Design of a 2 MeV Cyclotron

BY THE CYCLOTRON KIDS

PETER V. HEUER

HEIDI T. BAUMGARTNER

http://thecyclotronkids.org

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1. Introduction

1.1 About the Cyclotron Kids

Heidi Baumgartner and Peter Heuer are high school seniors who met at Kopernik Observatory astronomy camp in 2006 and decided to sketch a design of a particle accelerator to pass the time. Although at first just an intellectual exercise, the project became a full-fledged effort when they realized that building one was within their capability, and using a cyclotron they would be able to create antimatter. They began to do extensive research on particle accelerators, and over time drew detailed designs.

Heidi and Peter quickly realized that they would not be able to afford the components of the accelerator by themselves, no matter how much they skimped or scrounged for parts. Unceasingly motivated by their dream of creating exotic particles, they began to write letters to companies and science centers to seek sponsorship of their project. While people were generally supportive of their idea, Peter and Heidi did not find anyone willing to grant them the sum that they required. After an article about them appeared on *SymmetryBreaking,* the blog of the popular particle physics magazine *Symmetry*, they received a donation of some vacuum components. They were also invited to the science radio show *Stump the Professor*, hosted by Princeton mathematics professor Fred Ebert. Shortly after that in May 2008, they sent an email to Fred Dylla of the American Institute of Physics, still seeking help in achieving their goal. He forwarded their message to Andrew Hutton, Assistant Director of Thomas Jefferson National Accelerator Facility in Newport News, VA.

Glad to see young people so interested in physics, Andrew Hutton invited the Cyclotron Kids to build their accelerator at Jefferson National Lab. He offered to help them find all the necessary parts and materials for their cyclotron, and even provided lodging for their stay at the lab. Most importantly, he arranged for Heidi and Peter to be guided by professionals to ensure that their design would be sound as well as safe.

The two Cyclotron Kids worked on making final improvements to their design throughout the 2008/2009 school year, and were prepared to have parts machined by the summer. Currently, the coils and yoke of the electromagnet are being manufactured, to be shortly followed by the vacuum chamber and other components. Heidi and Peter are at the moment building their radiofrequency electronics system.

Looking ahead, the accelerator will hopefully be completed in late 2009 or early 2010. After the Cyclotron Kids attain their first proton beam, they will spend time perfecting their accelerator and testing various configurations of its components. Within the next few years, they will experiment with antimatter production and other interesting applications of their cyclotron.

1.2 Key Design Information

Our main goal in building the cyclotron is to create antimatter through pair production from proton collisions (12.1). This reaction requires a minimum energy to occur, which determining our required energy of 2.045 MeV (3.1).

Required Energy	2.045 Mev (3.1)
Theoretical Max. Energy	2.85 MeV (2.2)
Dee Diameter	12’’
Magnetic Field Density	1.6 Tesla (8.1)
Cyclotron Frequency	24 MHz (2.3)
Number of Beam Rotations	240 Turns (2.4)
Vacuum in Chamber	10^{-7} Torr, ~10^{-5} with H_2
Design Beam Current	2 mA

The equation for the energy of the beam is:

$$K.E. = \frac{q^2B^2r^2}{2m} \text{ (2.2)}$$

The energy of the cyclotron can be increased by either increasing the magnetic field density (B) or the radius of the dees (r). Since increasing the diameter of the dees increases the size and thus the cost of the magnet, the magnetic flux density should be maximized. Most iron magnetically saturates at approximately 1.7 Tesla, so our magnet is designed for to yield a maximum of 1.6T.

With a 1.6 Tesla field, a dee diameter of 12’’ gives us a theoretical maximum energy of 2.85MeV.

The frequency of an ion’s orbit in the magnetic field equals the frequency of the oscillating voltage applied to the dee. To solve for the frequency, we apply the formula:

$$f = \frac{Bq}{2\pi M} \text{ (2.3)}$$

Thus we find our maximum operating frequency, 24 MHz.

In order to observe a significant number of pair production events, we need a minimum of .0126 Coulombs of protons striking a target. Assuming the target is irradiated in 100 seconds, we require a beam current of 126 µAmperes (5.4). Our design can produce a beam current of up to 200 mA (5.4), giving us a safety margin.

2. About the Cyclotron

2.1 History of the Cyclotron

The Cyclotron was conceived by Ernest Orlando Lawrence in 1931, and was fabricated and further developed with the help of Stanley Livingston. Before their invention, the foremost method of charged particle acceleration was using a linear series of vacuum tubes charged with an electrical potential that progressed down the tubes, pulling with it the accelerating particle. Lawrence's stroke of genius was his realization that much higher energies could be attained in a smaller vacuum chamber if the particle's path was confined to a circle using a magnetic field. In this system, the particle would be repeatedly accelerated by the same electrodes that oscillated in electrical potential at a specific frequency. He initially called his idea a "proton merry-go-round," and it officially became known as the cyclotron. His invention earned him the Nobel Prize in physics in 1939.

2.2 Cyclotron Operation

The cyclotron consists of two hollow D-shaped electrodes called dees, each excited with an oscillating electrical potential. A strong, uniform magnetic field orthogonal to the plane of the dees is created by placing the dees between the poles of an electromagnet. The acceleration takes place in an evacuated chamber, which is necessary in order to prevent the charged particles from colliding with air molecules and scattering. The particles to be accelerated are formed in the center of the dees, typically with a device that ionizes a gas. They are drawn into the dee of opposite charge of the ion. The dees then switch polarity and the ion is accelerated into the opposite one. As the ion moves, its path is constrained to a circular shape by an axial magnetic field. As the particle gains energy from each acceleration across the gap between the dees, its radius of curvature increases and it spirals further away from the center. When it attains the desired energy, its path can be intercepted by a target or detector. It could also be extracted from its spiral path by means of an electrostatic deflector.

> *"Dr. Livingston has asked me to advise you that he has obtained 1,100,000 volt protons. He also suggested that I add 'Whoopee'!"*
>
> —Telegram to Lawrence from his secretary on August 3rd, 1931

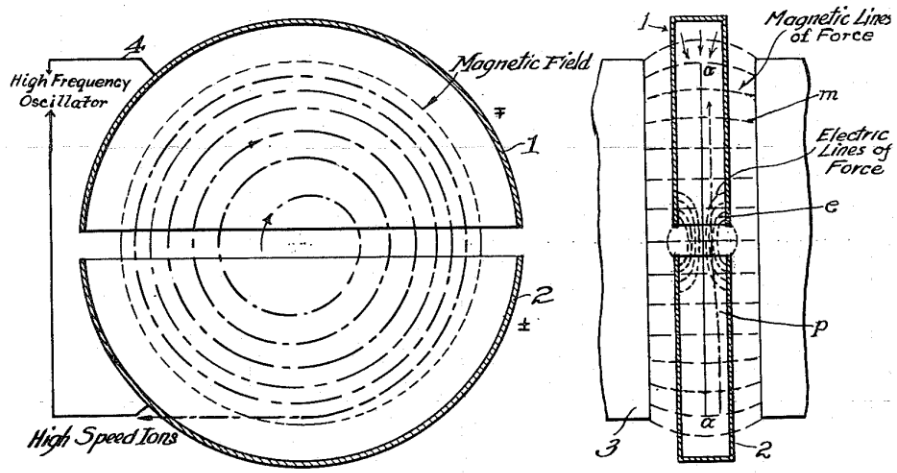


Fig. 2.1 Cyclotron schematic from E.O. Lawrence's original patent[1]

In practice, it is possible to achieve the same effect with a single dee and a "dummy dee" that is simply a grounded piece of metal with an opening of the correct size. The single electrode is driven by the oscillating potential and repeatedly pushes and pulls the particles being accelerated across the gap between the dee and the dummy dee. As there is no electric field inside of the dee, the acceleration only takes place via the electric field in the gap.

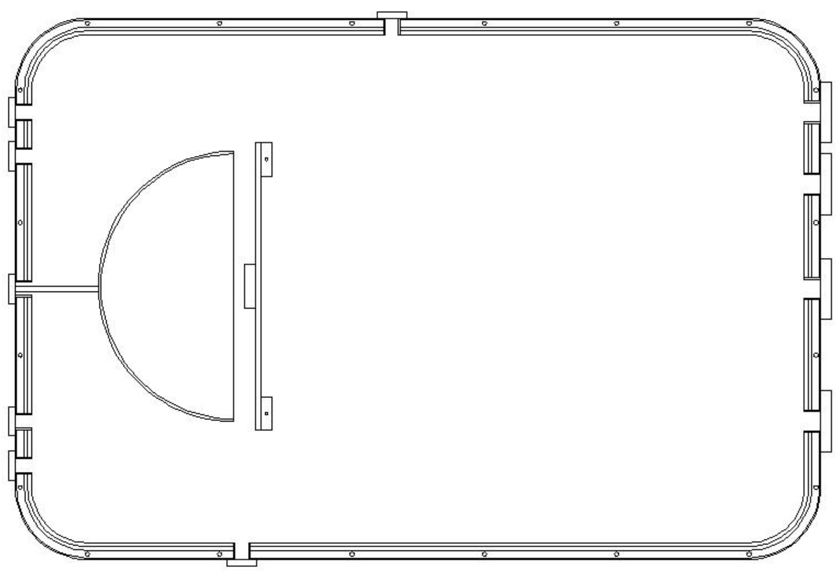


Fig. 2.2 Vacuum chamber with only one dee

[1] Lawrence, O. Ernest. "Method and apparatus for the acceleration of ions." U.S. Patent 1948384 20 Feb. 1934.

2.2 Force, Velocity, Energy

The equations relating the parameters in a cyclotron are derived as follows.

The force on a particle in a magnetic field is given as:

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

Since a magnetic field causes a charge's path to follow a circular path, the magnetic force on a particle in such a field will equal the centripetal force (as all values are ideally consistently orthogonal, sine terms and vector signs are omitted):

$$qvB = \frac{mv^2}{r}$$

$$v = \frac{qBr}{m}$$

Using the definition of kinetic energy and substituting the above term for velocity:

$$K.E. = \frac{1}{2}mv^2 = \frac{1}{2}m\left(\frac{q^2B^2r^2}{m^2}\right)$$

$$K.E. = \frac{q^2B^2r^2}{2m}$$

2.3 Oscillation Frequency

The period of cyclotron (denoted by τ), is defined as the time it takes for the accelerated particle to complete one circular orbit in the magnetic field. It also is the period of the oscillation of the driving electric potential placed on the dee. The length of a circular orbit divided by the velocity at which the particle is traveling yields τ:

$$\tau = \frac{2\pi r}{v} = \frac{2\pi r}{\frac{qBr}{M}}$$

$$\tau = \frac{2\pi M}{Bq}$$

The frequency in Hertz is the reciprocal of τ:

$$f = \frac{1}{\tau} = \frac{Bq}{2\pi M}$$

Angular frequency, ω, is also often used to describe the cyclical motion of charged particles in the cyclotron.

$$\omega = \frac{2\pi}{\tau} = 2\pi f$$

$$\omega = \frac{qB}{M}$$

2.4 Beam Revolutions

It is often useful to know the number of revolutions that the beam makes during the time it is being accelerated.

