

**CHARACTERIZING THE PERFORMANCE OF
THE HOUGHTON COLLEGE CYCLOTRON**

By

Daniel Haas

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

Bachelor of Science

Houghton College

May 5, 2009

Signature of Author

Department of Physics
May 5, 2009

.....
Dr. Mark Yuly
Professor of Physics
Research Supervisor

.....
Dr. Brandon Hoffman
Assistant Professor of Physics

CHARACTERIZING THE PERFORMANCE OF THE HOUGHTON COLLEGE CYCLOTRON

By

Daniel Haas

Submitted to the Houghton College Department of Physics
on May 6, 2009 in partial fulfillment of the
requirement for the degree of
Bachelor of Science

Abstract

The Houghton College Cyclotron briefly accelerated hydrogen ions for the first time in 2007 before a discharge from the dee to the chamber wall damaged the glass insulation and “dee” electrode. To prevent this from happening again, a new vacuum chamber and 15 cm diameter “dee” electrode was designed and constructed. Placed between the poles of a 1.1 T electromagnet, low pressure gas was released into the chamber where a filament, through electron collisions, ionized the gas. The ions were accelerated by an alternating RF electric field and forced to travel in a spiral path by the electromagnet. The new chamber and “dee” has successfully accelerated protons, molecular hydrogen and helium. Eventually, the $d(d,n)^3\text{He}$ reaction will be used to produce neutrons for use in small-scale nuclear experiments.

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

TABLE OF CONTENTS

Chapter 1 - Introduction	7
1.1 History of Nuclear Research	7
1.2 Particle Accelerators	7
1.3 The Cyclotron.....	11
1.3.1 Operating Principles.....	11
1.3.2 The First Cyclotron	13
1.3.3 Development of the Cyclotron	14
1.3.4 Small Cyclotrons	16
1.3.5 The Houghton College Cyclotron	18
Chapter 2 - Cyclotron Theory	21
2.1 Cyclotron Resonance	21
2.1.1 Ion Frequency.....	21
2.1.2 Harmonic Frequencies.....	24
2.1.3 Ion Energy.....	25
2.1.4 Ion Path Length	27
2.2 Electrostatic and Magnetic Focusing	28
2.2.1 Electrostatic Focusing.....	28
2.2.2 Magnetic Focusing.....	32
2.2.3 Vertical Motion of the Ions	37
2.3 RF System	38
2.4 Relativistic Effects	43
Chapter 3 - The Houghton College Cyclotron	46
3.1 Chamber	47
3.2 Dee and Dummy Dee	51
3.2.1 Dees.....	51
3.2.2 Filament	54
3.3 Magnet.....	54
3.4 Modified Faraday Cup.....	56
3.5 Vacuum System.....	57
3.6 Electrical System.....	58
Chapter 4 - Results	61

4.1	Calibrating the Cyclotron	61
4.1.1	Achieving Resonance	61
4.1.2	Calibrating the Pickup Probe	65
4.1.3	Magnetic Field Calibration	66
4.1.4	RGA Scan Analysis	67
4.2	Acceleration Results.....	69
4.2.1	Hydrogen Ions.....	69
4.2.2	Helium Ions	73
Chapter 5 -	Conclusion	77

TABLE OF FIGURES

Figure 1. Cockroft and Waltons' high-voltage accelerator.....	8
Figure 2. Diagram of Sloan and Lawrence's linear resonance accelerator..	9
Figure 3. A diagram of cyclotron operation	12
Figure 4. Lawrence's diagram of the first cyclotron.....	13
Figure 5. Photograph of Lawrence and Livingston's 1.22 MeV cyclotron.....	14
Figure 6. Photograph of Lawrence and Cooksey's cyclotron in 1936.....	16
Figure 7. Photograph of the Houghton College cyclotron chamber and dee (2006).....	19
Figure 8. Resonance curve for hydrogen.....	20
Figure 9. Motion of an ion moving through a magnetic field.....	22
Figure 10. Cyclotron frequency versus B-field.....	23
Figure 11. Harmonic frequencies.....	24
Figure 12. Diagram of harmonic frequency acceleration.	25
Figure 13. Ion energies as a function of magnetic field strength.....	26
Figure 14. Diagram of dee coordinate axes	29
Figure 15. Vertical and horizontal electric field components in the cyclotron.	30
Figure 16. Electrostatic focusing between the dees.	31
Figure 17. Diagram of magnetic focusing.....	32
Figure 18. Azimuthally varying magnetic field	36
Figure 19. Vertical motion of accelerating ions	37
Figure 20. Diagram of the RF circuit.	38
Figure 21. Phasor diagram for the potential between the dees	41
Figure 22. Potential across the dees	42
Figure 23. Relativistic effects on cyclotron frequency	44
Figure 24. Photograph of the Houghton College Cyclotron.....	46
Figure 25. Scale drawing of chamber	48
Figure 26. Scale drawing of lid	49
Figure 27. Photograph of the chamber	49
Figure 28. Photograph of the chamber fully assembled.....	51
Figure 29. Photograph of the dee and dummy dee.....	52
Figure 30. Scale drawing of the dee and dummy dee.....	53
Figure 31. Magnetic field strength as a function of distance from the center of the magnet	55
Figure 32. Magnetic field strength as a function of current.....	55
Figure 33. Diagram of the modified Faraday cup.....	56
Figure 34. Diagram of the vacuum system	58
Figure 35. Schematic of the Houghton College cyclotron's electrical system.....	60
Figure 36. Block diagram of RF system	63
Figure 37. Plot of dee voltage gain vs. frequency.	64
Figure 38. Plot of SWR.....	65
Figure 39. Plot of pickup probe calibration.....	66

Figure 40. Plot of $B_{\text{Lid}}/B_{\text{Dee}}$	67
Figure 41. RGA scan prior to accelerating hydrogen ions.....	68
Figure 42. RGA scan prior to accelerating helium ions	68
Figure 43. Beam current as a function of magnetic field for accelerated H^+ at 3.55 MHz.....	70
Figure 44. Full hydrogen scan at 3.55 MHz.....	71
Figure 45. Full hydrogen scan at 6.04 MHz.....	73
Figure 46. Helium scan at 3.485 MHz.	74
Figure 47. Hydrogen scan at 3.485 MHz	75
Figure 48. Second helium scan at 3.485 MHz.....	76

INTRODUCTION

1.1 History of Nuclear Research

Interest in nuclear research can be dated back to the beginning of the 20th century, in large part due to the contributions from Ernest Rutherford. Rutherford, now acclaimed as one of the greatest scientists of the 20th century, was an experimental scientist who devoted most of his time to studying the atom. For his work, Rutherford was awarded the Nobel Prize in 1908 [1]. In 1919, Rutherford observed the disintegration of nitrogen nuclei due to naturally occurring alpha particles originating from radium and thorium [2]. This phenomenon indicated that the nucleus could be excited or disintegrated in much the same way that an atom could. These results immediately stimulated interest in the nucleus. Eight years later, in an address to London's Royal Society, Rutherford expressed his interest in seeing the creation of alpha and beta particles with energy far greater than those from naturally radioactive sources [3]. His belief was that the ability to artificially create these particles would allow for the controlled and precise study of nuclei. Artificial creation of alpha and beta particle beams is made possible by devices called particle accelerators. Further enhancing interest in particle accelerators was the work of Russian physicist George Gamow in 1928. Gamow studied the probabilistic wave function of the nucleus and determined it was possible that energies of only 500 keV or less would be sufficient to penetrate and disintegrate light nuclei [2]. Though difficult to obtain in nature, these energies could be obtained using machines.

1.2 Particle Accelerators

Motivated by these findings, particle accelerator research became an intensely studied field of science over the following decades. In 1932, the first successful nuclear disintegration of ions was achieved by J.D. Cockroft and E.T.S. Walton using a high-voltage production technique. Their design (see Figure 1) used a complex arrangement of rectifiers and capacitors which allowed steady potentials of up to 800 keV to be obtained [4]. A potential of this magnitude was enough to accelerate hydrogen ions which would, according to the calculations of Gamow, disintegrate their Li target.

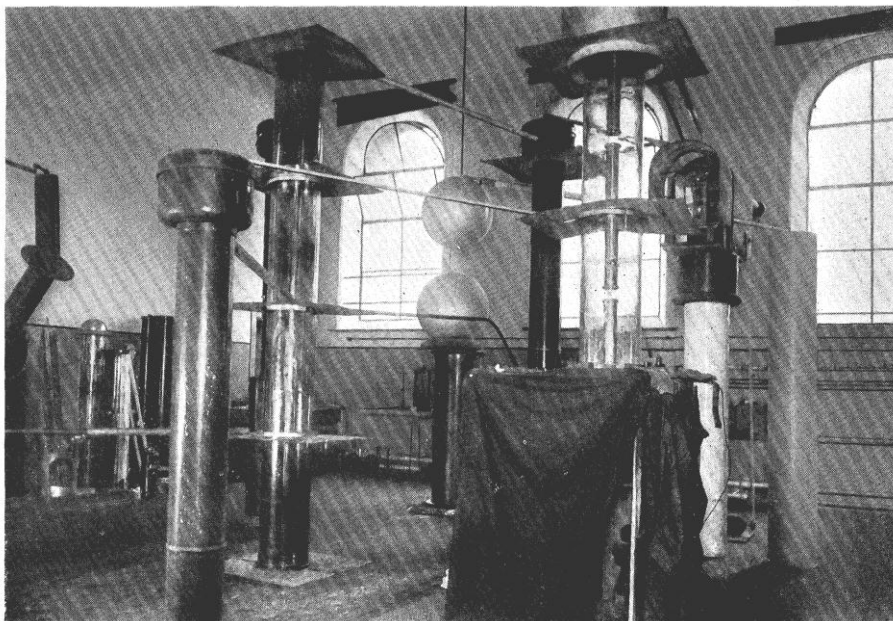


Figure 1. Cockroft and Waltons' high-voltage accelerator. The large columns consist of a complex arrangement of rectifiers and capacitors, contributing to the massive size of the accelerator. Figure taken from Ref. [4].

Upon completion of the high-voltage apparatus, Cockroft and Walton performed a series of experiments on different light nuclei [5]. The disintegration of Li into two alpha particles and by-products was observed using voltages between 70 and 500 kV. Gamow's calculations showed that a 600 keV proton would disintegrate the Li nucleus with a probability of 0.187 (nearly one out of every five times). Cockroft and Walton's experiment revealed, however, that about one million 600 keV protons would be required to disintegrate a single Li molecule. Thus, artificial nuclear disintegrations were more difficult to obtain than originally presumed and would require more advanced equipment.

Although it was successful in accelerating ions to several hundred keV, the technique of using static high voltages to accelerate ions used by Cockroft and Walton had definite ion energy limitations. E.O. Lawrence and D.H. Sloan, researchers at the University of California, Berkley, noted that not only do experimental difficulties significantly increase with high-voltage production, but the equipment needed for such production is cumbersome and impractical for most labs to use [6].

A solution to this problem was first recognized by R. Wideroe in 1929 [7]. Although Wideroe was the originator of this work, it was later expanded upon by Sloan and Lawrence in 1931. Since a high voltage accelerator had so many problems associated with it, Wideroe, Sloan and Lawrence accelerated ions by a series of relatively low voltages. After passing through several potential differences, the ions would be accelerated to energies far greater than any single high voltage source could achieve. This technique became known as linear resonance acceleration [7]. The following discussion of how linear resonance acceleration works is based on the 1931 experiment performed by Sloan and Lawrence [6].

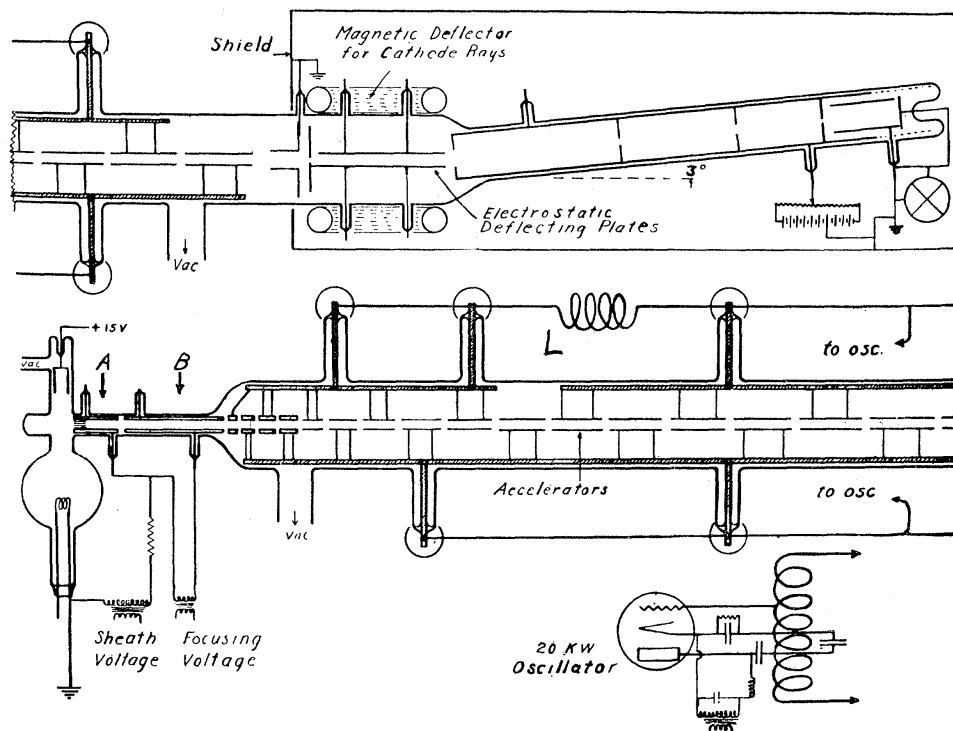


Figure 2. Diagram of Sloan and Lawrence's experimental apparatus. A high frequency oscillating voltage was applied to a series of copper tubes (accelerators) evenly distributed along the length of the apparatus. Between the accelerators, the ions would be accelerated by the voltage source. Within the copper tubes they drifted in a field-free region. Figure taken from Ref. [6].

As seen in Figure 2, in linear resonance acceleration a high frequency alternating voltage source was connected to a series of evenly spaced copper tubes (called accelerators) placed along the length of an accelerating path. Between each set of accelerators, the ions were accelerated by the potential

difference that existed in this region. Once the ions made it inside an accelerator, they were shielded from the electric field, allowing them to move at a constant velocity until they reached the end of the accelerator. While the ion was travelling within the copper tube, the potential on the accelerators was switched by a 60 cycle oscillator so that the ion would be accelerated to the next tube rather than repelled. At each acceleration gap (the region between the copper tubes), the ions would continue to gain more and more energy until they reached the end of the accelerators with an energy much greater than any single potential difference through which it passed. Using this method of acceleration, Sloan and Lawrence were able to obtain singly charged mercury ions with energy equivalent to that of passing through a 1.26 MV potential difference, a potential nearly twice that achieved by Cockroft and Walton [4]. Lawrence believed that this method could be extended and ions of 10 MeV would be possible.

One thing that Lawrence and Sloan had to consider in this design is the speed of the ions as they traveled through the accelerators. As the ions passed through successive accelerators, their speed increased. Since the acceleration gaps were equal and the oscillator frequency was kept constant, the length of the copper tubing was increased with each successive tube such that the time it took the ions to pass through an accelerator was constant for every accelerator along the length of the device. The lengths of the tubes increased as the square root of the tube number. In all, the apparatus contained 30 tubes each adding to the total apparatus length of 114 cm.

Linear resonance proved to be a useful technique for obtaining high energy particles and is the basic principle still used in some accelerators today. It avoided the problem of high-potentials by using a series of small potential differences to accelerate the same ion. It also required only a single resonant frequency for every acceleration gap. Moreover, it did not suffer from the relativistic limitations of other devices, such as the cyclotron, since relativity could be accounted for by adjusting the size of the copper accelerators. All that being said, there was one significant drawback: its length. The particles used by Sloan and Lawrence were heavy ions such as mercury. Small ions, such as protons and alpha-particles, are far more likely to interact with the nucleus than large ions and are, therefore, more desirable [7]. Accelerating protons and alpha particles to the same energy as Sloan and Lawrence's mercury ions, however, would require a particle accelerator roughly fourteen times longer than theirs [7]. This significant increase in accelerator length is the result of the mass difference between the mercury ions and protons. Given the same amount of kinetic energy, the lighter ions will travel faster

and, therefore, farther than heavy ions. It was apparent, however, that increasing the length of the linear resonance accelerator by a factor of fourteen was impractical at this time. Space limitations made this feat cumbersome for many facilities and would have necessitated the modification of pre-existing facilities or the construction of new ones. Thus, a new method of acceleration, magnetic resonance, was devised.

1.3 The Cyclotron

The cyclotron was first conceived by E.O. Lawrence in 1929 while he was reading Wideroe's work on linear resonance acceleration. In 1930, Lawrence wrote an article in *Science* [8] outlining a proposal for the cyclotron. Citing a need for acceleration methods without the use of high-voltages, Lawrence believed that he could use a magnetic field, along with Wideroe's resonance principle, to create high energy ions while avoiding the difficulties previously mentioned. Along with M.S. Livingston, a graduate student at the University of California, Berkley, Lawrence embarked on the project.

1.3.1 Operating Principles

A great advantage of the cyclotron is the relatively simple physical principle on which its operation is based. It works in the following manner, as described in Ref. [9]. Two "Dee"-shaped, hollow electrodes called "dees" (labeled A and B in Figure 3) are placed in a vacuum chamber between the poles of a magnet. The dees are coplanar and oriented perpendicular to the magnetic field. A high-frequency oscillating voltage is applied to the electrodes creating an electric field between them. When an ion is introduced into the system between the dees at point a, it experiences an accelerating force due to the electric field between them and begins to move with a given velocity towards dee A. Charged particles moving through a magnetic field oriented perpendicular to their direction of motion will experience a force perpendicular to both the magnetic field and the motion of the particle. Since this force is always perpendicular to the direction of motion of the ion, it will cause the ion to travel in a circular orbit. Once the ion has traveled a full half-circle, it will again reach the potential difference at point b located between A and B.

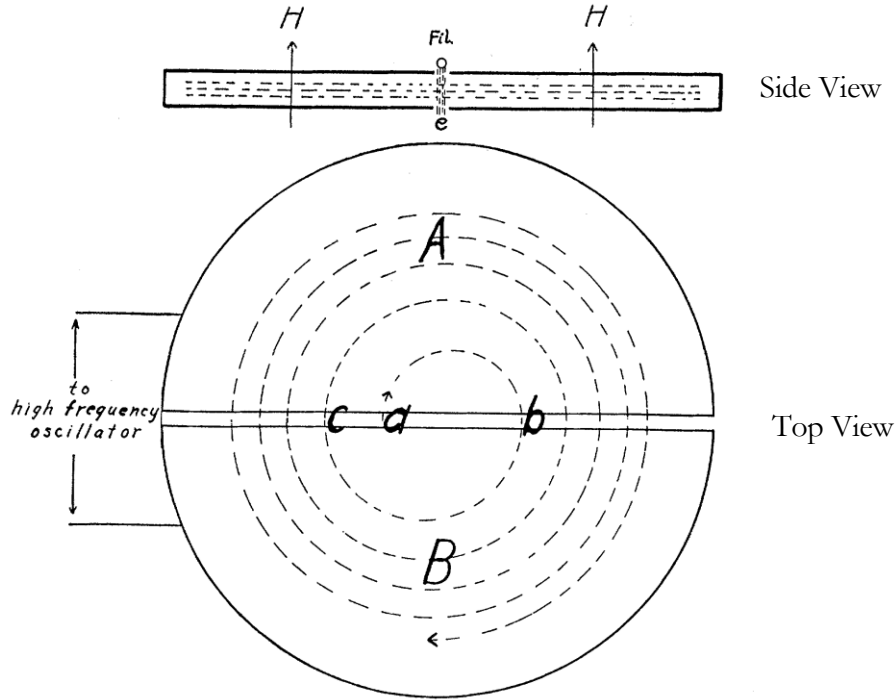


Figure 3. A diagram of cyclotron operation. An ion is created at 'a' in an electric field between two, dee-shaped electrodes A and B. The ion is accelerated by the electric field and passes through the first electrode, A. Since the system is placed in a magnetic field, the ion will follow a semicircular path back towards the gap between A and B. The polarity of the potential switches before the ion reaches the gap and accelerates it at point b. Before the particle reaches point c, the polarity on the dees switches again. This process continues until the outer rim of the dees is reached. Figure taken from Ref. [9].

