A PRELIMINARY DESIGN FOR A SMALL PERMANENT MAGNET CYCLOTRON

By

Barry Thomas King

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

Bachelor of Science

Houghton College

December 2002

Signature of Author…………………………………………………………………...

<div align="right">

Department of Physics
January 20, 2003

</div>

………………………………………………………………………………………..

<div align="right">

Dr. Mark Yuly
Associate Professor of Physics
Research Supervisor

</div>

………………………………………………………………………………………..

<div align="right">

Dr. Ronald Rohe
Associate Professor of Physics

</div>

A PRELIMINARY DESIGN FOR A SMALL PERMANENT MAGNET CYCLOTRON

By

Barry Thomas King

Submitted to the Department of Physics
on January 20, 2003 in partial fulfillment of the
requirement of the degree of
Bachelor of Science.

Abstract

A small cyclotron is being constructed using a 0.5 T permanent magnet and a vacuum chamber containing a single brass RF electrode. In this design the magnetic field strength may be modified by adjusting the separation of two iron pole pieces, which will be sealed to the chamber using vacuum grease. The chamber will be filled with low pressure hydrogen gas which will be ionized by electrons from a cathode at the center of the chamber. The required 3.6 to 11.5 MHz RF power will be supplied by a commercial RF amplifier. A diffusion pump backed by a voluntary forepump and a liquid nitrogen cold trap will be used to evacuate the chamber. Expected energies are 37.5 keV and 87.7 keV for protons and 18.7 keV and 43.8 keV for deuterons.

Thesis Supervisor: Dr. Mark Yuly
Title: Associate Professor of Physics

TABLE OF CONTENTS

LIST OF FIGURES

ACKNOWLEDGMENTS

Chapter 1

INTRODUCTION

1.1 History and Motivation

The first nuclear scattering experiments were performed by H. W. Geiger and E. Marsden under the supervision of E. Rutherford in 1911 [1]. Since that time scattering experiments have been the predominant method for learning about nuclei and the interaction of subatomic particles. In Rutherford's seminal experiment, alpha particles, obtained from a naturally occurring radioactive source, radium, were scattered from a thin gold foil, and were detected using a zinc sulfide screen as seen in Figure 1.1. The importance of this work was that information could be learned about the structure and interactions of nuclei by measuring the angular distributions of the scattered particles.
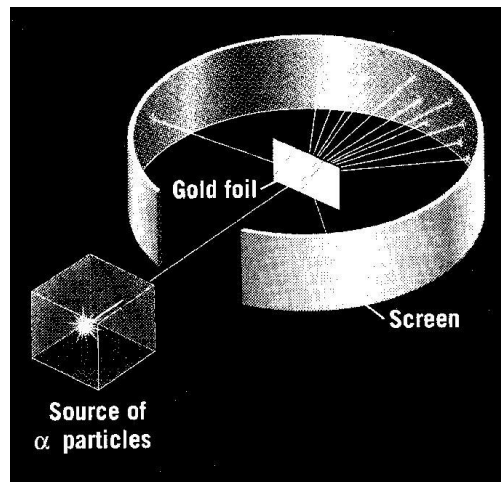
[Figure 1.1] A diagram of Rutherford's gold foil experiment taken from Ref. [2]. Alpha particles from a radioactive source were scattered from a gold foil and detected on a scintillating screen.

One problem with Rutherford's setup was the inability to control the flux and energy of the alpha particles emitted. In order to perform more sophisticated scattering experiments a machine that could artificially accelerate particles to controlled energies and intensities was needed. Thus began the development of particle accelerators. The origin of the cyclotron is closely linked to the creation of other early accelerators, and it is for this reason that this discussion will begin with the Cockroft-Walton generator which was the first accelerator to disintegrate an atom, then the Van de Graaff generator which achieved higher energies, followed by the earliest conceptions of the linear accelerator which led to the design of the cyclotron.

1.1.1 The Cockroft-Walton Generator

The first of the early accelerators to obtain success was developed by John Cockroft and Ernest Walton at the Cavendish laboratory in Cambridge England. By using voltage multiplier circuit, as seen in Figure 1.2, they achieved a potential of 800 kV in 1931 [3].
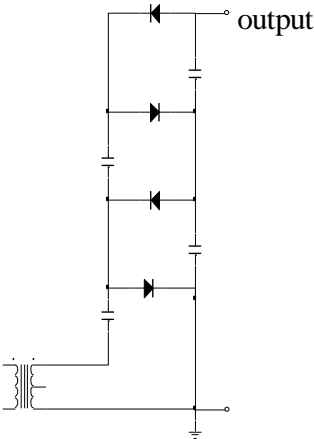
[Figure 1.2] A schematic of a Cockroft-Walton High Voltage generator. The rectifying diodes allow for each capacitor to be charged in parallel on each half-cycle and alternatively discharged in series, thus multiplying the voltage.

The voltage multiplier circuit charges all the capacitors in parallel on each half cycle, and alternately discharged in series. Thus, in Figure 1.2 the final output potential will be four times as great as the input voltage. Cockroft and Walton used this potential to charge the end of an eight foot hollow evacuated tube, and in 1932 they fused proton nuclei with Li nuclei resulting in two He nuclei [3]. This was the first nuclear reaction using artificially accelerated particles. While this machine was useful, its maximum energy is around 1 MeV [4]. The insulation would breakdown above a certain voltagbe and a discharge would occur. One solution was to immerse the apparatus in a high pressure insulating gas, which lowered the chance of arcing; however, these machines were too bulky for this to be a practical solution [5]. So the maximum potential of the Cockroft-Walton generator remains at around 1 MeV, much less than the 9 MeV limit for the Van de Graaff and the 20 MeV limit for the Cyclotron. Even with this limit, however, Cockroft-Walton generators are still used today, often as pre-accelerators to inject particles into larger accelerators, such as the linear accelerator at Los Alamos Neutron Science Center (LANSCE) [6].

1.1.2 The Van de Graaff Generator

Another successful particle accelerator was developed by Robert Van de Graaff in 1931 at Princeton University, who charged hollow conducting spheres using an insulated belt to transfer charge as seen in Figure 1.3 [7]. Charge would be sprayed onto the insulated belt and then carried up to the hollow metal sphere at the top, where the charge would be removed. Even though the sphere itself was increasing in potential, the charge could be removed from the belt inside the sphere, because the electric field is zero inside a conductor [6]. In 1931 he achieved a potential difference of 1.5 MV. He was also able to use this potential to accelerate protons down evacuated tubes [6]. This machine also experienced arcing problems, however, it was possible to operate the device inside a high pressure gas chamber, but even so there were practical limits on how big the machine could be made, limiting the final energy to about 9 MeV [6].

Other methods were developed to increase the final energy. In an accelerator called a tandem accelerator, a negative ion would be created and accelerated towards a positive Van de Graaff high terminal, then inside the terminal it would be stripped of its extra electron, and several others resulting

in a positive ion, by collision with gas molecules and accelerated again, by the same positive terminal [5]. Even without this innovation, the Van de Graaff generator was a powerful tool for confirming the theories of classical nuclear physics [5].
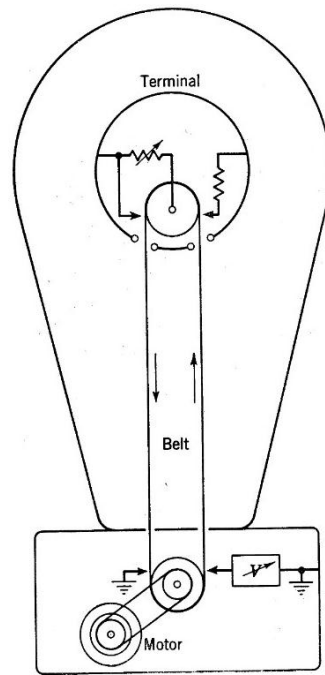
[Figure 1.3] A diagram of a Van de Graaff Generator taken from Ref [6]. By using two generators charged to opposite polarities an even higher potential difference could be achieved.

1.1.3 The Accelerator Tube

A problem shared by the Cockroft-Walton and the Van de Graaff accelerators was the evacuated acceleration tube. Both of these electrostatic generators used voltages that were so high that spurious discharges in the acceleration tube would ruin the operation of these machines [5]. One solution was to use voltage dividers along the acceleration tube to spread the voltage drops out over several electrodes. In this way there would be less chance for a spark to discharge the accelerating electrode.

