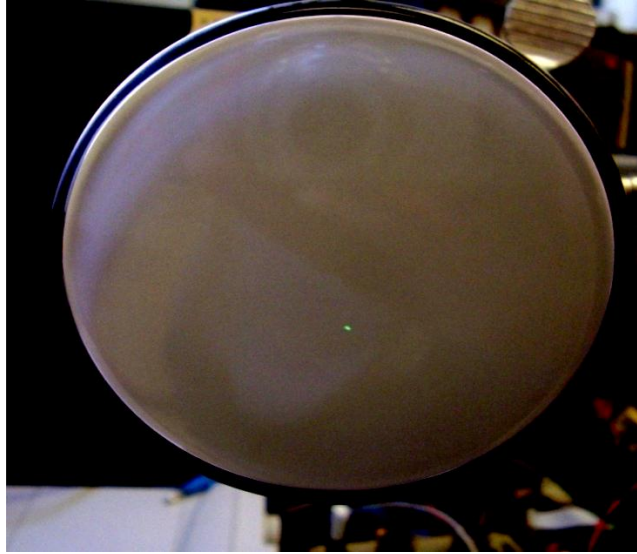


Figure 33. The beam spot on the CRT screen. With the control circuit the focus of the beam spot can be altered, the beam deflected horizontally and vertically and the accelerating voltage controlled.

1.1.9 Operating the Electron Gun

After successfully controlling a cathode ray tube with the control circuit, the same circuit was used to control the electron gun mounted on the vacuum system of the accelerator as in Figure 35. Again, the filament was powered by 6 V from a GW Instek GPS-3030DD power supply which was floating and the control circuit was operated with 8.9 V from a separate Protek 3032B power supply. Figure 34 shows the beam spot which could be deflected across the screen and focused.



Figure 34. The focused beam spot generated by the control circuit operating the electron gun.