Because of the high-frequency oscillator attached to the voltage source, the direction of the electric field will have changed its direction before the ion reached point b. Thus, the ion will be accelerated towards electrode B. Continuing to move in a circular path, the ion will eventually reach point c at which time the electric field is again pointing in its original direction accelerating the ion towards electrode A. This cycle continues until the ion reaches the outer edge of the electrodes. Since the particle is accelerated over and over again, its final energy is much greater than the original accelerating potential placed across the electrodes. Accelerating particles in this way is possible because the period of each ion orbit is the same regardless of its radius. In other words, a single RF frequency is used to accelerate an ion from rest to its final energy. A mathematical description of this phenomenon will be given in Chapter 2.

1.3.2 The First Cyclotron

In 1931, M.S. Livingston completed his doctoral thesis, entitled “The Production of High Velocity Hydrogen Ions Without the Use of High Voltages,” which describes the first test of the magnetic resonance principle. Used primarily for testing the feasibility of the resonance principle, this first cyclotron focused less on the energies that the cyclotron was capable of producing than on whether the principle worked.

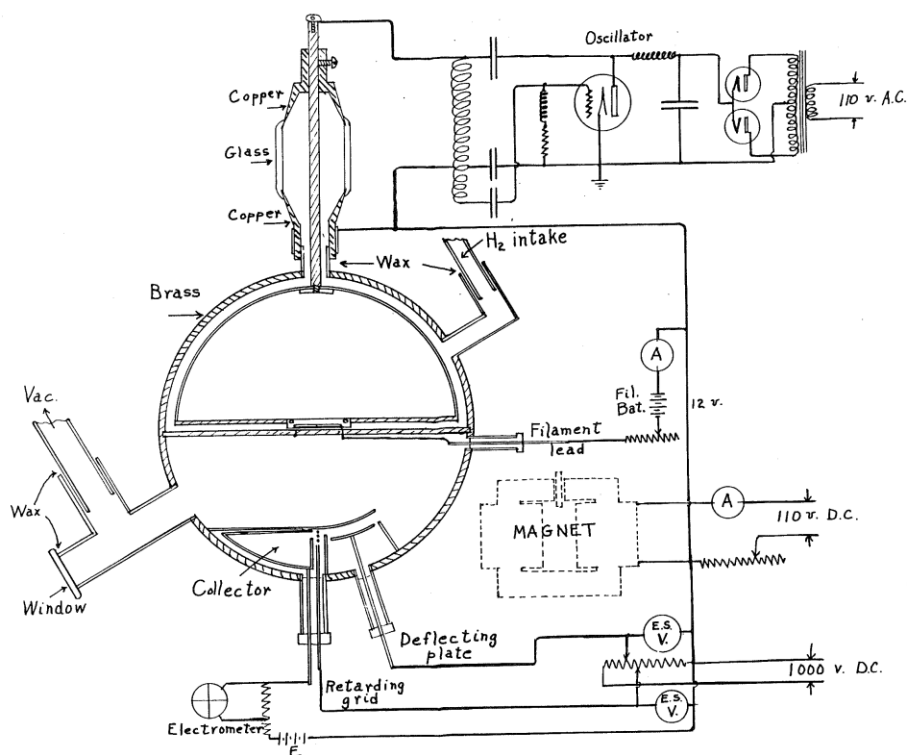


Figure 4. Lawrence's diagram of the first cyclotron. The RF oscillator circuit is attached to the dee electrode. The filament lead supplied power to the filament responsible for ion creation. A deflecting plate was used to direct the ion beam at a retarding grid, allowing the current to be measured with an electrometer. Figure taken from Ref. [10].

The dees of the cyclotron were connected to a 10 kV high frequency oscillator and placed within a 0.55 T magnetic field (he borrowed a 1.3 T magnet for some of the tests) [10]. Livingston placed a collector at a radius of 4.5 cm from the center of the chamber and performed a series of experiments

(see Figure 4). Operating with 2000 V on the high frequency oscillator, Livingston was able to obtain a 0.3 nA beam of 80 keV hydrogen ions and later noted that he obtained a maximum amplification of 82 times the original accelerating potential [10]. This proved the validity of the resonance accelerator principle.

1.3.3 Development of the Cyclotron

Although Livingston proved the resonance principle, particle accelerators were already capable of producing ions on the order of 80 keV. The first cyclotron to reach energy levels greater than those previously achieved was completed in 1932 by Lawrence and Livingston [9]. Higher energies were made possible by increasing the size and strength of the magnet. For this cyclotron, a 24 cm (9.45 inch) diameter hollow brass dee electrode and a 1.4 T magnet were used. To simplify the resonant circuit, the oscillating high frequency potential was applied to only one of the dees, the other dee being held at ground. Thus, ions were accelerated in the same manner as before. Using a 4 kV potential between the dees, this cyclotron was able to produce 1.22 MeV protons.

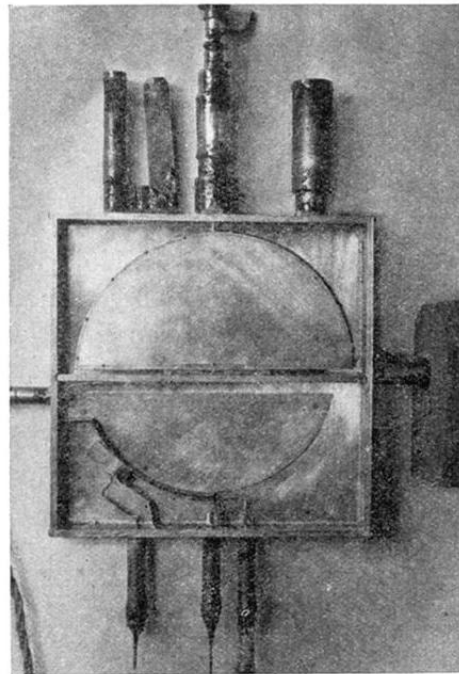


Figure 5. Photograph of Lawrence and Livingston's 1.22 MeV cyclotron. The dee electrodes were made of brass and were hollow to allow the ions to travel through a field free region. The bottom dee is smaller than the top dee because this allowed the ions to be more readily extracted once they reached their final radius. Photograph taken from Ref. [9].

In 1934, Lawrence and Livingston published a paper updating their progress in cyclotron research [11]. Over the two years between papers significant changes in the cyclotron were made, though the underlying principle remained intact. The chief difference between this cyclotron and the one completed in 1932 was the size of the apparatus in general. As will be shown in Chapter 2, the maximum attainable energy of the cyclotron mostly depends on the radius of the acceleration region and the strength of the magnetic field. For this reason, the dees were each increased to a diameter of 20 inches, the oscillating high voltage source was increased to a potential of 20 kV, and the magnetic field was increased to 1.8 T. Another key difference was the resonating potential which was now applied to both dees. Applying opposite potentials to the two dees yielded twice the acceleration per oscillation than holding one of the dees at ground since the relative potential between the two was increased. Although increasing the relative dee voltage does not directly affect the maximum attainable energy, the ions will experience a greater accelerating force causing them to reach their final energy with fewer orbits. Since the ions spent less time in the chamber, the probability that they collided with air molecules and fell out of resonance decreased and a more intense beam of ions was collected. These changes made possible the acceleration of hydrogen ions to energies of up to 5 MeV [11].

A third paper was published in 1936 by Lawrence and Cooksey [12]. This cyclotron used the same 27-1/2 inch magnet that was used in 1934, altering the cyclotron design itself rather than the size or strength of the acceleration region. The primary focus was the filament; the apparatus designed to create ions. In 1934, two filaments were placed at the center of the cyclotron supported by copper pipes extending from the wall to the center parallel to both dees. Since the filament supports only came out of one side of the chamber, an asymmetry of the electric field was created which could disrupt the resonance of the ions. To correct this, Lawrence and Cooksey ran the filament supports over top one of the dees, avoiding interaction with the electric field (Figure 6). Although the magnet remained the same, Lawrence and Cooksey made a new set of electrodes, each 24 inches in diameter and made entirely out of copper. These were slightly larger than the 20 inch dees used previously and contained a more advanced means of ion beam extraction. Finally, the high frequency oscillating voltage was operated between 50 and 100 kV (though it was never precisely measured). This cyclotron was able to produce a maximum current of 20-25 μA , 6.3 MeV deuterons and 0.1 μA , 11 MeV alpha-particles.

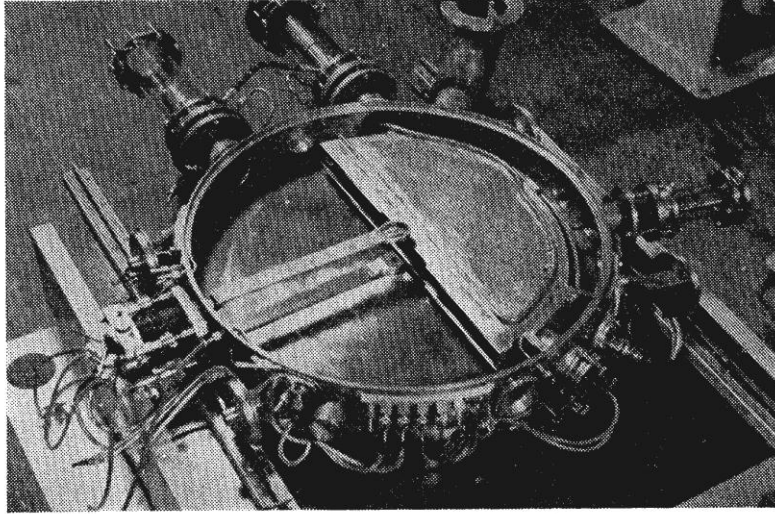


Figure 6. Photograph of Lawrence and Cooksey's cyclotron in 1936. One can see two radial supports coming from the wall of the chamber towards the center. These supports hold the filament in place. Note that the left dee, over which the filament is placed, has been removed in this photograph. The extraction system can be seen on the rightmost dee, a small ridge on the outer rim. Photograph taken from Ref. [12].

The trend of increasing the energy limit of the cyclotron continued over the following decades. As of 2008, the highest energy cyclotron in the world was at TRIUMF (TRI-University Meson Facility), a nuclear and particle physics research center located on the campus of the University of British Columbia (Canada). With an 18 m diameter, 5.6 T magnet, this cyclotron produces negatively charged hydrogen ions of energy up to 500 MeV [13]. At this energy relativistic corrections must be made in the design of the cyclotron.

1.3.4 Small Cyclotrons

It may seem as though now that large 500 MeV cyclotrons have been constructed, there is little point in constructing small cyclotrons similar to those originally built by Livingston and Lawrence. This could not be farther from the truth. A number of small cyclotrons have been built and used for a wide range of purposes since Livingston and Lawrence first completed their cyclotron in 1931. The purpose of this section is to highlight some notable small cyclotrons and the motivation for their construction.

Thanks in part to the relatively simple design and cheap materials of the cyclotron, small cyclotrons have been the topic of research for several undergraduate students. In 1954, a group of students at Iowa State University became the first undergraduates to successfully build and use a cyclotron in nuclear experiments [14]. Using a 1.7 T magnet with a 10 inch pole diameter, this cyclotron was capable of producing 1.5 MeV protons. Unlike Livingston's original small cyclotrons, this cyclotron used two dee electrodes, each 8.9 inches in diameter, instead of the single dee design. The 1.5 MeV protons created by this machine were of high enough energy to perform a variety of experiments. Another more recent undergraduate cyclotron was worked on by Jeffrey Smith at Knox College in Galesburg, Illinois (2001) [15] as a senior honors project. Smith's cyclotron featured an 8.9 inch radius, 2 T magnet and would have been capable of producing 1.53 MeV protons. Like the Iowa State Cyclotron, this cyclotron used a two dee electrode system, applying ± 3750 V to each. This high dee potential allowed the ions to be quickly accelerated, avoiding collisions with residual molecules in the chamber. Smith's cyclotron also possessed a mechanism for extracting the beam from the chamber. Once the ions reached the outer regions of the dees, a 32,000 V potential was used to guide the ions on a path through a port in the chamber wall where they could then be aimed at a target. Although Smith claims that the primary purpose for this cyclotron was the experience he obtained in building it, he admitted that the cyclotron would be used by future students in a series of low-energy nuclear scattering experiments.

Cyclotron projects have not been limited to undergraduate studies. In 1947, four high-school students and their teacher in El Cerrito, California, teamed up to build a cyclotron as an after school project [16]. Working during most of their free time, the boys constructed this cyclotron in three months at a total expense of only \$500 (equivalent to roughly \$4800 in 2008). Though the exact dimensions of the cyclotron are not given, this cyclotron was reportedly capable of producing 1 MeV ions. Their goal was to produce radioactive isotopes for use in experiments. To avoid radiation hazards when the machine was running, water tanks three feet wide were used as shielding between the operators and the cyclotron itself.

In 2002, a paper was written by cyclotron enthusiast Fred Niell detailing the small cyclotron he built from scratch as a high school senior in 1994 [17]. Niell's goal was to build a cyclotron with dimensions similar to that of Lawrence and Livingston's first cyclotron [10]. To do this, he first built a 0.67 T, 4.5 inch diameter magnet from soft iron ore and 13.5 gauge wire wrapped around the core.

The chamber itself was made out of a 6 inch diameter stainless steel wall with two 6 inch diameter aluminum lids. Unlike Livingston's cyclotron, Niell used a two dee system in which one dee was 0.5" larger than the other. Rather than designing a beam extraction system, Niell placed his targets directly in the beam path of the larger dee but outside the smaller dee, making use of the 0.5" gap. Niell's intention for the cyclotron was to produce a number of different high energy ions by using filaments containing Mg, Al, Be and B.

An interesting application of a small cyclotron is the Berkeley low energy cyclotron [18]. Built by graduate student K.J. Bertsche, this cyclotron (nicknamed the "cyclotrino") was designed to detect carbon-14 for use in mass spectrometry. Key features of the cyclotron included a 12 inch, 1 T magnet and a single dee design making the cyclotron capable of producing a 40 keV beam of ions. Since carbon-14 ions have a different charge-to-mass ratio than carbon-13, carbon-12 and ^{14}N ions, the cyclotron frequency was set to the resonant frequency of the carbon-14 atoms causing the other ions to fall out of resonance. Thus, only the carbon-14 ions were successfully accelerated and, therefore, collected. Carbon-14 is an important isotope that can be used in the radioactive dating of objects.

1.3.5 The Houghton College Cyclotron

Construction of the Houghton College Cyclotron began in 2001. The motivation for undertaking this project was to construct an accelerator that could be used for future undergraduate nuclear scattering experiments using low-energy neutrons. Since neutrons have no charge and, therefore, are able to pass through the chamber, the cyclotron design did not need or include a beam extraction system. Neutrons are obtained by filling the chamber with a deuterium gas. Once the deuterium molecules become ionized, deuterium ions (deuterons) will be accelerated towards and collected on a copper target, holding some of the deuterons in place. As more deuterons are accelerated towards the target, deuteron-deuteron reactions take place as either $\text{d(d,n)}^3\text{He}$ or $\text{d(d,p)}^3\text{H}$. A second way to setup these deuteron-deuteron reactions is to use a deuterated polymer in place of the copper target. Protons created in these reactions ionize molecules in the chamber wall as they pass through it, losing energy in the process and are, therefore, of no use outside the chamber. Neutrons with maximum energies of 2.8 MeV, however, pass through the wall unaffected and can be used for further inelastic scattering experiments.



Figure 7. Photograph of the Houghton College cyclotron chamber and dee in 2006. The chamber had an inner diameter of 15.2 cm and was made out of soldered brass. The dee and dummy dee were made out of copper plates and measured 14.5 cm in diameter. Photograph taken from Ref. [21].

As was the case with Lawrence's cyclotron, the Houghton College cyclotron has gone through several stages of development. At its origin, it was designed to use a 0.5 T permanent magnet with a 15.2 cm pole face diameter [19]. A permanent magnet had the advantage of reducing the complexity in design and also reduced the amount of power necessary to run the cyclotron [20]. Moreover, Houghton College already owned such a magnet. Construction on the vacuum chamber, a brass ring with an inner diameter of 15.2 cm, was underway by the winter of 2003. The system for evacuating the chamber was completed and successfully tested by the end of 2004. In 2005, the permanent magnet was replaced with the electromagnet currently in use. With an electromagnet, the magnetic field could be turned off and avoided the problem of attracting tools and other objects to the magnet while the cyclotron was being worked on. A second advantage of the new magnet was the increased field strength, measuring 1.1 T at the maximum current of the power supply, which correlated to higher energy ions. Completed by the end of 2006 were the chamber (see Figure 7), Faraday cup, magnet and diffusion pump cooling system, dee electrodes, and initial RF system [21]. After the RF system was

completed, the first simultaneous testing of all systems occurred in the spring of 2007 in which hydrogen was successfully accelerated [22] (see Figure 8). Unfortunately, a discharge from the dee to the chamber wall damaged the insulation and the cyclotron became inoperable. It is the purpose of this current paper to describe progress since 2007.

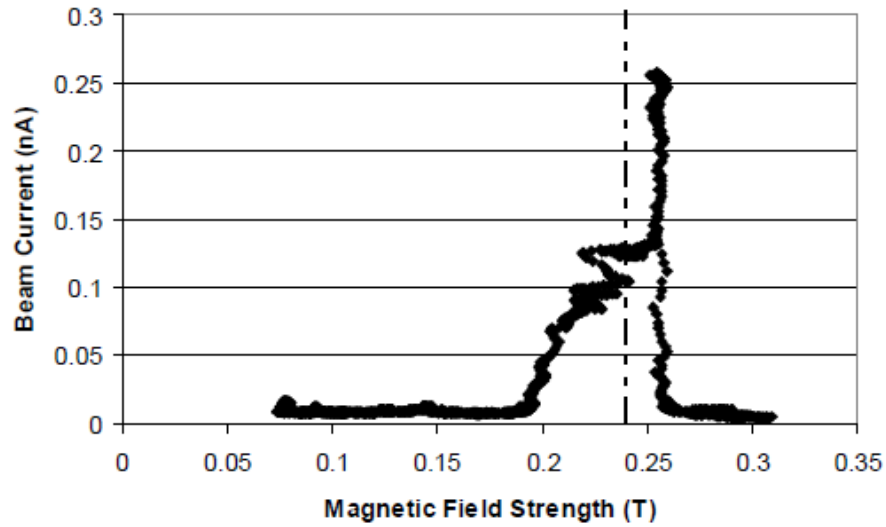


Figure 8. Resonance curve for hydrogen in 2007. The vertical axis is the beam current and the horizontal axis is the magnetic field strength. With an 840 V, 3.65 MHz oscillating potential on the dees, hydrogen should be in resonance at 0.24 T as represented by the dashed line. The actual resonance occurred at just under 0.26 T. The discrepancy may be due to an inaccurate calibration for the magnetic field. Figure taken from Ref. [22].

CYCLOTRON THEORY

Livingston and Lawrence realized that the cyclotron was practical for accelerating ions because of the simple principle on which it was based. Unlike other accelerators at that time, the cyclotron's design did not call for high voltages or large equipment. Using primarily a magnet and an oscillating potential, it was capable of accelerating ions to energies in excess of 5 MeV. This section describes the operating principle of the cyclotron.

2.1 Cyclotron Resonance

2.1.1 Ion Frequency

As pointed out in Chapter 1, the cyclotron is a magnetic resonance accelerator because ions are accelerated repeatedly by an oscillating electric potential within a magnetic field perpendicular to the particle orbit (See Figure 3). In order for the ions to be accelerated, they must remain in resonance with the oscillating potential. The frequency of oscillation necessary for resonance can be determined in the following manner [10].

The force on a charged particle travelling through a magnetic field (see Figure 9) is given by

$$\vec{F} = q\vec{v} \times \vec{B} \quad (2.1.1)$$

where q is the charge of the ion, v is the ion's velocity, and B is the magnetic field strength. Since the force must always be perpendicular to both $\mathbf{v}$ and $\mathbf{B}$, the ion will begin to move in a circular path. The centripetal force necessary for an object to remain in circular motion is given by

$$F = \frac{mv^2}{r} \quad (2.1.2)$$

where r is the radius of the ion's circular orbit. In the cyclotron, the centripetal force is supplied by the magnetic force so we can equate Equation (2.1.1) with Equation (2.1.2). Solving for angular velocity ω yields

$$\omega \equiv \frac{v}{r} = \frac{qB}{m}. \quad (2.1.3)$$

Finally, the orbit frequency of the ion is given by

$$f = \frac{q}{2\pi m} B. \quad (2.1.4)$$

Surprisingly, from this equation it can be seen that the ion frequency does not depend on either velocity or radius. It depends only on the magnetic field and the charge to mass ratio of the ion. This is because as the particle speeds up, its radius increases and, therefore, has to travel a longer path. Amazingly, the time necessary to complete one revolution always remains the same. Since it is independent of velocity or radius, the same frequency can be used to accelerate the ion from small orbits to its maximum orbit. This principle makes possible the fixed-frequency cyclotron.