1.1.4 The Linear Accelerator

Another solution to the problem of high voltages was to accelerate particles in many low voltage steps. In 1928 Rolph Wideröe published an article describing a resonance linear accelerator in the German journal *Archiv für Electrotechnik* [8]. He devised a way to accelerate an ion twice, using three hollow cylindrical electrodes. An alternating electric field was applied between the outer two electrodes and the center electrode. The frequency of alternation was in resonance with the K^+ and Na^+ ions that Wideröe accelerated [9]. The ions would initially be accelerated towards the first electrode, then, while the ions passed through the electrode, the polarity would be switched. When the ion left the electrode, it would again be accelerated toward the second electrode.

This led eventually to the development of the modern linear accelerator. By placing many of these electrodes end to end, with varying lengths and using the correct rf frequency, the ion would be accelerated towards the first electrode, corresponding to stage A in Figure 1.4, and then while traveling through the electrode, the polarity would switch. When the ion passed out of the first electrode it would be accelerated again, in stage B, this time being repulsed by the first electrode, and attracted by the second. While passing through the second electrode, the polarity would again be switched, only to leave and be accelerated again in stage C, and so on right through to stage E.
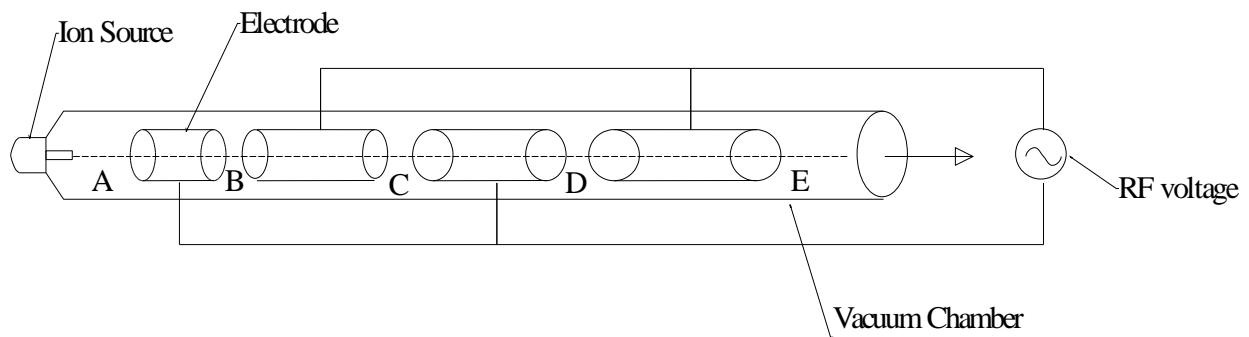

[Figure 1.4] A diagram of a linear accelerator, using an rf voltage to accelerate particles in resonance. This accelerator uses five stages, A B C D and E.

These electrodes would have to be of increasing length in order to keep the higher speed particles in resonance with the rf voltage, as seen in Figure 1.4. These accelerators are still in use today, and obtain some of the highest power, such as the linear accelerator used at LANSCE which produces a 1 mA 800 MeV proton beam [10].

1.1.5 The Cyclotron

The article by Wideröe inspired Ernest Orlando Lawrence, then associate professor at the University of California Berkeley, to design the first cyclotron in 1929. He found the article and wondered "…might it not be possible to use two electrodes over and over again by sending the positive ions back and forth through the electrodes by some sort of appropriate magnetic field arrangement." [11] He found that by using an oscillating electric field and uniform magnetic field perpendicular to the plane of motion he could accelerate a charged particle along a spiral path, as seen in Figure 1.5.

RF Amplifier
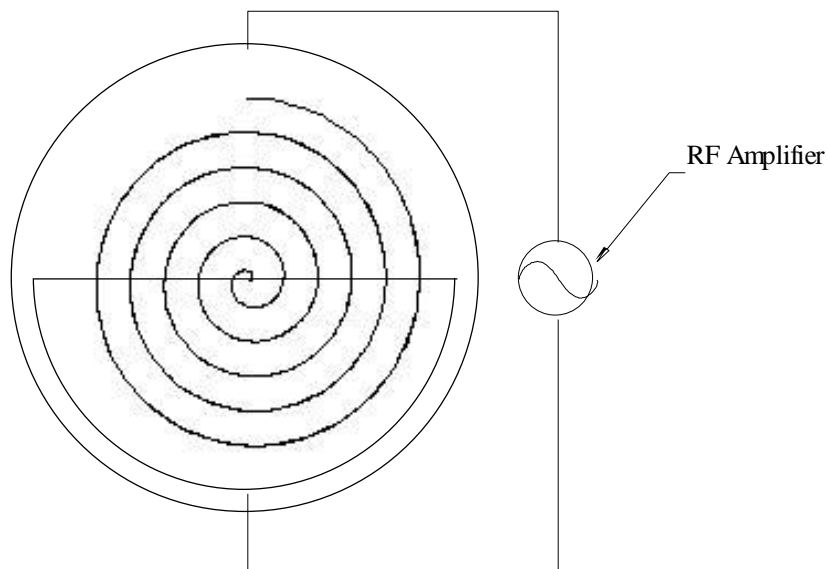
[Figure 1.5] A diagram showing the spiral path of charged particles in a cyclotron. Because the period of oscillation is independent of the radius, the rf source can be of a fixed frequency.

6

The reason this design works is that the time it takes a charged particle to travel around in its orbit is independent of the orbit radius. In the summer of 1930, Lawrence suggested "a study of the resonance of hydrogen ions with a radiofrequency electric field in the presence of a magnetic field" to Milton Stanley Livingston, then a graduate student, as a topic for his graduate thesis [8]. In January 1931 Livingston and Lawrence successfully completed the first cyclotron. The vacuum chamber was 4.5 inches in diameter, and it used a 1.8 kV oscillating voltage to produce protons with kinetic energies of 80 keV. In April 1931 Livingston published his doctoral thesis "The Production of High Velocity Hydrogen Ions Without the Use of High Voltages." [12] Later that summer an 11-inch cyclotron was completed that produced 1.1 MeV protons [13]. In the next ten years, nearly a dozen cyclotrons were built around the United States, at University of Michigan, Cornell, Princeton, University of Rochester, Columbia, Washington University at St. Louis, Bartol Research laboratory, University of Illinois, University of Indiana, Purdue, Carnegie Institution of Washington, Harvard, and MIT [6]. Cyclotrons quickly achieved their maximum energy, which is limited by relativistic effects to approximately 20 MeV. The immediate advantage to the cyclotron was its high energy output relative to the other accelerators of that era. Also, due to focusing effects, cyclotrons are capable of producing large beam currents and are relatively compact for the final energies achieved.

Although cyclotrons reached their energy limit nearly 60 years ago, and there are many other accelerator designs that obtain much higher energies, as seen in Figure 1.6, Cyclotrons are still viable particle accelerators. Cyclotrons are relatively inexpensive to build, and are an efficient source of mono-energetic charged particles with energies below 20 MeV. In fact, there have been a number of small cyclotrons built by high school students [14,15] and undergraduate students [16,17]. The University of Helsinki completed construction of their cyclotron, used for radio-pharmaceutical research, in 1998 [18]. Also, Tri University Meson Facility (TRIUMF) at the University of British Columbia Vancouver BC has developed a design for a commercial cyclotron that produces a 1 mA beam of 30 MeV protons [19]. These are just a few examples of the prolific life the cyclotron still has.

