

**THE DESIGN OF A SMALL  
CYCLOTRON**

By

Sharon C. Tuminaro

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

Bachelor of Science

Houghton College

December 2003

Signature of Author.....

Department of Physics  
December 17, 2003

.....

Dr. Mark Yuly  
Associate Professor of Physics  
Research Supervisor

.....

Dr. Ronald Rohe  
Associate Professor of Physics

# THE DESIGN OF A SMALL CYCLOTRON

By

Sharon C. Tuminaro

Submitted to the Department of Physics  
on December 17, 2003 in partial fulfillment of the  
requirement for the degree of  
Bachelor of Science

## **Abstract**

A small cyclotron capable of producing a 45-170 keV proton beam or a 20-85 keV deuteron beam is being designed and constructed at Houghton College. In this design, low pressure hydrogen gas will be ionized by a filament inside the acceleration chamber, which will contain a single RF accelerating electrode. The chamber will be evacuated by a diffusion pump backed with a rotary forepump and a liquid nitrogen cold trap. The magnetic field produced by a permanent magnet (nominal field strength 0.5 T) may be altered using an adjustable pole separation. The motivation, theory, and overall design will be covered in this thesis, with a special emphasis on the design and construction of the vacuum system.

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

## TABLE OF CONTENTS

<b>Chapter 1 ~ Introduction</b> .....	5
1.1 Motivation .....	5
1.2 History .....	5
<b>Chapter 2 ~ Theory of Operation</b> .....	8
2.1 Description of Cyclotron .....	8
2.2 Theory .....	9
<b>Chapter 3 ~ Cyclotron Design</b> .....	12
3.1 Chamber .....	12
3.2 Magnet .....	14
3.3 Vacuum System .....	16
3.4 Electrical Controls .....	22
<b>Chapter 4 ~ Conclusions</b> .....	24
<b>Appendix A</b> .....	25
<b>Appendix B</b> .....	30
<b>References</b> .....	32

## TABLE OF FIGURES

<b>Figure 1.</b> Lawrence's original cyclotron design.....	6
<b>Figure 2.</b> Livingston's 4 inch cyclotron .....	7
<b>Figure 3.</b> The path of an accelerating particle within a cyclotron chamber.....	8
<b>Figure 4.</b> A simplified diagram of the chamber .....	12
<b>Figure 5.</b> A side view of the chamber.....	12
<b>Figure 6.</b> A top view of the cyclotron chamber with components. ....	13
<b>Figure 7.</b> The permanent magnet.....	15
<b>Figure 8.</b> The vacuum system schematic.....	17
<b>Figure 9.</b> Rotary pump schematic .....	18
<b>Figure 10.</b> The CIT-Alcatel rotary pump. ....	18
<b>Figure 11.</b> The cold trap.....	19
<b>Figure 12.</b> The cold trap and diffusion pump .....	20
<b>Figure 13.</b> The diffusion pump schematic .....	21
<b>Figure 14.</b> The plumbing system schematic.....	22
<b>Figure 15.</b> The circuitry for the vacuum system.....	23
<b>Figure 16.</b> Magnetic field measurements for the top pole face of the magnet. ....	25
<b>Figure 17.</b> Magnetic field measurements 3/8 inch down from the top pole face.....	26
<b>Figure 18.</b> Magnetic field measurements 3/4 inch down from the top pole face.....	27
<b>Figure 19.</b> Magnetic field measurements 1 and 1/8 inches down from the top pole face. ...	28
<b>Figure 20.</b> Magnetic field measurements of the bottom pole face.....	29
<b>Figure 21.</b> Control panel for the vacuum system.....	31

## *Chapter 1*

### INTRODUCTION

#### **1.1 Motivation**

A small cyclotron is being constructed in the Houghton College Physics Department for the production of low energy proton and deuteron beams. From deuteron-deuteron collisions, neutrons will be produced at energies of approximately 2.2 MeV that can be used in future nuclear physics experiments which will require a neutron source. These experiments can be used to study properties of nuclei through neutron scattering.

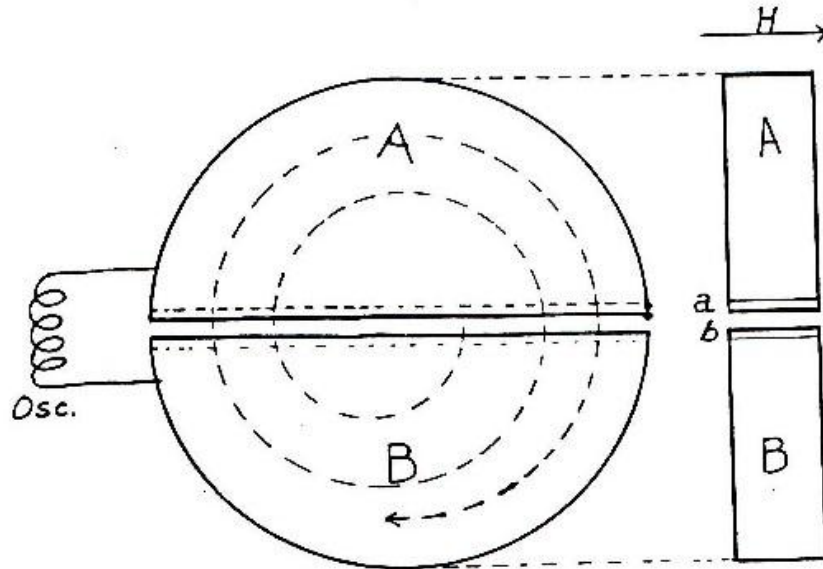
Cyclotrons are useful for small laboratories because they do not require extremely high voltages or the space used by linear accelerators. This particular design is unique in that the cyclotron uses a permanent magnet, where as most other cyclotrons use electromagnets. This design makes the cyclotron more convenient and saves the electricity needed to power an electromagnet.

#### **1.2 History**

The cyclotron was first designed by Ernest O. Lawrence, a member of the faculty of the University of California, in 1930 [1]. It was developed for the purpose of producing high energy particles without the use of high voltages for the study of the nuclear properties of atoms [1]. The original idea was inspired by Rolf Wideröe [2], who suggested using an oscillatory electric field to create a type of linear accelerator [3]. Lawrence modified this idea by changing the particle's path to a circular orbit, and he and his student N. E. Edlefsen presented the original cyclotron design in 1930 [1].

The original design was that of semicircular hollow electrodes between two grids that maintained an electric field free area, and the electrodes were placed in an evacuated chamber that was positioned in a magnetic field. The electrodes oscillated polarity, creating an alternating the electric field to accelerate ionized particles, which traveled in circular motion due to the magnetic field. Lawrence wrote in the original presentation, "Because the radii of the circular paths are proportional to the velocities of the protons the time required for traversal of a semicircular path is independent of the radius of the circle. Therefore once

the protons are in synchronism with the oscillating field they continue indefinitely to be accelerated on passing through the region between the grids, and spiraling around on ever-widening circles gain more and more kinetic energy from the oscillating field” [1].



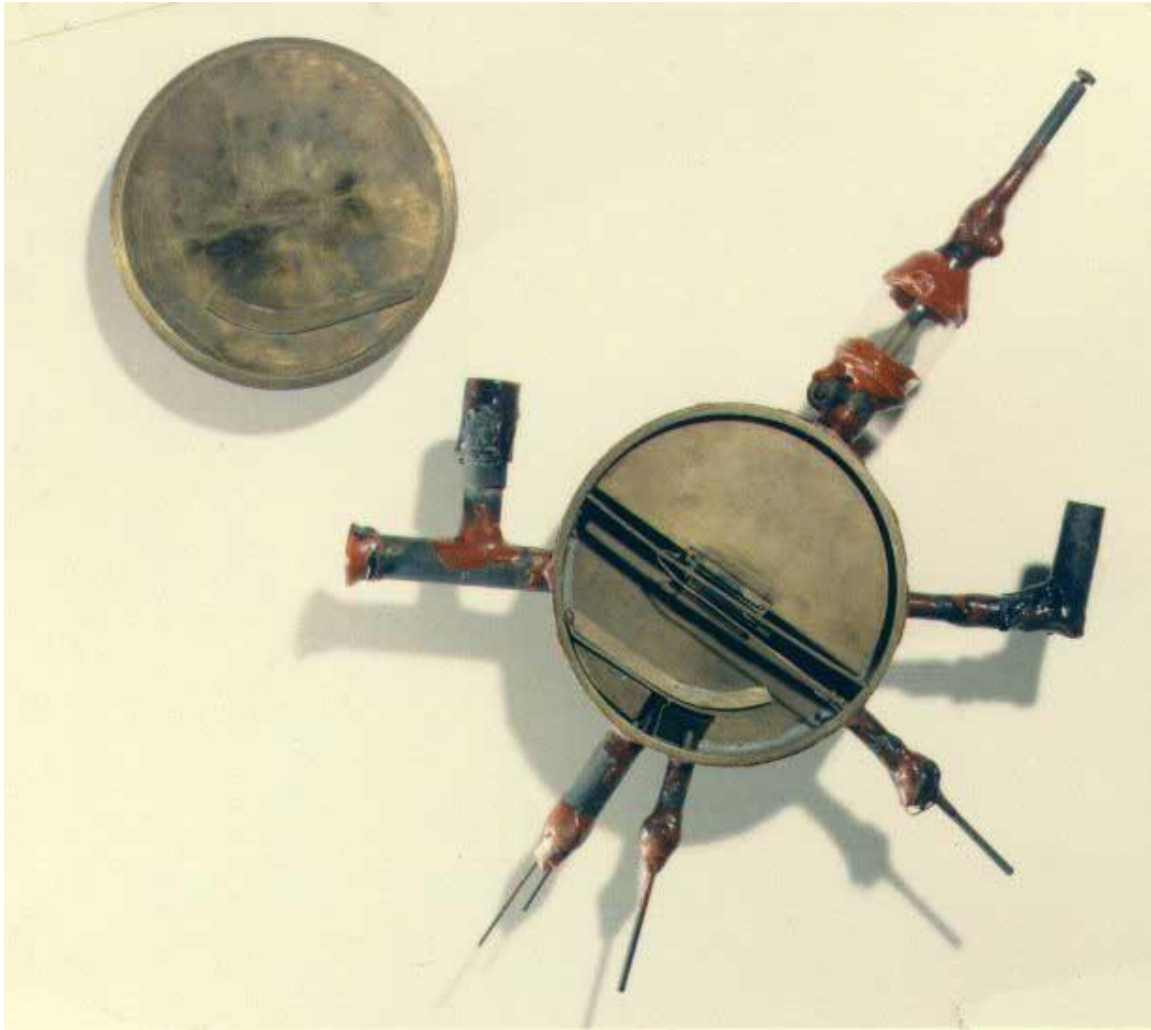
**Figure 1.** The original design consisted of two semi-circular oscillating electrodes within a magnetic field with a grid of wires to create an electric field free area. (The picture is taken from Livingston's thesis written for his doctorate in 1931 [2]).