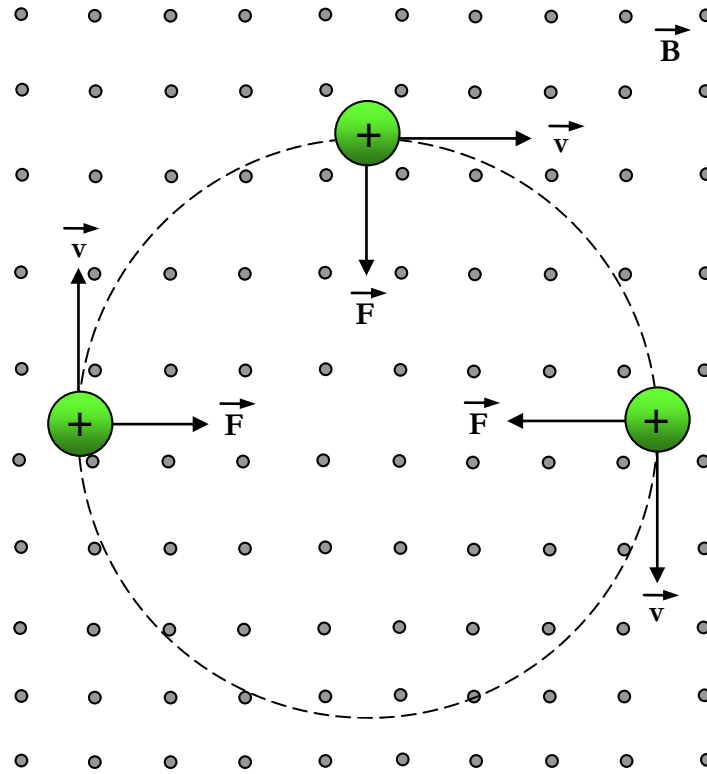


Figure 9. Motion of an ion moving through a magnetic field. The gray circles represent a magnetic field pointed out of the page. From Equation (2.1.1), the force exerted on the ion moving through the field must be perpendicular to both $\mathbf{v}$ and $\mathbf{B}$. This creates the centripetal force necessary for the ion to travel in a circular path.

As seen in Figure 10, the frequency forms a linear relationship with the magnetic field, where the slope is determined by the type of particle being accelerated [10]. Using this relationship, the magnetic field and frequency can be set to a value such that it will only accelerate particles with the appropriate charge to mass ratio. In other words, accelerating protons requires different f and B values for resonance than accelerating deuterons. Ions with identical charge-to-mass ratios, such as deuterons and alpha-particles, will have the same frequency-magnetic field dependence for resonance.

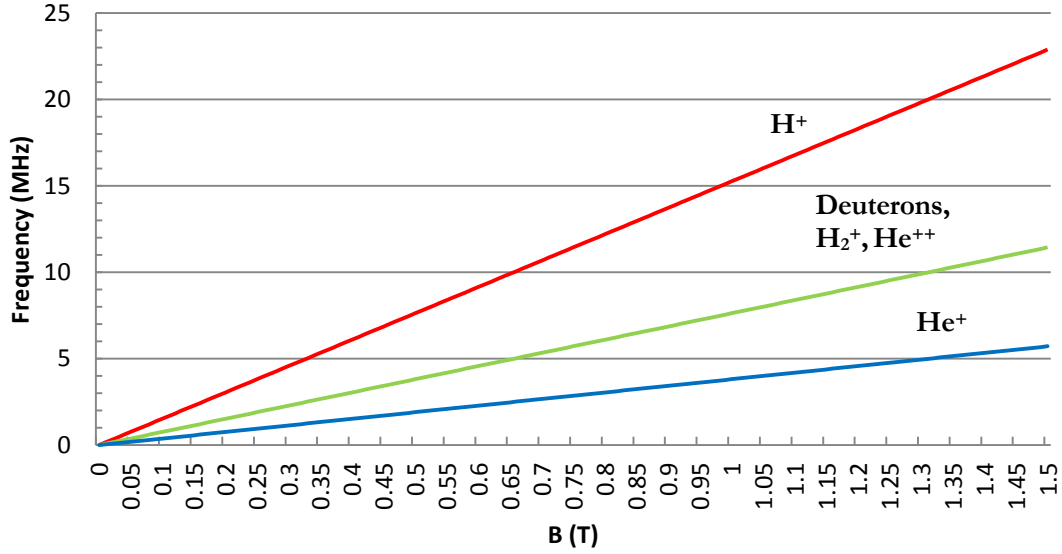


Figure 10. The cyclotron frequency versus B-field. The blue, red and green lines represent the linear relationship between frequency and magnetic field required for resonance for H^+ , H_2^+ , and He^+ ions respectively. Since He^{++} , deuterons and H_2^+ ions have identical charge to mass ratios, they share the same line. Calculated using Equation (2.1.4).

As Figure 11 shows, the potential difference between the dees varies with time sinusoidally. For this reason, the potential across the dees is only at a maximum for a short time. Ions do not, however, have to reach the acceleration region when the potential is at a maximum to remain in resonance. As long as they pass through this region when the potential is oriented for acceleration, they will remain in resonance until they have been fully accelerated. When ions are accelerated at potentials less than the maximum, they will simply have to complete more orbits before they reach the outer edge of the dee [23].

2.1.2 Harmonic Frequencies

Although Figure 10 seems to indicate that, at a given RF frequency, there is only a single value for the magnetic field, B , which will accelerate an ion, this is not entirely true. It is possible for ions to be accelerated at magnetic fields of B/n where n is an odd numbered integer. The resonance peaks resulting from this phenomenon are called harmonic peaks.

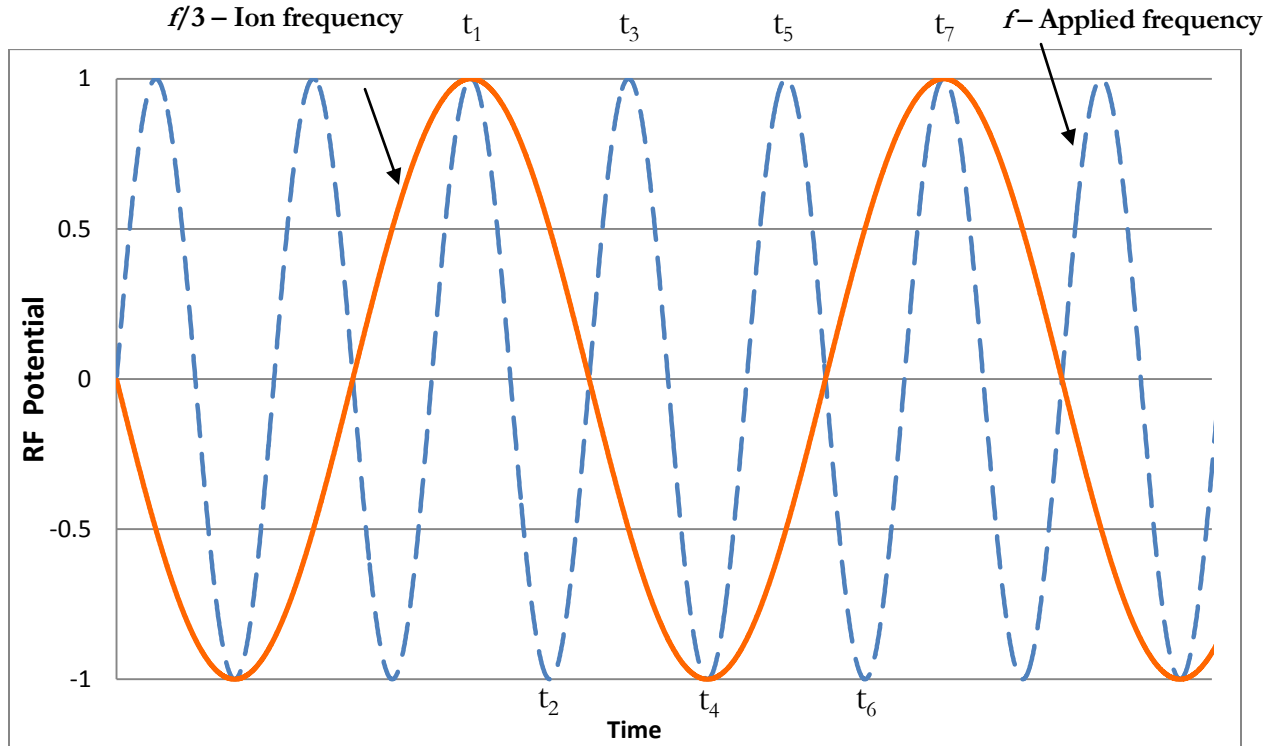


Figure 11. Graph displaying harmonic frequencies. If an ion being driven at f is accelerated at $B/3$, it will sweep out a circular path with a frequency of $f/3$. Since f and $f/3$ are identical whenever the ion crosses the potential difference (i.e. t_1 , t_4 , and t_7), ions can be accelerated at both B and $B/3$ for a single driving frequency. This is only true for odd-numbered harmonics of the driving frequency, such as the case shown above.

Harmonic peaks were first discovered by Livingston [10]. He found that at an applied frequency of f , acceleration occurred at the predicted magnetic field of B as well as at $B/3$. A frequency of $f/3$ would normally be required to accelerate ions at this magnetic field. Figure 11 and Figure 12 show how this can be understood. If the magnet is set to $B/3$ and an ion is accelerated by the potential between the

dees at t_1 , the ion must sweep out a path with an orbital frequency of $f/3$ as described by Equation (2.1.4). While the ion is within the field free region of the dee, the applied potential (with frequency f) will change polarity at t_2 and t_3 before it is in phase with $f/3$ at t_4 . At this time, the ion has finally reached the acceleration gap and is once again accelerated by the potential difference (see Figure 12). In other words, the ion remains in resonance even though it is travelling with an orbital frequency one third that of the driving frequency. Note that this only works if the two frequencies are odd harmonics of one another.

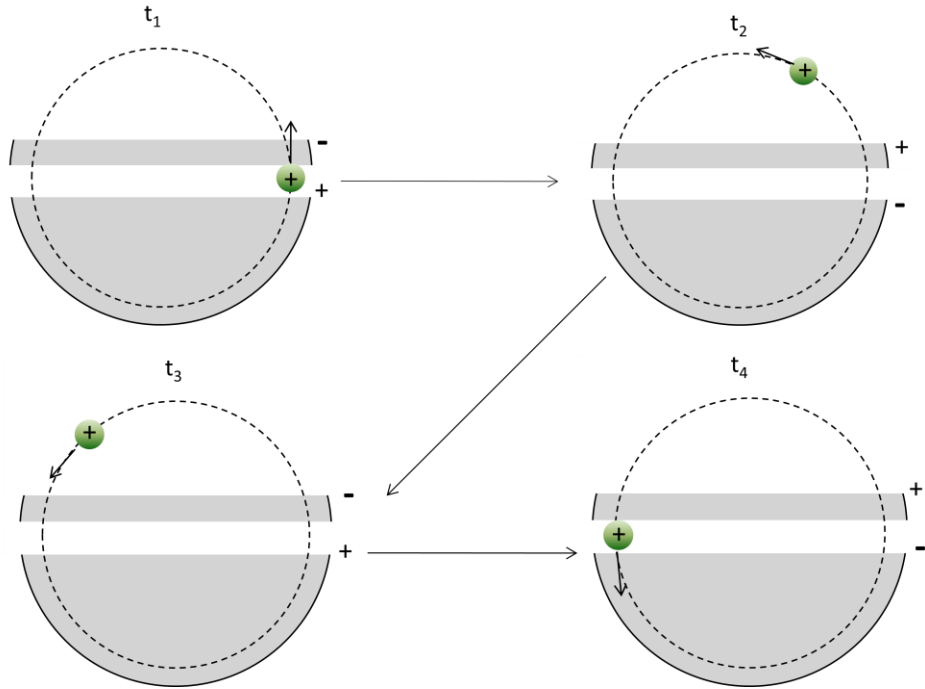


Figure 12. Diagram of harmonic frequency acceleration. The potential on the dees changes with frequency f . At t_1 , the ion is accelerated by the potential difference at a magnetic field of $B/3$ correlating to an ion frequency of $f/3$. This means the polarity switches at t_2 and t_3 while the ion is in the field free region and is unaffected by the change. At t_4 , the ion reaches the acceleration region as the polarity changes so as to accelerate the ion in the other direction. Thus, it will remain in resonance.

2.1.3 Ion Energy

Ion energies can be determined in a similar manner. For an ion passing through an electric field, the energy gained will be equal to

$$T = nqV = \frac{1}{2}mv^2 \quad (2.1.5)$$

where T is the kinetic energy of the particle, V is the potential, n is the number of times the ion crosses the potential, and q is the charge of the ion. Solving Equation (2.1.3) for v

$$v = \frac{qBr}{m} \quad (2.1.6)$$

and substituting into Equation (2.1.5), the kinetic energy obtained is

$$T = \frac{q^2B^2r^2}{2m} \quad (2.1.7)$$

where r is the radius of the ion's path at the point of detection.

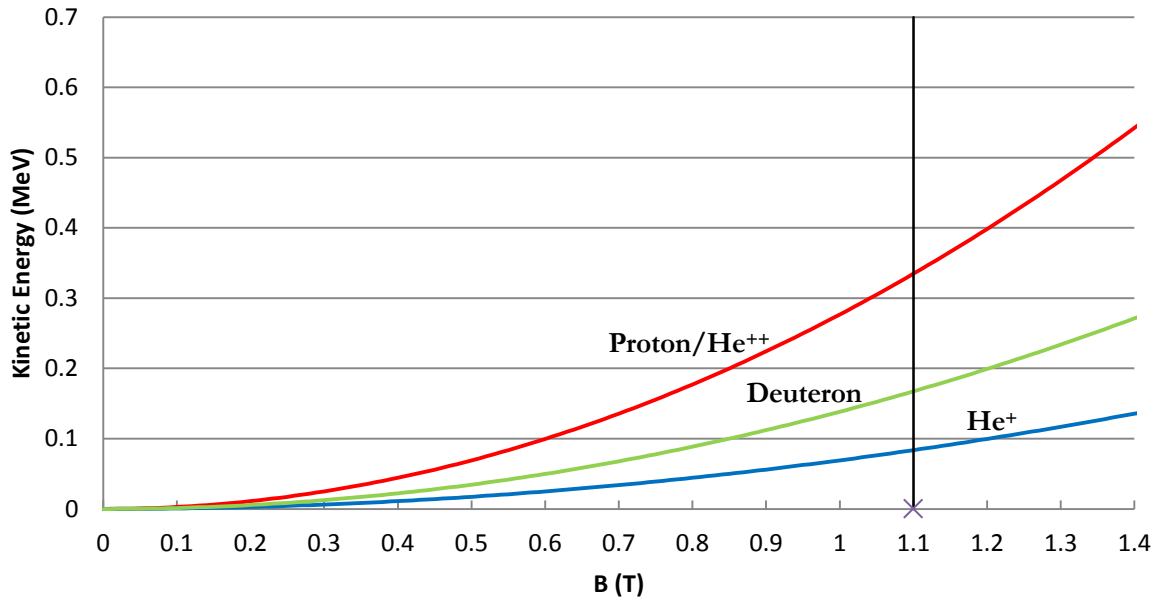


Figure 13. Graph of ion energies as a function of magnetic field strength for various ions. These energies were calculated for the Houghton College cyclotron with a maximum radius of 7.6 cm. The vertical line represents the 1.1 T limit of the Houghton College cyclotron's electromagnet. These values were determined using Equation (2.1.7).

There are two things to notice from Equation (2.1.7), which is graphed in Figure 13. First, the energy increases with the square of the magnetic field as well as the square of the radius of the ion orbit. In

other words, even slightly increasing either of these two parameters can make a large change in the final ion energy. Secondly, it is clear that the final energy depends not on the potential placed across the dees, but rather on the ion being accelerated, the magnetic field, and the radius of the acceleration region. Increasing the potential on the dees decreases the number of orbits needed for the ion to accelerate to its final velocity, thereby reducing the chances that the ion will collide with neutral atoms and fall out of resonance [7]. Using Equation (2.1.7) and the upper limit of the Houghton College cyclotron's radius (7.6 cm), the theoretical upper limit energies of protons, doubly-ionized helium (alpha-particles), deuterons, and singly-ionized helium can be calculated for the Houghton College cyclotron to be 0.335 MeV, 0.335 MeV, 0.167 MeV and 0.084 MeV respectively.

2.1.4 Ion Path Length

Since the ion is travelling in a circular path, its total distance traveled will be much greater than the radius of its final orbit. The total path length traveled by the ion can be determined in the following manner.

Rearranging Equation (2.1.6) for r , the radius of the ion orbit, gives

$$r = \frac{mv}{qB}. \quad (2.1.8)$$

The ion radius changes when its velocity changes. In other words, the radius increases with increasing energy. For a given dee potential, the velocity of the ion can be found by rearranging Equation (2.1.5) to get

$$v = \sqrt{\frac{2nqV}{m}} \quad (2.1.9)$$

where n is the number of times the ion passed the acceleration region. Substituting Equation (2.1.9) into Equation (2.1.8), the radius of the ion path becomes

$$r = \frac{m}{qB} \sqrt{\frac{2nqV}{m}} = \frac{1}{B} \left(\frac{2nmV}{q} \right)^{1/2}. \quad (2.1.10)$$

Each time the ion is accelerated, it will travel one half-circle before it is accelerated again and its radius increases. Thus, its path length through the dee is given by the sum of the half-circles that the ion traverses,

$$D = \sum_{i=r_0}^r \pi r_i = \sum_{n=0}^N \frac{\pi}{B} \left(\frac{2nmV}{q} \right)^{1/2} \quad (2.1.11)$$

where, r is the final radius of the ion orbit and N is the total number of times the ion is accelerated. For a given final radius then, the number of total revolutions can be determined in Equation (2.1.10) and then summed over in Equation (2.1.11).

This equation assumes that the acceleration happens instantaneously and that the dees are aligned such that they make a perfect circle. These approximations are better for smaller dee separations.

As an example, protons accelerated at a frequency of 3.485 MHz, magnetic field of 0.23 T, dee potential of 750 V, and a radius of 5.95 cm will travel a total path length of 1.58 m. He^+ ions similarly accelerated but with a magnetic field of 0.91 T will travel a total path length of 5.95 m.

2.2 Electrostatic and Magnetic Focusing

Ions are created at many different locations within the chamber. Without a means of focusing the ions, they would scatter in all directions. As a result, many of the ions will miss the collector and some will actually collide with the dees and be lost. Focusing the ion beam is important as it produces a higher current beam of ions. It is this aspect of focusing, however, that can prove to be a major challenge to developers in ion beam production equipment [24]. In Lawrence and Livingston's cyclotron, ions made numerous rotations within the chamber sweeping out total path lengths several meters long, yet they had to be focused on a target merely 1 mm in diameter [9]. Arguably one of the most useful features of the cyclotron is how it focuses the ion beam, a task it accomplishes with Electrostatic and Magnetic Focusing. As Rose describes, it is the inhomogeneity in these fields which is mostly responsible for ion beam focusing in the cyclotron [25].

2.2.1 Electrostatic Focusing

When a potential is placed between the dee electrodes, an electric field is created in this region. As charged particles pass through this electric field, they experience a force in the direction of the field

$$\vec{F} = q\vec{E}. \quad (2.2.1)$$

This is the force that accelerates ions in a cyclotron. As shown in Figure 15, even though the potential is applied directly across the two electrodes, the electric field is not perfectly uniform across this region. As a result of this inhomogeneity, the electric field will have both horizontal and vertical components creating what is called an “electrostatic lens.”

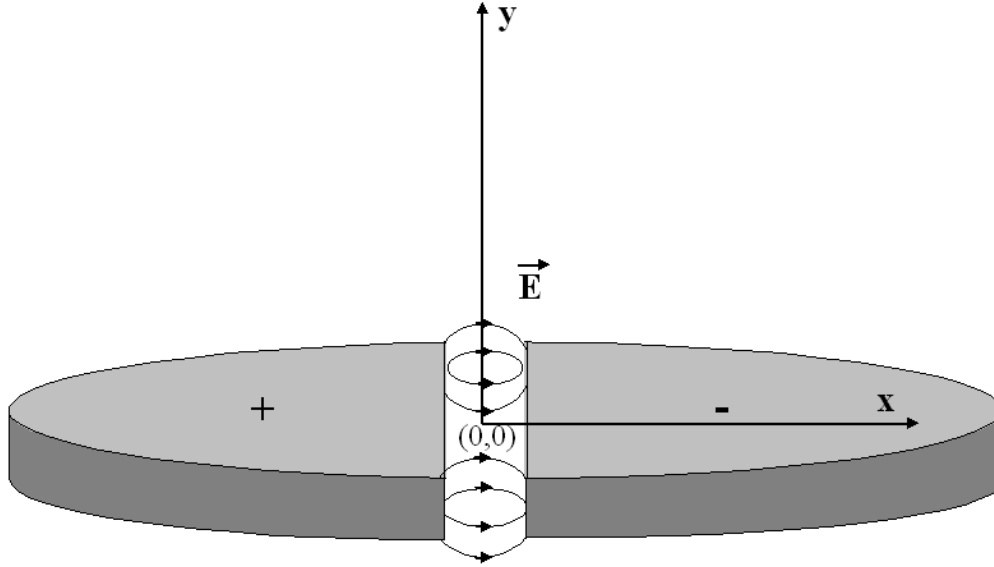


Figure 14. Diagram of the coordinate axes used in Figure 15. The axis along the plane of the dees perpendicular to the gap is the x-axis. The axis oriented perpendicular to the plane of the dees is the y-axis. Given the axes shown, the z-axis would be coming out of the plane parallel to the dee edges (not shown). The electric field is not uniform in the region between the dees.