1.2 Purpose

The purpose of our project is to design and begin construction of a small cyclotron usable at a small nuclear physics laboratory. We then hope to use the accelerator for nuclear experiments suitable for undergraduate research projects.
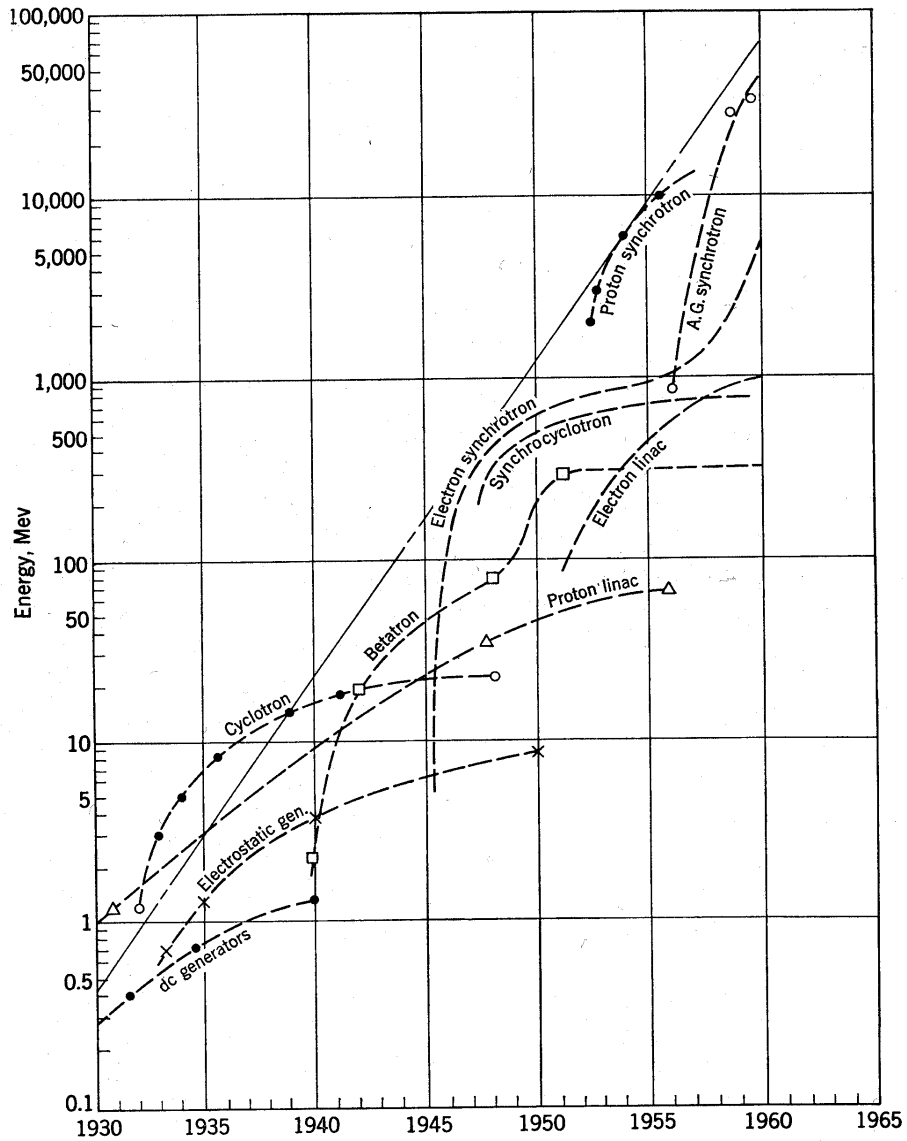
[Figure 1.6] A graph of the maximum output energy versus year between 1930 and 1965 for various types of particle accelerators from [6].

8

THEORY OF CYCLOTRON OPERATION

Cyclotrons operate using the principle of magnetic resonance, meaning a particle's frequency of revolution inside the cyclotron is independent of the orbit radius. Magnetic and electric focusing of the particles into a tight beam, the lack of phase stability, and relativistic effects on the accelerated particles will also be addressed in this chapter.

2.1 Magnetic Resonance

The operating principle of a cyclotron is magnetic resonance, in which an rf electrode applies an accelerating voltage in resonance with the frequency of oscillation of a charged particle moving in a magnetic field. A charged particle will move in a circular orbit when traveling in a magnetic field perpendicular to the plane of its orbit. The centripetal acceleration that keeps the charged particle moving in a circle is supplied by the Lorentz force, yielding

$$F = \frac{mv^2}{r} = qvB \qquad (2\text{-}1)$$

where q is the charge of the particle, B is the magnetic field, m is the particle mass, r is the orbit radius, and v is the velocity of the particle. The time it takes to complete one orbit, called the period (T), is the distance traveled divided by the velocity of the particle. The frequency with which the particle orbits is thus given by

$$f = \frac{1}{t} = \frac{v}{2r\pi} \qquad (2\text{-}2)$$

and is called the cyclotron frequency. Solving Eq. 2-1 for v and substituting in Eq. 2-2 yields

$$\frac{v}{2r\pi} = \frac{qB}{2m\pi} \quad . \qquad (2\text{-}3)$$

It is worth pointing out the independence of the cyclotron frequency on the orbit radius r. A particle takes the same amount of time to travel a larger orbit as it does a smaller one. In this way it is possible to use a fixed rf frequency. On each successive orbit, the particle will receive a "kick" each time it enters or leaves the electrode and the path of the particle is approximately a spiral, as seen in Figure 2.1.
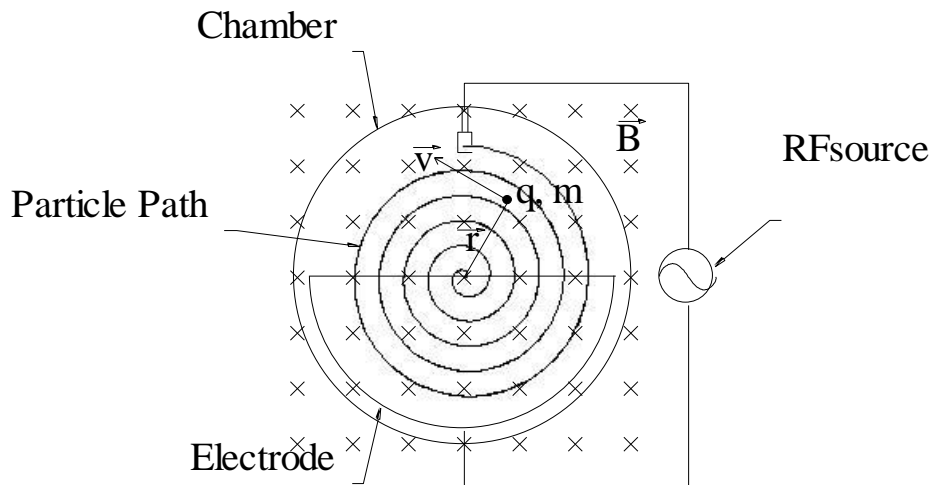
[Figure 2.1] The spiral path of a particle of mass m, charge q, and velocity v moving in a magnetic field B as it is accelerated by the alternating potential on the electrode.

Looking at the non-relativistic definition of kinetic energy yields

$$T = \frac{mv^2}{2} = \frac{q^2 B^2 R^2}{2m}$$
(2-4)

where R is the final radius of the particle. It is worth noting that any increase in the final radius R, or in the strength of the magnetic field yields a quadratic increase in the final kinetic energy.

2.2 Magnetic Focusing

Although the main principle of a cyclotron is magnetic resonance, there is an assumption that the particle will never deviate from the median plane, and that the particle always moves perpendicular to the magnetic field. This is not generally the case. If the magnetic field were completely uniform, and if

the particle had a transverse velocity component when it was ionized at the center, it would follow a helical path and collide with the chamber wall. Fortunately, magnets tend to have a slight decrease in magnetic flux with radius. A radial decrease in the magnetic field by about two to three percent from the central field to the final radius provides the best beam intensity for low energy cyclotrons [6]. Thus the magnetic field takes on a slight convex shape, as shown in Figure 2.2
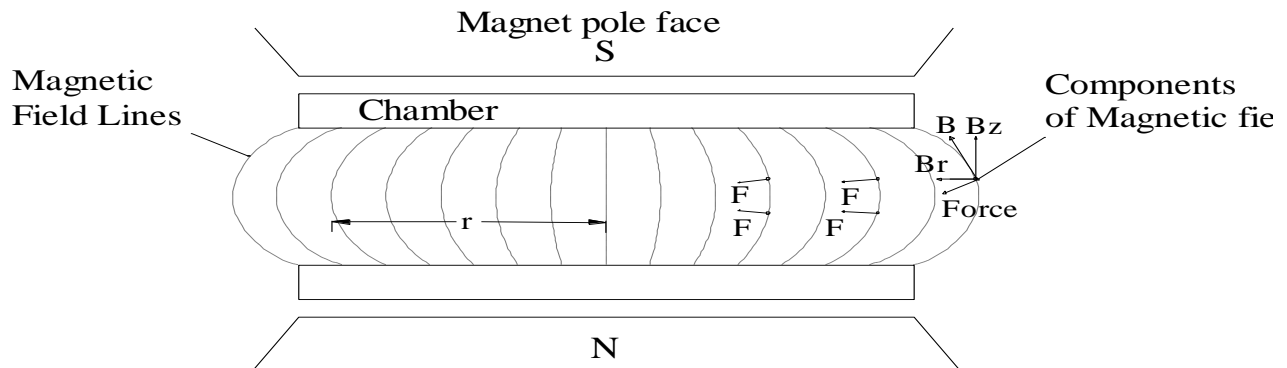
[Figure 2.2] A radially decreasing magnetic field, with components of the field. The Lorentz forces on particles moving into the page are shown .