Each time the particle traverses the electric field across the gap, it gains a certain amount of energy. We apply a 10kV potential over the 2 centimeters of the gap, an electric field strength of 500,000 V/m. The particle gains 10keV on each revolution, until it attains the final energy of 2.4 MeV or more. Thus a perfectly synchronous particle makes a minimum of 240 revolutions. The spacing between revolutions narrows with increasing radius.

3. Proton Energy Requirements

3.1 Minimum Energy for Pair Production

Our goal is to create and detect positrons, which are the antimatter counterpart of electrons. They are formed in a process called pair production, so named because a positron and electron are simultaneously created as a pair. The mechanism by which pair production would occur from colliding a proton beam with a stationary target is from the decay of a virtual photon that mediates the electromagnetic interaction between the proton and a nucleus. If the photon is the correct energy in the gamma range, it may decay into an electron-positron pair. The likelihood of this reaction occurring is small, but measurable.[2]

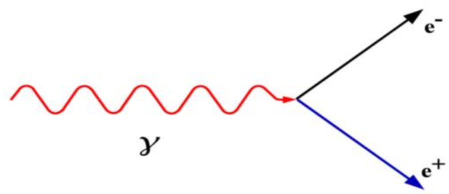


Fig. 3.1 Pair production Feynman diagram

In order for pair production to occur from a proton collision, the incident particle must have a certain minimum energy. Contrary to what one may think, the energy that needs to be added to an incident particle in order to create secondary particles is actually much higher than just the rest energy of the secondary particles. This is only true in the center-of-mass frame between the particles and not the lab frame. For example, the rest energy of an electron and positron is 0.511 MeV. To create a pair, the proton must be accelerated to at least 2 x 0.511 MeV more than its rest energy, but this is only within the center-of-mass frame. With respect to the lab frame of reference, the proton actually needs more energy to provide the secondary particles with some initial velocity as well.

To do this, we must consider the particle four-vectors with respect to different reference frames.

In the lab frame, one proton is accelerated and the other, in the target, is stationary. The four-vectors of the two protons are given as:

$$p_1 = \gamma(1,0,0,\beta)938.27231\,MeV$$

$$p_2 = (1,0,0,0)938.27231\,MeV$$

Where γ and β are the relativistic factors for the incident proton in the laboratory frame.

[2] Stephens , W.E., Staub, H. "Search for Pair Production ". Physical Review Volume 109 No. 4 . Feb 15, 1958. <http://prola.aps.org/abstract/PR/v109/i4/p1196_1>.

Before the collision, the protons have the following 4-vectors in the center-of-mass frame (in which the protons have equal and opposite velocities pointing toward the center of mass):

$$p_1 = \gamma_{cm}(1,0,0,\beta_{cm})938.27231\ MeV$$

$$p_2 = \gamma_{cm}(1,0,0,-\beta_{cm})938.27231\ MeV$$

In the same frame of reference, after the collision the electron, positron, and protons have the 4-vectors:

$$p_1 = (1,0,0,0)938.27231\ MeV$$

$$p_2 = (1,0,0,0)938.27231\ MeV$$

$$p_{e-} = (1,0,0,0)0.51099906\ MeV$$

$$p_{e+} = (1,0,0,0)0.51099906\ MeV$$

The energy conservation between conditions before and after collision in the center-of-mass frame gives:

$$\gamma_{cm} = \frac{mc^2 + m_c c^2}{m_p c^2} = 1.00054462$$

We can rearrange the Lorentz factor using the frame-invariance of the dot product before and after the collision:

$$\gamma = \gamma_{cm}^2(1 + \beta_{cm}^2) = 2\gamma_{cm}^2 - 1$$

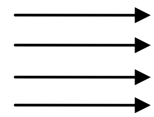
Therefore, the required kinetic energy is:

$$K.E. = (\gamma - 1)938.27231\ MeV = 2(\gamma_{cm}^2 - 1)938.27231\ MeV$$

$$K.E. \approx 2.045\ MeV$$

3.2 Visualization

<u>Laboratory Frame</u>

Before	**After**
	
$\beta_1 = \beta = \frac{v_0}{c}$ $\beta_2 = 0$	All particles move with velocity $v \approx \frac{v_0}{2}$

<u>Center-of-Mass Frame</u>

Before	**After**
	
$\beta_1 \approx \frac{v_0}{2c}$ $\beta_2 \approx -\frac{v_0}{2c}$	All particles at rest.

4. Vacuum Chamber

The vacuum chamber slides between the poles of the electromagnet and is necessary to stop stray gas molecules, like air, from interfering with the proton beam. In order to pass through the walls of the vacuum chamber, cables and lines are placed on vacuum feedthroughs mounted on flanges that bolt to the side of the chamber.

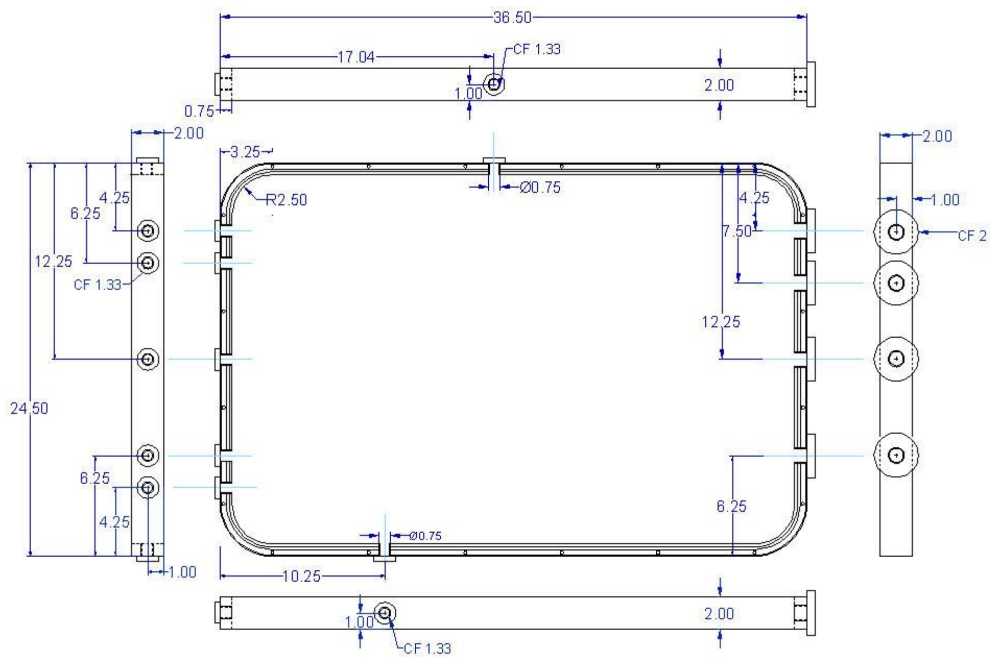


Fig. 4.1 Vacuum chamber with dimensions

4.1 Physical Details

The vacuum chamber consists of a 36.5’’x 24.5’’ steel chamber with a top and bottom lid. The walls are made of 3/4’’ thick steel bars rolled to the specified radii. The top and bottom are made of 3/16’’ steel plates. The bottom plate is welded to the chamber wall, while the top plate is bolted on for easy removal. The entire height of the chamber is 2”.

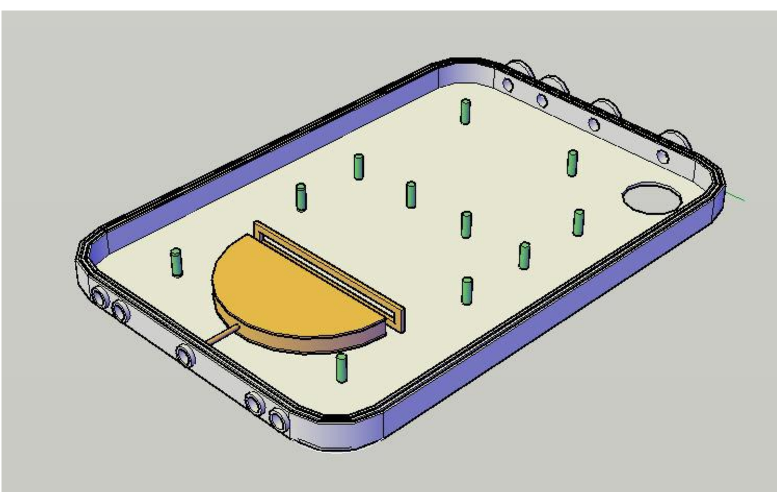


Fig. 4.2 3D rendering of vacuum chamber

The vertical space in the interior of the chamber has to be kept as large as possible for equipment to be able to fit. However, the overall height cannot exceed 2”, and thus the top and bottom plates of the chamber are made as thin as possible, 3/16”. However, the top and bottom plates of the chamber would bow and possibly even implode if they did not have more points at which they were supported. This is why there are cylindrical steel supports tack-welded to the bottom of the chamber, placed in such a way as not to interfere with the positioning of any essential components, and not allowing for any portion of the area of the chamber to deflect any more than a few hundredths of an inch.

A significant factor in the design of a vacuum system is the conductance of the vacuum line. Conductance is defined as the capacity to allow a volume of gas to pass from one end of the vacuum line to the other in some unit of time. In other words, higher conductance means more efficient pumping and thus better vacuum. Conductance can be improved by using larger diameters of tube and by avoiding bends in the vacuum pipe. For these reasons, we decided to extend the chamber out of the magnet and mount the vacuum pump underneath the chamber instead of through a port on the side like the other feedthroughs. This allows us to use both a larger tube (4'' rather than 2 ¾'') and avoid a 90° bend.

All objects inside the chamber must be "vacuum-safe." Ordinary electrical insulation cannot be used in very low pressure vessels, the plastic outgases compounds that contaminate the vacuum. Instead of plastic wire insulation, we use ceramic "fish spine" beads to insulate wires that are OFC (oxygen-free copper). We also have to take care to carefully clean all vacuum surfaces with isopropanol or acetone before sealing the chamber and pulling vacuum. The chamber must be assembled in a clean environment, and anyone handling parts must wear gloves.