By looking at the electric field components as a function of horizontal distance between the dees, a better understanding of how these fields focus ions can be obtained. In Figure 15, the dotted line represents the electric field in the x-direction and the solid line represents the field in the y-direction. The position $x=0$ corresponds to the mid-point between the two dees. If a particle enters this region from the left ($x=-7$ cm) and above the central plane, it will experience a focusing vertical force and accelerate back towards the central plane. Thus, the particle will gain a velocity, Δv_y , towards the central plane. As the particle then crosses the gap between the dees (passes $x=0$), it will eventually experience a second, defocusing vertical force in the opposite direction of the first causing it to

accelerate away from the central plane. This acceleration changes the velocity of the particle by an amount $-\Delta v'_y$ (away from $y=0$). Changing the vertical velocity in this manner will cause the particle to oscillate about the central plane. Notice, however, that while this is occurring, the particle is being accelerated along the horizontal direction and is, therefore, speeding up. In other words, the particle will spend more time in the focusing region than the defocusing region resulting in Δv_y being greater than $\Delta v'_y$. Thus, the net change in velocity points towards the central plane [26].

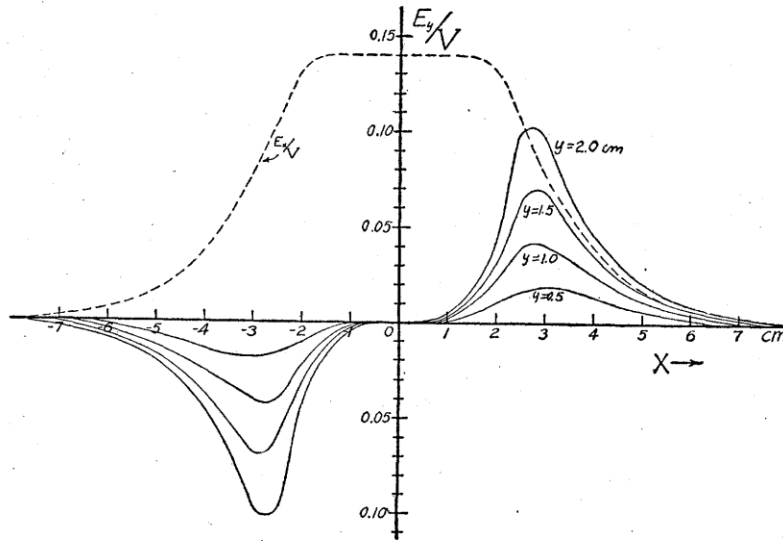


Figure 15. The electric field components within a cyclotron as a function of horizontal and vertical position. This graph is plotted for the case when the height of the dees and the separation between the dees are the same. The solid lines represent the electric field in the y -direction and the dotted line represents the field in the x -direction. In this graph, $x=0$ corresponds to the middle point between the two dees. Figure taken from Ref. [26].

Figure 16 shows the path that a particle will take as it passes through the electric field. The force on a positive particle will be in the same direction as the electric field lines drawn. Thus, when a positive particle enters the field it is first focused towards the central plane. Upon exiting the field, the particle is defocused away from the central plane but over a shorter period of time because of the speed of the particle. The net impulse, therefore, is focusing towards the plane [25].

Although electrostatic focusing always occurs, the efficiency of the focusing effect is dependent on both the height and separation gap of the dees. It turns out, that the magnitude of the vertical electric

field near the center increases as the ratio of the separation distance (d) to dee height (b) decreases. Because of this principle, R.R. Wilson found that dees with a d/b less than 0.4 are more effective at focusing an ion beam than dees with a $d/b=1$ and it is, therefore, desirable to minimize d/b [26]. The Houghton College cyclotron has a dee separation of $d=0.635$ cm and a dee height of $b=1.27$ cm for a $d/b=0.5$.

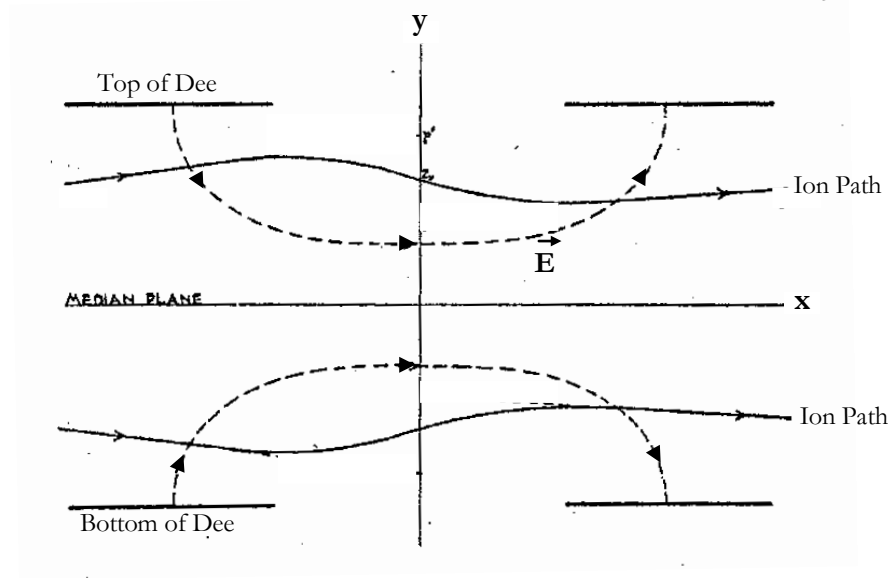


Figure 16. Diagram of electrostatic focusing between the dees. The focusing is a two step process. Ions entering the electric field from the left are first focused toward the median (or central) plane by the electrostatic "lens." Upon exiting the lens, the ions are defocused. Since the ions are being accelerated along x in this region, the ions are focused for a longer period of time then they are defocused. Thus, the net effect is that of focusing. Note: the vertical components of the field have been exaggerated in this diagram. Figure modified from Ref. [25].

Although the electric field plays a role in ion beam focusing, its role is limited. First, electrostatic focusing affects only low energy particles with radii much smaller than the actual dee radius [25]. Because the dees are conductors, an electric field cannot be present deep within the dee. The only electric fields occur because of fringe effects near the entrance of the dee. Figure 15 shows this effect as the solid lines (representing vertical electric field components) become smaller farther away from $x=3$. Furthermore, the focusing effects from the magnetic field are of greater magnitude than those of the electric field for larger ion velocities and generally dominate the overall focusing [26].

2.2.2 Magnetic Focusing

Like the electric field mentioned above, the magnetic field is not perfectly uniform across the chamber but instead decreases with the radial distance from the center. This gradient is responsible for the automatic focusing nature of the magnetic field.

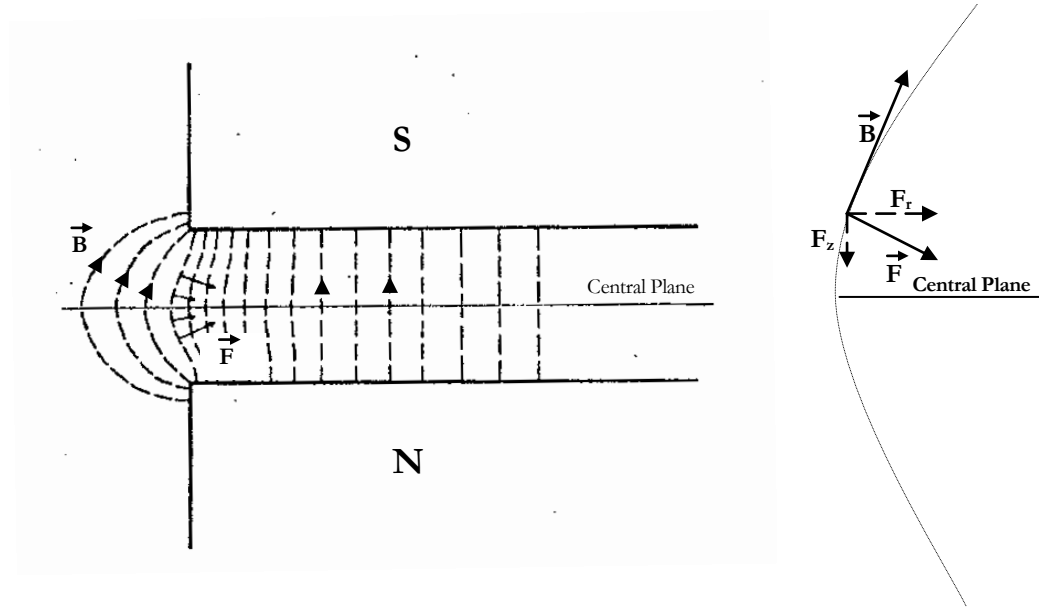


Figure 17. Diagram of magnetic focusing. The lines between the magnet poles represent the direction of the magnetic field in this region. The curvature of the fringe magnetic field near the edges of the cyclotron applies a force on the ions, represented by the lines pointed towards the central plane. This force acts to focus the ion beam during acceleration. The figure on the right is an enlarged view of a single magnetic field line detailing the forces involved. The horizontal components of these fields have been exaggerated. Figure on left modified from Ref. [25]

The focusing works in the following manner. Recall from Equation (2.1.1) that the magnetic field will exert a force on a moving charged particle that is perpendicular to both the particle's velocity and the direction of the magnetic field. If the magnetic field is uniformly perpendicular to the ion's motion, the resulting force causes the ion to travel in a circular path as shown in Figure 17. If the field is not perfectly perpendicular to the plane of motion, however, the cross product in Equation (2.1.1) will have both a vertical (F_z) and a radial (F_r) component to the force [2]. The radial component causes the ion to remain in circular motion and the vertical component causes the ion to move back towards the central plane, focusing the ion beam.

Recall that the resonance in Equation (2.1.4) assumes that the magnetic field is entirely perpendicular to the ion motion. In other words, this equation indicates that it is possible for the ions to fall out of resonance because of magnetic focusing. The fringe field, however, occurs only near the outer edge of the magnet so Equation (2.1.4) is valid for most of the ion path length. Moreover, the fringe field is small enough that it would take a large number of rotations for the ion to fall completely out of resonance. Thus, the ion will reach its final radius before this occurs.

Notice that when the ion is accelerated towards the central plane, it will actually travel past the plane becoming out of focus again. Once on the other side of the plane, the ion will be focused back towards the central plane by the magnetic field in this region. This process repeats itself several times causing the ion to oscillate about the central plane (or axis). The motion of the ion about the central plane can be determined as follows [2]. To be consistent with previous diagrams, consider a cylindrical coordinate system where r is the radius from the origin, θ is the angle in the x - z plane from the x -axis, and y is the height above the x - z plane. For an ion in an electric and magnetic field, the vertical equation of motion is

$$\frac{d}{dt}(m\dot{y}) = eq + q\dot{r}B_\theta - qr\dot{\theta}B_r \quad (2.2.2)$$

where m is the mass of the ion, y is the coordinate perpendicular to the dees, r is the radius of the orbit, q is the charge of the ion, and the dot notation means taking the derivative with respect to time. As mentioned above, the magnetic field must decrease radially for the ions to be focused. Mathematically, this is described by

$$B_y = B_0 \left(\frac{r_0}{r} \right)^n \quad (2.2.3)$$

where B_y is the vertical component of the magnetic field being measured, B_0 is the value of the magnetic field along the central plane, r_0 is the distance to the ion along the central plane, r is the total distance to the ion and n is a constant depending on the magnet and has the value

$$n = -\frac{r}{B} \frac{dB}{dr}, \quad (2.2.4)$$

where B is the magnet strength and r is the distance from the center. For small oscillations about the central plane, Equation (2.2.3) can be simplified by a power series to get

$$B_z = B_0(1 - \frac{n\Delta r}{r_0}) \quad (2.2.5)$$

where Δr is the difference between r and r_0 . For this situation, Maxwell's equation is

$$\vec{\nabla} \times \vec{B} = 0 \quad (2.2.6)$$

which means that

$$\frac{\partial B_z}{\partial r} = \frac{\partial B_r}{\partial z}. \quad (2.2.7)$$

Solving Equations (2.2.5) and (2.2.7) for B_r , the radial component of the magnetic field, yields

$$B_r = -\frac{nB_0 z}{r_0}. \quad (2.2.8)$$

Using this value for B_r in Equation (2.2.2), disregarding the electric field (for magnetic focusing), and noting that the angular component of the magnetic field is zero, Equation (2.2.2) becomes

$$\frac{d}{dt}(m\dot{y}) = \frac{qvB_0 ny}{r_0} \quad (2.2.9)$$

where the product $r\dot{\theta}$ became v . It was shown that at equilibrium,

$$\frac{mv^2}{r_0} = -qvB_0. \quad (2.2.10)$$

Solving for B_0 and substituting into Equation (2.2.9), the equation of motion becomes

$$\frac{d}{dt}(\dot{y}) = -\omega^2 ny \quad (2.2.11)$$

where

$$\omega = \frac{v}{r_0}. \quad (2.2.12)$$

The equation of motion of a simple harmonic oscillator is given by

$$\frac{d}{dt}(\dot{x}) = -\omega_0^2 x \quad (2.2.13)$$

Note that Equation (2.2.11) is in the form of a harmonic oscillator where

$$\omega_0 = \omega n^{1/2}. \quad (2.2.14)$$

Thus, the motion of an ion being focused by a radially decreasing magnetic field will resemble that of a harmonic oscillator with a frequency of

$$f_y = \frac{\omega}{2\pi} n^{1/2} = f_0 n^{1/2} \quad (2.2.15)$$

where f_0 is the resonant frequency of the cyclotron given in Equation (2.1.4), f_κ is the frequency about the central plane, and n is the magnet radial index defined by Equation (2.2.4).

From these equations, it can be seen how the gradient of the magnetic field affects the frequency of oscillation about the central plane. The fact that the magnetic field can focus over the entire acceleration region is one reason why the magnetic focusing effect is more significant than the electrostatic focusing which occurs only at low energies [25].

Although the magnetic field in Figure 17 appears to diverge only near the edge of the magnetic field, magnetic focusing becomes more effective if this gradient exists to a small degree at any distance from the center. Oftentimes, magnetic focusing can be increased by shaping the magnet poles. By experimentally placing iron “shims” near the center of the magnetic field, Lawrence and Cooksey were able to create a less uniform magnetic field across the acceleration region, yielding a more focused beam [12].

A second method for improving beam focusing is by using an azimuthally varying magnetic field. As shown in Figure 18, placing triangular shaped shims in different sectors of the magnet pole face results in an azimuthally varying magnetic field [27]. Regions of large magnetic fields (denoted H) are called “hills” and regions of smaller magnetic fields (denoted V) are called “valleys.”

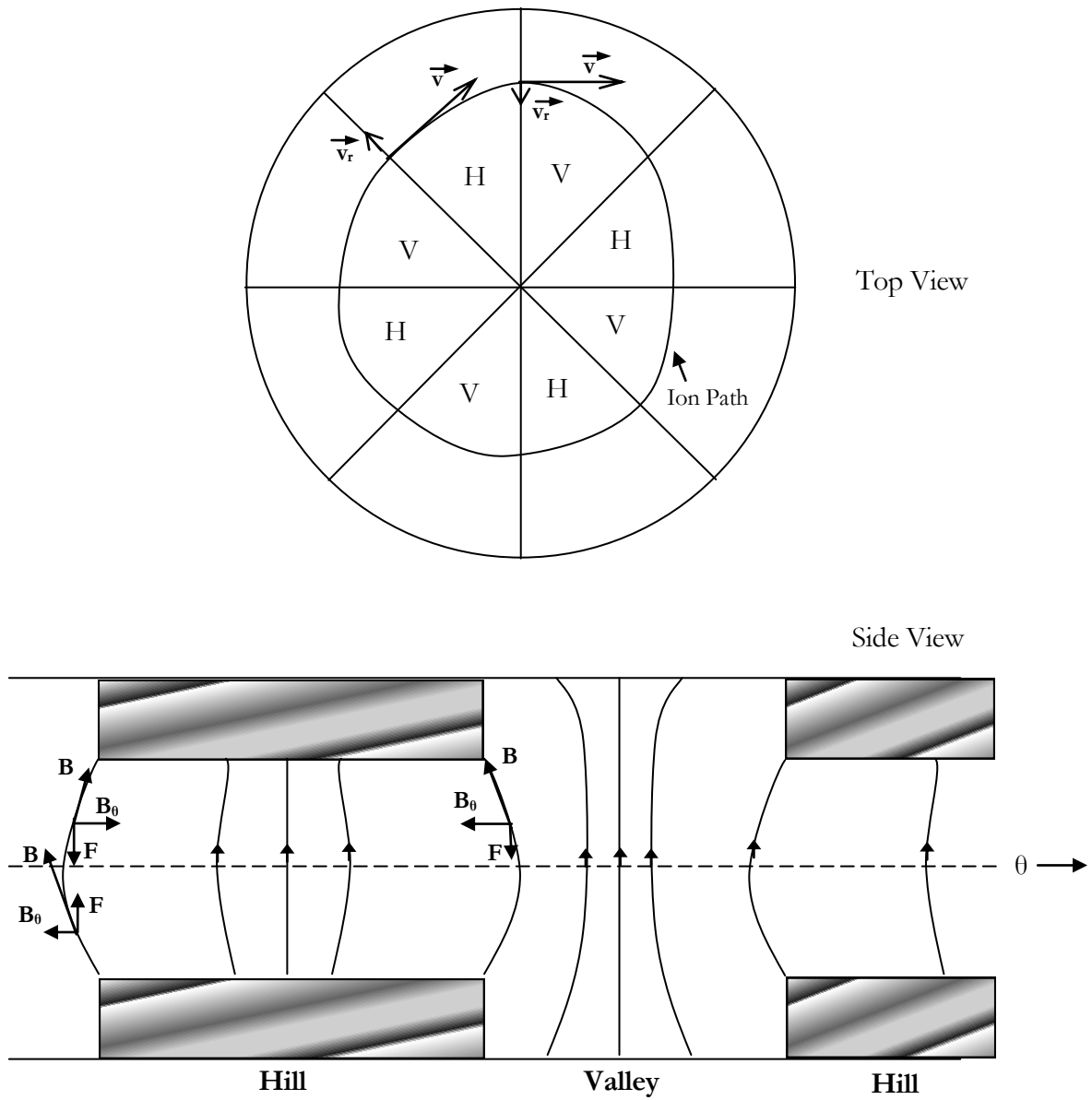


Figure 18. Azimuthally varying magnetic field. Hills (H) represent regions of larger magnetic fields and valleys (V) represent regions of smaller magnetic fields. Because of this azimuthal variation, ions do not travel in a circular path and, as a result, have a radial component between two regions. In the side view diagram, the x-axis represents increasing θ and the radial velocity is pointed into the plane of the page. Fringe fields between the two regions have an azimuthal component which applies a force on the particle. In agreement with Equation (2.1.1), this force is oriented towards the central plane because of the ion's radial velocity.

Because of this field irregularity, an ion does not travel in a circular path but instead sweeps out an irregular shaped curved polygon path as shown in the top view of Figure 18. Since the ion is not

travelling in a perfectly circular path, it will have a radial component to its velocity when crossing the boundary between hills and valleys. Meanwhile, fringe fields between the boundaries have an azimuthal component (B_θ) as shown in Figure 18. Thus, when an ion with a radial velocity (v_r) passes through this fringe field, a force (F) oriented towards the central plane is exerted on the ion in agreement with Equation (2.1.1). This force acts to focus the beam of ions.

This type of field shaping is most commonly used in isochronous cyclotrons. Isochronous cyclotrons have a radially increasing magnetic field to account for relativistic changes in the ion's frequency (see Section 2.4). Since the magnetic field is increasing, magnetic focusing as discussed in the beginning of this section no longer applies. Isochronous cyclotrons, therefore, rely on an azimuthally varying magnetic field to focus the ion beam.