Due to the bowing of the magnetic field a particle deviating from the median plane will experience a restoring force due to the Lorentz force and therefore oscillate about the median plane. This force is due to the B_r component of the B field. The z-component B_{zo} of the magnetic field at some radius r_o can be related to the same quantity B_z at a slightly different radius r by

$$\frac{B_z}{B_{z0}} = \left(\frac{r}{r_0}\right)^{-n} \tag{2-5}$$

where n is called the field index, defined by

$$n = -\frac{r}{B_z}\frac{dB_z}{dr} . \tag{2-6}$$

This may be obtained from Eq. 2-5 as follows. First take the natural logarithm of both sides to get

$$-\ln B_z - \ln B_{z0} = n[\ln r - \ln r_0].$$ \hfill (2-7)

Now, take the derivative of both sides arriving at

$$n\frac{1}{r} = -\frac{1}{B_z}\frac{dB_z}{dr}$$ \hfill (2-8)

which yields Eq. 2-6 when solved for n. It is worth noting that according to maxwells equation for static fields in free space,

$$\nabla \otimes B = 0$$ \hfill (2-9)

$$\frac{dB_z}{dr} = \frac{dB_r}{dz}.$$ \hfill (2-10)

For small values of z, B_r can be obtained from Eq. 2-7 and Eq. 2-6 as follows

$$B_r = z\frac{dB_r}{dz} = z\frac{dB_z}{dr} = -(B_z nz/r).$$ \hfill (2-11)

The vertical restoring force acting on a particle deviating from the median plane will be supplied by the Lorentz force.

$$F = qvB_r = -qvB_z nz/r = qB_z nz\omega = m\frac{d^2z}{dt^2}$$ \hfill (2-12)

where $\omega = v/r = qB_z/m$. Thus the equation of motion is

$$\frac{d^2z}{dt^2} + nz\omega^2 = 0$$ \hfill (2-13)

which is the equation for a simple harmonic oscillator if n is positive, that is to say, the z component of the magnetic field decreases with radius. The equation of motion has the solution of

$$z = A\sin\left(n^{1/2}t\omega + \alpha\right) \tag{2-14}$$

where A and α are constants fixed by the initial conditions, i.e. the velocity of the particle when it is first ionized. Thus the particle will oscillate around the median plane. These transverse oscillations are caused by the radial component of the magnetic field. Because the energy of the transverse oscillations remains essentially constant while the strength of the radial component of the magnetic field increases with radius the amplitude of the oscillations will decrease towards the end of the spiral, focusing the beam.

2.3 Electric Focusing

As a particle passes through the electric field between the electrode and the grounded chamber it follows a path similar to the one in Figure 2.3, though this is greatly exaggerated.
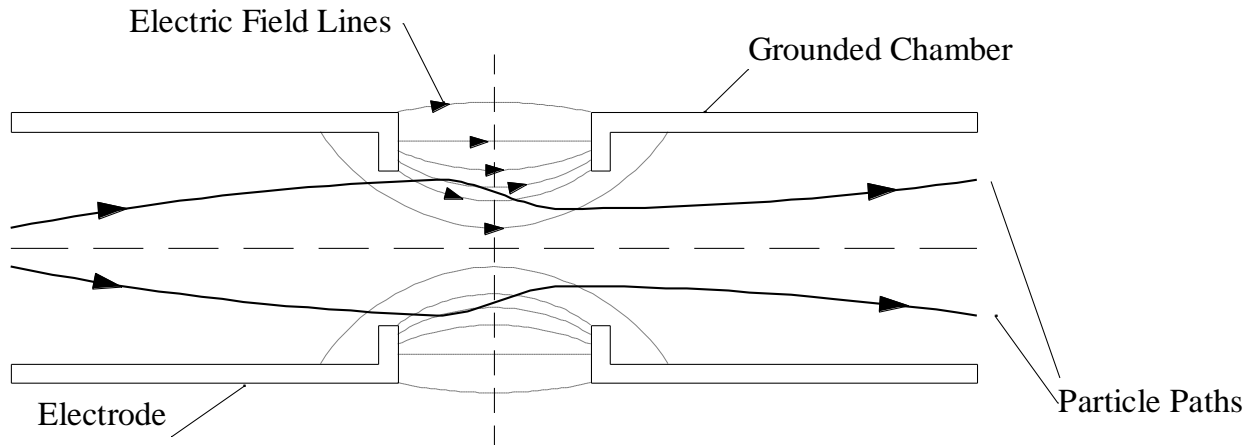
[Figure 2.3] An exaggerated path of particles traveling in a cross section of the electric field shown by dotted lines between the electrode and the chamber.

As the particle enters the electric field it is deflected inward by the curvature of the field lines if it is deviating from the median plan. This section of the electric field is referred to as the convergent field. As it leaves the electric field region, it is deflected outward, by the same curvature of the field.This section of the field is called the divergent field. The particle spends more time in the convergent field region than in the divergent because it is accelerated as it passes through the field, thus, the net effect is focusing. This effect is only noticeable in the first few revolutions, when the relative change in velocity between the electrodes is greatest.

The previous discussion, however, assumes that the particle always passes through the electric field when the field is at maximum strength, and that the field is constant in time while the particle is passing through it. This is not the case. The voltage between the gap oscillates as seen in Figure 2.4.
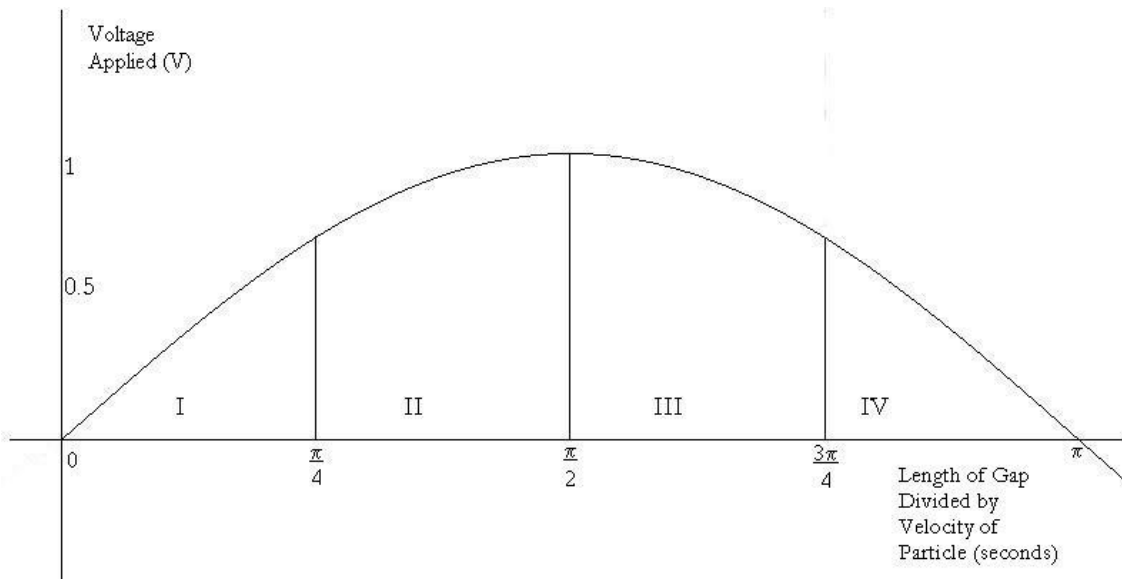
[Figure 2.4] The magnitude of the oscillating voltage across the electrodes
versus time, with the first half cycle divided into four sections.