4.2 Vacuum Ports

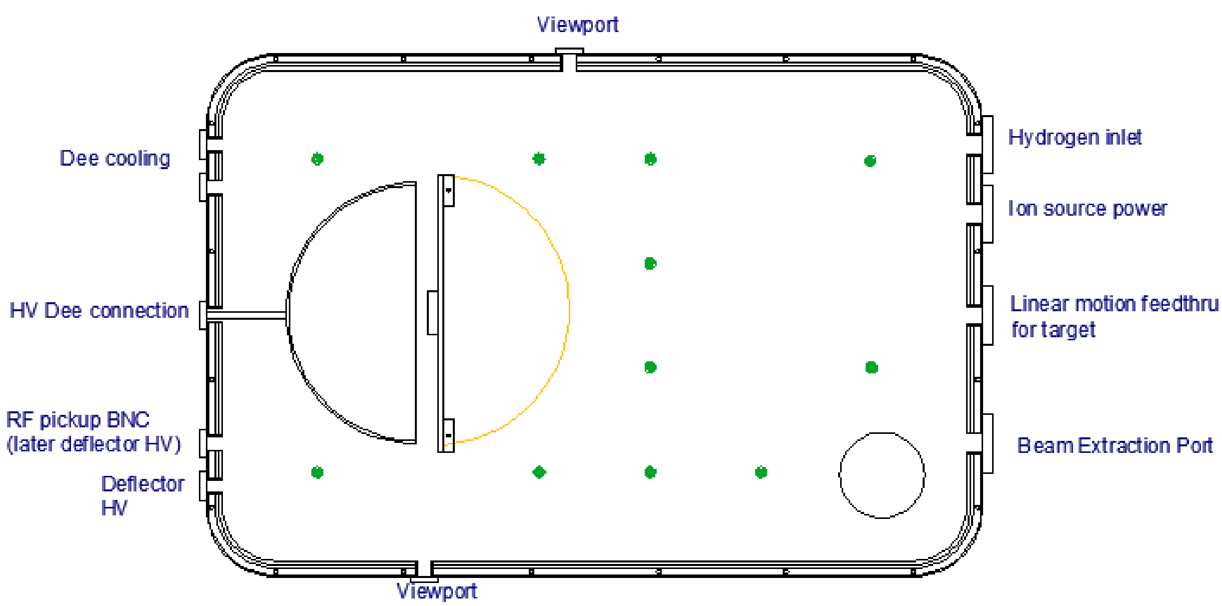


Fig. 4.3 Vacuum chamber with labeled ports

As specified in the above technical drawing, most of the vacuum ports are CF 2 3/4'' vacuum flanges welded onto tubes welded into the chamber. The five ports on the left side of the chamber, on the side of the dee, are CF 1 1/3'' flanges. This side of the chamber is slid through the magnet poles when the chamber is removed. The vacuum port on the bottom of the chamber is a CF 6 ¾'' flange for maximum conductance.

Part	Description	Part	Description
Vacuum inlet	Attaches the vacuum system to the chamber	H_2 inlet	Delivers hydrogen to the proton source
Dee feedthrough	Supplies power to the dee	Target linear motion feedthrough	Moves the target and detectors
Dee coolant inlet	Carries cooling water to the dee	Power feedthrough	Powers the proton source ionizer and electrostatic deflector
Viewports	Allows us to observe the interior	Beam Port	Where the beam extracts out of the chamber.

One man's vacuum is another man's sewer.
- N. Milleron, Res. Dev., #9, 40 (1970)

4.3 Vacuum Pumping System

Our vacuum chamber is relatively small and easy to pump down. A small commercial pump could easily achieve the level of vacuum we require; however, in order to produce the protons we are accelerating, we must inject a significant volume of hydrogen into the chamber (5.4), which must then be rapidly removed. Thus a very important consideration in selecting a vacuum pump is its pumping speed, in addition to the maximum vacuum it is able to attain.

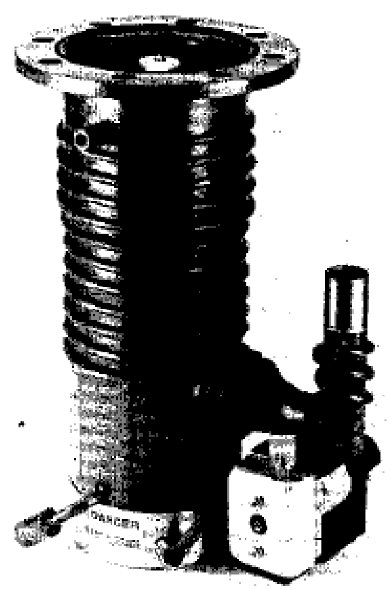


Fig. 4.4 Varian M4 vacuum pump

The pump we have obtained is a Varian M-4 diffusion pump backed by a roughing pump. The diffusion pump is theoretically capable of reaching an ultimate vacuum of 10^{-9} torr and pumping a volume of 1000 liters/second. Since we are only planning on operating at 10^{-7} torr without hydrogen (10^{-5} torr with hydrogen) the maximum vacuum gives us a generous safety margin. In addition, 1000 L/s is a sufficient pump speed to remove the excess hydrogen from the chamber before it builds up and decreases the beam quality.

Although a large diffusion pump obviously carries out the task we require, it does have drawbacks. A diffusion pump operates using vaporized oil, some of which can leak back into the chamber and contaminate the vacuum. In order to prevent this problem, we have a liquid nitrogen trap above the vacuum pump. As the vaporized oil passes through the trap, it cools and condenses before reaching the chamber. The vacuum stack also incorporates a large gate valve allowing us to isolate the pump from the chamber, a leak valve, a vacuum gauge, and a steel bellows. The gate and leak valves allow us to safely depressurize the chamber. The steel bellows allow us to move around the stack easily by allowing us some vibrational isolation.

4.4 Mean Free Path

The mean free path of a particle (λ, the average distance that a particle travels between collisions), in a vacuum of a certain pressure is given by the equation:

$$\lambda = \frac{RT}{\sqrt{2}\,\pi d^2 N_A P}$$

Where R is the universal gas constant (8.3145 J/mol K), T is the temperature in Kelvin, N_A is Avogadro's number (6.0221 x 10^{23}), and P is the pressure. Assuming that most of the stray particles in the chamber are H_2 molecules, the approximate mean free path at various pressures is given by the following table.

We can easily calculate the path length of the beam using the number of turns the particle beam take, 240 (2.4) and the diameter of the dee. We find that that the path length of the particles is on the order of 10^2 meters. For beam losses to be kept to a minimum, the mean free path must be about equal to or greater than the path length of the particle. Therefore the vacuum pressure should be maintained at approximately 10^{-6} torr.

Pressure	**Mean Free Path**
10^{-1} torr	10^{-3} meters
10^{-2} torr	10^{-2} meters
10^{-3} torr	10^{-1} meters
10^{-4} torr	10^{0} meters
10^{-5} torr	10^{1} meters
10^{-6} torr	10^{2} meters
10^{-7} torr	10^{3} meters
10^{-8} torr	10^{4} meters
10^{-9} torr	10^{5} meters

5. Ion Source and Beam Characteristics

The ion source is situated in the center of the cyclotron, directly between the dees. Protons for acceleration are formed by ionizing hydrogen; deuterons (deuterium nuclei) can be formed the same way by ionizing deuterium. In order for the hydrogen to be injected into the vacuum chamber without compromising the purity of the vacuum, a vacuum pump of sufficient speed is needed to remove the unionized hydrogen (4.3).

The line into the vacuum chamber containing the hydrogen is terminated adjacent to an electron-emitting filament. The electrons from the filament strip away the electrons around the hydrogen ions, leaving protons that are pulled away by the potential on the dees. The motion of electrons in the plane of the dees is greatly constrained by the magnetic field, and they are forced into making tight spirals around the axis of the magnetic field (since electrons have a mass that is nearly 2,000 times smaller than the mass of protons, their radius of curvature in the magnetic field will correspondingly be 2,000 times smaller than that of protons).

5.1 Capillary Ion Source

It is convenient to confine the ionization region to a column in the center of the dees. Such a column is termed a chimney, and it constitutes a capillary ion source. The chimney is mounted on a block of machineable ceramic holding in place an electron-emitting filament and the end of the hydrogen line into the chamber. A small hole in the side of the chimney allows protons to exit. The edges of the hole must be made as thin as possible to decrease the likelihood of the extracted ions exiting the ion source at an angle.

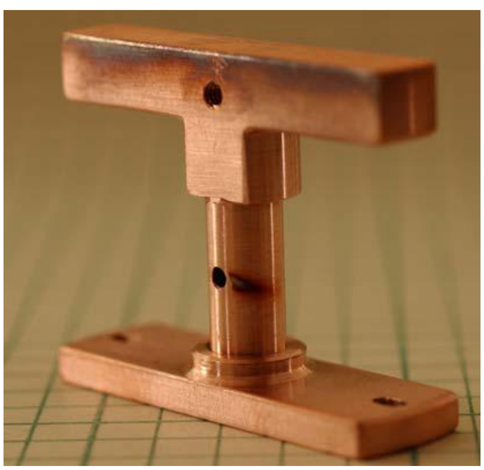


Fig. 5.1 Rutgers cyclotron capillary ion source

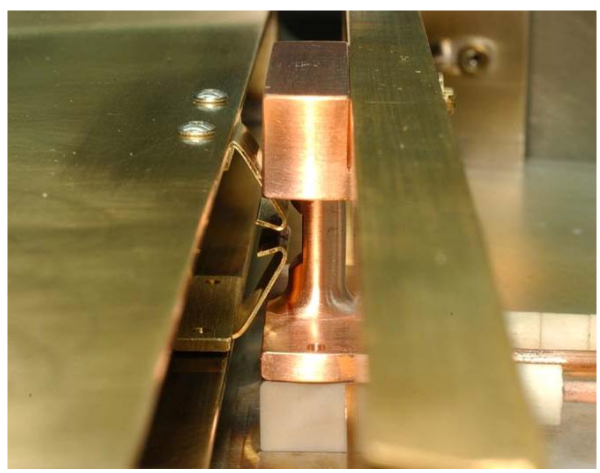


Fig. 5.2 Rutgers cyclotron ion source mounted in typical position. Visible pullers bolted to dee.