2.2.3 Vertical Motion of the Ions

In both electrostatic and magnetic focusing, the focusing force imparts a vertical velocity (perpendicular to the plane of the dees) to the ion. Furthermore, the magnitude and direction of the imparted velocity change in such a way so as to oscillate the particle about the central plane. Thus, it is of interest to briefly discuss the overall vertical motion of the particle.

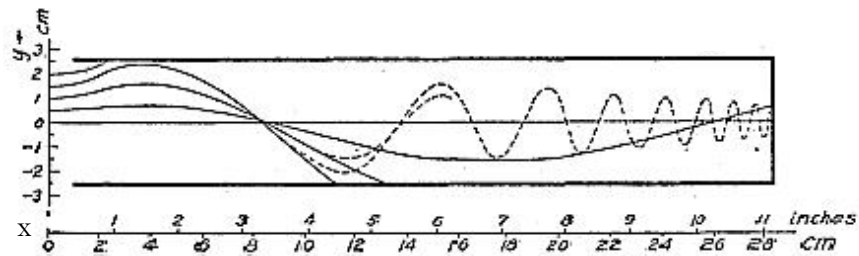


Figure 19. Vertical motion of accelerating ions. The solid lines represent the motion of particles being electrostatically focused only and the dotted lines represent particles being focused by both electrostatic and magnetic fields. The y-axis represents the starting height of the particle relative to the central plane. The x-axis represents the radius of the ion path with $x=0$ correlating to the mid-point between the dees. A peak dee voltage of 90,000 V was used for each of the curves. Figure taken from Ref. [26].

Theoretical calculations for the particle's motion were worked out individually by M.E. Rose [25], R.R. Wilson [26] and B.L. Cohen [28], each yielding slightly different results. Though none of the results

are of the same form, they describe similar paths for the vertical motion of accelerating particles. Wilson plotted his results and they are given in Figure 19.

At small radii, the focusing is mostly the result of electrostatic focusing (represented by the solid line in Figure 19). Particles starting out too high above the central plane strike the dee and are immediately lost. As the particles reach larger radii, the magnetic field begins to play a larger role and ion beam magnetic focusing becomes more apparent (the dotted line represents both focusing forces). Note that the ion's motion will resemble that of a damped oscillator [26]. Using a long, copper tubing probe, Wilson experimentally measured the height of ions at different radii and found that the theory agreed well with the experimental data [26]. Cohen's theoretical predictions years later for the vertical motion of ions in the Oak Ridge National Laboratory Cyclotron showed similar results [28].

2.3 RF System

Section 2.1 derived the resonant frequency of a particle being accelerated by an oscillating electric field within a magnetic field. This section describes a technique to generate this field by using the LC tank circuit shown in Figure 20. The conducting dee electrode has capacitance and, therefore, functions as a capacitor [29]. An inductor in parallel with the dee capacitance then creates a tuned LC circuit which resonates strongly at a particular frequency. Energy can be injected into this resonant circuit by means of another inductor whose field couples to the first. For a sharply resonant circuit, the voltage across the dee capacitor can be very large.

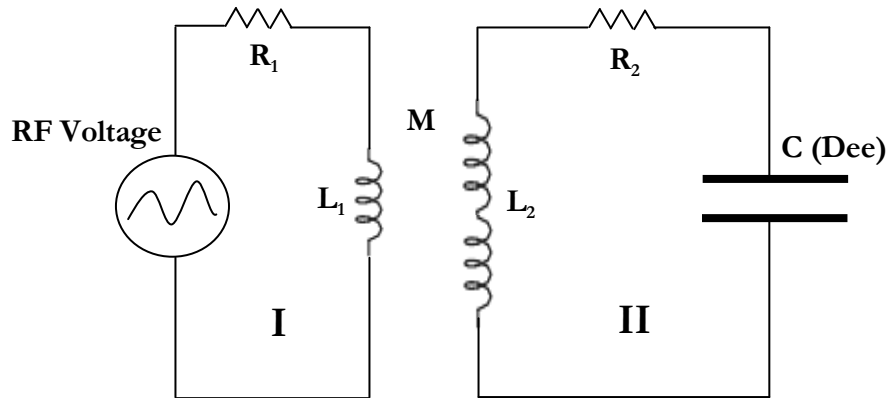


Figure 20. Diagram of the RF circuit. The RF circuit is made up of an RF voltage source, an internal resistance, two inductors (L_1 and L_2) and the Dee capacitor. The two circuits shown (I and II) are connected through mutual inductance.

Applying Kirchoff's voltage law to the two circuits in Figure 20, the following relations can be obtained

$$R_1 I_1 + L_1 \frac{dI_1}{dt} - M \frac{dI_2}{dt} = E e^{i\omega t} \quad (2.3.1)$$

$$R_2 I_2 + L_2 \frac{dI_2}{dt} - M \frac{dI_1}{dt} + \frac{\int I_2 dt}{C} = 0 \quad (2.3.2)$$

where I_1 , L_1 and R_1 represent the current, inductance and internal resistance of the first circuit, I_2 , L_2 and R_2 represent the current, inductance and internal resistance of the second circuit, M represents the mutual inductance between the two circuits and E is the voltage applied to circuit I with a frequency of ω . In order to find the voltage across the dee capacitor, this system of equations needs to be solved for I_2 . Letting

$$I_1 = A e^{i\omega t} \quad (2.3.3)$$

$$I_2 = B e^{i\omega t}, \quad (2.3.4)$$

Equations (2.3.1) and (2.3.2) can be differentiated and simplified to the forms

$$A(R_1 + L_1 i\omega) - B(Mi\omega) = Az_1 - B(Mi\omega) + E \quad (2.3.5)$$

$$B\left(R_2 + L_2 i\omega - \frac{i}{C\omega}\right) - A(Mi\omega) = Bz_2 - A(Mi\omega) = 0 \quad (2.3.6)$$

where z_1 and z_2 are the overall impedance of each circuit given by

$$z_1 = R_1 + L_1 i\omega \quad (2.3.7)$$

$$z_2 = R_2 + L_2 i\omega - \frac{i}{C\omega}. \quad (2.3.8)$$

Solving (2.3.5) for B and substituting this value into equation (2.3.6), values for both A and B can be found:

$$A = \frac{E}{z_1 + \frac{M^2 \omega^2}{z_2}}, \quad (2.3.9)$$

$$B = \frac{i\omega ME}{z_1 z_2 + M^2 \omega^2}. \quad (2.3.10)$$

Using these values for A and B, the current through each circuit can be obtained from Equations (2.3.3) and (2.3.4).

$$I_1 = \frac{E e^{i\omega t}}{z_1 + \frac{M^2 \omega^2}{z_2}} \quad (2.3.11)$$

$$I_2 = \frac{i\omega M E e^{i\omega t}}{z_1 z_2 + M^2 \omega^2}. \quad (2.3.12)$$

These equations can be simplified by making the following substitutions

$$z_m = i\omega M \quad (2.3.13)$$

$$E' = E e^{i\omega t} \quad (2.3.14)$$

where z_m is the impedance from the mutual inductance and E' is the initial potential as a function of frequency. The equations for the currents then become

$$I_1 = \frac{E'}{z_1 - \frac{z_m^2}{z_2}} \quad (2.3.15)$$

$$I_2 = \frac{E'}{\frac{z_1 z_2}{z_m} - z_m}. \quad (2.3.16)$$

Finally, the potential across the capacitor is equal to

$$V_c = X_c I_2 = \frac{I_2}{\omega C} = \frac{E'}{\omega C \left(\frac{z_1 z_2}{z_m} - z_m \right)} \quad (2.3.17)$$

Thus, given values for the inductance, internal resistance, dee capacitance, applied potential and oscillating frequency the potential across the dees can be determined from Equation (2.3.17). Note that since the three impedance terms (represented by z) contained imaginary components, this final

voltage is a complex number. Writing out the components of the complex number, the voltage across the dees becomes

$$V_c = \frac{EM}{C(D^2 + G^2)}(D - iG) = V_{cm}(D - iG) \quad (2.3.18)$$

where

$$D = L_2 R_1 \omega - \frac{R_1}{\omega C} + \omega L_1 R_2 \quad (2.3.19)$$

$$G = \omega^2 L_1 L_2 - R_1 R_2 - \frac{L_1}{C} - \omega^2 M^2. \quad (2.3.20)$$

Only the real part of the potential actually accelerates the ions. Thus, the magnitude of the real component of Equation (2.3.18) must be determined. This is done by projecting the magnitude of the potential onto the real axis (see Figure 21).

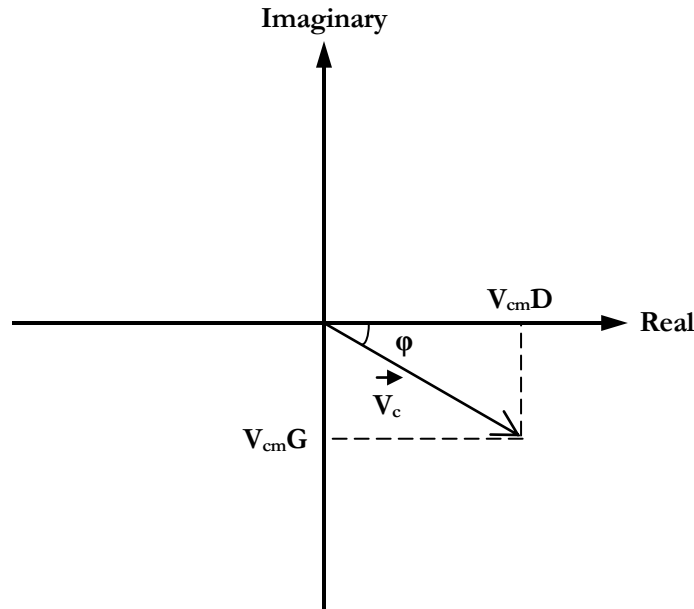


Figure 21. Phasor diagram for the potential between the dees. The real component of the potential would be $V = |V_c| \cos \phi$ where $\phi = \tan^{-1}(G/D)$.

The measured potential between the dees then is

$$V_{dee} = |V_c| \cos(\omega t + \varphi) = \frac{EM}{C\sqrt{D^2+G^2}} \cos(\omega t + \varphi) \quad (2.3.21)$$

where

$$\varphi = -\tan^{-1} \frac{G}{D}. \quad (2.3.22)$$

Equation (2.3.21) says that the voltage between the dees is dependent on the angular frequency of the RF source, ω . When V is at a maximum, the frequency of the circuit is called the resonant frequency and denoted ω_0 (see Figure 22).

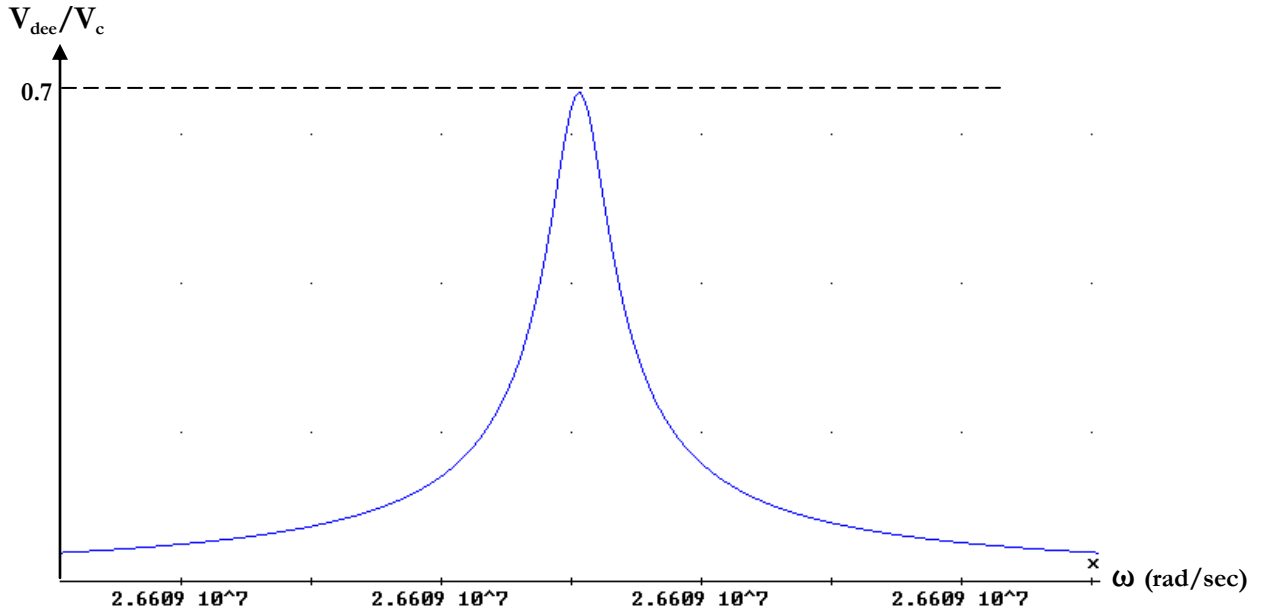


Figure 22. Diagram of potential across the dees. The x-axis represents the angular frequency, ω , of the circuit and the vertical axis represents the magnitude of the amplification across the dees. This graph was plotted using Equation (2.3.21) with values $R_1=10 \ \Omega$, $R_2=1.0 \ \mu\Omega$, $L_1=0.9\mu\text{H}$, $L_2=10.7\mu\text{H}$, $C=132 \text{ pF}$ and $M=2.4 \times 10^{-14} \text{ H}$.

At the resonant frequency, the potential curve forms a peak. The quality factor (often referred to as the Q-factor or Q-number) of the circuit is a measure of the sharpness of this resonance peak and is given by the equation [35]

$$Q = \frac{\omega_0}{\Delta\omega} \quad (2.3.23)$$

where Q is the quality factor and $\Delta\omega$ is the width of the resonance peak at half the maximum. Large Q -values correlate to a small $\Delta\omega$ compared to ω_0 and indicate sharp peaks; small Q -values indicate broad peaks and a large $\Delta\omega$ relative to ω_0 . High Q -values are desirable because they indicate a low rate of energy loss for the oscillating potential.

2.4 Relativistic Effects

From the previous discussion on cyclotron theory, it may not be clear what limits the ion energies possible in the cyclotron. Up until this point, the only real limitations were from the size and strength of the magnet as indicated by Equation (2.1.7). It turns out, however, that relativistic effects play a larger role in limiting the ion energy than does any component of the cyclotron apparatus. Relativity limits the final energy by destroying resonance and focusing of the ion beam [30].

According to special relativity, the mass of a particle can be thought of as changing with its velocity such that

$$m = \frac{m_0}{\sqrt{1 - \frac{v^2}{c^2}}} \quad (2.4.1)$$

where m is the mass of the particle, m_0 is the rest mass, v is the particle's velocity and c is the speed of light [31]. This mass change is unnoticeable in most situations because for velocities much smaller than c , the difference between the mass and rest mass becomes negligible. Substituting this value for the mass into Equation (2.1.4) for the resonance frequency yields

$$f = \frac{qB\sqrt{1 - \frac{v^2}{c^2}}}{2\pi m_0}. \quad (2.4.2)$$

Writing this equation in terms of the original cyclotron frequency, f_0 ,

$$f = f_0 \sqrt{1 - \frac{v^2}{c^2}} \quad (2.4.3)$$

it becomes apparent that the frequency necessary for resonance decreases as the velocity (or energy) of the particle increases. In other words, the angular velocity of the particle will decrease as it travels to larger radii [32], destroying the very principle on which the fixed-frequency cyclotron was based. However, for most small cyclotrons f is very nearly f_0 . For the Houghton College cyclotron, a proton travelling with energy 0.35 MeV will have a resonant frequency of $f=0.9999996f_0$ and even a 5 MeV proton from Lawrence's cyclotron [11] had a resonant frequency of only $f=0.995f_0$ (determined from Equations 2.1.5 and 2.4.3).

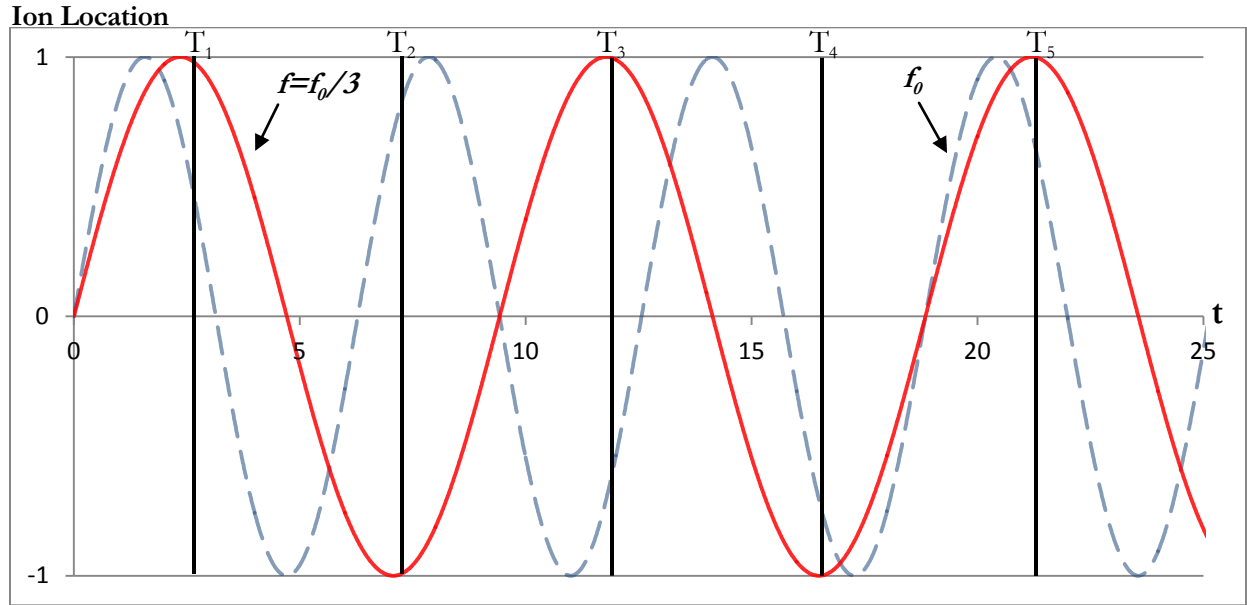


Figure 23. Diagram of relativistic effects on cyclotron frequency. The x-axis represents time and the y-axis represents the location of the ion with the peaks corresponding to between the dees. The ion is travelling with a frequency of $f_0/3$ where f_0 is the driving frequency. The ion will be accelerated at times T_1, T_4 , and T_5 . The ion falls out of resonance, however, at T_2 and T_3 and is decelerated in these regions. These decelerations limit the ion's final energy.

When particle velocities are relativistic, however, the difference between f and f_0 becomes significant. Consider the situation shown in Figure 23. In this case, the frequency of the ion is two-thirds that of the driving frequency (f_0). In the figure, the ion is located between the dees when the sine curve with frequency f is at a maximum or a minimum. The potential oscillating at the driving frequency (depicted by the dashed sine curve with frequency f_0) will accelerate the ion when both curves are either positive or negative. Thus, the ion will be accelerated at times T_1, T_4 and T_5 in Figure 23. If one

curve is positive and the other negative, the ion is no longer in resonance and will be decelerated (T_2 and T_3). From this example, it can be seen that ions can still be accelerated by the cyclotron to higher energies as long as the phase difference between peaks remains less than $\pi/2$ [30].

Trouble arises, however, when the ion crosses the potential when the phase difference between peaks is greater than $\pi/2$. At this point, the polarity across the dees is oriented such that it repels the ion, decelerating it. After decelerating for a while, the ion will loose enough energy such that it enters into another acceleration period of the potential. This motion repeats itself and the ion frequency will oscillate about some average frequency. In other words, the average final energy of the ions will correlate to this average frequency. Thus, these oscillations are what eventually limit the energy of the cyclotron [32].

Since phase shifts only occur with each pass through the potential difference, one way around this energy limit is to increase the potential on the dees [33]. Increasing the potential reduces the number of orbits necessary for a particle to reach the outer edge of the dee thereby reducing the number of times that a frequency shift can occur. This, of course, has its own practical limit as discussed in the history of high-voltage particle accelerators.

There are two other solutions for the energy limit problem. Note from Equation (2.1.4) that it would be possible to offset the relativistic affect on the frequency if the magnetic field is increased at the same rate as the increase in ion mass. This proves to be a complex solution, as radially increasing the magnetic field destroys the focusing principle discussed in Section (2.2.2). In order to maintain beam focusing, Thomas found that the magnet has to increase with the polar angle of the ion [34] in a way similar to that depicted in Figure 18. This way, the azimuthal component of the field will focus the ion while the magnetic field is increasing with larger radii. The second solution is to decrease the frequency of the oscillating potential at the same rate that the resonant frequency of the particle is decreasing. This method of obtaining higher energies is more practical and is the basis of the Synchro-Cyclotron (or frequency-modulated cyclotron) [32].