If the particle entered the electrode gap during region I in Figure 2.4, it would find the field increasing as it traveled through the gap, and it would leave during region II. Thus the divergent field would be stronger and the net effect would be defocusing. This situation is referred to as

14

negative phase. If the particle entered the gap during region II, the field would be strongest during the focusing region. The particle would leave the gap during region III or IV and the net effect would be focusing. This situation is referred to as positive phase. Because the magnetic field decreases radially, the frequency of the oscillations of the particles will decrease slightly with radius. Thus the phase of the particles will increase with every pass. Once the phase of the particle reaches 90° the particles will no longer be accelerated because the voltage will already be changing polarity as it passes through the gap. It would only take a few cycles, on the order of 12, for most cyclotrons to have reached this velocity. This means that a high voltage would be required to accelerate the particle to its final energy. But the purpose of a cyclotron is to avoid high voltages. The solution to this problem is to apply a radio frequency oscillating voltage to the electrode that is slightly less than the cyclotron frequency given at the center of the field, but greater than the cyclotron frequency corresponding to that near the edges. Thus the phase would start off getting negative, i.e. the particle would be entering the electrode gap in region I of Figure 2.4, until it passed that region where the cyclotron frequency became less than the applied radio frequency, then the phase would begin to increase again, i.e. the particle would begin entering the electrode gap during region II of Figure 2.4. This means a much lower voltage would be required to accelerate the particle to its final energy.

2.4 Phase Stability

The discussion of phase stability will be limited to a qualitative one. Phase stability refers to the automatic correction of a particle that is orbiting slightly out of synch with the frequency of the rf voltage applied to the electrodes. In linear accelerators phase stability exists. If a particle is moving too fast, it won't receive a large acceleration as it enters the gap, and a particle that is a little behind will receive a large. In this way all the particles tend to approach the same phase, and arrive in little bursts at the end. Because of magnetic resonance, meaning all the particles arrive at the gap in the same amount of time, there is no phase stability in a cyclotron. That is to say, a particle that is traveling too fast will not slow down, and a particle that is traveling too slow will not speed up. They will each receive the same amount of "kick" every time they pass through the

electrode gap. Particles that enter the gap during a large potential difference receive a big "kick" and take fewer revolutions to reach their final energy, whereas particles that enter the gap during a small potential difference receive a small "kick" and take many revolutions to reach their final energy. Because of the lack of phase stability, precise tuning of the rf frequency applied to the electrodes is vital. Instead of a pulsed beam from a linear accelerator, the cyclotron outputs a continuous beam.

2.5 Relativistic Effects

The energy limit of the cyclotron is due to relativistic effects. As noted, the primary operating principle of the cyclotron is magnetic resonance. But particles of different masses will not have the same resonance frequency. Once the relativistic increase in mass becomes noticeable, the resonance principle of the cyclotron is upset. For protons, which have a rest mass of roughly 1000 MeV, once the particle has been accelerated to 10 MeV the mass has been changed by about 1%, which has a frequency shift of 1%, or about 36 kHz, for our B field. However, the heavier the ion, the higher the energies that can be obtained. A solution to this problem was the synchrotron suggested by Edwin McMillan in 1945 [6]. In short, the applied frequency of the synchrotron was made to vary with the ion revolution frequency. Thus, resonance was maintained, and the energy limitation is removed, at the cost of having a pulsed beam and therefore lower beam current.

C h a p t e r   3

CYCLOTRON DESIGN

The description of the design for our cyclotron will be broken down into three sections: the magnetic field, the chamber, and the vacuum system.

3.1 Magnetic Field

The magnetic field will be provided by a permanent magnet that was originally manufactured by the Indiana Steel Products Company to be used in a nuclear magnetic resonance machine. Its pole face diameter is 15.2 cm, and the air gap is 3.8 cm. The magnetic field is uniform at 0.493 T, to within one percent, out to a radius of 6.19 cm, as shown in Figure 3.1. Rough calculations from Eq. 2-6 show the field index n is about 0.0081. The RF electrode radius is 7.14 cm containing the full uniform region of the field. A moveable Faraday cup will allow collection of the particles before they enter the non-uniform field. The magnetic field was measured using a model 5070 F. W. Bell gauss/tesla meter. Measurements were taken every 0.48 cm radially at several angles, using circular template constructed on AutoCAD. The template allowed precise placement of the tesla meter for accurate measurements. Spacers were used to make the same measurements at different heights between the pole faces. Figure 3.1 was constructed from one set of these measurements. The energy obtainable using this field, as per Eq. 2-4, should be 37.5 keV for protons and 18.7 keV for deuterons. With the possibility of using gray iron as our sealing plates for the chamber, we will reduce the air gap between the poles of the magnet to 1.3 cm thereby increasing the magnetic field to roughly 0.75 T. If this field proves uniform enough, it would increase the final energy of accelerated particles to 87.7 MeV for protons and 43.8 MeV for deuterons.
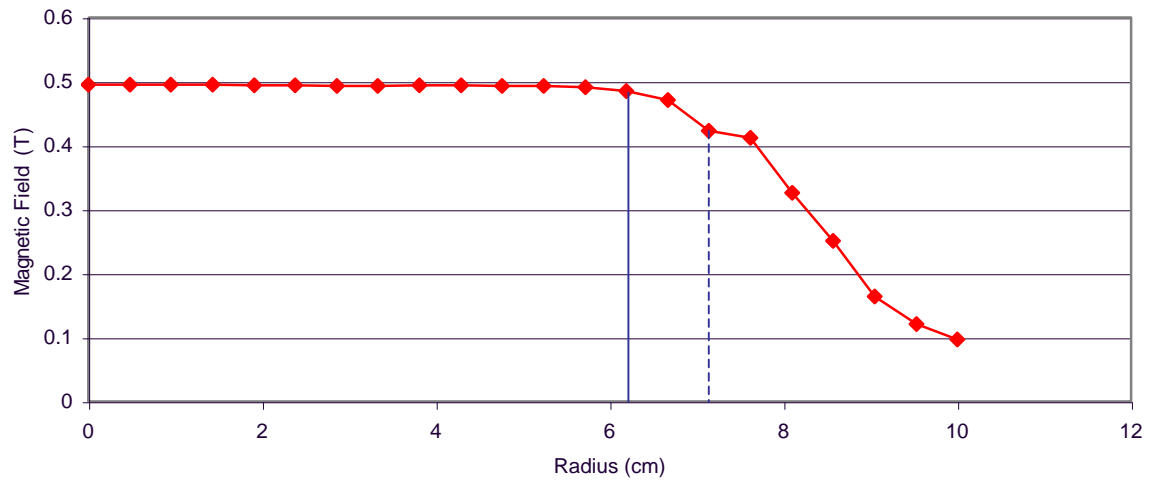
[Figure 3.1] Axial magnetic field as a function of radius. Measured values are represented by diamonds. The solid vertical line represents the end of the uniform region, and the dashed line the extent of the electrode.

3.2 Chamber Design

The vacuum chamber for our cyclotron will have an inside diameter of 15.2 cm as seen in Figure 3.2. The chamber will be made in three sections. The central section, measuring 2.5 cm high, will be a hollow brass cylinder. It is being constructed by making two brass flanges 0.6 cm thick with inner diameter of 15.2 cm and outer diameter of 16.5 cm. A thin brass sheet with height of 2.5 cm will be curved and soldered together to create a ring of diameter 15.2 cm. This ring will be soldered onto the two 0.6 cm flanges to create the hollow cylindrical chamber. The chamber will be made vacuum tight by sealing two metal plates to it using vacuum grease. The metal plates will be made of either aluminum or iron. Aluminum plates will not interfere with the magnetic field, and iron plates, if machined correctly, will increase the magnetic field while maintaining uniformity. The chamber was designed with a single RF electrode, diameter 14.3 cm, powered by an RF amplifier through a feedthrough in the chamber wall (see Figure 3.3). The rest of the chamber will be grounded to create the potential difference. Copper pipes of 0.6 cm and 0.95 cm diameter will be soldered to the side walls of the chamber to allow for gas intake and evacuation respectively. A small filament in the center