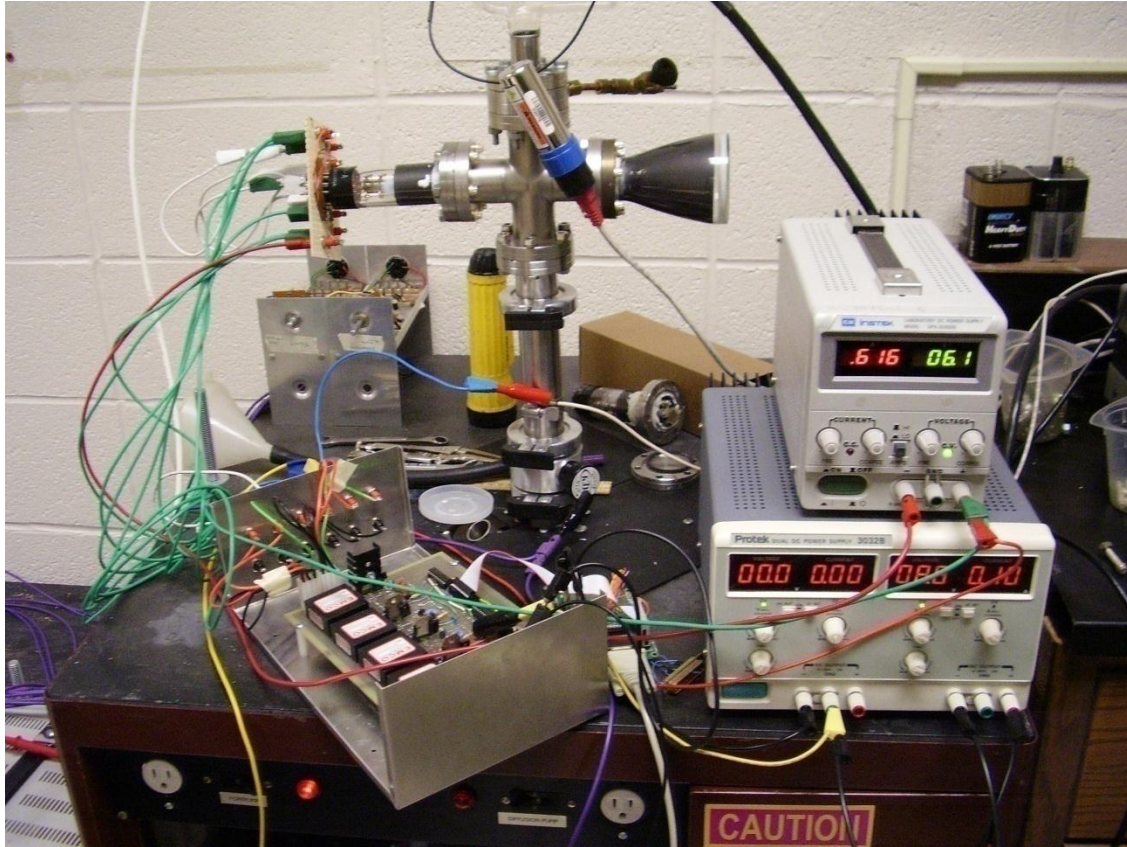


Figure 35. The control circuit operating the electron gun. The control circuit was powered by an external 8.6 V power supply. The filament was powered by a floating external power supply rather than the control circuit.

Despite setting the voltage on each electrode via the computer and checking that voltage with a voltmeter, some problems were noticed. The beam spot moved off the screen when the voltage difference between the deflection grids and ground was measured with an RSR MS8264 multimeter. The beam spot changed shape from a sharp circular point to a blurry vertical line on the screen when measuring the voltage difference between the focusing electrode and ground with the multimeter. This raises the question as to how well the output voltage of our EMCO chips is known as the voltages on the electrodes must change when measurements are performed in order for these effects to be observed. As the EMCO chips should be able to output 0.75 mA [32], and as the resistance in the voltmeter is approximately 10 M Ω , there should be little difference in the beam spot when performing measurements. For example, assuming the voltmeter resistance is 10 M Ω , if 300 V is the voltage on the electrode,

$$I = \frac{300 \text{ V}}{10 \times 10^6 \Omega} = 30 \mu\text{A} \quad 4.3$$

Thus, the voltmeter is only expected to draw 30 μA of current, which is much less than the 0.75 mA which the EMCO chips can supply. If the EMCO chips were unable to supply the 30 μA of current, the voltage on the electrode would drop. From this calculation, it is very surprising that there is a voltage drop at all, especially as the EMCO chips are supposed to be able to supply much more current.

There are a few possible explanations for the voltage drop. It may be that the Protek 3032B power supply cannot supply enough current to all the different EMCO chips at the same time plus the voltmeter. It may be that the electron gun is drawing too much current, and adding the voltmeter is too much. However, neither of these solutions seems likely due to the fact that very little current will be drawn through the resistor compared to the mA that the circuit EMCO chip should be able to supply.