THE HOUGHTON COLLEGE CYCLOTRON

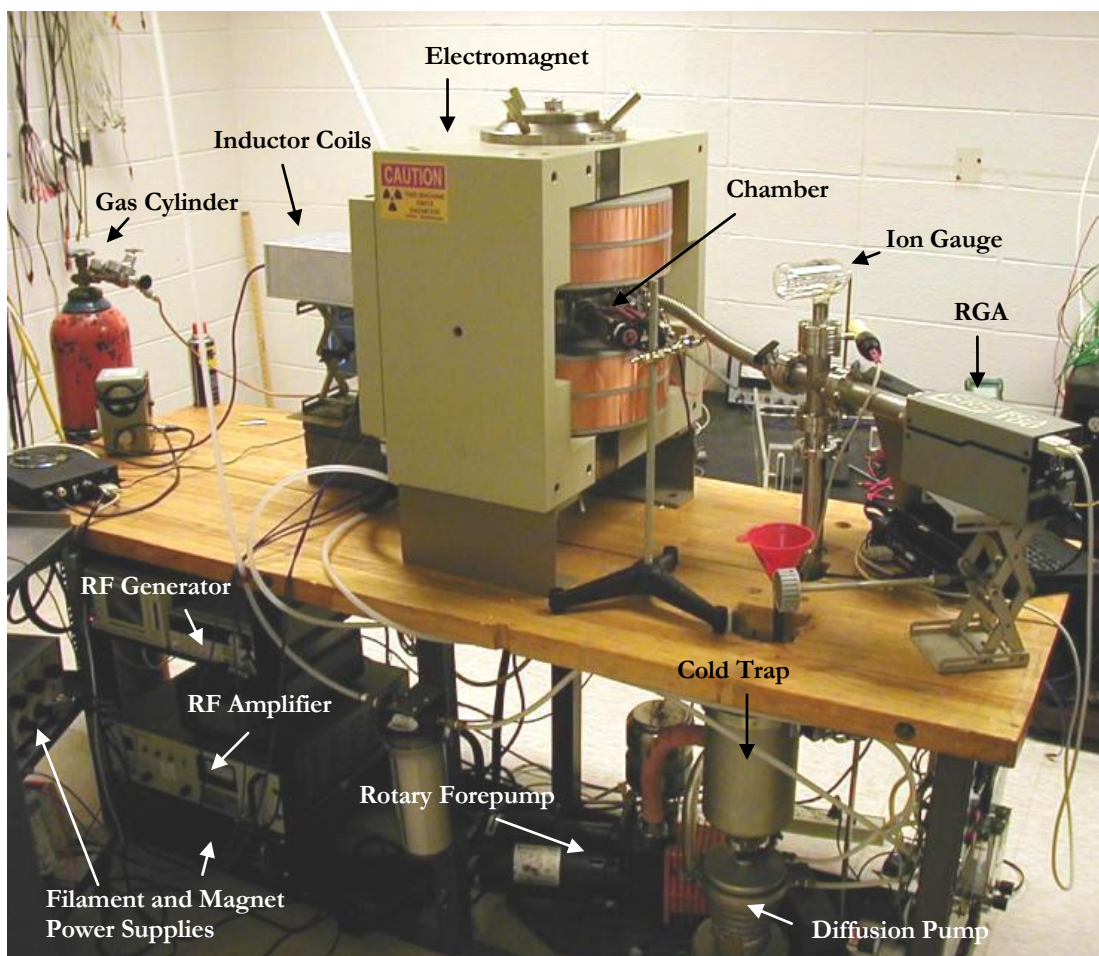


Figure 24. Photograph of the Houghton College Cyclotron. Present in this photo are the electromagnet, chamber, vacuum system, RF system, filament power supply, gas system, ion gauge, and RGA device.

In the spring of 2007, the Houghton College cyclotron successfully accelerated hydrogen for the first time. Shortly after this, a spark between the dee and the chamber wall damaged insulation on the dees and the cyclotron stopped working. From this time on, the chamber was no longer able to hold the

high vacuum necessary for acceleration. For this reason, construction of a new chamber and dee began in the fall of 2007. A photograph of the cyclotron is given in Figure 24.

3.1 Chamber

The motivation for creating a new chamber and dee was three-fold. First, as mentioned above, the old chamber was no longer capable of sustaining an appropriate vacuum. Secondly, the chamber completed in 2006 did not fully utilize the full pole face of the electromagnet. Both the magnet and the inner diameter of the chamber measured 15.2 cm. Since the inner diameter was only 15.2 cm, the dee electrodes (14.5 cm diameter) had to be smaller than the pole face, reducing the maximum energy attainable. Finally, the chamber and dee constructed in 2006 were each designed to be a single unit. The chamber wall was soldered brass and the dee and dummy dee were glued together using glass insulators. Furthermore, the filament and filament insulation were glued to the dee and dummy dee. This design strategy made it impossible to fix a single component of the apparatus, such as the insulation, without replacing the entire piece. The new chamber design (Figure 25) allowed the chamber, dees, dummy dee and filament to be disassembled using screws so that if repairs were needed, they would be isolated to only the given part.

The Houghton College cyclotron's vacuum chamber was made from a 2.54 cm thick, 20 cm by 20 cm plate of 6061T6 aluminum. Mounting the aluminum sheet on a rotary table, a ring with an outer radius of 9.9 cm and an inner radius of 8.7 cm was milled out making up the chamber wall. Keeping the wall mounted on the rotary table, ten 1.27 cm diameter holes were drilled into the side at equally spaced 36 degree intervals. Ten Kurt J. Lesker half-nipple KF-16 flanges 4 cm long and 1.27 cm in diameter were fastened to these holes using Hysol® Loctite 1C vacuum epoxy. These flanges are used for connecting viewing ports, the faraday cup, the vacuum system, the gas flow needle valve, the HV pickup voltage probe and the RF feedthroughs to the inside of the chamber. Viewing ports located on either end of the chamber allow the operator to see the filament or dees while the cyclotron is running. The HV pickup voltage probe is simply a twist of wire placed inside the chamber, isolated from the dee. When the dee is at a high positive potential, a small current is induced in the wire. When the potential on the dee switches to a high negative potential, the current in the wire flows in the opposite direction. This small oscillating current in the wire can then be measured. Since the current flowing through the wire is proportional to the dee voltage, the pickup probe can be calibrated (see Section 4.1.2) and used to find the potential on the dees.

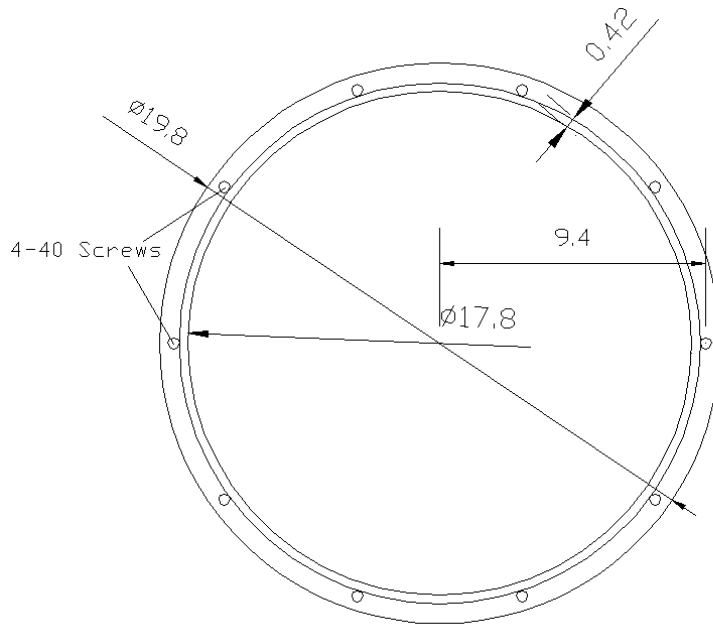


Figure 26. Scale drawing of lid. The lid of the chamber has a diameter of 19.8 cm. The o-ring groove is at a diameter of 19.8 cm. The o-ring groove is at a diameter of 17.8 cm and the center of the screws are at a diameter of 18.8 cm. Dimensions are in cm.

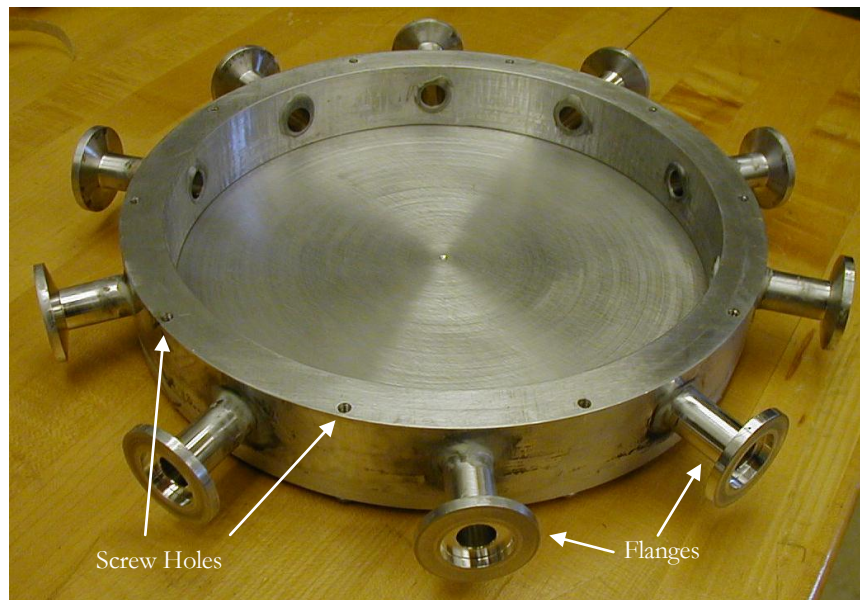


Figure 27. Photograph of the chamber. The dees, filament, and bottom lid have been removed allowing the interior of the chamber to be seen.

Two circular lids with radius of 9.9 cm were milled out of 0.65 cm thick plates of 6061T6 aluminum and fastened to the chamber wall using ten 2-56, ½ inch brass screws. These ten screws were equally spaced 36 degrees from one another in the chamber wall at a radius of 9.4 cm from the center. Since the chamber needs to maintain pressures on the order of 10^{-6} torr, o-rings were used to seal the lids. A 0.205 cm deep, 0.262 cm wide groove was milled into each lid at an inner radius of 8.9 cm. A 177.47 mm inner diameter, 3.52 mm cross section -262 Viton o-ring was placed in each groove before the lids were fastened to the chamber wall. To make room for a filament and to avoid another electrical discharge from the filament to the lid, a 0.3 cm deep circular depression was milled out of the bottom of the upper lid. On the top side of the upper lid, a small groove 1.85 mm deep, 5.65 mm wide and 10.2 cm long was milled out. When the cyclotron was in operation, a TEL-Atomic SMS 102 magnetic Hall Effect probe was placed within this groove, which allowed magnetic field strength measurements to be made. Scale drawings and photographs of the lid are shown in Figure 26 and Figure 28 respectively.

During the summer of 2008, this new chamber was connected to the vacuum system and tested. With the forepump connected directly to the diffusion pump, a pressure of 3.9×10^{-6} torr was maintained, the lowest pressure recorded for this cyclotron. When the cyclotron was in operation, the total gas pressure in the chamber was generally between 8×10^{-6} and 2×10^{-5} torr.

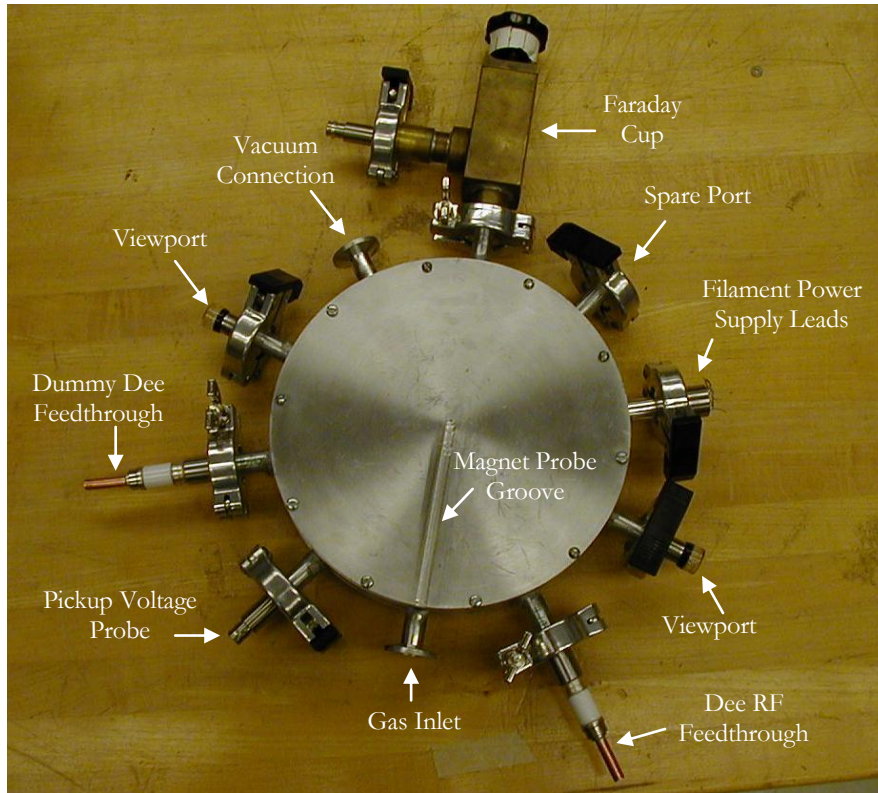


Figure 28. Photograph of the chamber fully assembled. When the cyclotron is operating, a magnetic field probe is placed in the groove and the chamber is placed between the magnet pole faces. The RF system attaches to the dee feedthrough, gas is let into the system through the gas inlet port, the dee voltage is measured by the pickup probe, the dummy dee feedthrough is attached to ground, the viewports allow the filament and dees to be seen, the vacuum system is attached to the vacuum connection port, the faraday cup measures the beam current and the filament power is attached to the filament leads.

3.2 Dee and Dummy Dee

3.2.1 Dees

In order to accelerate the ions travelling through the magnetic field, a pair of Dee-shaped electrodes (commonly referred to as dees) is needed. Unlike most large cyclotrons, the Houghton College cyclotron has only a single dee and a corresponding dummy dee. A dummy dee is a narrow electrode (not shaped like a dee) and is used in place of a second dee because it frees up space within the chamber to be used for beam extraction or internal targets. In this cyclotron, the dummy dee is held at ground while the dee oscillates between positive and negative high voltages. Thus, acceleration is

achieved in the same manner that a two dee configuration accelerates ions, but at half the potential difference. A circular ring of 6061T6 aluminum, 1.27 cm thick, 0.59 cm wide, and 16.5 cm in diameter, formed the walls for both the dee and dummy dee. Two 5052 aluminum sheets, 0.132 cm thick, were then fastened to the top and bottom of the ring respectively using eight, 2-56 brass screws forming an enclosed circular disk. To vent the screw holes, a small hole was drilled in the side of each screw hole using a No. 55 drill bit. The screw holes need to be vented so that they do not trap air or water and slowly outgas when the dee is placed in the vacuum chamber. The disk was then cut through the center using a 0.635 cm milling tool, creating two separate dees, each 7.94 cm long with a 0.635 cm space between them. Keeping one of the dees for use, the second dee had the end of its semi-circle removed leaving a dummy dee only 3.18 cm wide (Figure 29). Four machinable ceramic strips, each roughly 2.53 cm long, 0.77 cm wide and 0.18 cm thick, hold the two dees together at the appropriate separation gap of 0.635 cm.

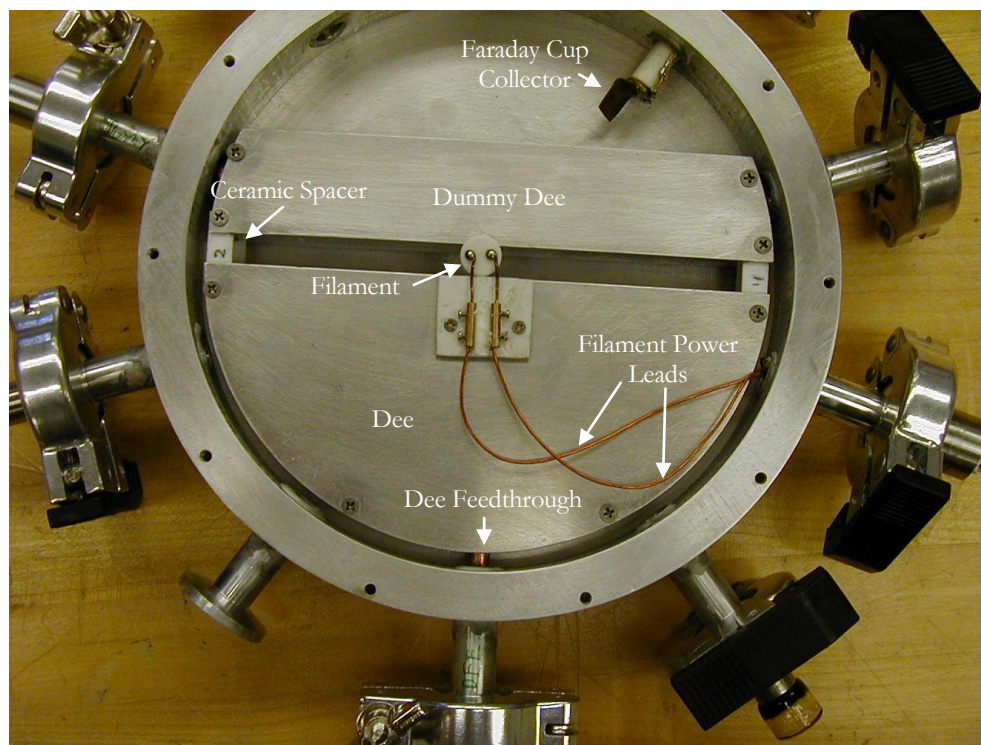


Figure 29. Photograph of the dee and dummy dee. In this photograph, the dee and dummy dee are suspended within the chamber by RF feedthroughs. When functioning, the dee will oscillate between positive and negative high voltage and the dummy dee will be held at ground. The separation between the dees is fixed. This region of space is known as the acceleration gap and is roughly 0.635 cm wide.

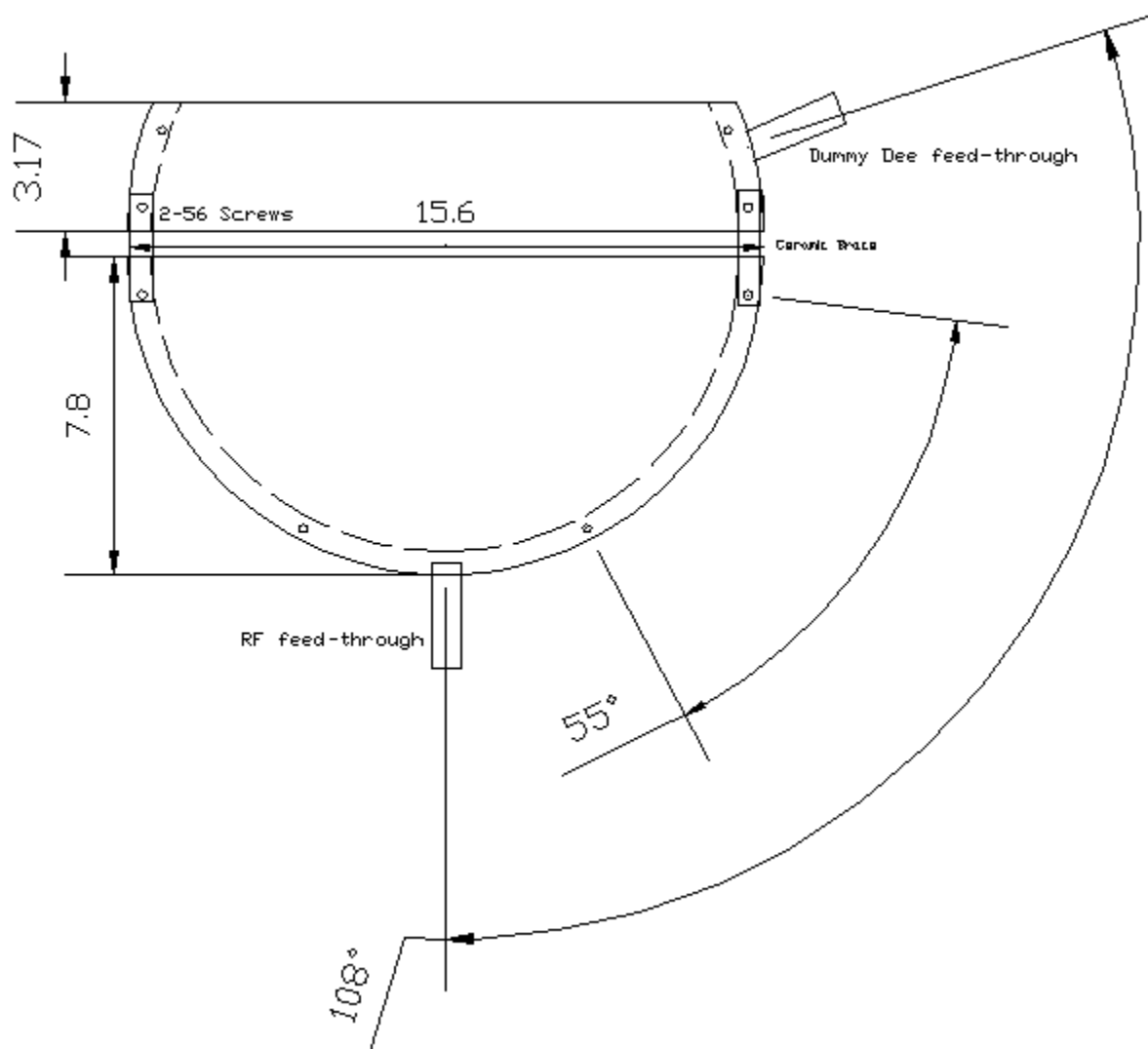


Figure 30. Scale drawing of the dee and dummy dee. The dee and dummy dee were milled out of a single circular plate of aluminum. The dee is roughly 15.6 cm in diameter and the dummy dee is 3.17 cm long. The dees are fastened by 2-56 screws oriented around the outer rim of the dee. Ceramic strips connect the dees, holding them parallel to one another. All dimension in cm.