of the chamber will release electrons which ionize the gas. A 5.08 cm x 1.00 cm glass window attached by vacuum epoxy to the chamber wall will allow observation of the interior of the chamber.
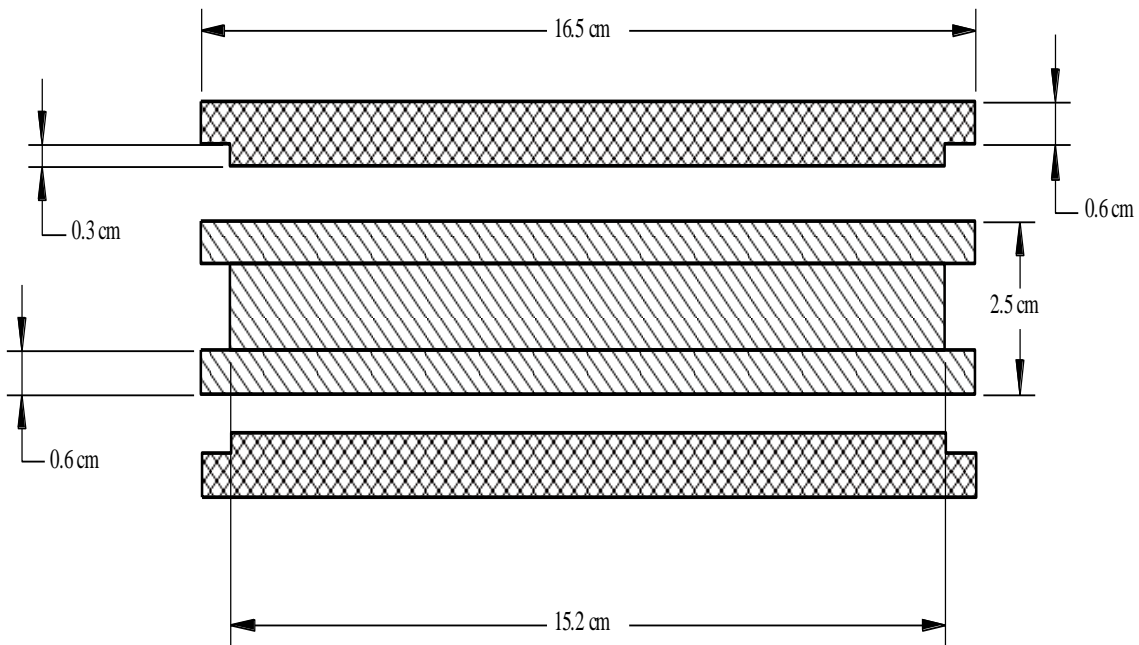

[Figure 3.2] A lift-away drawing of the brass chamber with sealing plates, the electrode and feedthroughs are not shown.

A Faraday cup made of aluminum attached to a bellows opposite the RF electrode will collect the particles. The bellows will allow the Faraday cup to be positioned at the appropriate radius. A retarding grid attached to the front of the Faraday cup will eliminate loss of secondary electrons. As the particles are collected in the Faraday cup, they may strike the back wall and release secondary electrons. The grid will be at some negative potential, controlled by a potentiometer , and the cup will be connected to ground via an electrometer as seen in Figure 3.4. The electrode will be powered by an rf amplifier that will have a frequency range of 3.6 MHz to 11.5 MHz to provide the necessary accelerating voltage. The filament will be powered by a 12 V source connected to a potentiometer in order to adjust the temperature of the filament
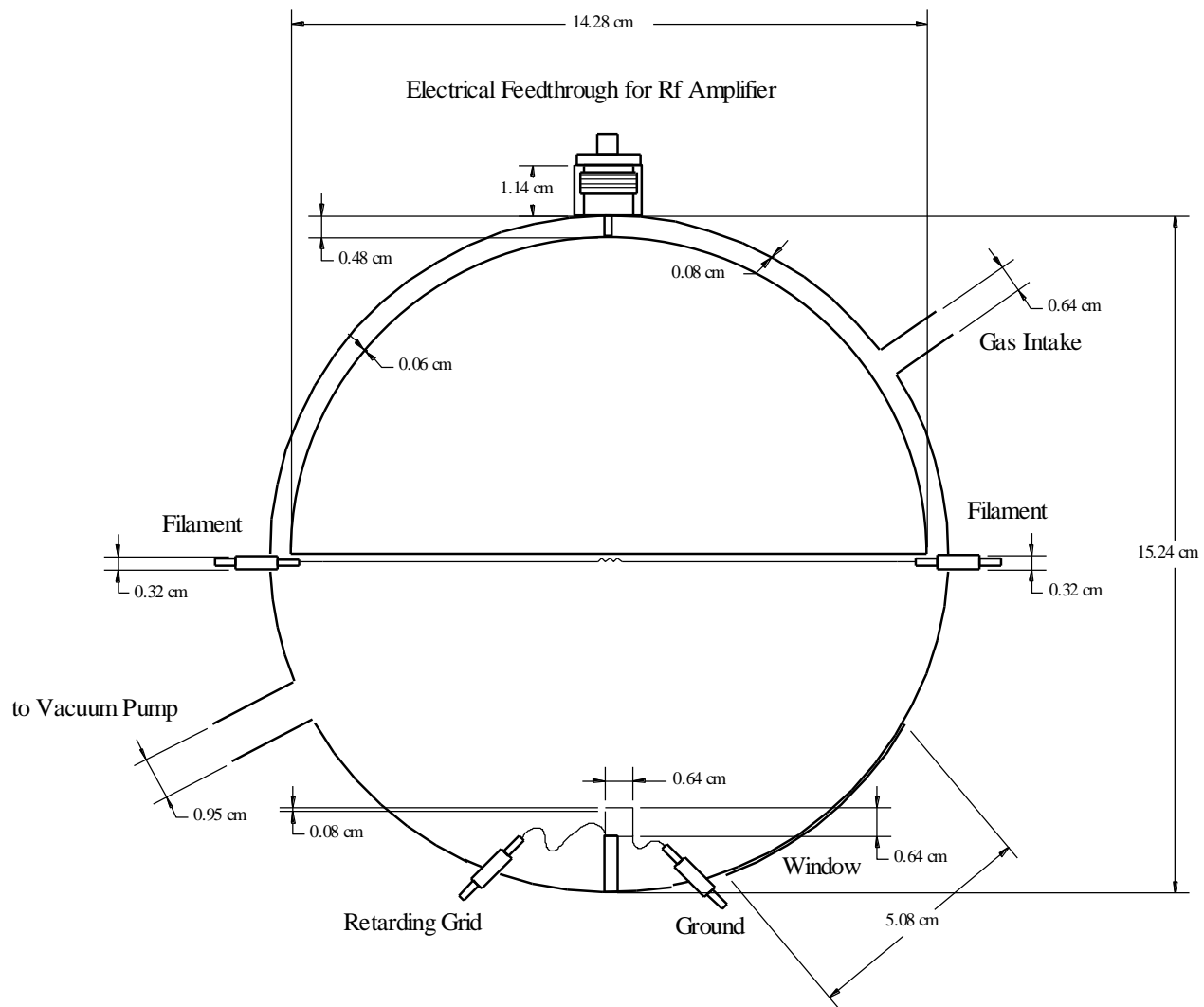
[Figure 3.3] Mechanical drawing of chamber showing electrical feedthroughs for the electrode, filament, and Faraday cup. Also shown is the gas intake, vacuum pipe and window. The bellows for positioning the Faraday cup are not shown.