To increase the extracting electric field in the region, bent strips of metal called “pullers” are bolted to the dee and brought near the hole in the chimney.

5.2 PIG Ion Source

A PIG (short for Penning Ion Gauge) ion source is a modification of the capillary ion source. Like in the capillary ion source, in the PIG ion source an electron-emitting cathode material is placed at the bottom of a chimney column. At the top of the chimney, there is another cathode that repels the electrons, pushing them in the opposite direction. The strong magnetic field prevents the electrons from traveling sideways, by curving their path into a tight spiral. Therefore, a high electron density forms in the chimney and a higher percentage of hydrogen gas is ionized, resulting in a higher beam current and less leakage of hydrogen into the chamber.

5.3 Thermionic Electron-Emitting Materials

The optimization of electron-emitting materials is a topic that has been thoroughly investigated in literature about vacuum tubes. A material emits electrons if enough energy is imparted to it to exceed its work function. The work function of a metal can be lowered if it is coated with an oxide compound, which is typically obtained from the decomposition of alkali earth metal carbonates that are settled onto the base metal.[3]

Thoriated tungsten filaments are a common choice, and they have the advantage of being able to withstand heating to high temperatures. However, tungsten quickly degrades in a hydrogen environment. Oxide-coated nickel base metals are optimal for the environment inside the cyclotron vacuum chamber. A metal mesh is more desirable than a filament because of its larger surface area and the many contours in the metal that concentrate the electric field and provide breakout points for electrons to leave the metal.

5.4 Beam Current

Around 0.0126 Coulombs of beam current is needed to observe a significant number pair production events.[4] Assuming that a sample is irradiated with this charge within 10 seconds, the beam current must about 1.26 mA. To add a margin of safety, our chimney ionizer is designed around producing a beam current of 2 mA.

The actual efficiency of our ionizer must be determined empirically, but again allowing for a large margin of error we assume that it will initially only have a 5% ionization efficiency. Converting 2 mA into Coulombs of charge per second and then moles per second, we arrive at a value of a necessary input of 1.04×10^{-11} moles of diatomic hydrogen per second. (See section 9.2)

[3] Hadley, CP. "Oxide-Coated Emitters". Electron Tube Design. Radio Corporation of America,1962.

[4] Stephens , W.E., Staub, H. "Search for Pair Production ". Physical Review Volume 109 No. 4 . Feb 15, 1958. <http://prola.aps.org/abstract/PR/v109/i4/p1196_1>.

5.5 Initial Ion Orbits

To determine whether the ions extracted out of the capillary ion source will hit or clear the chimney on their first orbits, it is necessary to plot the initial orbits of the ions. Assuming a magnetic field in the positive z direction and an electric field varying in the x direction, the following equations can be written.

First, the Lorentz force and Newton's second law are expressed:

$$m\frac{d^2x}{dt^2} = e(E + B \times \frac{dy}{dt})$$

Because the magnetic field is orthogonal to the electric field and thus the direction of motion of the beam, the sine term of the cross product is unity, and the expression can be equivalently rewritten:

$$m\frac{d^2x}{dt^2} = eE + eB\frac{dy}{dt})$$

The electric field varies sinusoidally according to this equation:

$$E = E_0 \cos{(\omega t + t_0)}$$

Additionally, the angular frequency of the particle and the applied electric field orbiting in the magnetic field, ω, can be expressed as follows:

$$\omega = \frac{Be}{m}$$

Substituting these terms into the original equation and using overdot notation for time derivatives:

$$\ddot{x} = \ eE_0 \cos(\omega t + t_0) + \omega\dot{y}$$

The ion's motion in the y-direction is dependent upon the magnetic field strength and the velocity in the x-direction.

$$m\frac{d^2y}{dt^2} = eB \times \frac{dx}{dt}$$

$$\ddot{y} = \omega\dot{x}$$

Solving the derivatives provides a set of parametric equations describing the position of the ions at any subsequent time.

$$x = \ \frac{eE_0}{2m\omega^2}[-\sin\omega t_0 \sin\omega t + t\sin\omega(t + t_0)]$$

$$y = \frac{eE_0}{2m\omega^2}[-\cos\omega t_0 \sin\omega t - 2\sin\omega t_0\,(1 - \cos\omega t) + \omega t\cos(\omega t + \omega t_0)]$$

EFFECT OF MAGNETIC FIELD

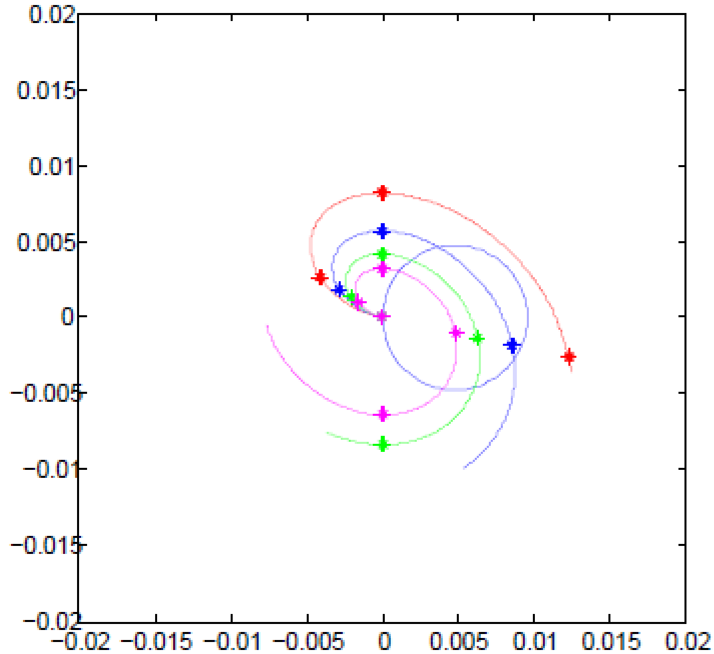


Fig. 5.3 MATLAB plot of initial ion orbits in the cyclotron, with an applied voltage of 10kV over a 2cm gap, with varying magnetic field. The spirals are modeled for field values of: 1.0T, 1.2T, 1.4T, and 1.6T, from the smallest radius to the largest, respectively. Stars denote the location of the particle when the phase of the electric field is at a multiple of pi/2—that is, it's at a maximum or minimum. The blue circle represents the capillary ion source tube where the ions originate.

The above plot shows the ease with which the ions can clear the ion source in their initial revolutions in lower magnetic fields. This plot does not take into account the more intense extraction field provided by the pullers (fig. 5.2). Optimization of the shape and size of the pullers will have to be empirically determined. Once pullers are installed, the ions will be able to clear the ion source at higher magnetic field values.

EFFECT OF ELECTRIC FIELD STRENGTH

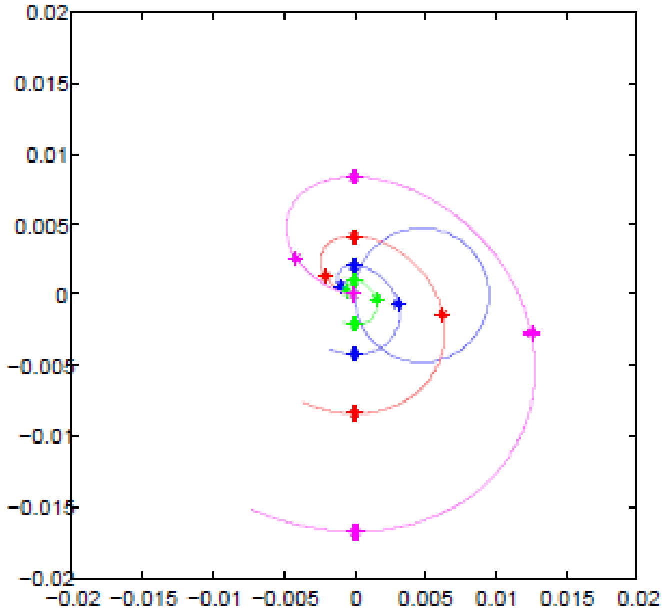
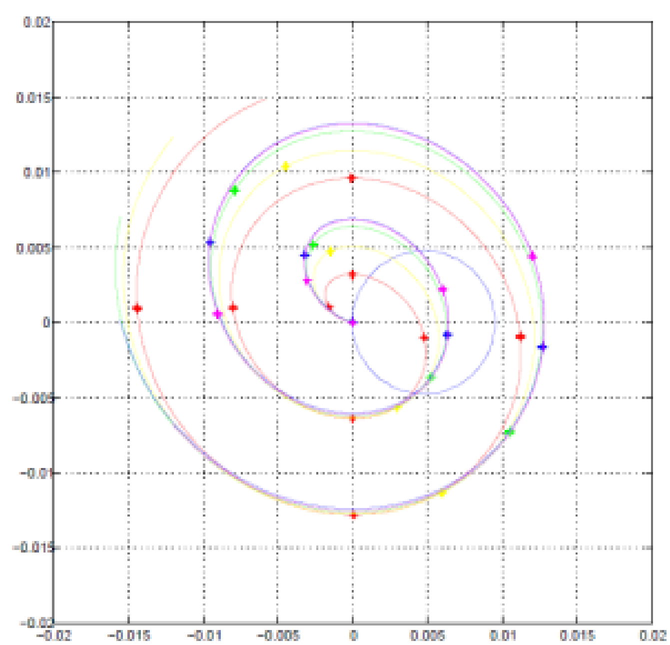


Fig. 5.4 MATLAB plot of initial ion orbits in the cyclotron, at a 1.4 Tesla magnetic field and varying electric fields. From least to greatest spiral radius, the applied potentials across the 2cm gap are: 2.5 kV, 5kV, 10kV, and 20kV. Again, this plot does not take into account the pullers. It is likely that without them, the cyclotron will have to be operated without a chimney tube in the center. It is not necessary to have a capillary ion source; simply a filament between the dees will also yield a stream of protons.

EFFECT OF INITIAL ELECTRIC FIELD PHASE

Fig. 5.5 MATLAB plot of initial ion orbits, exiting the ion source at various phases of the oscillating electric field. From smallest to largest radius, the phases of the electric field increment in steps of pi/4, from 0 to pi. The stars mark the locations of the ions at phases of multiples of pi/2. This plot is of the orbits at 1.6T and a 10kV potential, once again, not taking into account the effects of the pullers.



This figure illustrates the point that the maximum electric field is optimal for extracting ions from the capillary ion source. Ions that don't originate at maxima of the electric field tend to rapidly become asynchronous with the cyclotron frequency, and do not cross the accelerating gap at the appropriate time. It is interesting to note that all the particle paths converge at the opposite side of the ion source than the direction they were initially extracted in., though the radii of their path initially differ significantly.