The design was developed further by another graduate student, Milton Stanley Livingston, who presented it in his thesis for a doctorate in physics in 1931 [3]. The improved cyclotron (Figure 1) consisted of a brass chamber with grids to provide the deflecting potentials and keep the inside of the hollow plates free of an electric field. The chamber was evacuated using a mercury vapor diffusion pump with an oil forepump, and then  $H_2^+$  ions were released into the chamber so that the pressure was at  $2 \times 10^{-5}$  mm Hg. The filament used for ionizing particles was a tungsten radio tube filament coated with oxide, 2 mm in diameter, 2 cm in length. The magnetic field was provided by an electromagnet with a field strength of 5500 gauss. A Faraday cage, retarding grid, and deflecting plates served as a collection system that was used to measure the current in the proton beam. The maximum radius possible with the collection cup was 4.50 cm. The cyclotron was able to produce protons with energies of 80,000 eV with an oscillating potential of only 2 keV [3].

With the cyclotron a functioning success, Lawrence and Livingston were able to build larger models. In 1932, a magnet with an 11 inch pole face was used that produced a field of

14,000 gauss. Protons of 1.2 MeV were produced, using only a 400 V accelerating potential [4]. A larger magnet with a pole face of 27 inches, producing a field of 18,000 gauss, was used in 1934 to obtain hydrogen molecule ions having energies of 5 MeV [5].

Professor Ernest Lawrence received the Nobel Prize in physics in 1939 for his invention of the cyclotron.



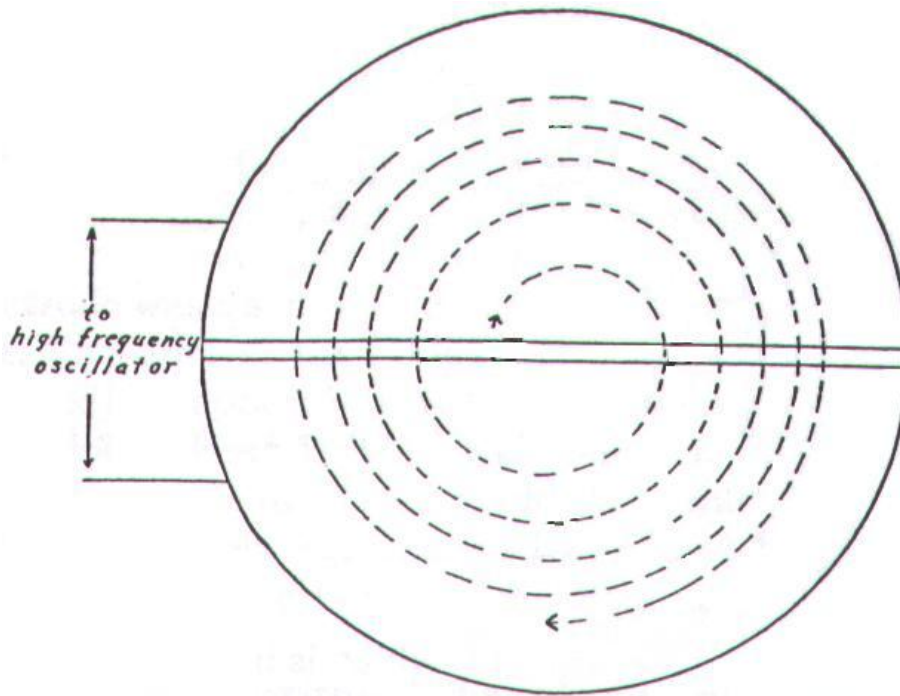
**Figure 2.** Livingston's 4 inch cyclotron is shown above. It was used in the experiments for his thesis, written in 1931. The D-shaped plates are the oscillating electrodes, the attached pipes are connections to the vacuum system and gas source. Other extensions are used as electrical connections to the oscillating circuit, filament, deflecting plate, retarding grid, and several meters.

## Chapter 2

### THEORY OF OPERATION

#### 2.1 Description of Cyclotron

A cyclotron is simply an accelerator which accelerates particles by using a magnetic field and an oscillating electric potential difference. The operating principle of the cyclotron is the fact that as the energy of the particle, and hence its orbital radius, increases, the required oscillating frequency is constant.



**Figure 3.** The path of an accelerating particle within a cyclotron chamber can be seen above. The particle travels with circular motion due to the magnetic field the chamber is in, and the particle accelerates due to the oscillating electric field created by the D-shaped electrodes. (Picture taken from Ref [4].)

A cyclotron consists of a circular hollow evacuated chamber within a magnetic field. The oscillating electric field within the chamber is produced by a pair of electrodes, which are shaped like two “D’s” or semi-circles placed close together to form a complete circle (Figure 2). Gas atoms are released into the chamber and ionized by a filament located at the center. Once the atom is ionized, the oscillating electric field exerts a force on the charged particle, causing it to increase its speed as it oscillates back and forth between the two electrodes.



The magnetic field forces the particle into circular motion. Therefore, the particle accelerates in an ever-widening spiral, resulting in an increase in the particle's energy along with its increasing velocity as the radius of the particle's path increases.

## 2.2 Theory

The basic elements of cyclotron theory are found in the Lorentz force, which describes the force acting on a charged particle in an electromagnetic field,

$$\vec{F} = q(\vec{E} + \vec{v} \times \vec{B}) \quad (1)$$

where  $q$  is the charge of the particle,  $\vec{E}$  is the electric field,  $\vec{v}$  is the particle's velocity, and  $\vec{B}$  is the magnetic field.

Since the electric field only provides an acceleration each time the particle crosses between the two electrodes, the motion of the particle inside the "D" chamber is due solely to the magnetic field. Therefore, the electric field component of the Lorentz Force can be ignored in this region, yielding:

$$\vec{F} = q(\vec{v} \times \vec{B}). \quad (2)$$

Since the velocity is perpendicular to the magnetic field, an inward, radially directed force will be produced:

$$F = qvB. \quad (3)$$

For circular motion to occur, there must be a central force with magnitude:

$$F = \frac{mv^2}{r} \quad (4)$$

where  $m$  is the particle's mass,  $v$  is the particle's magnitude of velocity and  $r$  is the radius of the particle's orbit. The two expressions for the force can be equated to find the velocity:

$$v = \frac{qBr}{m}. \quad (5)$$

Using Eq. 5 to solve for the frequency of the particle's orbit:

$$f = \frac{1}{\tau} = \frac{v}{2\pi r} = \frac{qB}{2\pi m}. \quad (6)$$

This is known as the “cyclotron frequency”. Because the mass and charge of the particle do not change, and the magnetic field is a constant, the frequency of revolution is also constant. The frequency of revolution is then matched with the oscillating frequency of the D-shaped electrodes so that the particle is accelerated twice with each revolution it makes around the chamber. The frequency is not dependant on the radius of the particle’s orbit.

The energy of the accelerated particles can be calculated. The non-relativistic kinetic energy can be used:

$$T = \frac{mv^2}{2} . \quad (7)$$

The non-relativistic expression is used because the velocity of the particle for a small cyclotron is relatively slow compared to light. For example, for the hydrogen ions that will be used in this particular experiment, the particle velocity for the proposed cyclotron can be calculated:  $q = 1.6 \times 10^{-19}$  C,  $B = 0.49$  T,  $r = 6.2$  cm, and  $m = 1.67 \times 10^{-27}$  kg. Therefore,

$$v = \frac{qBr}{m} = \frac{(1.6 \times 10^{-19} \text{ C})(0.49 \text{ T})(0.062 \text{ m})}{1.67 \times 10^{-27} \text{ kg}} = 2.91 \times 10^6 \text{ m/s} , \quad (8)$$

which is only about 1% of the speed of light.

Using Eq (5) in Eq (7),

$$T = \frac{mv^2}{2} = \frac{m}{2} \left( \frac{qBr}{m} \right)^2 = \frac{q^2 B^2 r^2}{2m} . \quad (9)$$

The resulting energies of the accelerated particles are quadratically dependent on the magnetic field and the maximum radius of the particle’s path. Therefore, any adjustments in either of these values will dramatically affect the final energies.

It is anticipated that two ions will be accelerated, protons and deuterons. Final energies for both of these beams have been calculated and can be seen in Table 1.

**Table 1.** The values, charge (q) and mass (m), for protons and deuterons, the magnetic field strength (B), and the radius (r) of the particle path for the small cyclotron are listed below, with the calculated energies for each particle.