Since the dee will reach potentials of a few kilovolts, it must be isolated from the grounded lids and walls of the chamber. To achieve this isolation, conducting feedthroughs enter the chamber through two of the flanges and screw into the dee and dummy dee. The feedthrough attached to the dee is connected to the high voltage RF signal and the feedthrough attached to the dummy dee is held at ground. These can be seen in Figure 29.

3.2.2 *Filament*

The Houghton College cyclotron accelerates ions formed from gas present in the vacuum chamber. An AET EM6G electron microscope filament thermionically emits electrons which collide with molecules in the chamber, ionizing them in the process. These ions, which are typically formed near the filament at the center of the chamber, are then free to be accelerated by the cyclotron. The electrons emitted from the filament are forced by the magnetic field to move in a spiral path towards the bottom of the chamber, eventually leaving the acceleration gap.

Since the accelerating potential exists only between the dees, the filament needs to be located in this region. Difficulty arises, however, because the RF voltage on the dee is typically between 1 and 2 kV, far greater than the 1-3 V DC placed across the filament. Thus, the filament and wires must be adequately insulated from the dee in order to prevent sparking. Insulation was supplied by a 2.33 cm by 2.71 cm machinable ceramic rectangle approximately 0.18 cm thick. This insulator was fastened to the top of the dee using two, 2-56 screws. Two barrel connectors, each 1.28 cm long and 0.32 cm in diameter, were glued to the ceramic insulator using Hysol ® Loctite 1C vacuum epoxy. Two copper wires soldered to the filament are screwed into one end of the barrel connectors, holding the filament suspended between the dee and dummy dee. Positive voltage and ground connect to the filament through two 0.0359 inch insulated magnet wires that are screwed into the other end of the barrel connectors, entering the chamber through a KF flanged power feedthrough (Figure 29). When in operation, the filament operates between 1-3 V at approximately 2 A of current.

3.3 **Magnet**

The magnetic field is created by a GMW Associates 3473-70 Electromagnet with 15 cm diameter poles and an adjustable separation gap ranging from 0 to 9.6 cm. At a pole separation of 3.85 cm, roughly the width of the chamber and its lids, a maximum magnetic field strength of 1.1 T can be reached with 50 A from a PowerTen R62B-4050 power supply. At such a high current, the electromagnet must be cooled by 18° C water flowing at 0.8 gallons per minute from a Haskris Co. A5H chiller to prevent overheating of the coils. The strength of the field decreases rapidly beyond the edge of the poles, but is very uniform at small radii. These fringe fields help to focus the ion beam as discussed in Chapter 2. The magnetic field strength as a function of current and distance from the center were measured using a TEL-Atomic SMS 102 magnetic Hall Effect probe and are compared with the manufacturers manual specifications in Figure 31 and Figure 32.

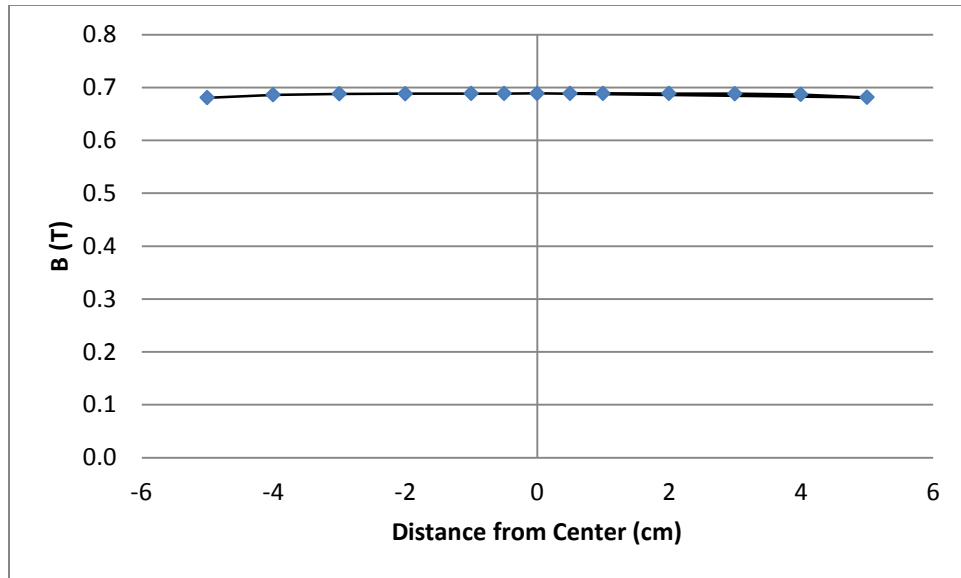


Figure 31. Nominal vertical magnetic field strength as a function of distance from the center of the magnet at a pole separation of 5 cm and magnet current of 30 amps.

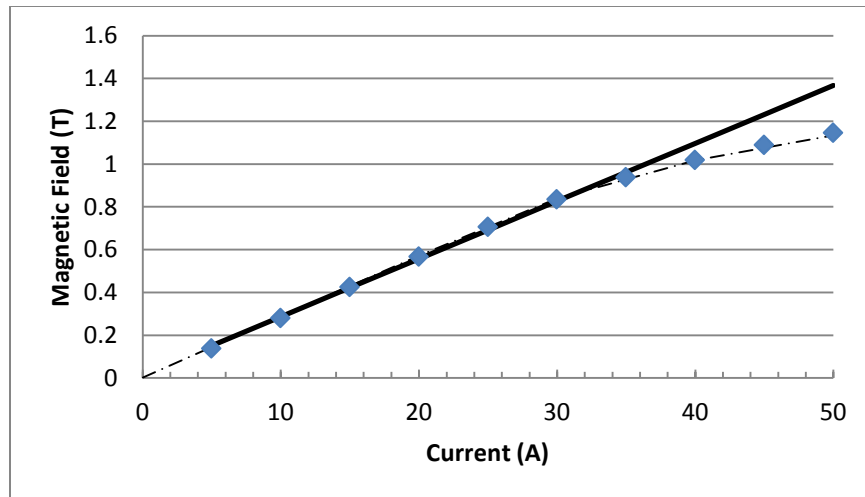


Figure 32. Measured (data points), nominal (dashed line), and calibrated magnetic field strength as a function of current measured at the center of the chamber at a pole separation of 4.0 cm. The best fit line, which follows the equation $B = 0.027I + 0.0169$, is valid only up until around 1 T. The magnetic field is oriented perpendicular to the pole faces.

3.4 Modified Faraday Cup

The ion beam current is measured using a modified Faraday cup. The modified Faraday cup, finished in 2005 and repaired in 2009, was constructed as follows. A right angle brass Veeco valve was used for the Faraday cup housing and bellows (see Figure 33). A grounded steel rod is screwed into the bellows at one end and a cylindrical ceramic insulator on the other end. A rectangular copper collector, 0.6 cm wide, 1.3 cm long and 0.05 cm thick, was attached to the ceramic insulation using a 6-32 screw. Current striking the collector is measured by a Keithley 617 programmable electrometer via a shielded MDC Vacuum Products KAP3 high vacuum coaxial cable that is connected to the copper collector and exits the Faraday cup through a BNC quick flange feed-through. Using the bellows, the position of the copper collector can be adjusted to radii between 5.95 cm and 7.0 cm from the center of the chamber.

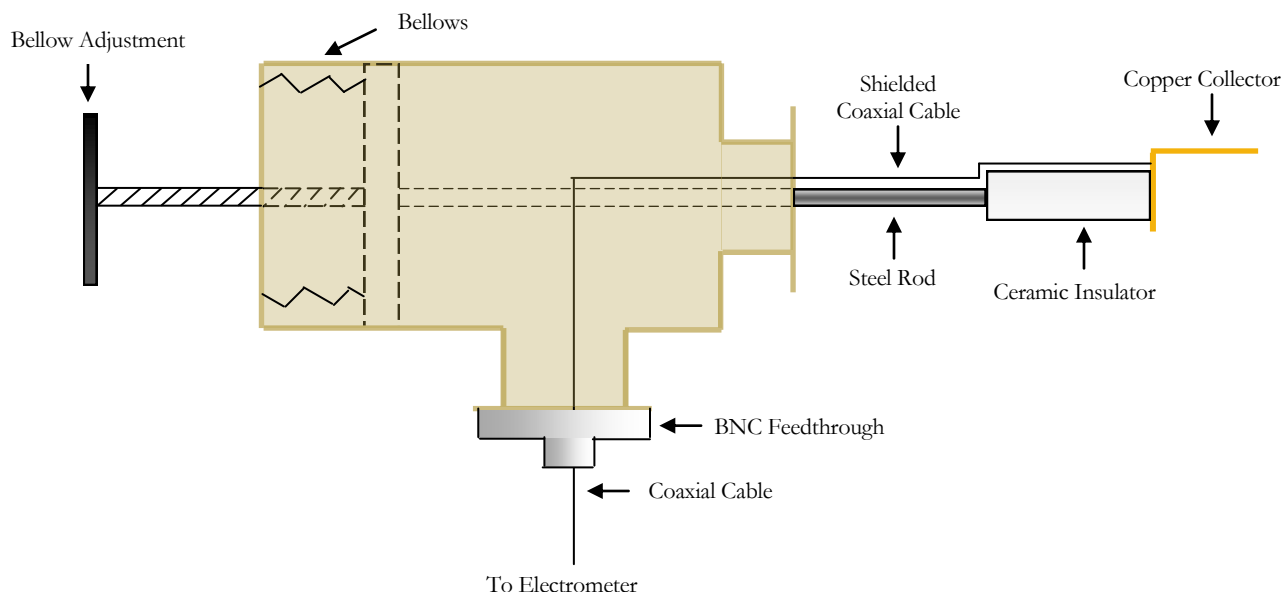


Figure 33. Diagram of the Faraday cup. A grounded steel rod, screwed into the bellows at one end, holds the collector inside the vacuum chamber. Current striking the collector travels down the coaxial cable and out through to the electrometer. Diagram not drawn to scale.

One potential problem when measuring the current is the presence of secondary electrons. When ions strike the collector, electrons will be ejected from the copper resulting in current measurements larger than the actual value. A possible solution to this problem is placing a grid at a negative potential

around the collector. Electrons ejected from the collector would be repelled and travel back towards the collector. This has not been implemented.

3.5 Vacuum System

At atmospheric pressure, ions cannot be accelerated freely. Thus, a vacuum system was used to reduce the pressure within the chamber to pressures low enough for ion acceleration. The Houghton College cyclotron uses the vacuum system depicted in Figure 34.

System evacuation begins with the CIT-Alcatel 2012A rotary forepump, which decreases the pressure to roughly 10^{-3} torr. Once at 10^{-3} torr, LN_2 is added to a Kurt J. Lesker cold trap and an Innovac R220 diffusion pump is turned on. A diffusion pump operates by vaporizing oil and forcing it, along with air molecules, towards the bottom of the pump away from the chamber. The purpose of the cold trap is to condense any vapors (air or oil) that may try to enter back into the system and to lower the energy of the gas molecules. With both pumps operating, the pressure inside the chamber dropped to roughly 10^{-6} torr. To determine the quantity and type of gases remaining in the chamber, an SRS RGA-100 (Residual Gas Analyzer) ionizes a fraction of the gas molecules remaining, separates the ions, and measures the partial pressure of ions according to their molecular weight.

There are four shutoff valves located at various places in the vacuum line. These valves allow the chamber to be isolated from the vacuum system so that it can be brought to atmospheric pressure without contaminating the entire system.

Two thermocouple gauges, a KJL-6000 near the rotary forepump and a CVG101 GA before the chamber, measure pressures as low as 10^{-3} torr. These gauges measure the pressure in the foreline and chamber respectively. A Duniway I-100-K Granville Phillips 275006 ion gauge, located immediately before the chamber, measures pressures from 10^{-3} to roughly 10^{-10} torr. Ion gauges emit electrons from a filament, ionizing surrounding gases. These ions are then attracted to a wire in the gauge held at a negative potential, creating a current through the wire. The current is proportional to the number of ionized gas molecules which is determined by the amount of gas in the vicinity of the gauge. Thus, the pressure of the gas can be determined. Together, the thermocouple and ion gauges cover the range of the vacuum system.

Leading into the other side of the chamber is an Edwards LV10K leak valve which allows small amounts of helium to enter the chamber to be ionized and accelerated.

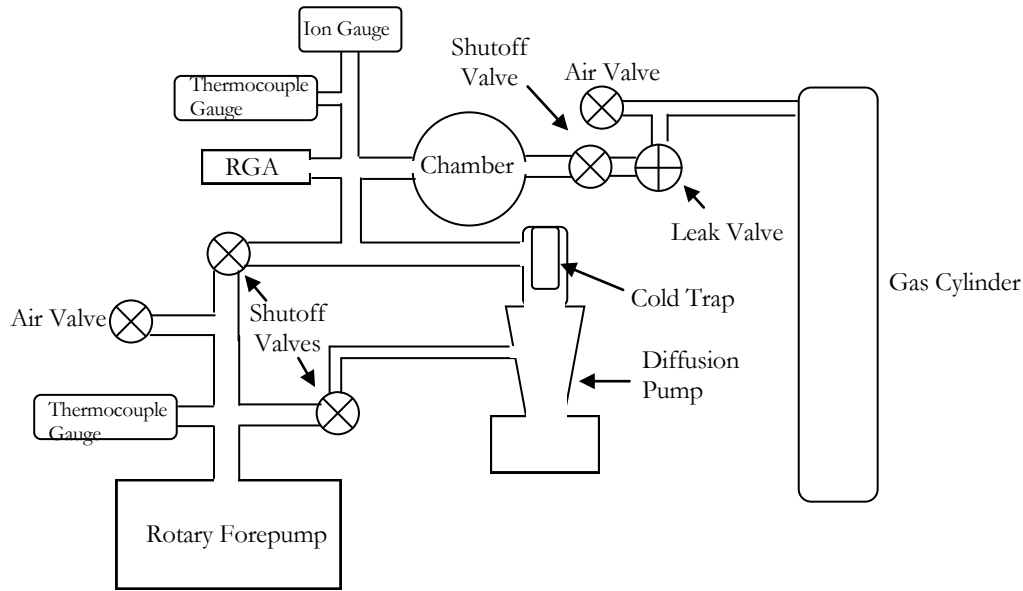


Figure 34. Diagram of the vacuum system. The rotary forepump gets the pressure down to 10^{-3} torr, at which point the diffusion pump is turned on. The system eventually reaches a pressure on the order of a 10^{-6} torr. A series of valves allows selected parts of the system to be isolated and brought up to atmospheric pressure without losing vacuum to the rest of the system. A gas cylinder is connected to the chamber via a leak and shutoff valve.

In the summer of 2008, the vacuum system was tested with the new chamber. At the time, there were concerns about leaks in the foreline so the forepump was connected directly to the diffusion pump with a rubber vacuum hose. This setup successfully evacuated the chamber to a pressure of 3.9×10^{-6} torr. During the spring of 2009, the vacuum system was connected as shown in Figure 34 with the chamber and dees completely assembled. After pumping on the system for several days, the pressure in the chamber was only 4.5×10^{-5} torr. Tests are currently underway to locate the leak in the foreline.

3.6 Electrical System

As discussed in Section 1.3.5, the ultimate goal of the cyclotron is to setup deuteron-deuteron reactions which would release neutrons with up to 2.8 MeV of energy. This would produce enough radiation to require that the cyclotron be operated remotely. The computer program which controls

and monitors all of the systems is being written using Labview Express 7.0. Information is sent and received from the computer through an Ethernet network by a National Instruments (NI) GPIB-enet converter (see Figure 35). Vacuum pressure readings from the ion and thermocouple gauges are controlled by an SRS FGC 100 Ion Gauge Controller which communicates via GPIB (General Purpose Interface Bus) with the ethernet converter. The Residual Gas Analyzer (RGA) is read by an RS232 serial port which is connected to a National Instruments RS232-GPIB converter. Once the information is converted to GPIB, it is converted to Ethernet by the NI GPIB-enet before being sent to the computer. The Keithly 617 Electrometer reads the current striking the Faraday cup and sends its information to the NI GPIB-enet converter before it is sent to the computer. A Powerten R62B-4050 power supply powers the magnets and connects directly to the NI GPIB-enet converter so that it can be controlled by the computer. The RF signal (described in Chapter 2) is generated by an HP 33120A Function Generator controlled by the computer through the NI GPIB-enet converter. Signals from the function generator are amplified by the ENI 155LCRH RF power amplifier and the RF power going into the RLC circuit is measured by the Bird 43 A RF power meter. Finally, the filament is powered by the Gwinstek GPS-3030DD DC power supply which is connected directly to the ethernet converter. Note that there is a second power supply, usually kept at -100 V, connected to the filament circuit. This floats the filament at -100 V relative to the grounded chamber. When electrons are emitted from the filament, they are repelled by this negative potential giving them more energy for ionizing the gas molecules.

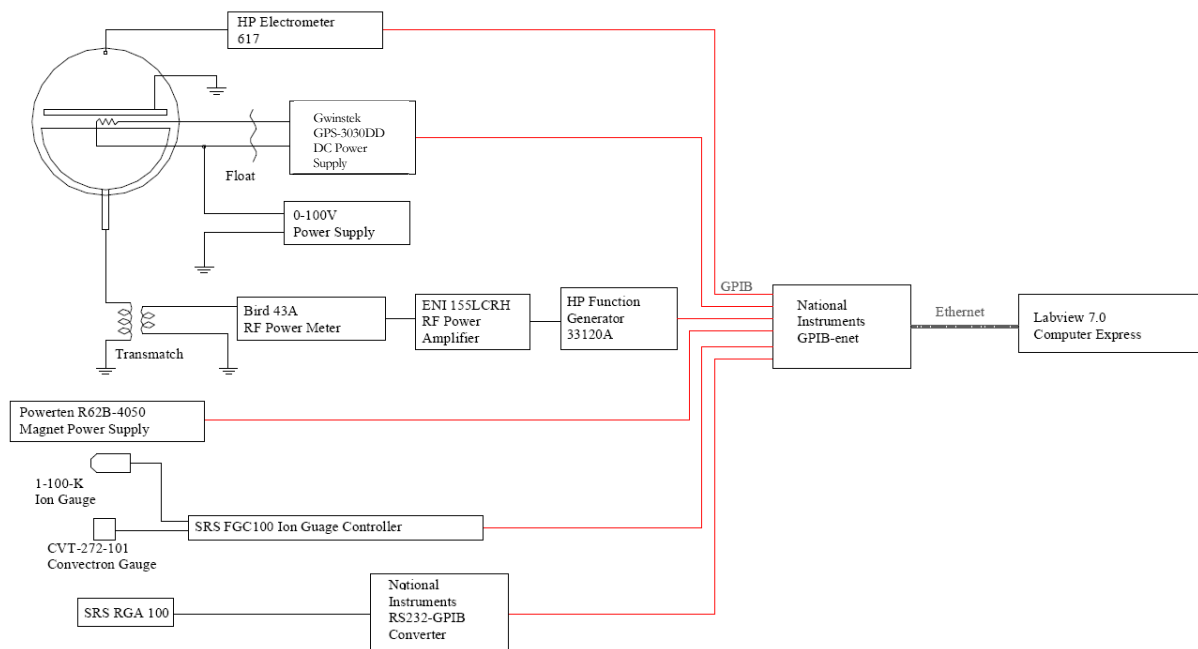


Figure 35. Schematic of the Houghton College Cyclotron's electrical system. All aspects of cyclotron operation can be controlled remotely by a computer via Ethernet with a program written in Labview 7.0. The Keithly 617 Electrometer and SRS FGC 100 Ion gauge controller both send their information directly to the NI GPIB-enet converter. The Unisource PG100 filament power supply, Powerten R62B-4050 magnet power supply, and HP Function Generator 33120A connect directly to the GPIB-enet converter and are controlled by the computer. The SRS RGA-100 is read through an RS232 serial port, converted to GPIB, then converted to Ethernet before being read in by the computer. The 100 V power supply connected to the filament floats the filament at -100 V relative to the grounded chamber.