20
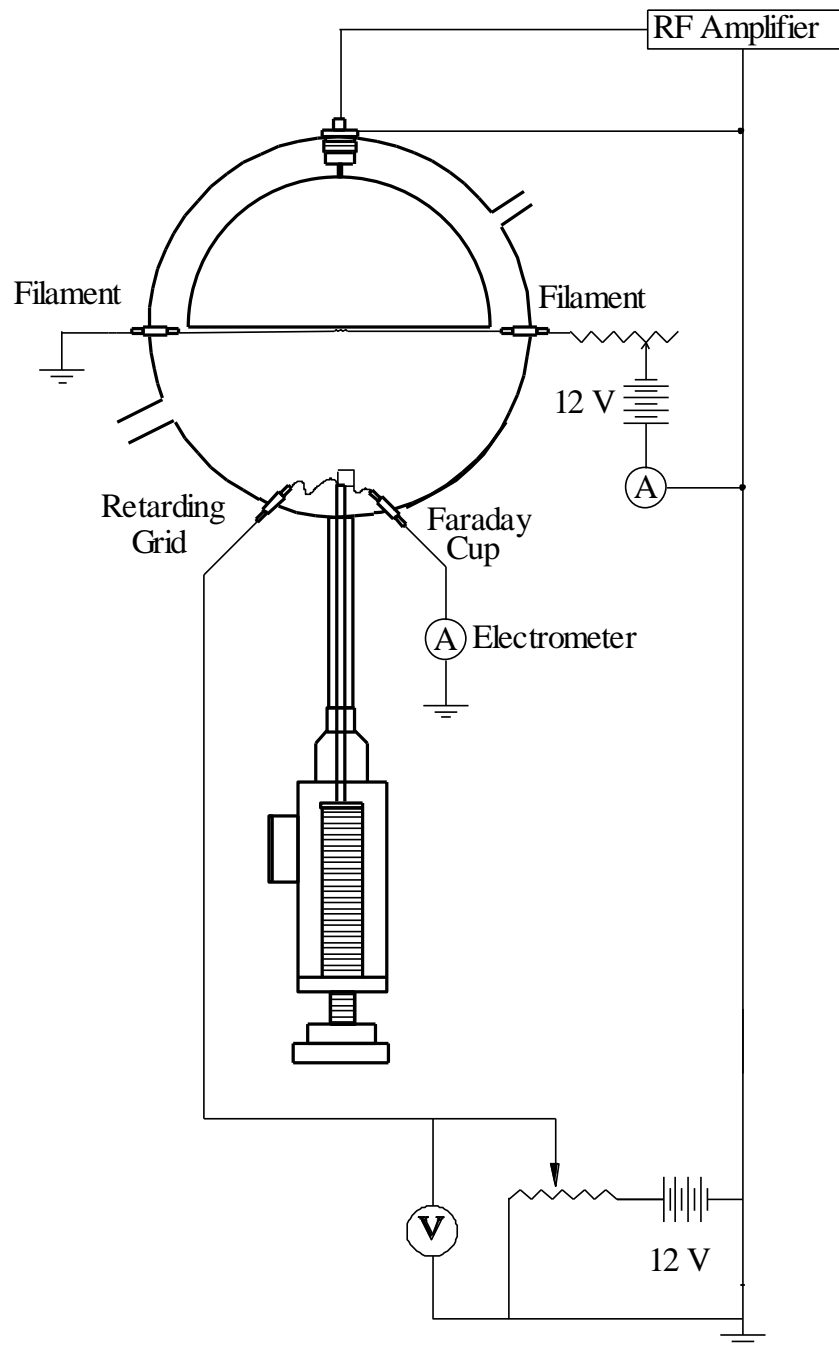
[Figure 3.4] An electronic schematic showing power supplies for the electrode, filament, retarding grid, and Faraday cup.
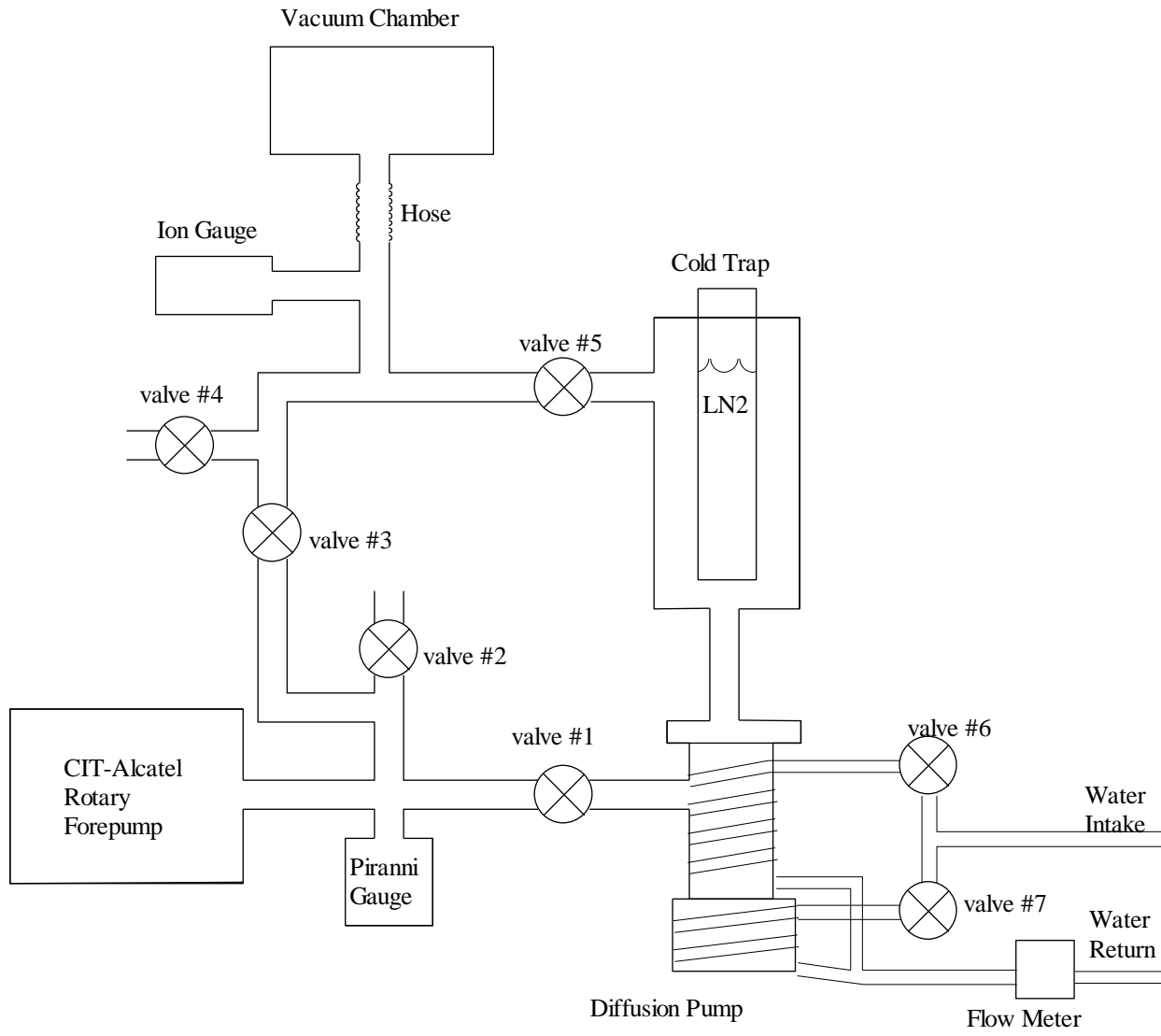
3.3 Vacuum System

As shown in figure 3.5 a diffusion pump backed by a rotary forepump and liquid nitrogen cold trap will evacuate the acceleration chamber. The vacuum chamber will be attached to the pumps with a flexible hose to allow the chamber to be positioned in the magnetic field. The chamber will first be roughed down by rotary forepump, with valves one and five open and all other valves closed. When the pressure is a few milliTorr, as measured by the Piranni gauge, the diffusion pump will be turned on, and liquid nitrogen added to the cold trap. Final pressure will be measured by the ion gauge to signal when operating pressure, between 1×10^{-6} and 2×10^{-5} Torr, has been reached. Cooling water for the diffusion pump will be controlled by valves six and seven. Valves four and two are used to return the vacuum system to normal pressure. Valve three and five can be closed off to allow the chamber to be worked on, without losing the vacuum in other components.

3.3.1 Liquid Nitrogen Cold Trap

Once the chamber has been roughed down the cold trap reservoir will be filled with liquid nitrogen. This cools any molecules in the trap, and prevents them from retaining enough kinetic energy to escape into the chamber.

3.3.2 Diffusion Pump

The diffusion pump is a 2 inch Kamlrok. It heats silicone diffusion pump fluid (DS-7040) in its bottom reservoir with an electrical heating element. The fluid is then diffused into the upper section of the pump where it attaches to gas molecules. The oil is then cooled by water pipes that are wrapped around the upper section and descends, pulling the gas with it. The gas is then removed by the forepump. The water pipes that run around the oil reservoir are used to return the pump to room temperature quickly when operation has ceased.

[Figure 3.5] A schematic drawing of the vacuum system, showing layout
of the forepump, diffusion pump, cold trap, gauges and valves.