Particle	q	B	R	M	$T = \frac{q^2 B^2 r^2}{2m}$
proton	$1.6 \times 10^{-19} \text{ C}$	0.49 T	0.062 m	$1.67 \times 10^{-27} \text{ kg}$	46 keV
deuteron	$1.6 \times 10^{-19} \text{ C}$	0.49 T	0.062 m	$3.35 \times 10^{-27} \text{ kg}$	23 keV

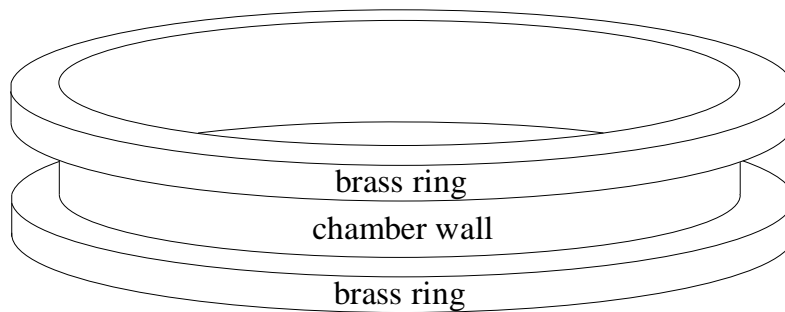
## Chapter 3

### CYCLOTRON DESIGN

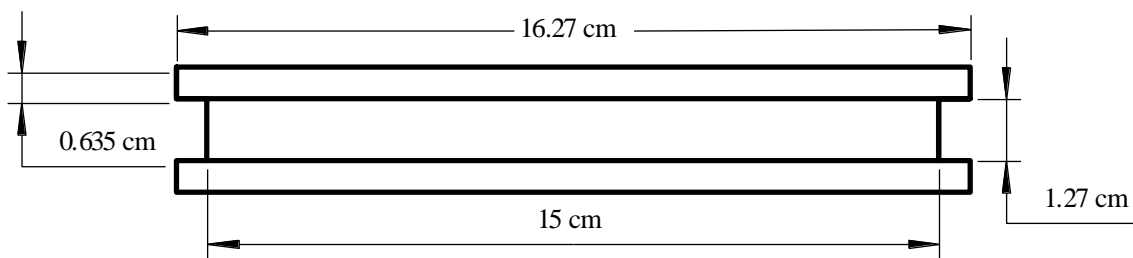
The cyclotron consists of several parts: an evacuated chamber in which the particles are accelerated, a magnet to provide the magnetic field inside the chamber, and a vacuum system. Other important elements are a special circuit that provides the oscillating voltage, a gas system to introduce low pressure hydrogen, and a collection system to monitor the beam current.

#### 3.1 Chamber

The cyclotron chamber, which is first evacuated, then into which the ions are released and accelerated, is made of brass and shaped like a short, round tin can. It consists of three main pieces that are soldered together: a wall that is made of a brass sheet formed into a ring, and two thicker brass rings that sandwich the wall. The inside diameter of the chamber is 15 cm.



**Figure 4.** The chamber consists of a brass sheet formed into a ring capped by two thicker brass rings. It will be fitted in between the pole faces of the magnet.

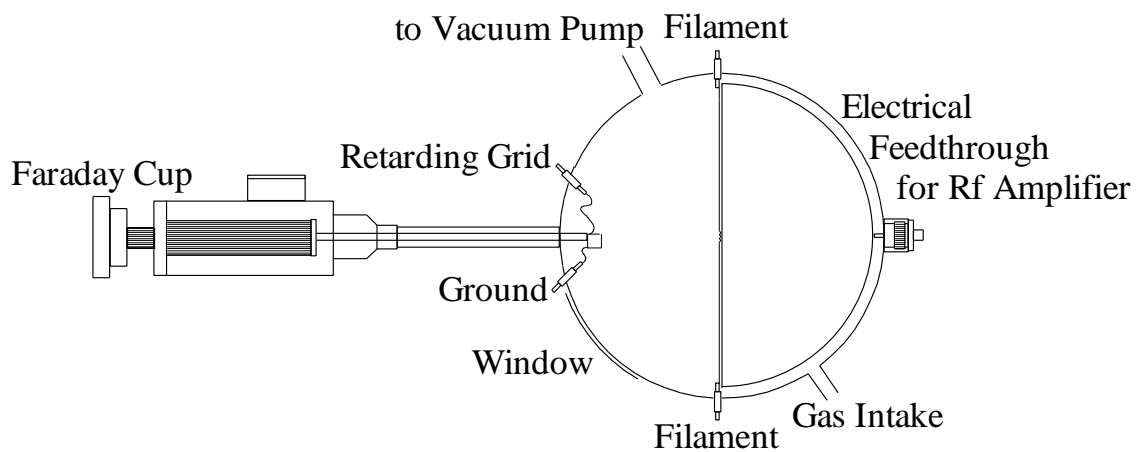


**Figure 5.** A side view of the chamber with its dimensions.

Several openings in the chamber wall, seen in Figure 6, will provide access to the gas source and vacuum system, as well as feed-throughs for the electrodes, filament connections, and several monitoring meters.

Inside the chamber is the electrode, which will be connected to an oscillator circuit. The D-shaped electrode is made of copper.

The chamber will be evacuated to reduce the collisions of the ionized particles with air molecules. Low-pressure ( $1 \times 10^{-5}$  torr) hydrogen gas will be used for the proton beam and deuterium gas for the deuteron beam.



**Figure 6.** A top view of the cyclotron chamber with the openings for the gas source, vacuum system, window, and electrical connections for the filament for ionizing the gas atoms, the oscillating circuit, the ammeter, and the retarding grid for measuring beam current.

The filament to ionize the gas will be located in the center of the chamber, at either the top or bottom of the chamber. The current design calls for a small tungsten filament from an old vacuum tube. A potential difference will be placed across the filament by a DC power source, and the particles ionized by electrons from the filament will then be accelerated by the oscillating electric field.

Other openings in the chamber wall are for connections to the Faraday cup, a device used to measure beam current. A retarding grid prevents secondary electrons, produced when protons hit the filament, from interfering with the current measurements from the ammeter. These measurements provide information for adjusting different parameters to maximize beam current. For example, they can be plotted versus different variables such as path

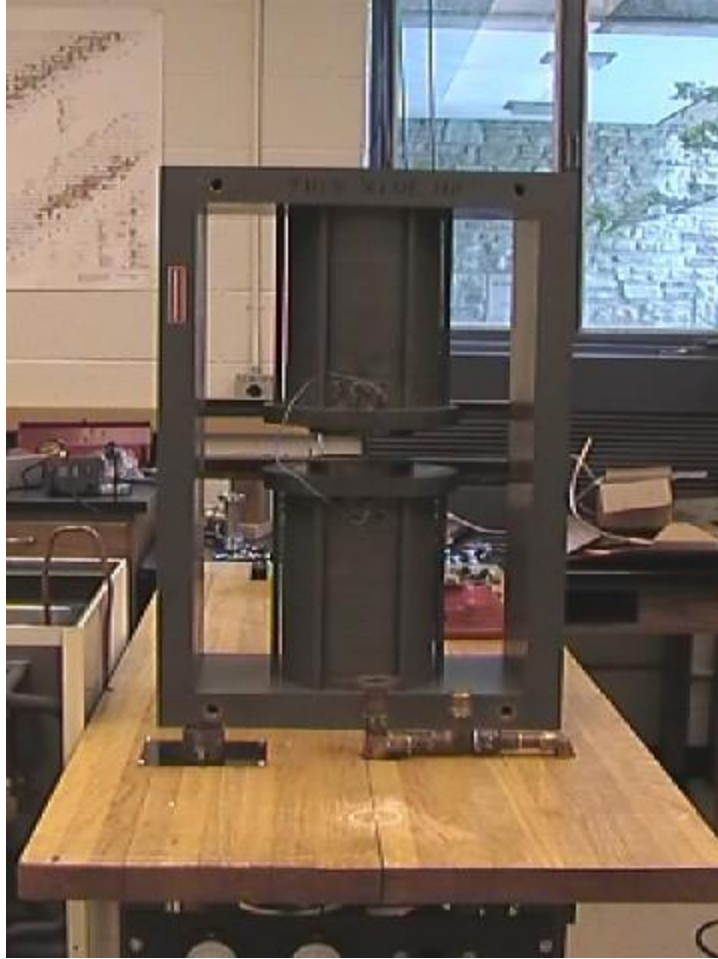
radius, filament voltage, cyclotron frequency, gas pressure, and electrode voltage. Values of these different variables that maximize beam current can be found in the graphs.

The Faraday cup is mounted on a set of bellows taken from a brass valve so that it can be manually extended and retracted. The placement of the cup affects the maximum energy since the energy of the beam is quadratically dependent on the radius of the accelerated particle's path. The maximum beam radius is 6.2 cm, giving a maximum energy of 46 keV for protons and 23 keV for deuterons. Calculations can be seen in Table 1 in Section 2.2.

The last opening in the chamber wall will be the largest and used as a window. The window itself would be made of either glass or Plexiglas, permitting a view of the glow from the ionized gas.

### **3.2 Magnet**

Most cyclotrons use electromagnets, however the magnetic field for the Houghton College cyclotron is created by a large permanent magnet with an average field strength of 0.49 T. (See Appendix 1 for plots of the measured magnetic field between the pole faces.) It was manufactured by Indiana Permanent Magnets, model # 34D552a. The pole face has an area of 183 cm<sup>2</sup>, with an air gap between the faces of 3.8 cm.