6. Radiofrequency Electronics System

The cyclotron requires around 10 kV to be present on the dee, at a frequency of 18-24 MHz depending on the strength of the magnetic field during operation (a higher magnetic field increases the frequency (2.3)). The signal is produced at the desired frequency by a signal generator. It is then amplified by an RF power amplifier to a peak-to-peak voltage of 10 kV. This signal is then transmitted via coaxial cable to the "coupling box" containing the RF matching network.

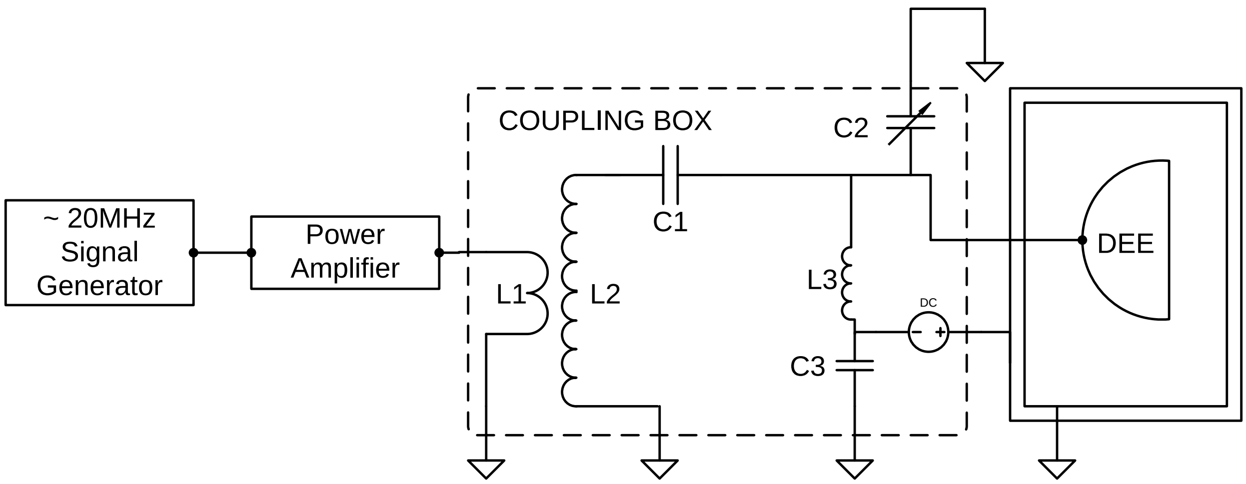


Fig. 6.1 RF system schematic

L1- Half-turn primary coil

L2- Multi-turn secondary coil, loosely coupled

L3- RF choke to protect the DC power supply which places a DC bias voltage on the dee for ion extraction purposes)

C1- High power RF transmitting capacitor to block DC from being shorted to ground. 1500 pF

C2- 5-100pF vacuum variable capacitor to tune the capacitance of the LC tank circuit

C3- RF filter capacitor, 700pF.

The matching network inside the coupling box contains two loosely coupled coils, which inductively transfer the power from a primary half-turn coil to a coaxial secondary multi-turn coil. The secondary coil is matched to the dee's self-capacitance and the value of the vacuum variable capacitor (C2), to resonate at the cyclotron frequency. The frequency varies with the magnetic field, and can be adjusted by changing the value of the vacuum variable capacitor.

The two coils are wound out of 1/4th inch copper refrigeration tubing. The two are aligned along a common axis and share a center point. It is necessary for the secondary coil to be cooled with oil or deionized water to dissipate accumulating heat, because even minute thermal expansion of the copper can change the inductor's value. At both ends of the coil, nylon tubing is attached using a Swagelok connector, completing the path for the water to flow to and from the manifold. Copper strap is soldered to the coil before the terminations, and bolted to the destination of the RF signal on the other end (either the chassis of the coupling box to ground, or the dee stem).

The transmission cables between the signal generator, power amplifier, and coupling box are RG-213 coaxial cable. The cable from the amplifier connects to the coupling box via a chassis-mount N-type connector. The cable on the other side of that junction, inside the coupling box, terminates in an alligator clip that clamps onto the end of the half-turn coil. The location of the wire along the coil is adjustable, allowing for fine tuning of the inductance or the primary coil.

The two coils are loosely coupled; their mutual inductance is approximately .01. The inductance of the primary coil should be kept as small as possible in order to minimize the coupled inductance of the primary into the secondary circuit. A single-turn primary achieves a low coupled inductance while still achieving sufficient coupling between the coils.

6.1 DC Offset

Superimposing a DC potential on the dee in addition to the RF signal is desirable for ion extraction purposes. Biasing the dee is accomplished by attaching it to the cathode of a DC power supply and placing a large capacitor in series with the secondary coil in the coupling box in order to prevent the DC current from shorting to ground. The DC power supply is isolated from the RF voltage by a high voltage choke coil wound on a ceramic or G10 core, which has a negligible DC resistance but poses a high impedance to an AC signal, effectively blocking it. There is a capacitor placed after the choke coil to short out any RF that was not blocked by the coil, in effect forming a low-pass filter. The optimal voltage and the exact effect of the DC potential on ion extraction from the capillary ion source will be a subject of investigation and experimentation.

> *"Electricity is really just organized lightning."*
>
> - George Carlin

6.1 Power Considerations

It is important to estimate the necessary power to drive the dee to obtain an RF power amplifier in the correct range. There are two contributions to the power dissipated by the tank circuit: its impedance and the loading by the proton beam.

At resonance, the tank circuit is purely resistive. The circuit resistance as estimated by the inherent resistance of its copper components is approximately 1 ohm. Thus, in order for the voltage over the dee to attain 1kV, the power into the circuit must be 1kW.

As the proton beam circulates between the dee and the dummy dee, it gains energy from the electric field formed from the potential put on the dee. The energy that is imparted into the particle beam must come from the RF power placed into the tank circuit. A simple estimate of the beam loading is as follows: assuming an achievable proton beam of 100µA accelerated to 2.4 MeV, the beam loading is 240 watts. Thus the power amplifier must be capable of attaining 1.24 kW. The capacity to drive the dee to higher voltages is desirable, so we will use an amplifier capable of attaining at least 1.5 kW.

6.2 Tank Circuit Characteristics

Dee Capacitance

The capacitance of the dee can be approximated by regarding it as a parallel-plate capacitor with the vacuum as the dielectric, using the following equation:

$$C = \frac{A\varepsilon_0}{d}$$

Where ε_0 is vacuum permittivity, $8.85 \text{ x } 10^{-12}\ \mathrm{F/m}$. Solving for the capacitance of the top and bottom plates of the dee, which has a radius of six inches and a distance of .5 inches from the top and bottom plates of the chamber, yields a capacitance of 25pF for each plate. Approximating the capacitance of the dee stem can also be done by regarding it as a flat plate in the center of the chamber, with an area of 1.5 square inches, though in actuality it is a rod of half-inch diameter. The sum of the individual capacitances results in a lumped capacitance of about 54pF.

To complete the tank circuit, an inductor having a value determined by the following equation is placed in series with the dee's capacitance.

$$L = \frac{1}{(2\pi f_0)^2 C}$$

Solving for L using the value $f_0 = 24\ MHz$, yields a necessary secondary coil inductance of 0.81µH.

If the cyclotron is operated at a lower frequency (which will be necessary if it is run at a lower magnetic field intensity) the characteristics of the tank circuit must be altered for it to resonate. At a magnetic field density of 1.0 Tesla, the cyclotron frequency drops to 14 MHz. With a fixed coil inductance, only the capacitance can be varied to adjust the resonant frequency of the circuit. At 14 MHz, the necessary capacitance becomes 158pF, an increase of over 100pF from the capacitance needed at 24 MHz. This establishes the value and the range of the variable capacitor.

6.3 Coupling Box Details

The equation describing the inductance of a single-layer air-core coil (in microhenrys) can be simplified to the following (d and l are in inches):

$$L\ (\mu H) = \frac{d^2 n^2}{18d + 40l}$$

Using this equation, the following specifications for the coil are determined:

Coil Diameter (d)	1.5 inches
Coil Length (l)	3.5 inches
Number of turns	7
Calculated Inductance	0.66µH
Distance between the centers of consecutive windings	.5 inches

The inductor is slightly less than the value needed to form a resonant circuit with the dee capacitance alone, because to reach the resonant cyclotron frequency, the small inductance can be compensated for with additional capacitance added with the variable capacitor in parallel with the circuit. For the circuit to resonate at 24MHz, 12 pF must be added. The primary half-turn diameter is 3 inches.

B (Tesla)	f (MHz)	C total (pF)	C variable (C2)
1	15.225	165.5633929	111.5634
1.1	16.7475	136.8292503	82.82925
1.2	18.27	114.9745784	60.97458
1.3	19.7925	97.96650468	43.9665
1.4	21.315	84.47111883	30.47112
1.5	22.8375	73.58373018	19.58373
1.6	24.36	64.67320035	10.6732
1.7	25.8825	57.28837125	3.288371

6.4 Dee Voltage: Phase Shift Considerations

The energy that the particle gains per revolution depends directly on the dee voltage. The number of times the particle orbits in the magnetic field is also dependent upon the voltage. The more times the particle crosses the acceleration gap, and the longer its path length, the more likely to become asynchronous with the cyclotron frequency or collide with stray molecules in the chamber. In establishing the minimum necessary dee voltage and maximum allowable path length, we need to consider the mean free path in the chamber as well as the phase stability of the particle.

Phase stability refers to the relation between particle's orbital phase and the phase of the sinusoidally oscillating electric field. Due to the receding magnetic field at higher radii and the relativistic mass increase of the particle with its increased energy, the particle takes slightly longer to make a complete revolution at larger radii. This causes asynchronization from the cyclotron frequency, or phase shift.

The angular velocity for a synchronous particle (one which follows the theoretical ideal path) is given as:

$$\omega_{rf} = \frac{qB_0}{M_0}$$

As the magnetic field drops off with radius and the mass increases, the actual angular velocity increases. We will not shift the frequency to accommodate this change in our fixed-frequency cyclotron.

$$\omega = \frac{qB}{M}$$

The phase of the particle when it crosses the acceleration gap is ϕ, measured from the voltage null where the field changes from being decelerative to accelerative. The change of phase is:

$$\frac{d\varphi}{dN} = 2\pi \frac{\omega_0 - \omega}{\omega} = 2\pi \frac{\frac{qB_0}{M_0} - \frac{qB}{M}}{\frac{qB}{M}} = 2\pi \left(\frac{MB_0}{M_0 B} - 1\right)$$

Since:

$$\frac{M}{M_0} = \gamma = \frac{E}{E_0} = \frac{E_0 + T}{E_0} = 1 + \frac{T}{E_0}$$

We can substitute and obtain:

$$\frac{d\varphi}{dN} = 2\pi \left(\frac{B_0 - B}{B} + \frac{B_0 T}{B E_0}\right)$$

Note that the first term represents the contribution from the decreasing field. The second term represents the phase shift caused by relativistic mass increase, expressed in terms of energy gained by the particle (T is the particle's energy increase).