3.3.3 Electrical System

The electrical controls are designed such that the diffusion pump cannot be turned on unless the forepump is turned on. When the forepump switch is thrown it energizes relay coil one, which turns on the forepump and energizes the variac. The diffusion pump switch energizes relay coil two, which

allows power to flow from the variac to the diffusion pump heating element. The power supplied to the diffusion pump heater is controlled by a variac, and is monitored by the voltmeter and ammeter shown in Figure 3.6.
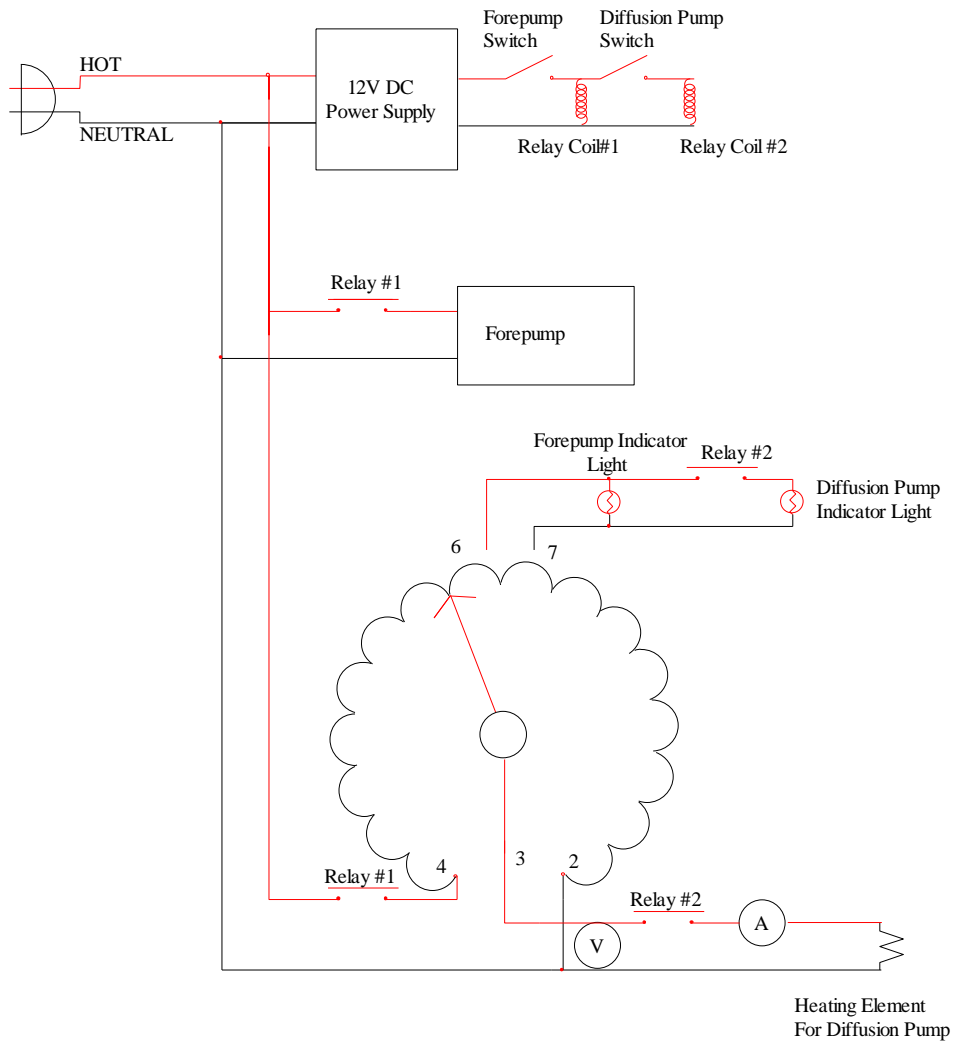
[Figure 3.6] The electrical controls for the vacuum system.

CONCLUSION

The vacuum system is nearly finished, and the chamber is under construction. Figure 4.1 is a picture of the magnet and nearly completed vacuum system.

[Figure 4.1] A photograph of the current status with magnet,
control panel, and nearly a completed vacuum system.

One long term goal of this project is to use it as a source of low energy neutrons. Although this machine will only generate 18.7 keV deuterons using the aluminum plates, it might be possible to use

the $D+D \rightarrow n+{}^3He$ reaction to yield neutrons with energies of 2.61 MeV. When two deuterons collide a proton is captured by one, making He^3 and liberating a neutron. This reaction yields an energy of 3.26 MeV, most of which is carried by the neutron. The cross section for this reaction is shown in figure 4.2.
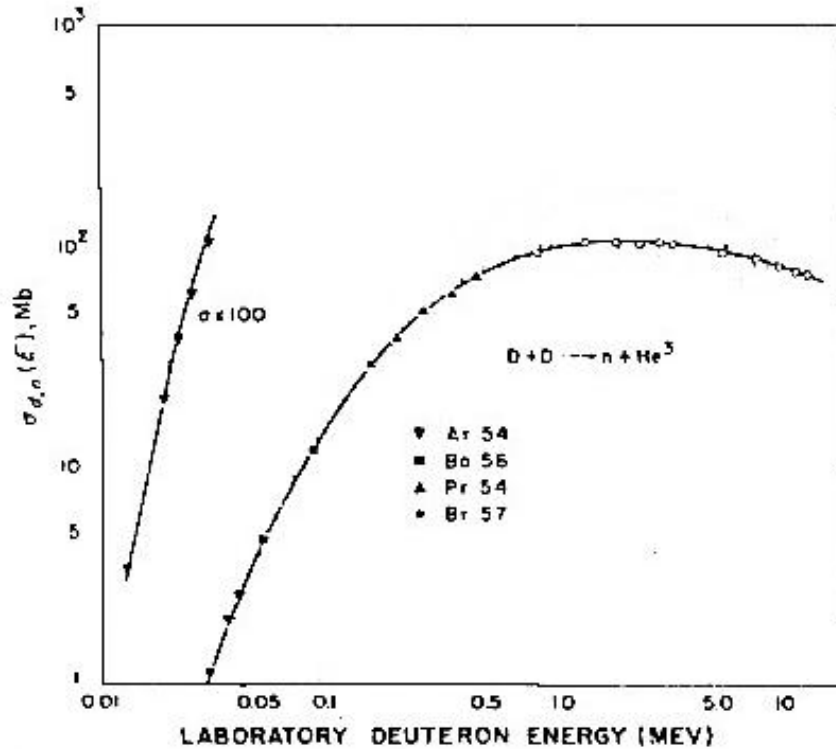
[Figure 4.2] Cross section versus deuteron energy for D + D → n +He^3
reaction taken from [20]. The energy from our machine will be in the 0.01
to 0.05 MeV range.

The incident deuteron energy would be approximately 18.7 keV for the aluminum field, and 43.8 for the iron field. A cross section of ~0.05 mb and ~1 mb respectively would be expected. A deuterium target could be placed in the Faraday cup that would yield a mono-energetic neutron source. The advantage to this is, while charged particles would need to be extracted, the neutrons will not interact with the magnetic field or the chamber, and would thus not need to be extracted. Such a source would be a very useful tool for undergraduate research projects in nuclear physics.

26

REFERENCES

[1] H. W. Geiger and E. Marsden. Philosophical Magazine **6** 25 (1913).

[2] John D. Cutnell and Kenneth W. Johnson. *Physics* (John Wiley & Sons, Inc. 2001)

[3] J. D. Cockroft and E. T. S. Walton, Proc. Roy. Soc. (London). **A136**, 619

[4] J. Rosenblatt *Particle Acceleration* (Barnes & Nobel 1968).

[5] Robert R. Wilson and Littauer Raphael *Accelerators: Machines of Nuclear Physic.* (Anchor Books 1960)

[6] M. S. Livingston and J. P. Blewett *Particle Accelerators* (McGraw – Hill Book Company 1962).

[7]R. J. Graaff, K. T. Compton, and L. C. Van Atta, Phys. Rev. **3** 3 (1933).

[8] M. S. Livingston, *Particle Accelerators: A Brief History* (Harvard UP 1969).

[9] Rolf Wideröe, Archiv für Electrotechnik **21** 387 (1928).

[10] "LANSCE: Facilities/ Linear Accelerator Specifications" http://lansce.lanl.gov/facilities/accelerator.htm. (Viewed Jan 04, 2003).

[11] Lawrence, Ernest O. "The Evolution of the Cyclotron." Nobel Lecture, December 11, 1951.

[12] Milton Stanley Livingston, Ph. D. Thesis, University of California. 1931.

[13] Ernest O. Lawrence and M. Stanley Livingston Phys. Rev **40** 19 (April 1932).

[14] Benjamin V. Siegel and Richard C. Sinnot, Physics Today August 1948.

[15] Fred Niell (private communication)

[16] Jeffrey C. Smith, Undergraduate Thesis, Knox College, 2001.

[17] "Rutgers Cyclotron" http://www.physics.rutgers.edu/~koeth/cyclotron/ (Viewed January 14, 2003).

[18] "Radiokemian Laboratorio" http://www.chemistry.helsinki.fi/radlab/esittely (Viewed January 4, 2003).

[19] Scientific Services Group "Small Production Cyclotrons Designed by TRIUMF." http://www.triumf.ca/welcome/sm-cyclotron.html. Updated Aug 12, 1998. Viewed Jan 13, 2003.

[20] J. B. Marion and J. L. Fowler Eds. *Fast Neutron Physics* (Interscience publishers 1960).