**Figure 7.** The permanent magnet used for the Houghton College cyclotron has an average field strength of 0.49 T. It has a pole face area of 183 cm<sup>2</sup> and an air gap length of approximately 4 cm. Since the energy of the beam is largely dependent of the magnetic field, the strength of the field will be increased by inserting iron plates between the pole faces so that they act as an extension of the pole faces themselves and increase the magnetic field strength by simply lessening the air gap between the pole faces. Using the formula for magnetic field strength from *Electromagnetic Fields and Waves* [6]:

$$B = \frac{NI}{A_g \left[ \frac{L_g}{\mu_o \cdot A_g} + \frac{L_p}{\mu \cdot A_p} + \frac{L_y}{\mu \cdot A_y} \right]}, \quad (10)$$

where NI is amp-turns,  $A_g$  is the area of the air gap,  $L_g$  is the distance between the pole faces,  $L_p$  is the length of each pole,  $A_p$  is the area of the cross section of the pole,  $L_y$  is the length of

the yoke,  $A_y$  is the area of the cross section of the yoke,  $\mu_0$  is the permeability of free space, and  $\mu$  is the permeability of iron.

When the iron plates are inserted, the magnetic field is strengthened, and its value can be calculated by using Eq. 10 in the ratio:

$$B = \frac{A_{g,o} \left[ \frac{L_{g,o}}{\mu_o \cdot A_{g,o}} + \frac{L_{p,o}}{\mu \cdot A_{p,o}} + \frac{L_{y,o}}{\mu \cdot A_{y,o}} \right]}{A_g \left[ \frac{L_g}{\mu_o \cdot A_g} + \frac{L_p}{\mu \cdot A_p} + \frac{L_y}{\mu \cdot A_y} + \frac{L_i}{\mu \cdot A_i} \right]} \cdot B_0 = 0.97 \text{ T}, \quad (11)$$

where  $A_i$  is the area of the iron plates and  $L_i$  is the thickness of the plates. The values for this experiment are  $B_0 = 0.49 \text{ T}$ ,  $A_{g,o} = A_g = A_{p,o} = A_p = 183.4 \text{ cm}^2$ ,  $L_{g,o} = 3.8 \text{ cm}$ ,  $L_{p,o} = L_p = 32 \text{ cm}$ , and  $L_{y,o} = L_y = 62 \text{ cm}$ ,  $A_{y,o} = A_y = 132.5 \text{ cm}^2$ ,  $L_g = 1.9 \text{ cm}$ ,  $L_i = 1.9 \text{ cm}$ ,  $A_i = 197.9 \text{ cm}^2$ ,  $\mu_0 = 4\pi \times 10^{-7}$  (unitless, permeability of free space), and  $\mu = 2000\mu_0$ . Substituting these values into Eq (11) yields  $B = 0.97 \text{ T}$ .

The enhanced magnetic field will increase the maximum energy; Table 2 below shows the predicted energies for the new magnetic field values.

**Table 2.** Calculated energies for proton and deuteron beams for the enhanced magnetic field.

Particle	Q	B	r	M	T
proton	$1.6 \times 10^{-19} \text{ C}$	0.97 T	0.062 m	$1.67 \times 10^{-27} \text{ kg}$	173 keV
deuteron	$1.6 \times 10^{-19} \text{ C}$	0.97 T	0.062 m	$3.35 \times 10^{-27} \text{ kg}$	86 keV

### 3.3 Vacuum System

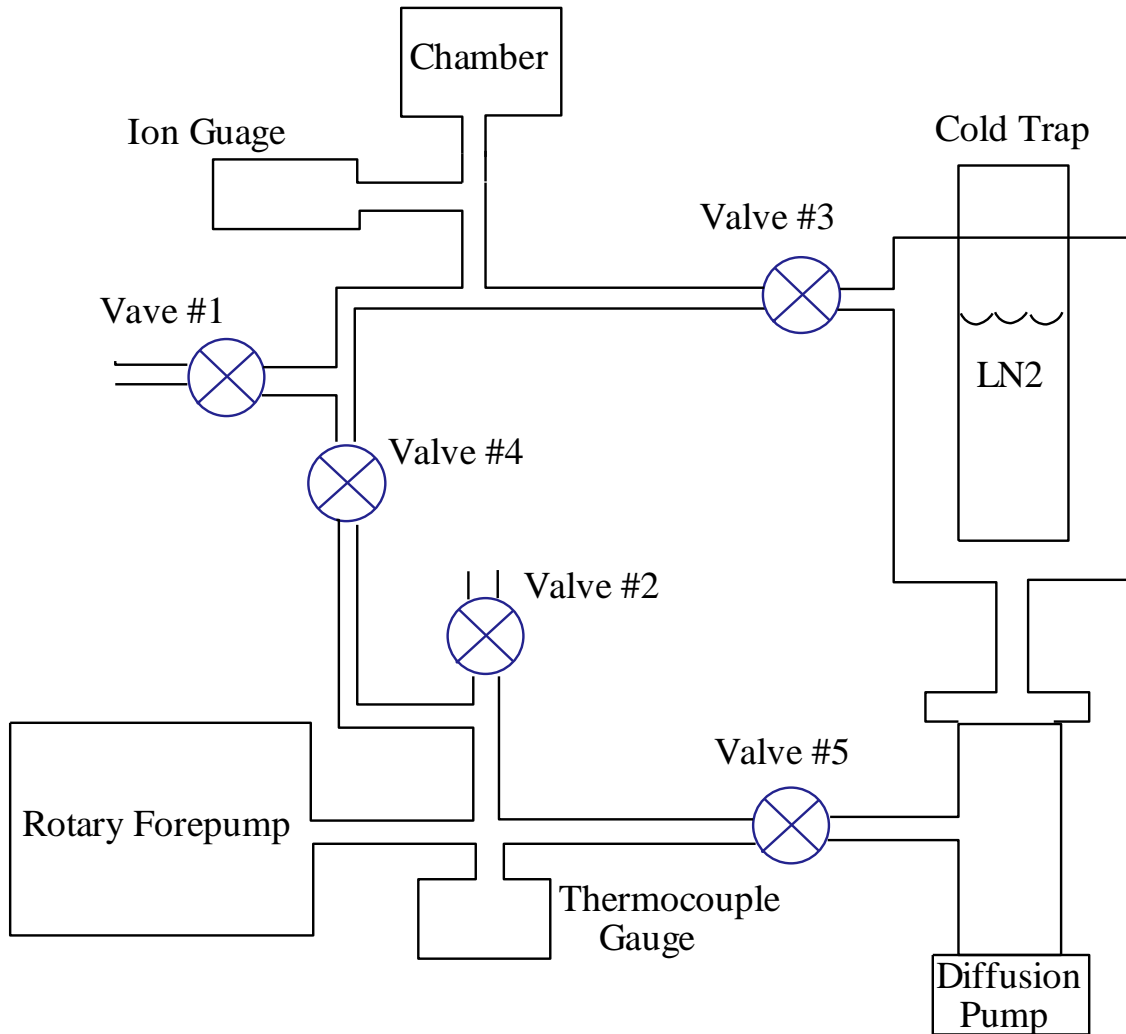
The vacuum system consists of three main components, a CIT-Alcatel rotary forepump, model 2012A, a liquid nitrogen cold trap, and a diffusion pump. The rotary forepump does the initial pumping and will reduce the pressure in the chamber to a few millitorr. The pressure will then be reduced to about  $10^{-7}$  torr by the cold trap and diffusion pump. (Figure 8)

A network of openings and valves are distributed throughout the system so that different parts of the system may be isolated, allowing for air leaks in the system to be more easily



detected and for the main chamber to be opened without letting air into the rest of the system. This reduces pumping time.

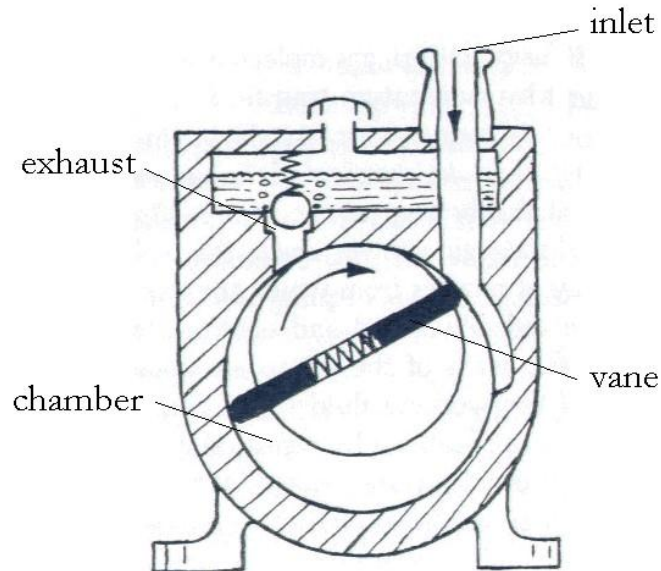
Ion and thermocouple gauges are also provided. The thermocouple gauge, type 6000, measures gas pressures from  $10^{-1}$  mm Hg to  $10^{-5}$  mm Hg, and the ion gauge, model 274 003K, measures pressures from  $10^{-4}$  mm Hg to  $10^{-9}$  mm Hg. [7]



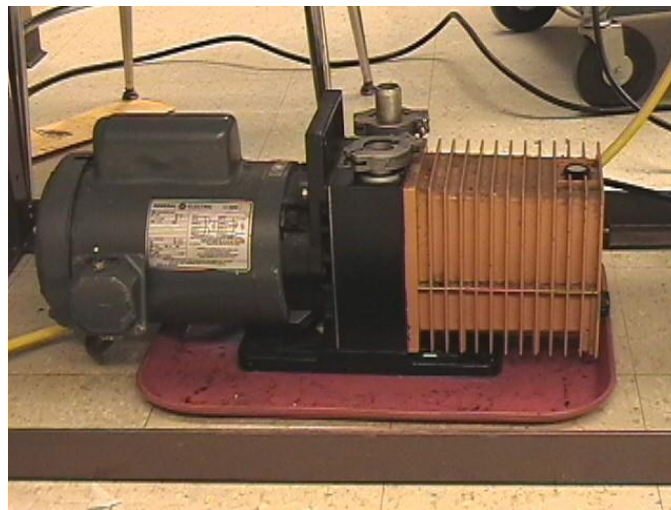
**Figure 8.** The vacuum system consists of a rotary forepump, liquid nitrogen cold trap, and diffusion pump. The valves are placed strategically throughout the system in order that different parts of the system can be isolated. Valves #1 and #2 can release air into the system when necessary. The gauges indicate the pressure in the system and the chamber.