With a field drop-off value of 0.03 T at the largest radius, the equation yields a phase shift of 1.8 degrees per turn. φ should be around $\pi/2$, so retarding nearly one degree per revolution, there is actually no way for any particle to stay perfectly synchronous the entire time, with a reasonable voltage over the dees. However, since only a very small fraction of particles are synchronous at any point in time, there are always some particles that accelerate at the optimal phase angle. It will be desirable to operate at as high a voltage as possible, but it is impossible to have such a high voltage as to keep the phase shift of an ideal particle under $\pi/2$. For a single particle to stay synchronous the entire time, we would need a dee voltage of 53 kV, which is out of the range of what we can practically achieve. Trying to adjust the frequency to compensate for the relativistic mass increase would not achieve much because the adjustment in frequency would be too slight to reliably regulate; it generally becomes necessary to use frequency modulation only above 20 MeV.

6.5 Dee Voltage: Particle Path Length

Dividing total energy (2.4 MeV) by the energy the particle gains per turn, we arrive at the number of revolutions the particle makes to attain the final energy.

Dee Voltage	**Total number of Revolutions**	**Avg. Revolutions per inch**	**Total Path Length**
.5 kV	4,800	800	90,500 inches (2,300 m)
1 kV	2,400	400	45,200 inches (1150 m)
2 kV	1,200	200	22,600 inches (570 m)
5 kV	480	80	9,050 inches (230 m)
10 kV	240	40	11,500 inches (300 m)
53 kV	45	7.5	850 inches (20 m)

As a compromise between a long path length and too high of a voltage that can cause excessive heating or sparking of the dee, we will use 10kVp-p.

7. ELECTROMAGNET YOKE

The electromagnet produces the intense, uniform magnetic field that permeates the vacuum chamber and curves the accelerated particle's orbits. It is comprised of two water-cooled copper excitation coils that produce the magnetic flux, and a steel yoke weighing two tons that provides a low-resistance path for the magnetic flux to travel through. This assembly will produce a homogeneous 1.6 Tesla magnetic field in the gap between the poles of the magnet.

7.1 YOKE DESIGN

The function of the magnet's steel yoke is to provide a path of high permeability for the lines of magnetic flux to travel through. Attaining the most intense magnetic field possible is the design goal of the electromagnet yoke. The two ways to increase the final energy of the accelerated particle are to increase either the radius of the dees or the density of the magnetic field. Since expanding the dees would require us to also make the pole faces of the magnet bigger (and thus the rest of it would become bigger as well), it proves more cost effective to use as high a magnetic field density as possible.

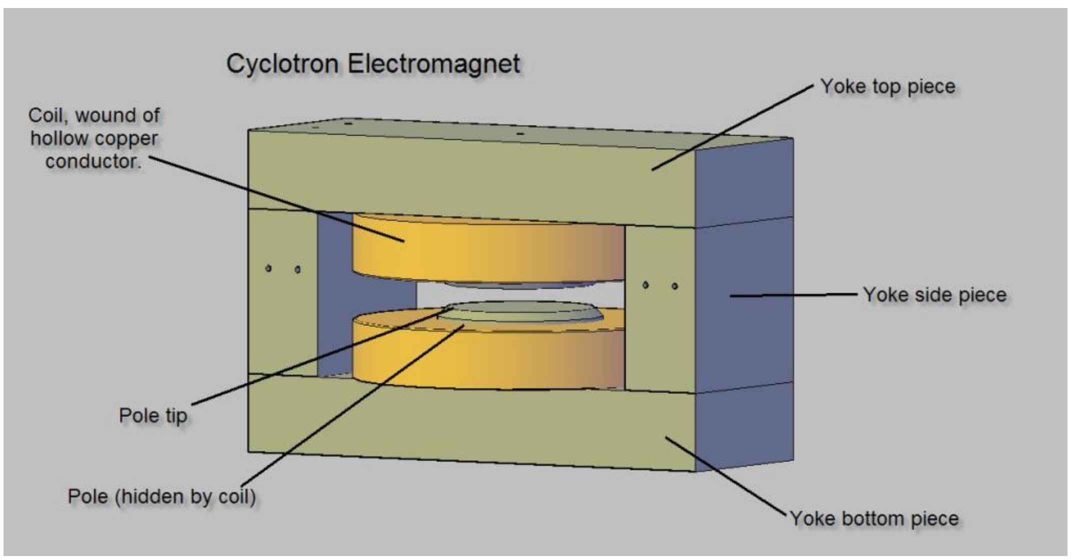


Fig. 7.1 Cyclotron electromagnet with labeled pieces

However, there are limitations to the strength of the field. Our magnet is constructed out of 1060 steel, which saturates at around 1.7 T; above this magnetic flux density the yoke is unaffected by further excitation. In order to prevent magnetic saturation, the arms of the yoke carry a 25% smaller flux density than the maximum: only 1.2 T. This is achieved by increasing their cross-sectional area by 25%.

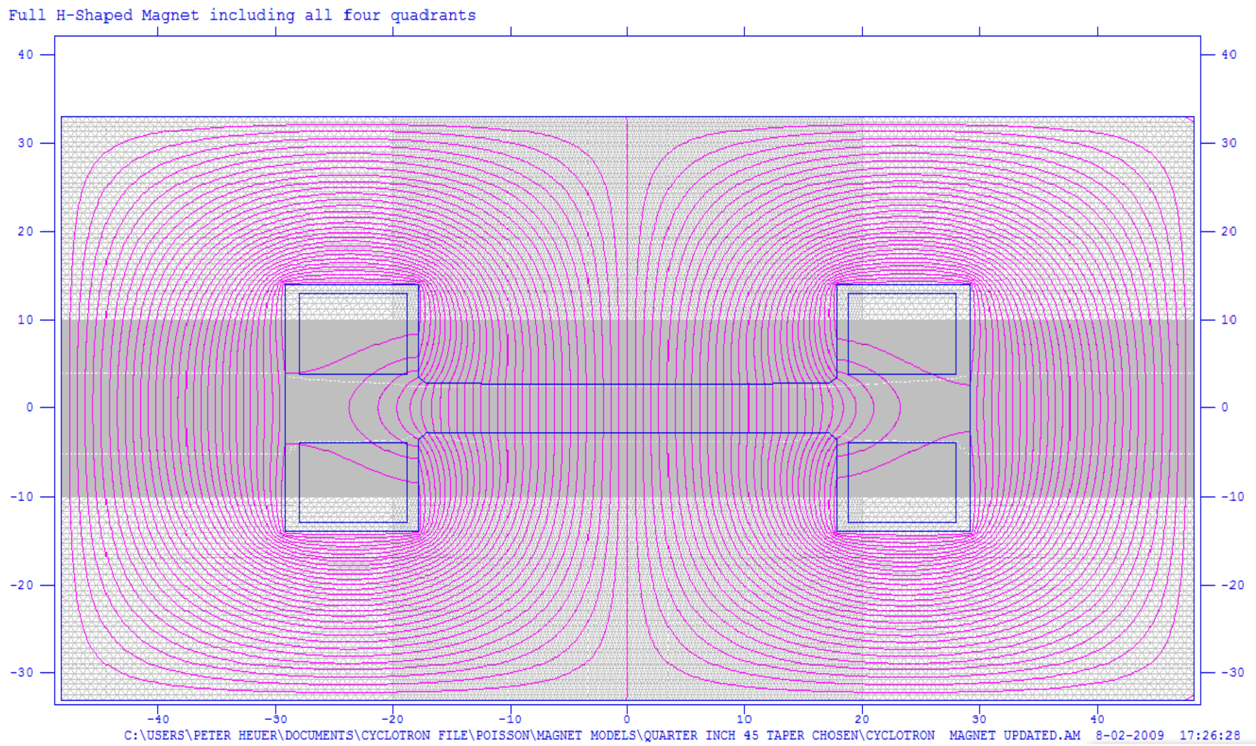


Fig 7.2 Poisson Superfish modeling of magnetic flux in the electromagnet

It is also possible to model the field inside the electromagnet yoke using software design for magneto- and electrostatic modeling. Poisson Superfish (PSF) is software developed by Los Alamos National Laboratory for the purposes of modeling accelerator components. We have written code for this software and applied it to our application, and the result is displayed in figure 7.2. It confirms that our magnet yoke design is sound, and that the flux density in any cross-sectional piece of the magnet does not exceed the saturation value of 1060 steel.

7.2 Pole Face Design

The tips of the magnet's poles most directly determine the shape of the magnetic field in the gap. It is necessary to have a homogeneous radial magnetic field, but the field must also gently drop off across the radius of the pole. The slightly curved magnetic field lines and the gradually decreasing field form a weak focusing effect that keeps the particle beam on its proper path.

The focusing effect can be understood if it is considered that few particles start their orbits in the cyclotron with no vertical momentum. The electric field extracting them from the ion source is not perfectly horizontal, and thus they are ejected at an angle. The curved magnetic field lines counter the vertical momentum and push the particles toward the median horizontal plane, causing them to oscillate around their circular ideal path, in what is called betatron motion. The magnetic field causes the betatron oscillations, which are actually beneficial in that they prevent the particles from continuing on their vertical trajectory and colliding with the walls of the chamber. It is necessary to implement a .02” convex taper from the center of the pole to the edge, to create sufficient bending of the magnetic field lines.

Additionally, the edges of the pole have a 45° taper. This is to prevent magnetic saturation at the edges of the pole. The field due to the taper also fringes less sharply at the edges.