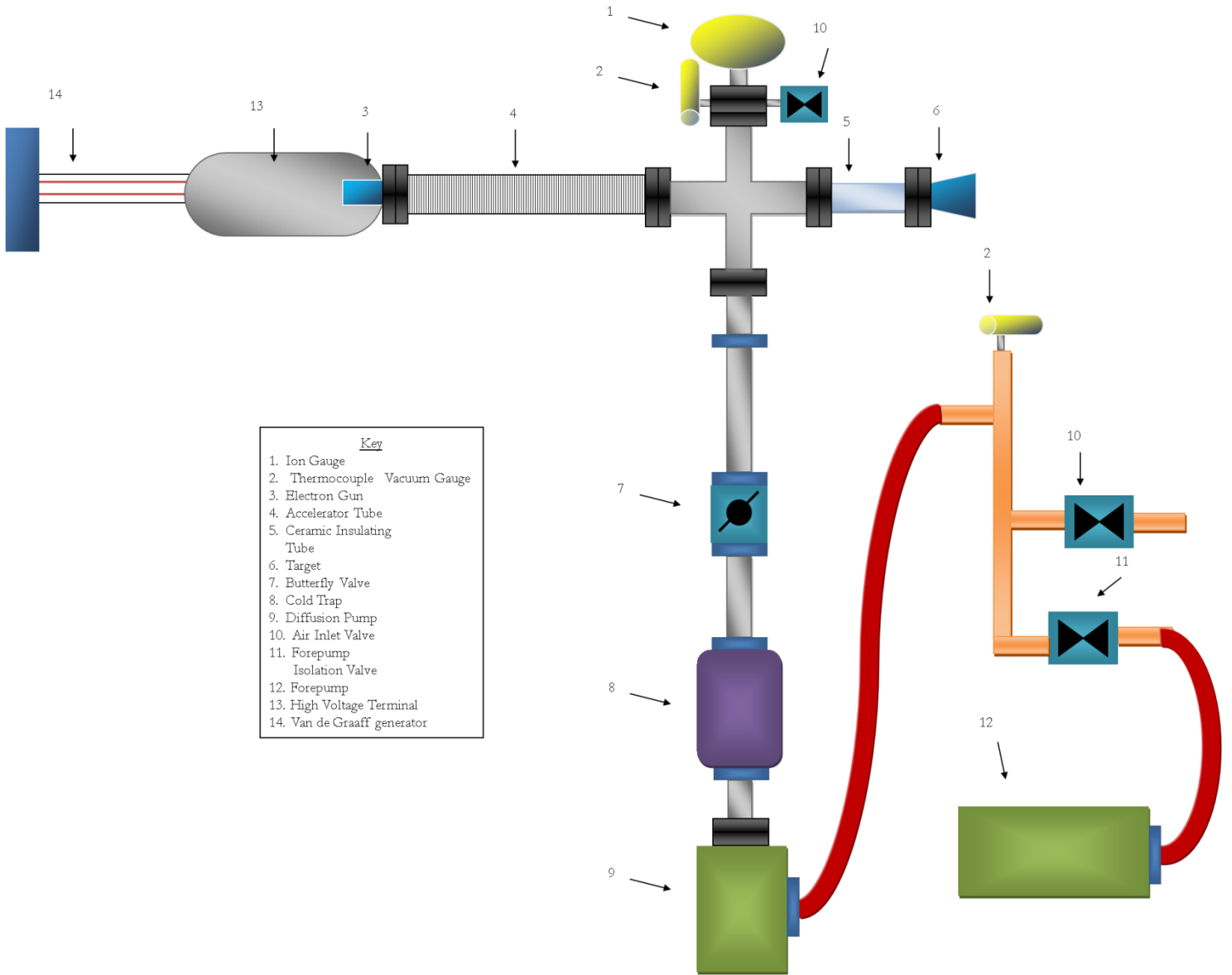
Chapter 5

CONCLUSIONS

A control circuit for controlling the electron gun inside the negative high voltage terminal of the Houghton College electrostatic accelerator has been constructed. Tests have been performed measuring the linearity of the output of this circuit and also measuring the voltage fluctuations of the amplifying circuit. The control circuit has successfully controlled the accelerating grid, deflection plates, cathode, and focusing grid of a cathode ray tube and also of the electron gun attached to the vacuum system, and on both a beam spot has been produced. The control circuit still needs to be tested while controlling the filament of the electron gun. Once this has been demonstrated, the electron gun needs to be mounted inside the high voltage terminal attached to the acceleration tube and tested. A final version of PBasic computer code needs to be written to control the electron gun. Also, computer code for controlling the electron gun over the network via LabView still needs to be written.