When initially evacuating the system, valves #1 and #2 are closed and all other valves opened. The forepump removes air from the entire system out through an exhaust tube. The forepump is sectioned into two volumes, which are divided by vanes attached to a rotor.

Gas enters one of the volumes through the inlet and is compressed within the chamber. It is then pushed out the exhaust hose through a one-way valve. Lubricating oil seals the space between the vanes and the walls of the chambers. [8]



**Figure 9.** The rotary pump is divided into two chambers where air is compressed by the rotating vanes and forced out through the exhaust tube. (Diagram taken from *Building Scientific Apparatus* [8].)



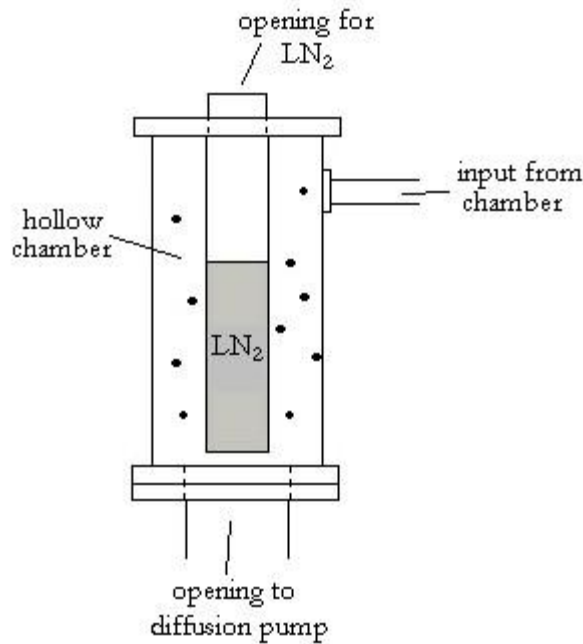
**Figure 10.** The CIT-Alcatel rotary pump does the initial roughing work within the vacuum system and brings the pressure down to a few millitorr.

The thermocouple gauge is attached to the system and measures the pressure based on the heat conductivity of the gas within the system and the filament of the gauge. A heated filament is placed within the gas and cooled by it. The heat conductivity of the gas affects

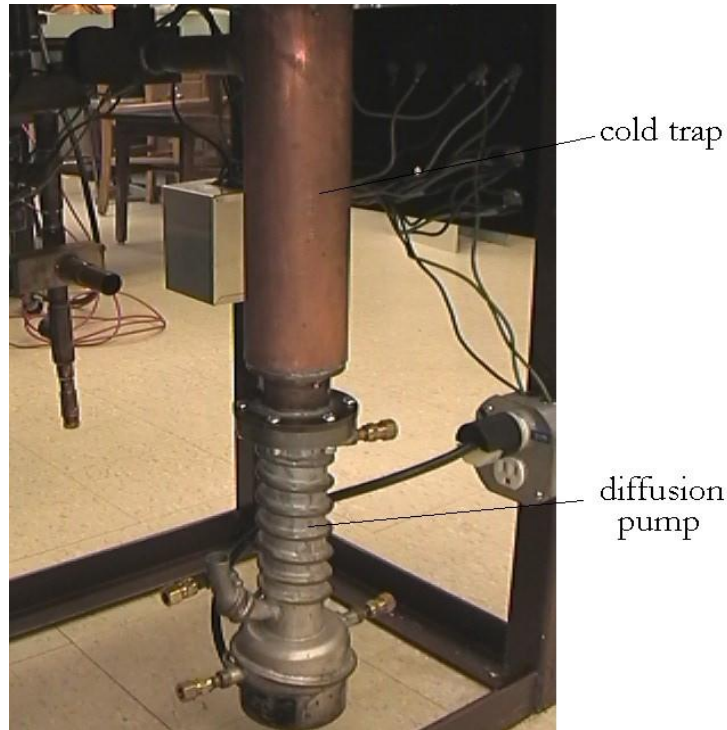
the temperature of the filament, and therefore the conductivity hinges on the gas pressure. The thermocouple gauge is reliable down to  $10^{-5}$  torr, which makes it sufficient for measuring the pressure during the roughing stage.

Once the thermocouple gauge indicates that the pressure is low enough, valve #4 is closed and the silicone oil diffusion pump started. The air pressure in the system must be down to a few millitorr before the diffusion pump is started or the oil in the diffusion pump will scorch, and the vapors will diffuse upward and contaminate the rest of the system. [8]

The liquid nitrogen cold trap works together with the diffusion pump. The cold trap consists of a hollow tube with a tube of smaller radius inside it, creating a small tank within a hollow chamber. (Figure 11) The small tank holds liquid nitrogen, which has a temperature of about  $-196$  °C, so it cools the air surrounding the internal tube. Air molecules flow from the cyclotron chamber into the hollow area of the cold trap, lose kinetic energy because of the cold temperatures, and are pulled down into the diffusion pump by gravity.



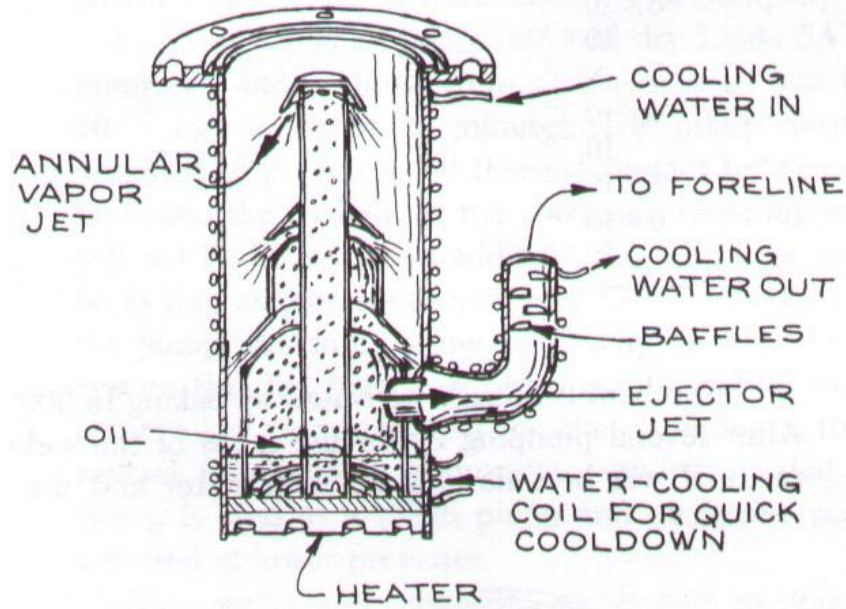
**Figure 11.** The cold trap moves air molecules down into diffusion pump where they can be removed from the system through the forepump.



**Figure 12.** The cold trap is made of copper and holds the LN<sub>2</sub> used to guide the air molecules into the diffusion pump. The diffusion pump vaporizes a working fluid a to move the air molecules out of the vacuum system.

The diffusion pump lowers the air pressure within the system when the pressure is reduced to a few millitorr. Air molecules that enter it from the liquid nitrogen cold trap are removed from the diffusion pump chamber through a momentum transfer.

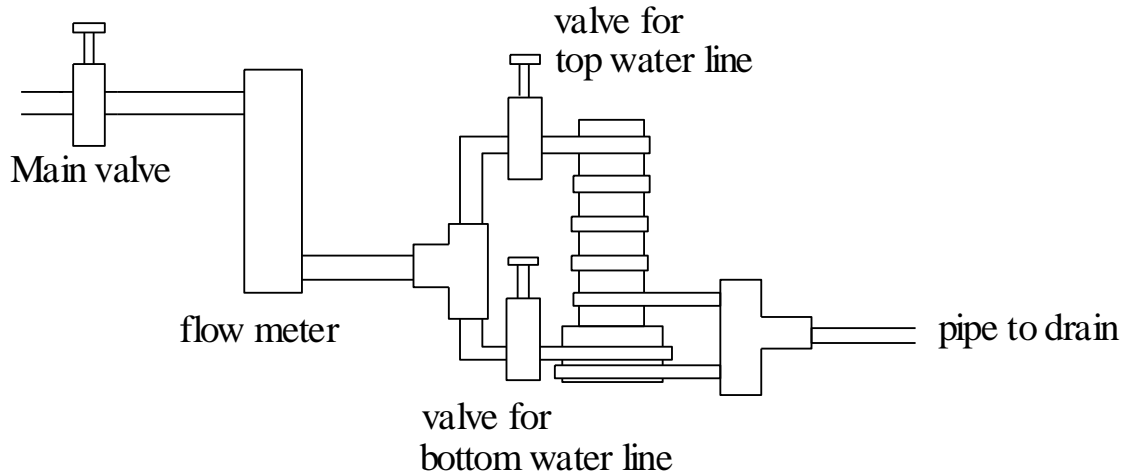
The chamber of the vapor diffusion pump is made of 2 inch Kamlrok and filled with a working fluid, DS-7040-500 silicone diffusion pump oil. A heater on the bottom of the chamber vaporizes the fluid. The vapor is then ejected downward and outward by a vapor-jet nozzle. (Figure 13) The walls of the diffusion pump are cooled by water pipes that are wrapped around the outside of the chamber. The vapor reaches the walls of the pump and is condensed by the cooler temperatures. The working fluid then flows to the bottom of the chamber, where it is vaporized and pumped upwards again. As the vapor is ejected downwards, it drags air molecules down with it to the bottom of the chamber, where the molecules are removed by the roughing pump.