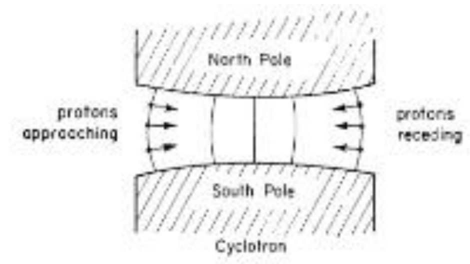


Fig. 7.3 Magnetic focusing effect
From: Livingood, John J. Principles of Cyclic Particle Accelerators. Princeton: Van Nostrand, 1961

Since the equation to determine the frequency at which we operate the cyclotron depends on the magnetic field, it’s important to keep the field consistent from the middle to the outside of the dees. In our simulations, at a dee radius of 6’’ the field is 1.57 T, a .08 T drop off from 1.64 T directly at the center.

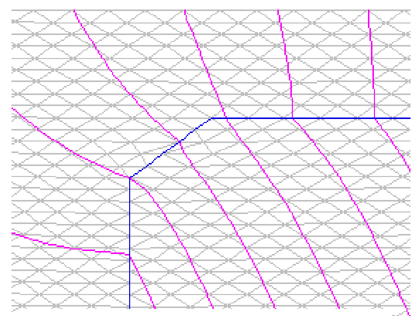


Fig. 7.4 Pole tip taper

> *“Oh no! Not the magnet!”*
>
> - Bender, Futurama

8. Electromagnet Coil Design

The magnet coils provide the magnetic field we use to restrict the particles to their circular orbits. We do this by running a current of 110A at 115V through 720 turns of water-cooled copper wire; 360 on each pole. The square, enameled magnet wire is hollow, allowing us to flow water through to keep it cool.

8.1 Coil Design

When designing our magnet coil, we started with the wire we had available. When properly cooled, our ¼''x1/4'' hollow copper conductor can safely carry up to 120A. Allowing a margin of safety, we designed our magnet to operate at 110A. Working from there, we used the basic equation for an electromagnet to find other values that worked to provide our design field of 1.6T:

$$B = \frac{\mu_0 NI}{g}$$

μ_0 is the permeability of free space. In order to use the magnet possible, it was desirable to keep the gap between the poles, g, as small as possible. After working through our vacuum chamber design, we decided a 2.13'' gap a reasonable size. Using these values, we then concluded that we needed 720 turns to reach 1.6T.

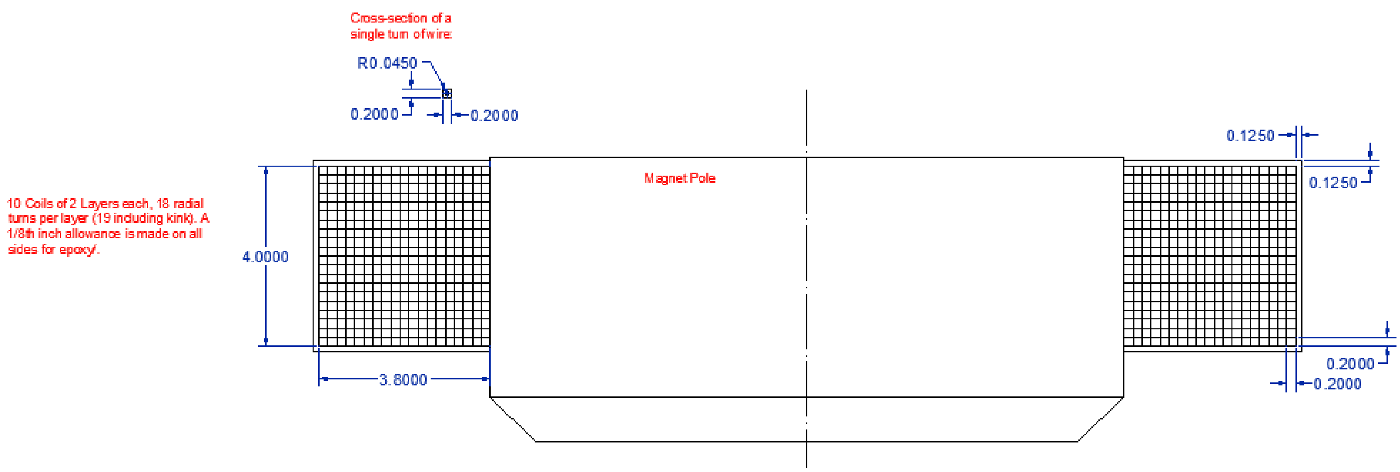


Fig. 8.1 Electromagnet coil cross-section

These 720 turns will be made up of two coils of 360 turns each on the two poles. The 360 turns will be comprised of ten double-turn layers informally called "double pancakes." The coil is ultimately 20 turns high and 18 turns wide. Once each pancake is wound, it is cast in epoxy to hold it together. After all the coil layers are completed, the whole assembly is potted in epoxy to hold the coil together as a unit.

Each pancake is created by measuring out enough wire for 36 turns; a couple hundred feet. The wire is stretched out and the spool is placed in the center of the wire. One half of the coil is wound and then secured. The other half of the wire is then wound in the opposite direction. The two leads end up on the same side of the coil. Using this type of winding allows for a more uniform field than a simple spiral winding.

8.1 Magnet Cooling

Because of the 110 ampere current running through the tightly wound coils of magnet wire, we must employ a cooling system to regulate the temperature. Our magnet can achieve a maximum temperature of 173 °F and will normally operate at no more than 142 °F.

By positioning water outlets so that each feeds into two double pancakes, we can deliver the water through a manifold with 12 spigots, six for each half of the magnet. Another 12 spigot manifold will be used to take return water back from the magnets. The way that layers are connected together in the double-pancake design combines the outputs in such a way that there are only 5 returns paths from each coil (fig. 8.2). Thus only 10 of the spigots on the return manifold are needed.

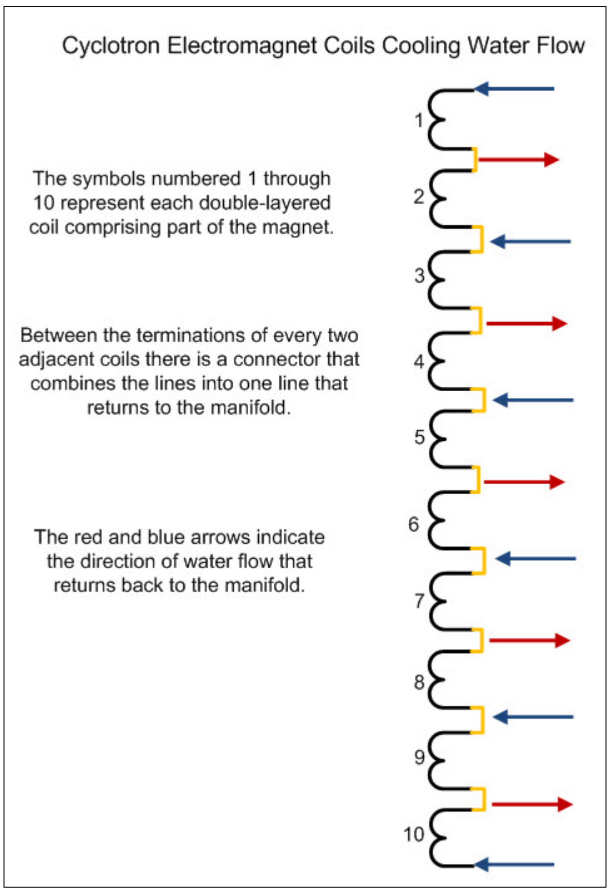


Fig. 8.2 Cooling water flow

Connectors for the ends of the magnet wire have been designed, providing both electrical connection and water connections. All of these connections will mount to a piece of G10 to prevent stress to the wire caused by the weight of the heavy power wires.

> *"So this is how the world works, all energy flows according to the whims of the great magnet."*
>
> \- Hunter S. Thompson

9. Target and Detector

A target or detector will be attached to the end of a linear motion feedthrough, intercepting the particle at its largest radius and final energy. It will be able to translate closer to the center of the dees and intercept particles at smaller radii and lower energies as well, so that we can characterize the energy spectrum inside the cyclotron and observe orbital instability.

Initial observations of the proton beam will be made by means of a phosphor-coated screen mounted on the end of the linear feedthrough. The screen glows in the visible spectrum when struck by the proton beam, and can be seen through a window port in the side of the vacuum chamber. At first, a closed-circuit video camera will be mounted on the port so it can be observed from a control center.

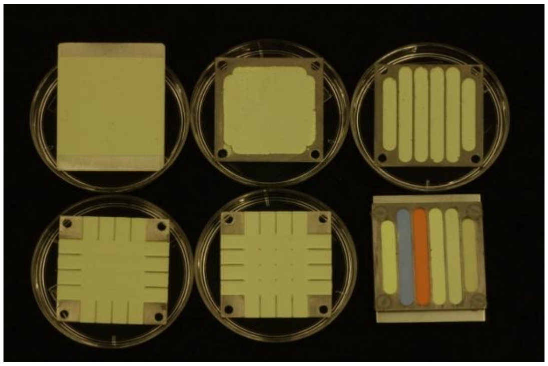


Fig. 9.1 Various configurations of phosphor screens, under normal light. All with the exception of the bottom right are P22 phosphor.

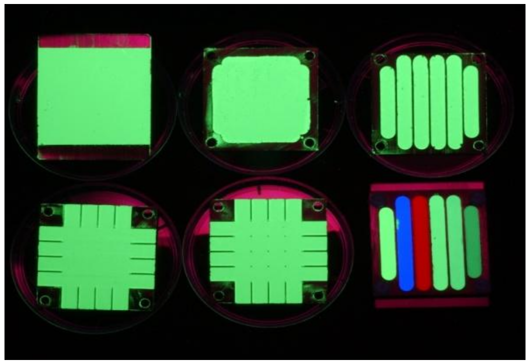


Fig. 9.2 Phosphor screens under UV light.

Thanks to Timothy Koeth for the images.

The beam will be more precisely characterized with a Faraday cup. Fluctuations in voltage and amperage on the Faraday cup will correspond to the intensity and current of the beam, respectively. This will allow us to make preliminary characterizations of the beam before it is used to irradiate a target.

9.1 Positron Detection

It will be necessary to extract the particle beam from the magnetic field (and possibly also the vacuum chamber) to achieve detection of positrons produced from proton collisions with a target. The beam will be extracted by using an electrostatic deflector plate biased at several kilovolts. The beam will be directed through a port in the vacuum chamber wall that is otherwise capped. Extraction is necessary because photomultiplier tube (PMT) detectors are extremely sensitive to magnetic fields, and do not work in their vicinity without heavy shielding.

To produce positrons, the protons of at least 2.045 MeV must collide with a target of heavy nuclei, in the form of a high-Z metal. We will experiment with proton collisions from tantalum and tungsten. When the electron positron pair annihilate, they produce two gamma rays of 511 keV, emitted in opposite directions (the deviation from the straight angle between them due to relativistic effects is negligible).