Appendix A

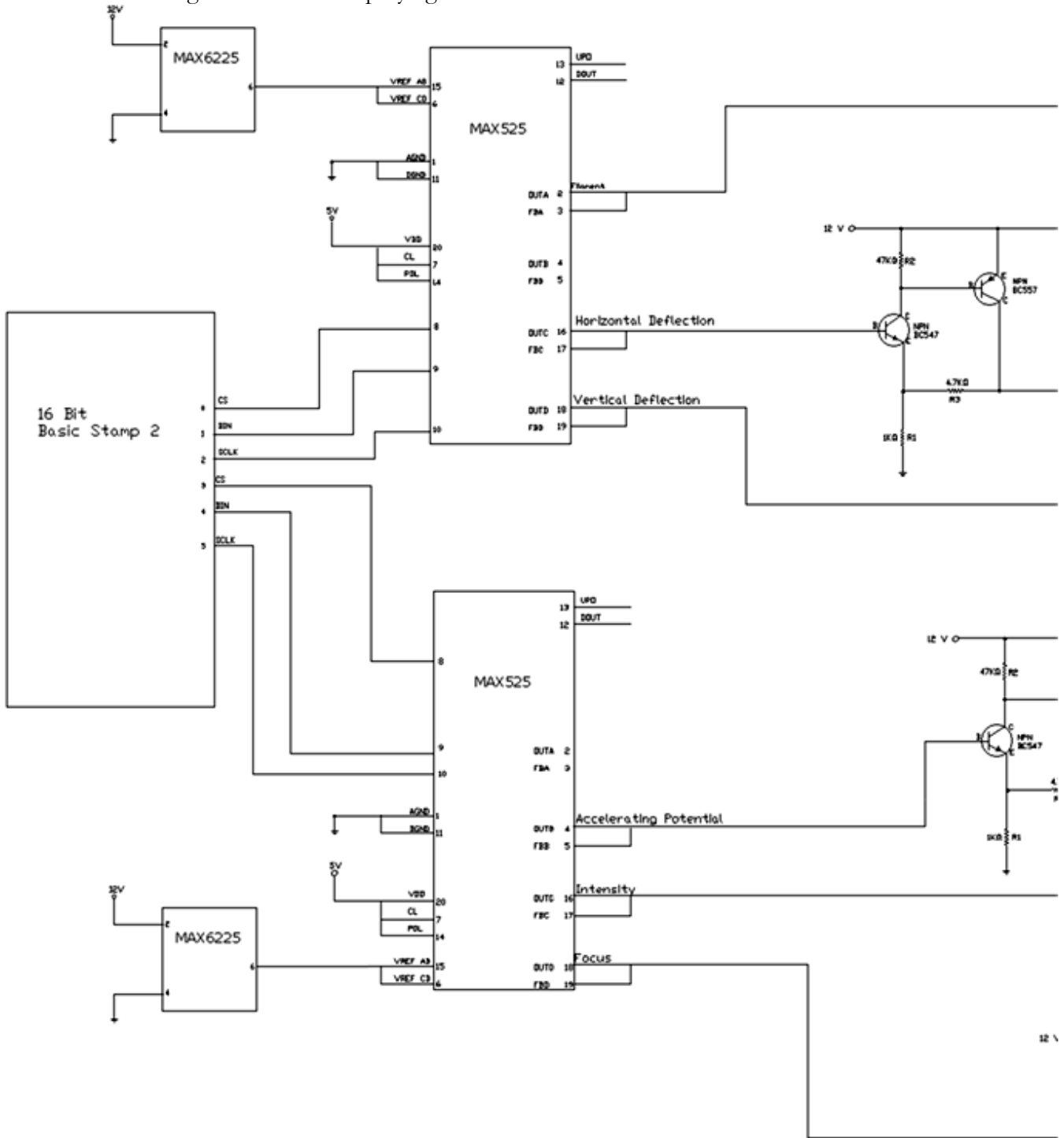
DRAWING OF APPARATUS

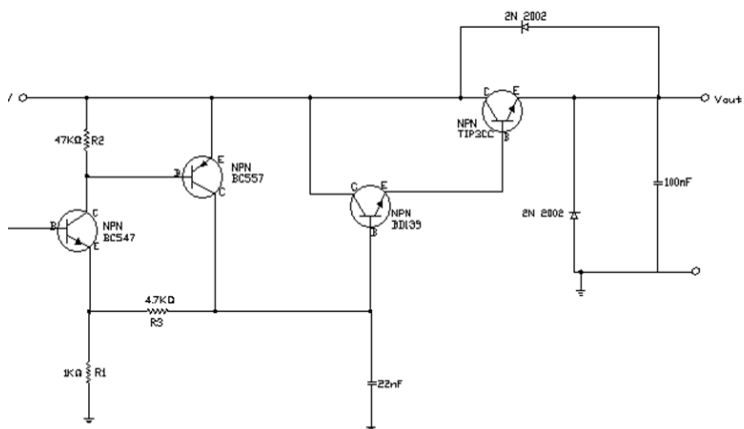
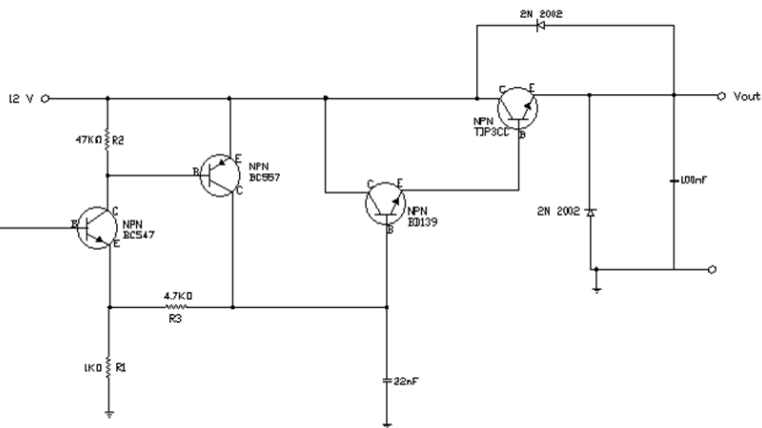