**Figure 13** The diffusion pump removes air molecules from the system through momentum transfer. A working fluid is vaporized by an internal heater and then ejected through nozzles into the chamber. The downward motion drags air molecules downward to the exhaust tube. (This figure is taken from *Building Scientific Apparatus* [8].)

A diffusion pump is capable of pumping down to about  $10^{-9}$  torr. Since the thermocouple gauge cannot accurately measure pressures less than  $10^{-5}$  torr, an ion gauge is needed to measure the final pressure in the system. The ion gauge contained a filament and grid. Electrons released from the filament are drawn to a grid. The space between the filament and grid is open to the chamber, and electrons accelerating toward the grid ionize the residual air molecules. The ionized particles are collected on a plate where their current is measured by a galvanometer. The ratio of the ion current to the electron current from the grid is proportional to the air pressure. [7]

A series of valves and water pipes were installed as a cooling system for the diffusion pump. A connection into one of the lab water lines leads to a control panel that holds the electronic and plumbing controls for the vacuum system. Two valves on the control panel direct the water flow to the two water lines that wrap around the diffusion pump. The top water line cools the walls of the diffusion pump chamber, and the bottom water line cools the part of the pump that holds the heating element. The water lines then rejoin and flow to a drain pipe. A flow meter on the control panel indicates the water flow (in gallons per meter) through the incoming pipe line.



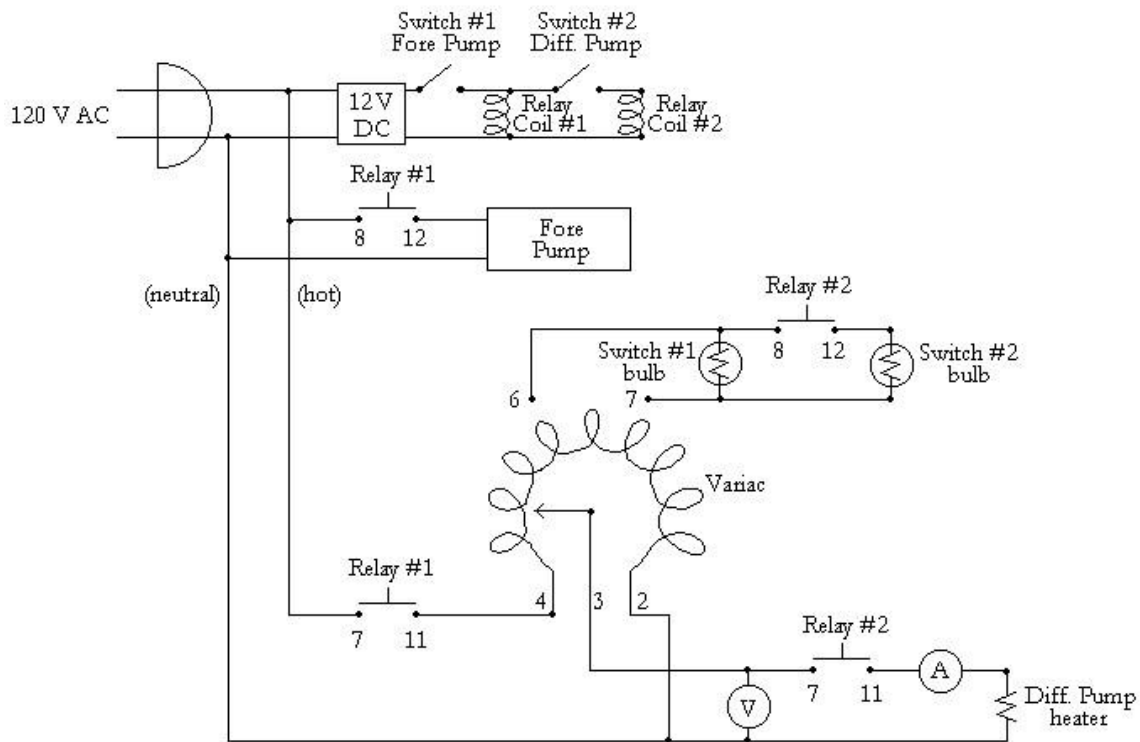
**Figure 14.** The top water line cools the walls of the diffusion chamber so that the vaporized silicone fluid will be cooled and condensed, and the bottom water line cools the part of the diffusion pump that contains the heating element.

### 3.4 Electrical Controls

The electrical controls for the vacuum pumps are very important because the diffusion pump should not be activated unless the fore pump is on and the pressure in the system down to a few millitorr. In order to ensure that the diffusion pump is not turned on prematurely, the circuit is designed so that the diffusion pump cannot be turned on unless the forepump is already running (Figure 15). This is done through the use of relays.

Switch #1 activates coil #1 in the first relay, so that contacts #8 and #12 on relay #1 connect and activate the roughing pump. However, switch #2, which closes the circuit for relay #2 and activates the diffusion pump, cannot power the diffusion pump unless switch #1 is closed. This guarantees that the roughing pump will be running when the diffusion pump is turned on.

The relays operate on the principle of electromagnetism. When the switch is closed, electricity flows, creating a magnetic field in the internal coil. The magnetic field attracts a metal bar which then closes the gap between the contacts. Therefore, when the switch is closed, the contacts are all connected and the circuit is operational. When the switch is opened, all of the contacts act like open circuits and no electricity is permitted to flow.



**Figure 15.** The circuitry for the vacuum system is designed to make sure the diffusion pump is not started unless the forepump is operating.

The variac controls the voltage across the heating element in the diffusion pump, anywhere within the range of 0 to 120V AC, which is supplied from a regular wall socket. A value of about 80 V is typically used. The voltmeter and ammeter monitor voltage across and current through the heating element. Measurements will be made in the future to find the optimal voltage.

## *Chapter 4*

### CONCLUSIONS

As of this time, construction of the chamber and the design of its circuitry has not been completed. The brass rings for the chamber have been assembled, but openings for the various controls and sources have not been cut. The vacuum system has not been tested yet, though testing is projected to occur in the spring of 2004.

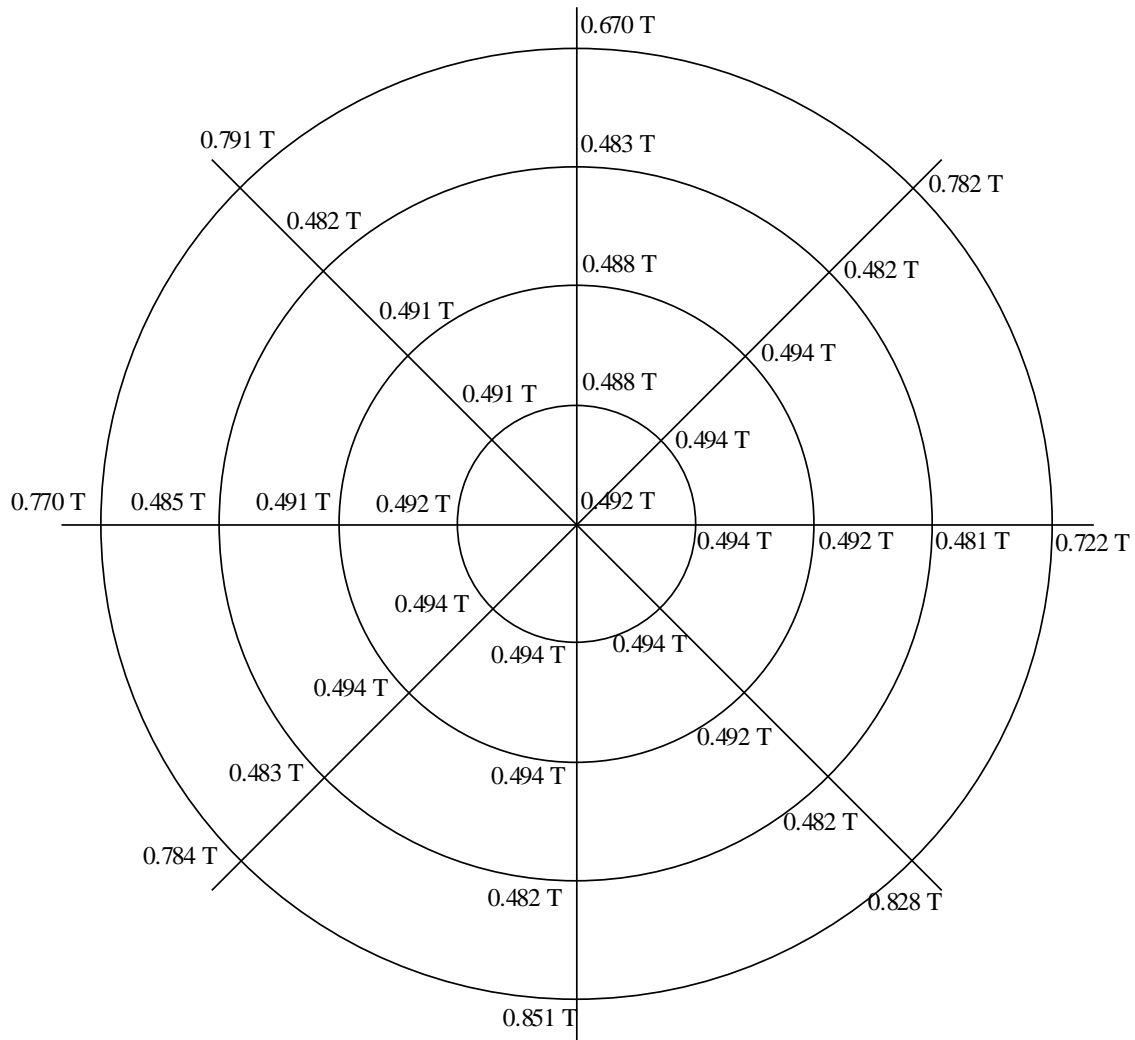
A gas handling system, filament, and RF amplifier have not yet been chosen or assembled. Once assembly of the cyclotron is completed, testing of the particle beam will begin and modifications will be made in order to maximize beam current. It is hoped to use this beam for future nuclear physics experiments in the laboratory.