Bismuth germinate (BGO) crystals scintillate when struck by 511 keV gamma rays. PMTs situated behind thin pieces of BGO crystals detect the light and scintillators from being struck by other products of the particle collision, a thin lead shield is placed in front of the crystal. It is also necessary to ensure that the PMTs are detecting the gamma rays produced by electron-positron annihilation and not from other stray events like cosmic rays. They are therefore situated in a way that forms a coincidence counter. Since the two gammas are emitted approximately in opposite directions, if two detectors facing each other on opposite sides of the target measure a reading simultaneously, then positron production is confirmed. To accommodate for a range of emission angles, an array of detector pairs can be set up in an array around the target.

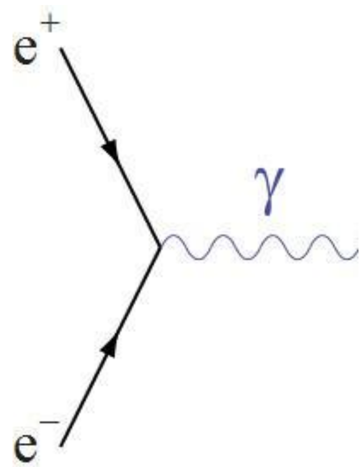


Fig. 9.3 Feynman diagram of electron-positron annihilation

10. EXPERIMENTS

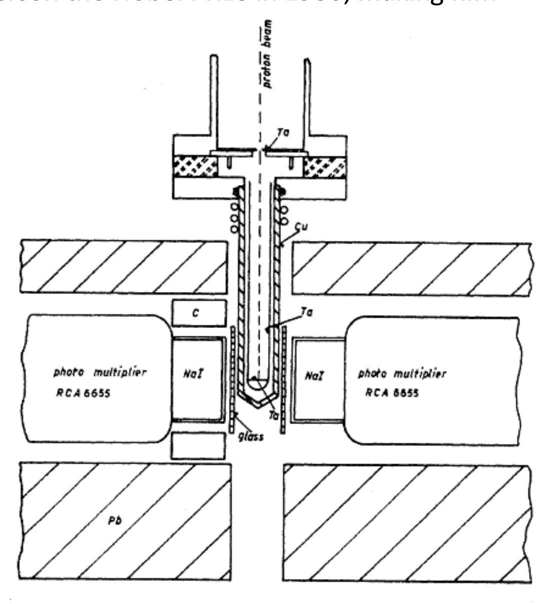
It will first be a challenge to make the cyclotron work perfectly, but once that is accomplished we will be able to do interesting research with our instrument. We plan to test various shapes and configurations of ion sources, magnet pole tip shapes, RF driving signals, and dee edges. Much of this will be for the purpose of optimizing the operation of our cyclotron, but there is also the potential to perform novel experiments with our apparatus.

> *"All life is an experiment. The more experiments you make the better."*
>
> - Ralph Waldo Emerson

10.1 ANTIMATTER PRODUCTION

The foremost experiment we will attempt is antimatter production. The discovery of antimatter in the form of positrons in cosmic rays won Carl David Anderson the Nobel Prize in 1936, making him the second youngest person to receive the award. Two decades later, E.O. Lawrence helped to construct the Berkeley Bevatron, a cyclotron built with the goal of discovering antiprotons, which it achieved in 1955 with a Cherenkov photomultiplier.

In the tradition of young ambitious scientists pursuing antimatter, we too have made this our goal. We aspire to be the first teenagers to produce and detect antimatter. We have designed the cyclotron to surpass the pair production energy threshold, which is slightly over 2.0 MeV. There is room left for installing a high voltage electrostatic deflector plate, and clearance was left with respect to the internal vacuum chamber supports to extract the beam.



10.1 Schematic diagram of positron detecting arrangement

Taken from: Stephens , W.E., Staub, H. "Search for Pair Production ". Physical Review Volume 109 No. 4 . Feb 15, 1958.

10.2 PROTON BEAM LITHOGRAPHY (P-BEAM WRITING)

Another exciting application of the cyclotron is proton beam lithography (also called p-beam writing). The advantage of etching materials using protons or other heavy ions is that heavy particles can penetrate far deeper into materials without scattering. Protons deposit their energy at a certain depth in materials called the Bragg peak, which is dependent upon the stopping power of the material and the energy of the incident particle. Electrons and x-rays cannot etch materials as deeply as protons and heavy ions, which gives accelerated charged particles in our energy range enormous potential in the development of nanotechnology, including photonics and biochips.[5]

Proton beam lithography is a very promising technology, and because it is such new technology, there is plenty of development to do. There are only several groups in the world doing proton beam lithography research, and there is currently no viable commercial apparatus for p-beam writing; there is some software and technology currently being developed at the Center for Ion Beam Applications at the National University of Singapore.[6] The Ion Beam Center at Surrey University is also doing p-beam research using focusing systems to attain microbeams for etching. When our accelerator is fully capable of attaining 2+ MeV protons, we intend to contribute to this type of research.

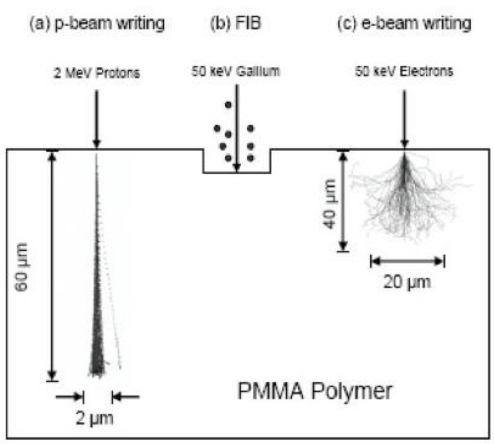


Fig. 10.1 Relative penetration depths of various particles into PMMA polymer

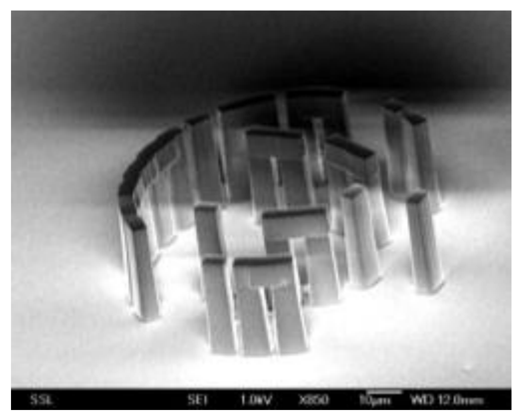


Fig. 10.2 1,000,000:1 scale model of Stonehenge, etched out of a single photoresist using a proton beam.
F. Watt, A.A. Bettiol, J.A. van Kan, E. J. Teo and M. B. H. Bresse, *"Ion Beam Lithography and Nanofabrication: A Review"*, International

> *"There is no such thing as a failed experiment, only experiments with unexpected outcomes"*
>
> \- Richard Buckminster Fuller

[5] www.pbeam.com/theory.php
[6] http://www.ciba.nus.edu.sg/

11. Safety Precautions

If used or operated improperly, the cyclotron becomes a hazardous instrument. Proper care must be taken in our design to eliminate avoidable hazards. We must also carefully document the operation of the cyclotron in order to minimize hazards to the operator or user.

11.1 Radiological Hazards

The most obvious hazard associated with a particle accelerator is radiation. Radiation can be a product of nuclear reactions or particle collisions, which may occur when the walls of the chamber are stuck by stray high-energy protons. For the most part, an accelerator of our size is incapable of creating enough radiation to pass through the steel chamber.

Even though previous accelerators of the 2 MeV energy range had no problems with hazardous radiation, it will be a necessary precaution to initially run the accelerator inside a concrete chamber (the ion injector test cave in the EEL building at JLab). Only after the acclerator's radiation emissions are quantified will it be permissible to operate it locally rather than from a distance.

11.2 Electrical Hazards

The magnet power supply presents a serious electrical hazard and is classified as a class 1 electrical device. In order to minimize the risk to the operator, all electrical connections in the magnet are covered. The connection rack on the magnet will be covered by a plexiglass shield to prevent any exposure to the contacts while active. The chassis of the electronics enclosure must also be connected to earth ground.

The RF system also poses a serious electrical hazard. All RF electronics are locked inside a closed chassis during operation. An interlock setup will ensure that the system cannot operate without the chassis being closed. All RF components are properly shielded to prevent contaminating the airwaves (we happen to be operating in two shortwave ham radio bands).

11.3 Magnetic Hazards

The 1.6 Tesla magnetic field used in the cyclotron must also be considered from a safety perspective. The magnetic field is most hazardous to individuals with pacemakers or similar devices. The surrounding area should be kept clear of electronic devices and ferrous metal objects.

11.4 The Safety Operations Manual

Above any other hazard, improper operation of the cyclotron can pose the most potential for injury. After assembling most of the cyclotron but before operating it, we will write a safety operations manual detailing every step of the operation of the cyclotron. Anyone operating the accelerator will be required to read over and understand the safety operations manual. This requirement will increase the effectiveness of all our other safety precautions, as well as helping users recognize any new hazards as they emerge.

12. Relativistic Effects

Relativistic mass increase with particle velocity is a problem in high-energy accelerators because the altered mass causes the particle to become asynchronous. In this document we have been using the nonrelativisitic forms of equations. This section shows that relativistic effects are not significant at our energy range.

Since:

$$m_r = \frac{E}{c^2}$$

At our maximum energy, the mass of the proton increases by m_r , corresponding to the energy gained.

$$m_r = 4.278388196 \times 10^{-30}\ kg$$

$$M_0 = 1.67262158 \times 10^{-27} kg$$

$$M = M_0 + m_r$$

Thus total mass of the accelerated particle will be $M = 1.67689997 \times 10^{-27} kg$. This is a 0.2858% increase in mass, which we will consider to be negligible. For practical purposes, the non-relativistic versions of our equations will be sufficient.

To further illustrate this point, we can consider the difference in the dee radius that the particle of increased mass would require.

Dee radius (relativistic):

$$r = \frac{M_0 v}{qB} = 1.4450 \times 10^{-1}\ m = 14.450\ cm$$

Dee radius (non-relativistic):

$$r = \frac{Mv}{qB} = 14.444 \times 10^{-1}\ m = 14.444\ cm$$

The difference between the radii when considering relativity is far smaller than the thickness of the dees. It is safe to say that this is insignificant.

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"Gratitude is a quality similar to electricity: it must be produced and discharged and used up in order to exist at all."

- William Faulkner

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