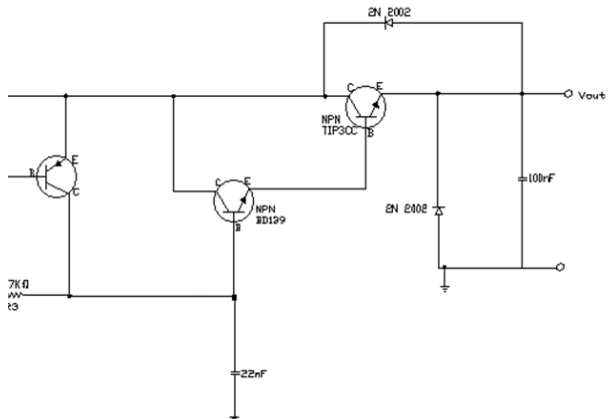
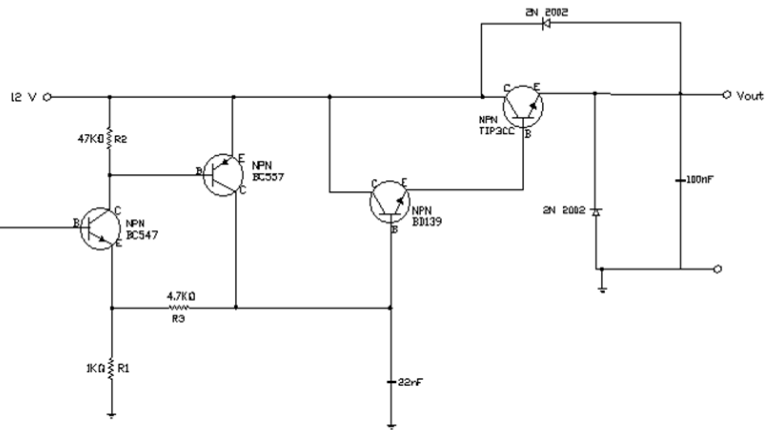
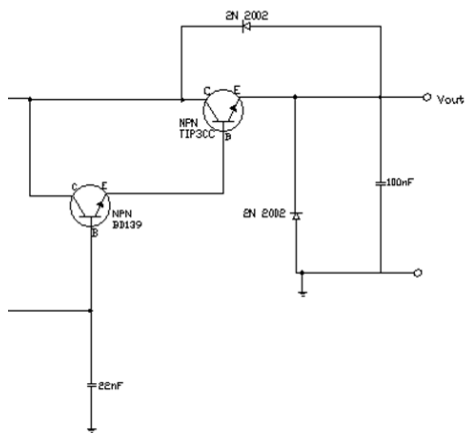
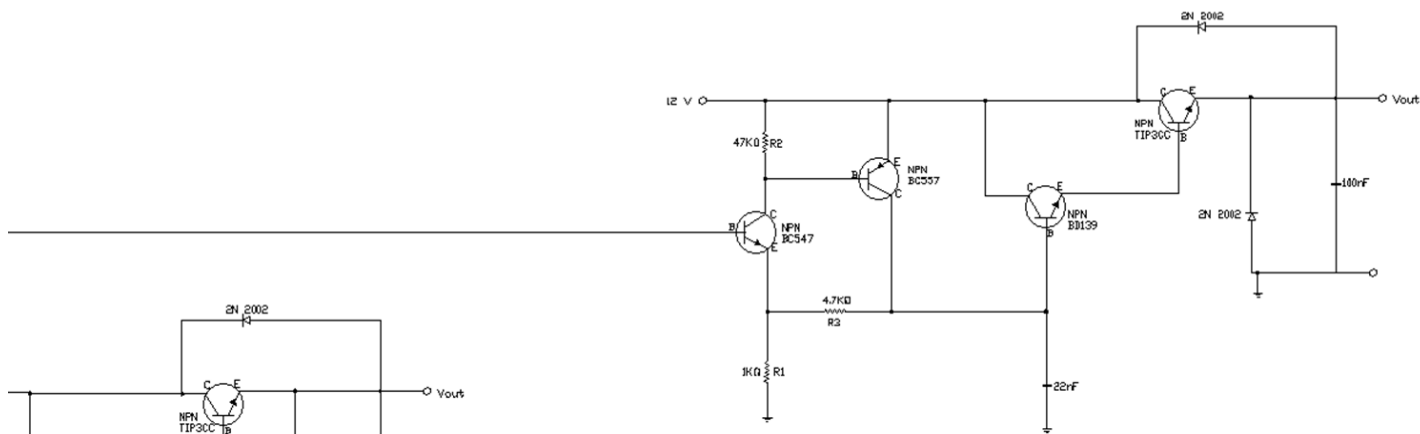