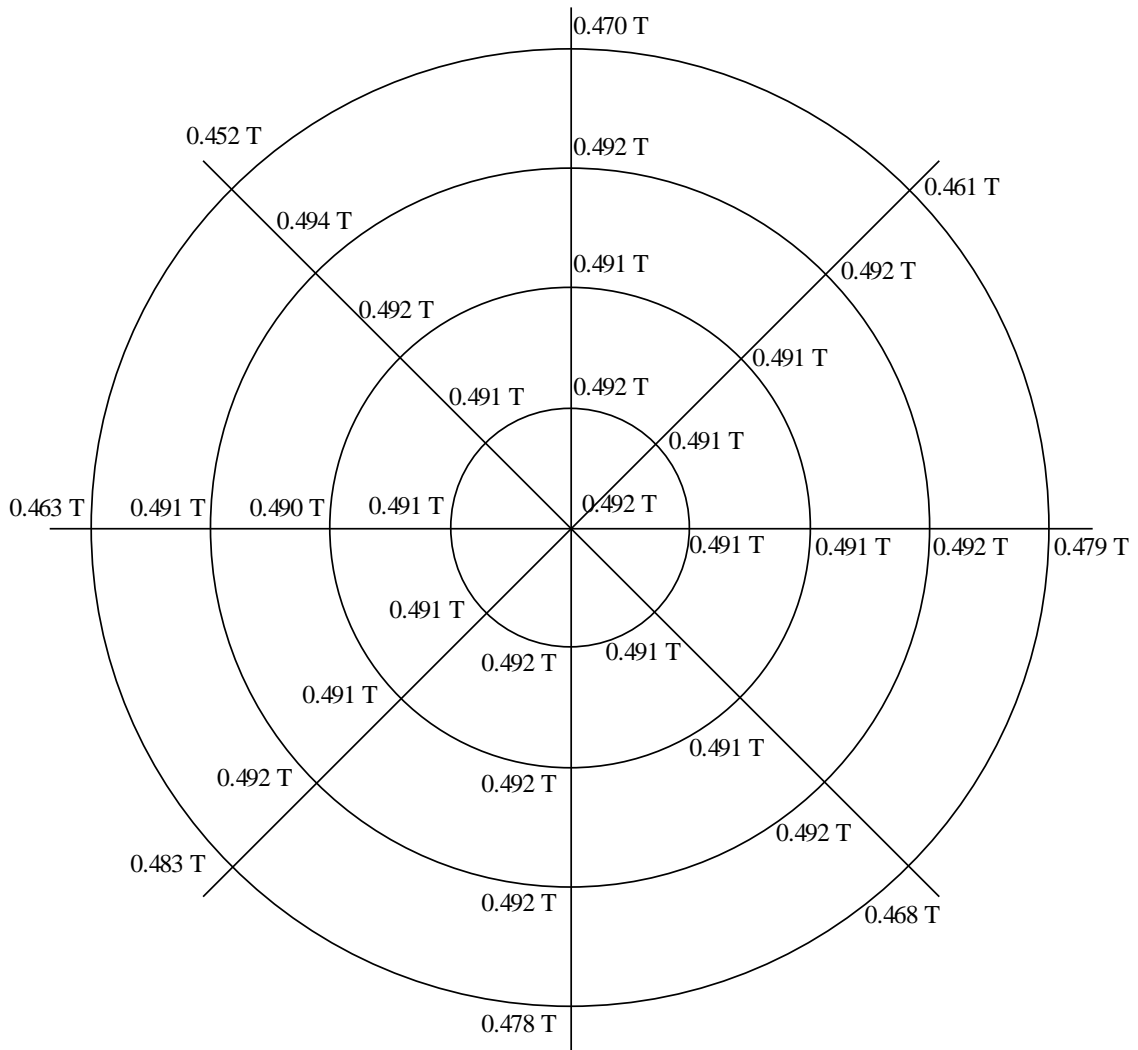
*Appendix A*

MAGNETIC FIELD MEASUREMENT PLOTS

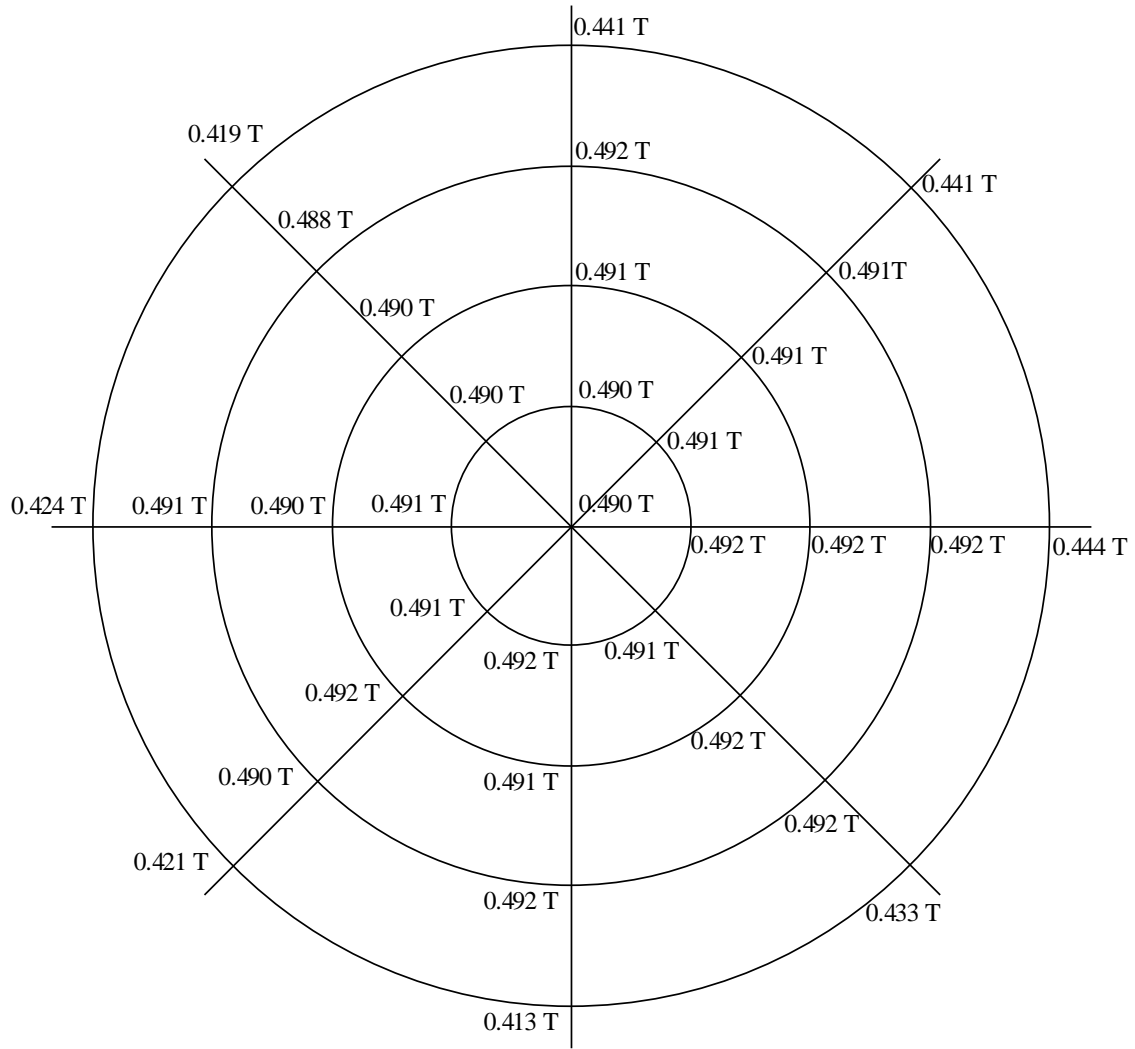
Detailed measurements of the magnetic field were made in planes parallel to the pole faces with the use of grids taped onto the pole faces. Measurements of five of these planes were made with a F.W. Bell Gaussmeter (Model 5070), with 3/8 inch distance between each of these planes of measurement. Measurements began at the center of the pole face and radiated out to a distance of 10 cm. Plots of these measurements can be seen below.



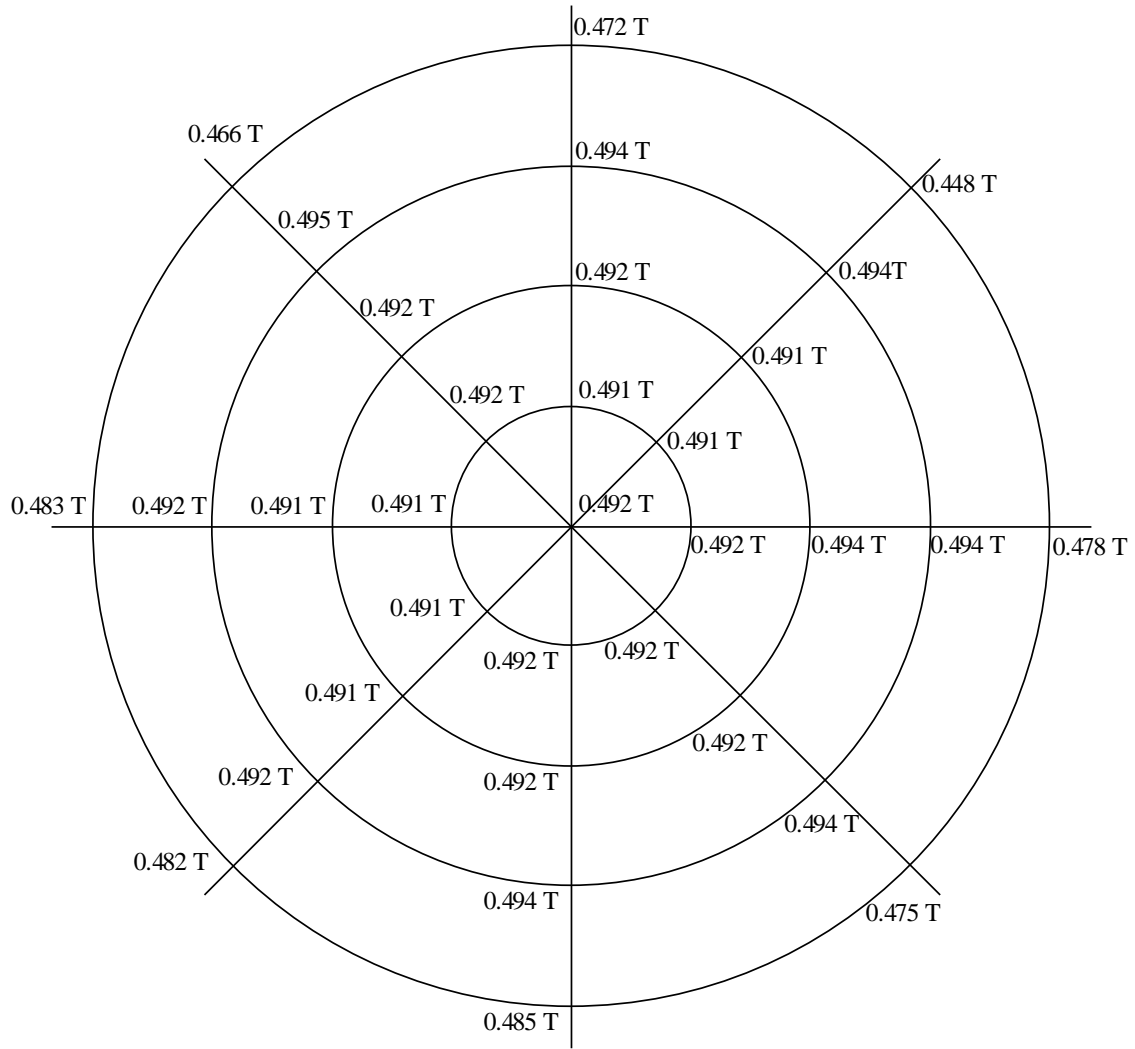
**Figure 16.** Magnetic field measurements for the top pole face of the magnet.



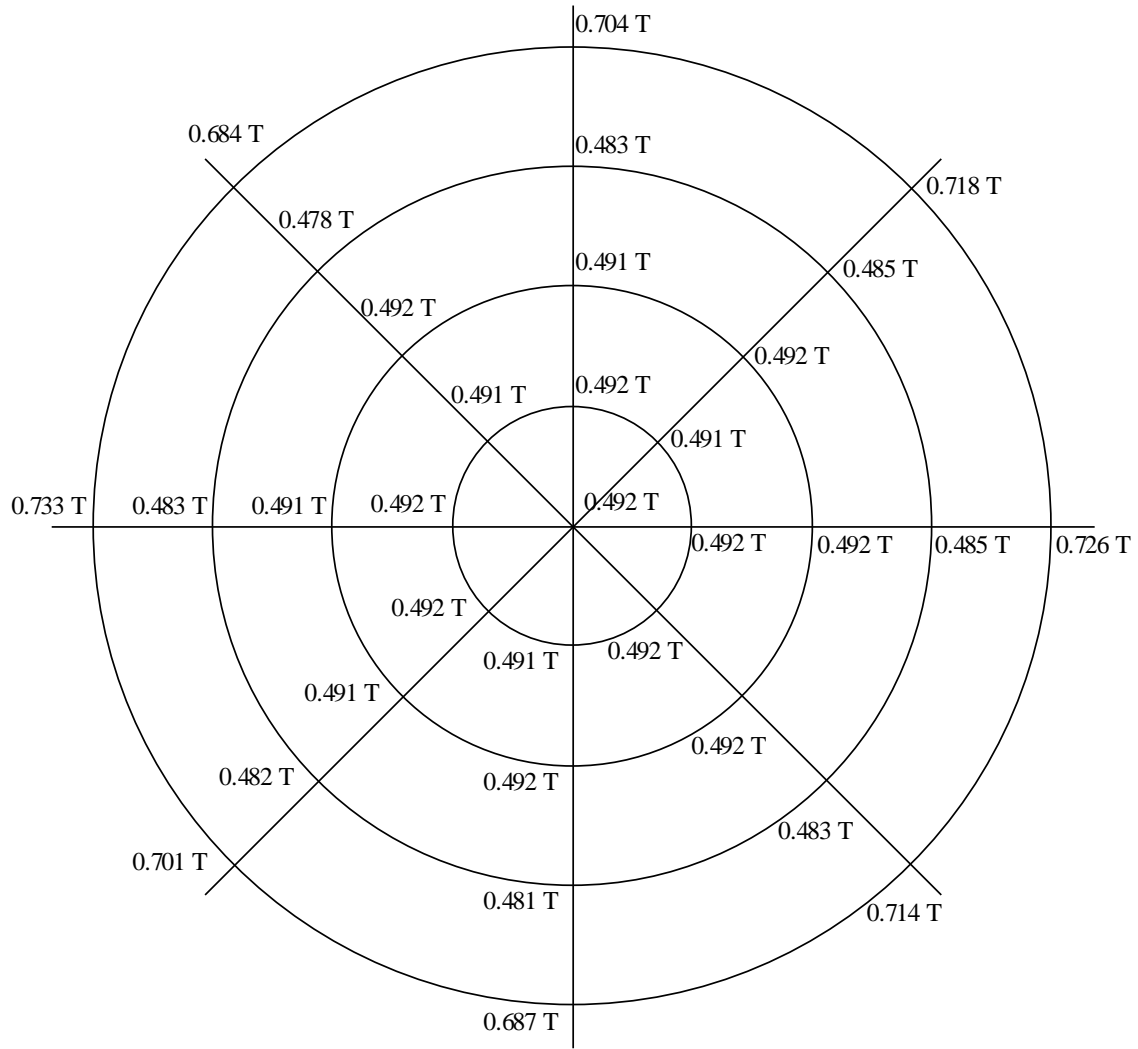
**Figure 17.** Magnetic field measurements 3/8 inch down from the top pole face.



**Figure 18.** Magnetic field measurements 3/4 inch down from the top pole face.



**Figure 19.** Magnetic field measurements 1 and 1/8 inches down from the top pole face.



**Figure 20.** Magnetic field measurements of the bottom pole face.

## *Appendix B*

### PROCEDURE FOR OPERATING THE VACUUM SYSTEM

A specific procedure is required for properly operating the vacuum system. If it is not followed, and the components are started out of sequence, oil scorching or streaming into the chamber may occur, which will require disassembly and cleaning of the entire system.

#### **Procedure**

1. Open valves #3 - #5 and tightly close air release valves #1 and #2.
2. Start the forepump using the indicated push button (labeled "FOREPUMP") on the control panel. The button is lit when the pump is on.
3. Monitor the piranni gauge and wait till it indicates that the air pressure is down to a few millitorr.
4. Fill the cold trap with liquid nitrogen.
5. Close valve #4.
6. Open the two water valves on the control panel (the diffusion pump cooling system).
7. Initiate the diffusion pump with the push button indicated on the control panel (labeled "DIFFUSION PUMP"). Make sure that the forepump is always operating whenever the diffusion pump is on.
8. Adjust the temperature of the heating element by using the variac dial on the control panel to increase the voltage across the heating element. Use the voltmeter and ammeter on the control panel to monitor the circuit.
9. When finished with the vacuum system, turn off the diffusion pump first by shutting off the voltage supply across the heating element. Allow the pump to cool and then shut off the diffusion pump by using the push button on the control panel. Close the water valves on the control panel.
10. Allow the fore pump to run for awhile after the diffusion pump is shut down before shutting it off. Once again, use the forepump button on the control panel.

For any changes that need to be made in the cyclotron chamber while the pressure in the system has been pumped down, close valves #3 and #4. Open valve #1 to release air into that section of the system, then open the chamber. To pump air out of it later, close valve #1, open valves #3 and #4 and proceed to operate the vacuum system.



**Figure 21.** Pictured above are the controls for the vacuum system. The top red button is the fore pump switch and the bottom red button is the diffusion pump switch. The left round gauge is the ammeter, and the round gauge on the right is the voltmeter. The dial on the right side of the panel controls the voltage placed across the heating element. The square gauge indicates the air pressure measured by the piranni gauge.

## References

- [1] E. O. Lawrence and N. E. Edlefsen, *Science* **72**, 376 (1930).
- [2] M. S. Livingston, “The Production of High-velocity Hydrogen Ions without the Use of High Voltages,” Ph.D. thesis, University of California, Apr. 14, 1931.
- [3] R. Wideröe, *Arch. Elektrotech.* **21**, 387 (1928).
- [4] E. O. Lawrence and M. S. Livingston, *Phys. Rev.* **40**, 19 (1932).
- [5] E. O. Lawrence and M. S. Livingston, *Phys. Rev.* **45**, 608 (1934).
- [6] Lorrain, Paul and Dale R. Corson. *Electromagnetic Fields and Waves*. W. H. Freeman and Co.: New York, 1970.
- [7] Strong, John. *Procedures in Experimental Physics*. Lindsay Publications: Bradley, Illinois, 1986.
- [8] Moore, John H., Christopher C. Davis, and Michael A. Coplan. *Building Scientific Apparatus*. Addison-Wesley Publishing Company, Inc.: Reading, Massachusetts, 1983.

Figure 2 was taken from the online archives of the American Institute of Physics at <http://www.aip.org/history/lawrence/epa.htm>.