Appendix B

COMPLETE ELECTRONICS SCHEMATICS

The following electronics diagram shows the control circuit to be placed inside the high voltage terminal including the transistor amplifying circuits.





Appendix C

DESCRIPTION OF COMPUTER CODES

The computer code for controlling the BS2 and control circuit is shown below. The programming language is P-Basic. Values are set for each DAC in the program in the code. The program is then sent to the Basic Stamp 2. Once the program is on the Basic Stamp 2, the values sent the DACs are fixed and cannot be changed without reprogramming the Basic Stamp 2.

```
' {$STAMP BS2}
' {$PBASIC 2.5}
```

```
' NOTE - THIS KEEPS A CONSTANT VOLTAGE. IT MUST ALREADY BE HIGH TO STAY HIGH.
```

```
CSpin    CON  1  'DAC chip select
SDOpin   CON  3  'Data out from BS2
CLKpin   CON  5  'SPI clock pin
CSpiB    CON 10  'DAC chip select for DAC 2
SDOpiB   CON 12  'Data out from BS2 for DAC 2
CLKpiB   CON 14  'SPI clock pin for DAC 2
DACaddr0 CON $1000 'DAC 1 address
DACaddr1 CON $5000 'DAC 2 address
DACaddr2 CON $9000 'DAC 3 address
DACaddr3 CON $D000 'DAC 4 address
DACwrite CON $4000 'DAC write data to outputsz
DACUPOon CON $6000 'DAC UPO on
DACUPOoff CON $2000 'DAC UPO off
DACshift CON $8000 'load from shift reg
DACreg   VAR Word 'DAC voltage value register
DACloc   VAR Word 'Location for voltage value
SPIreg   VAR Word 'Register sent with SHIFTOUT
DACreg = $000 'Default to 0V out
HIGH     CSpin 'De-select DAC
HIGH     CSpiB 'De-select DAC
PAUSE    500
```

```
Start:
```

```
'FOR DAC #2
DACloc =DACaddr0 'Load DAC zero
DACreg = $A00
GOSUB WRITE_TO_DCB
DACloc =DACaddr1 'Load DAC one
DACreg = $00
GOSUB WRITE_TO_DCB
```

```

    DACloc    =DACwrite    'Update DAC outputs
    GOSUB     WRITE_TO_DCB
'FOR DAC #1
    DACloc    =DACaddr0    'Load DAC zero
    DACreg = $000
    GOSUB     WRITE_TO_DAC
    DACloc    =DACaddr1    'Load DAC one
    DACreg = $000
    GOSUB     WRITE_TO_DAC
    DACloc    =DACaddr2    'Load DAC two
    DACreg = $000
    GOSUB     WRITE_TO_DAC
    DACloc    =DACaddr3    'Load DAC three
    DACreg = $000
    GOSUB     WRITE_TO_DAC
    DACloc    =DACwrite    'Update DAC outputs
    GOSUB     WRITE_TO_DAC
END
WRITE_TO_DAC:
    'DAC #1
    SPIREG = DACloc + DACreg
    LOW     CSpin          'Select DAC
    SHIFTOUT SDOpin,CLKpin,MSBFIRST, [SPIreg\16]
    HIGH     CSpin
    RETURN
WRITE_TO_DCB:
    'DAC #2
    SPIREG = DACloc + DACreg
    LOW     CSpiB          'Select DAC
    SHIFTOUT SDOpiB,CLKpiB,MSBFIRST, [SPIreg\16]
    HIGH     CSpiB
    RETURN

```

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