Chapter 4

RESULTS

Using the apparatus detailed in Chapter 3, the Houghton College cyclotron successfully accelerated hydrogen and helium ions for the first time in two years. After establishing resonance with the RF circuit, the chamber was evacuated to a pressure of roughly 2×10^{-5} torr and 2 A of current was run through the filament. Fixing the frequency at 3.55 MHz and scanning the electromagnet from 0 to 1 T, ion resonance peaks were obtained at magnetic fields near those predicted by Equation (2.1.4). Several other scans were performed and the analyses of these results are given.

4.1 Calibrating the Cyclotron

Before the cyclotron could be operated, the RLC circuit described in Chapter 2 was tuned to the resonant frequency, the HV pickup probe was calibrated, the magnetic field as a function of current was determined, the chamber was evacuated and a sufficient amount of gas was admitted with which to create ions.

4.1.1 *Achieving Resonance*

Recall the diagram of the RF circuit in Figure 20, consisting of a capacitor (the dee), two inductors and an RF source. Maximum power transfer of the circuit and, therefore, maximum voltage amplification on the dee occurs when the overall impedance of the circuit is a minimum. Minimum impedance occurs when Equation (2.3.18) is at a peak as shown in Figure 22. The frequency at which this peak occurs is called the resonant frequency. In order to find the resonant frequency of Equation (2.3.18), the derivative of the amplitude must be taken with respect to ω . This derivative must then be set equal to zero and the resonant frequency can be solved for. This turns out to be a lengthy derivation. Furthermore, this equation is itself an approximation as it considers neither the capacitance and inductance between the dee and the chamber wall nor the internal capacitance and inductance of the RF amplifier. As an approximation of minimizing the impedance, however, consider the overall impedance of a series RLC circuit given by [35]

$$Z = \sqrt{R^2 + Z_{LC}^2} \quad (4.1.1)$$

where Z is the impedance, R is the resistance, and Z_{LC} is the total reactance of the capacitor and inductor (Equation 4.1.2). Since R , L and C are fixed, this equation is minimized when

$$Z_{LC} = i \left(\omega L - \frac{1}{\omega C} \right) = 0 \quad (4.1.2)$$

or, in other words, when

$$\omega_0 = \frac{1}{\sqrt{LC}} \quad (4.1.3)$$

where ω is the angular frequency, L is the inductance and C is the capacitance. The frequency found above, ω_0 , is called the resonant angular frequency. The resonant frequency is

$$f_0 = \frac{1}{2\pi\sqrt{LC}} \quad (4.1.4)$$

For the Houghton College cyclotron, the capacitance is fixed by the characteristics of the dees and chamber but the inductor is variable. For this reason, the resonant frequency is adjusted by changing the inductance. Since an exact relation between the inductance and frequency is difficult to obtain, the approximate relation in Equation (4.1.4) can be used to get roughly the desired frequency.

The RF signal was created by a HP 33120A function generator, as shown in Figure 36, with a magnitude of between 100 and 300 mV. This signal was then amplified by an ENI 155LCRH RF power amplifier. The amplifier, however, had its own impedance which does not match the impedance of the RLC circuit. Thus, when the RF generator was set to the resonant frequency of the RLC circuit, the difference in impedance between the RF amplifier and the RLC circuit caused power to be reflected back towards the amplifier ultimately limiting the maximum potential placed across the dees. To fix this problem, an LDG Electronics AT-200PC tuner was placed between the power amplifier and the LC circuit. The AT-200PC computer program adjusted the capacitance and inductance of the tuner physically connected to the RF amplifier, changing the impedance of this circuit to match the RLC circuit. A perfect match occurs when the standing wave ratio (abbreviated

SWR) is 1:1. The SWR is a ratio of the maximum amplitude to the minimum amplitude of the RF signal.

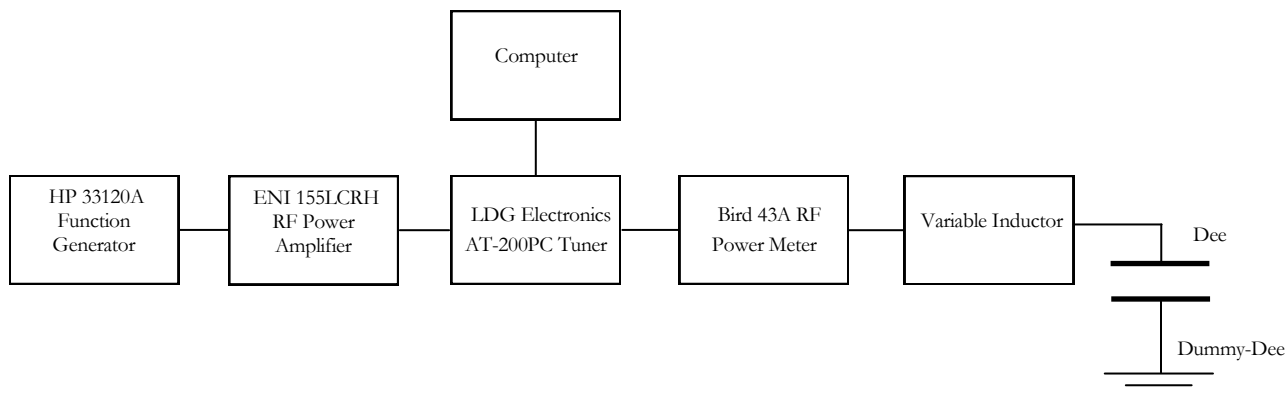


Figure 36. Block diagram of RF system. The RF signal is generated by the HP 33120A function generator and then amplified by the ENI 155LCRH RF power amplifier. Once amplified, the signal is sent through an LDG Electronics AT-200PC tuner which matches the impedance for maximum power transfer to the dee. The output power is measured by the AT-200PC Tuner computer program, the ENI RF power amplifier, and the Bird 43A RF power meter. The variable inductor is adjusted such that the desired resonant frequency can be obtained.

When tuning the circuit, the goal is to get the SWR as close to 1:1 as possible as this correlates to a maximum power transfer from the amplifier to the dee. The frequency at which this occurs is the resonant frequency for the circuit. Resonance of the Houghton College cyclotron was determined both manually and automatically and the two results were compared with one another.

To manually determine the resonant frequency, the RF generator was adjusted in steps of 0.5 MHz between 1.0 MHz and 6.0 MHz. At each frequency step, the input voltage was measured using a Gwinstek GDS-2204 oscilloscope and compared to the voltage on the dee being measured by a Cal Test Electronics CT2591 HV probe. Recall, that the dee voltage is a maximum at the resonant frequency. Once the frequency of the maximum voltage was approximately found using 0.5 MHz intervals, the RF generator was adjusted in steps of 0.1 MHz near the maximum voltage, between 3.0 MHz and 4.0 MHz. Again, the maximum voltage was found and a third sweep was performed using steps of 0.01 MHz near this new maximum, between 3.5 and 3.7 MHz. Figure 37 is a plot of the dee voltage gain as a function of frequency.

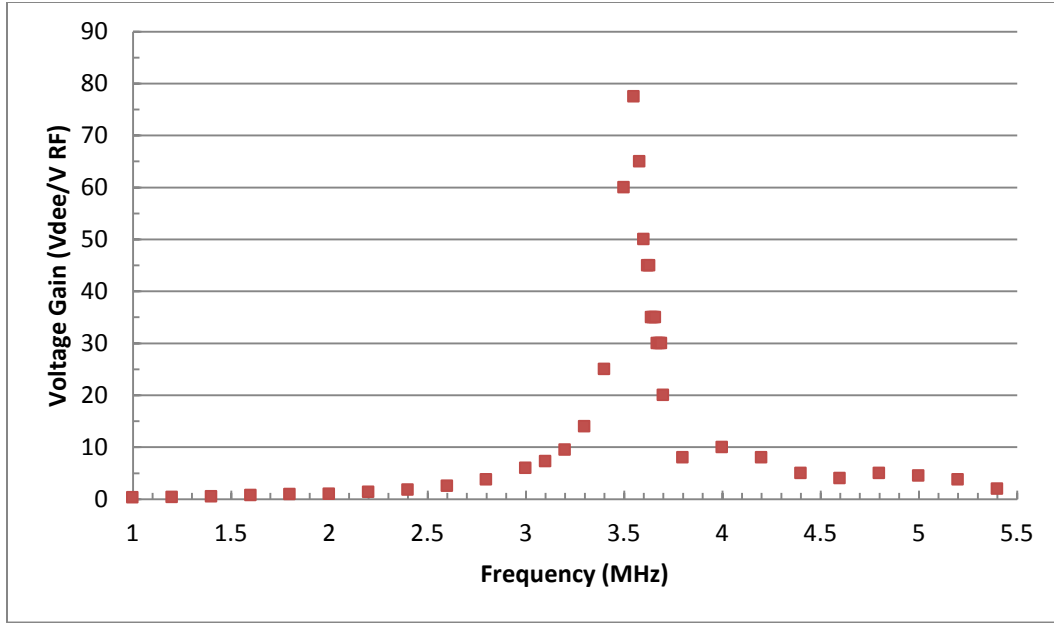


Figure 37. Plot of dee voltage gain vs. frequency. The data points represent the voltage gain between the RF amplifier and the dee. The voltage gain will be a maximum at the resonant frequency. For this plot, $f_0=3.55\text{MHz}$.

The peak in Figure 37 is the resonant frequency of the circuit. For this particular trial, the RF generator had an output of 200 mV (PP) and it can be seen that the resonant frequency occurred at $f_0=3.55$ MHz. At resonance, the AT-200PC tuner had a capacitor value of $C=92$ and inductor value of $I=40$. The quality factor (Q) is a measure of the sharpness of the peak. Q is related to the resonance frequency by Equation (2.3.23) [35]

$$Q = \frac{\omega_0}{\Delta\omega} \quad (2.2.23)$$

where $\Delta\omega$ is the width of the peak at half the maximum. Using the values $\omega_0=3.55$ MHz and $\Delta\omega=0.22$ MHz, the quality factor of the Houghton College cyclotron was determined to be $Q=16.1$. The previous chamber and dee constructed in 2006 had a quality factor of 22.

To automatically determine the resonant frequency, an AEA Via Bravo II Vector Impedance Analyzer was connected directly to the AT-200PC tuner shown in Figure 36 using an SO-239 antenna socket. The analyzer scans a range of frequencies and plots the SWR as a function of frequency. Its results were $f_0=3.63$ MHz at a SWR of 1.4:1 as shown in Figure 38.

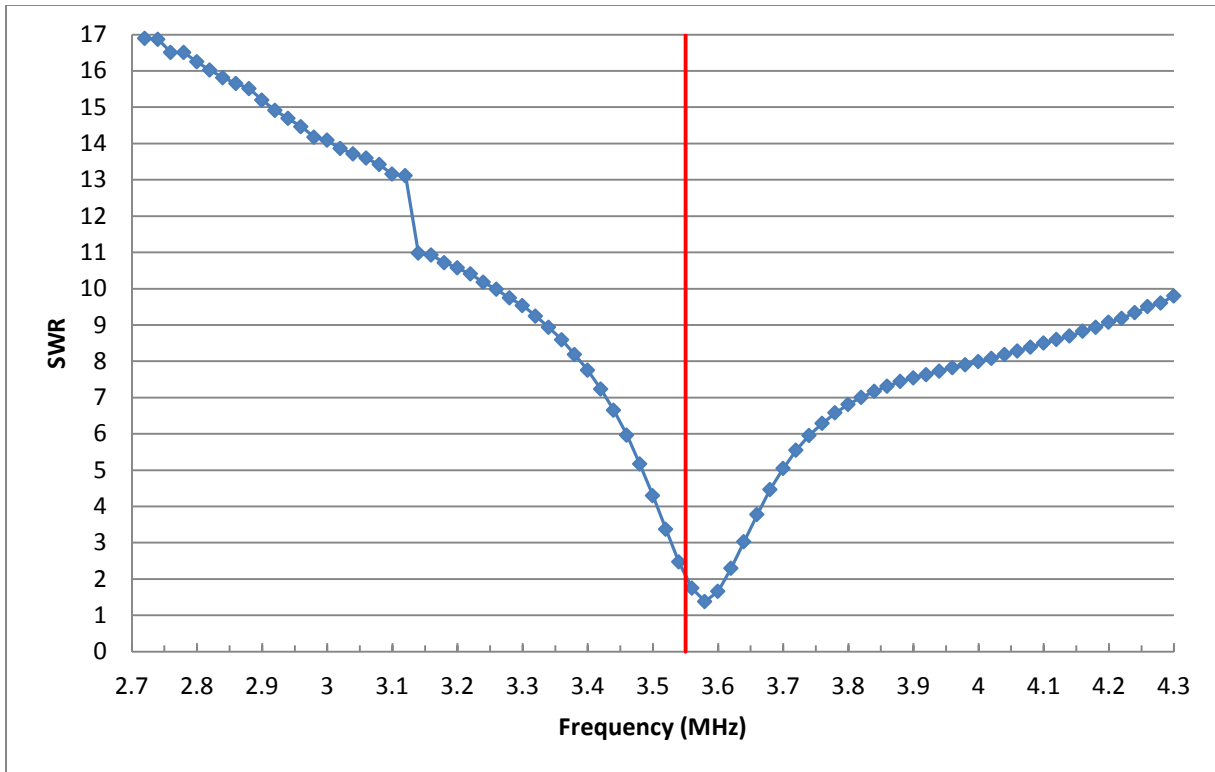


Figure 38. Plot of SWR from Via Bravo II analyzer. The vertical axis is the SWR and the horizontal axis is the frequency. Resonance occurs when the SWR is minimized, at a frequency of $f_0=3.63$ MHz and a SWR of approximately 1.4:1. The red vertical line shows the resonant frequency that was determined manually. The blue line represents the automatic sweep performed.

One possible explanation for the discrepancy between the automatic and manual calibration methods is that when the CT2591 HV probe was placed near the dee, the overall capacitance changed slightly. This would, of course, change the value of the resonant frequency.

4.1.2 *Calibrating the Pickup Probe*

When the cyclotron is in operation, the dee voltage cannot be measured by touching the dee with a probe. Since it is useful to know the potential across the dees, a pickup probe as described in Chapter 3 is used. The pickup probe records potentials lower than the actual dee voltage, so it must be calibrated. Probe calibration takes place with the chamber open to air so that a CT2591 HV probe can access the dee. While performing the frequency scan described in section 4.1.1, the pickup probe voltage was recorded at each interval. By comparing the CT2591 HV probe with the pickup probe, a

scaling factor can be determined as shown in Figure 39. It was determined that the real voltage was roughly 11,300 times the pickup voltage. The frequency of the RF system will affect the values recorded by the pickup probe. For this reason, the probe had to be recalibrated every time the frequency was adjusted. The results given here were for a frequency of 3.55 MHz.

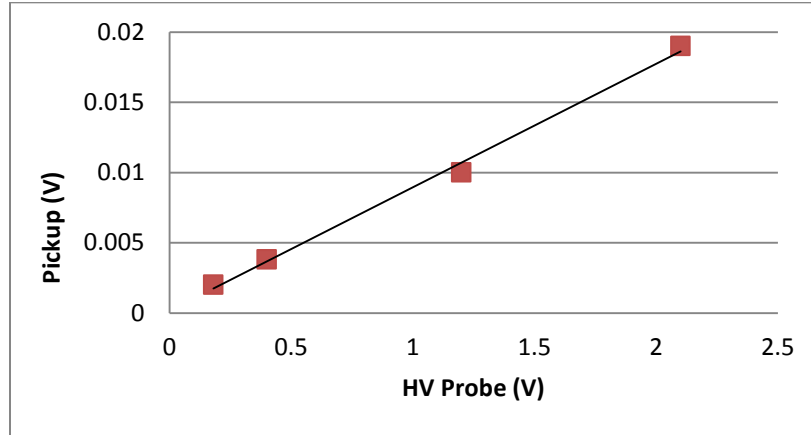


Figure 39. Diagram of pickup probe calibration. Pickup probe voltage as a function of the corresponding CT2591 HV probe voltage is graphed. A linear fit was performed and indicated that the real voltage was roughly 11,300 times the pickup voltage at an RF frequency of 3.55 MHz.

4.1.3 Magnetic Field Calibration

The magnetic field strength is adjusted by altering the current to the electromagnet. Since ions are only in resonance at certain magnetic fields for a given frequency, the magnetic field strength as a function of current needed to be determined. To do this, a TEL-Atomic Inc. SMS 102 Hall Effect probe was placed in the groove milled out in the lid. The magnetic field was measured as the current was adjusted from 0 to 50 A in 5 A intervals. These data were plotted (see Figure 32, Chapter 3) and a linear fit was performed. The equation of relation was found to be

$$B = 0.027I + 0.0169(\text{Tesla}) \quad (4.1.5)$$

where B is the magnetic field strength (measured in Tesla) at the top lid and I is the current through the electromagnet. Note that this equation is only valid for magnetic fields up to 1 T. Beyond this point, the magnetic field no longer increases linearly with the current. A probe could not be placed between the dees when the cyclotron is in operation, so a relationship between the magnetic field at

the lid and the magnetic field between the dees had to be determined. Again, the current was adjusted from 0 to 50 A in 5 A intervals while the magnetic field strength was measured both between the dees and at the lid. The results were plotted and a linear relationship between the two locations was found and plotted in Figure 40. Magnetic field measurements at the lid were on average 0.3 % higher than measurements made between the dees.

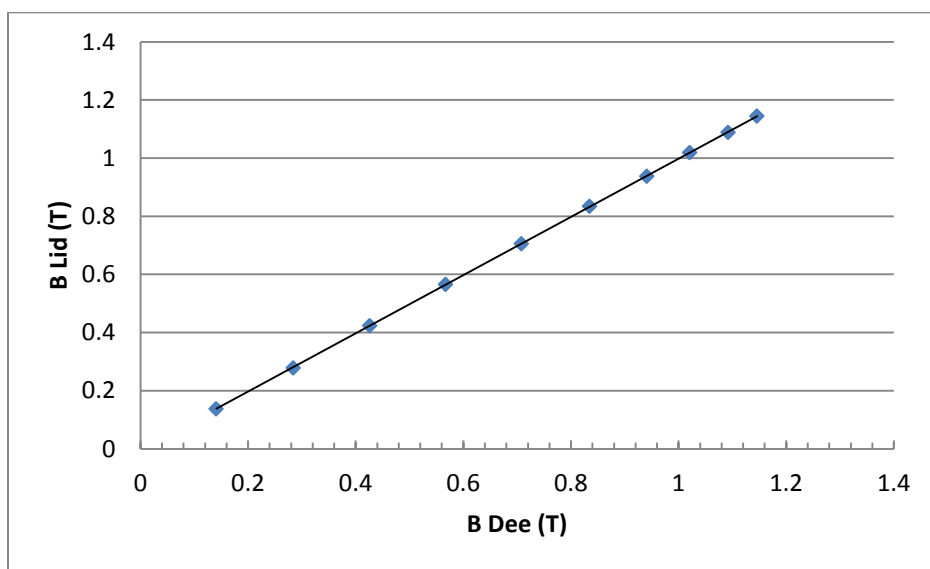


Figure 40. Plot of B_{Lid}/B_{Dee} . The magnetic field at the lid is plotted against the magnetic field at the dee at several different currents between 0 and 50 A. A linear fit was performed giving the relationship between the two probe locations. It was determined that the lid measurements were roughly 0.3% larger than the dee measurements over the range of the magnet.

One potential problem with calibrating the magnetic field to the current through the electromagnet is that of hysteresis. Because of this, adjusting the current through the magnet to a given value will not always correlate to the same magnetic field.

4.1.4 RGA Scan Analysis

A vacuum of roughly 2×10^{-5} torr or less was maintained inside the chamber to reduce the number of ion collisions with gas molecules. In the Houghton College cyclotron, this pressure is a combination of air, water, hydrogen and helium molecules. Although low pressures are needed to avoid collisions, there must also be a sufficient amount of gas present for creating ions (either hydrogen or helium).

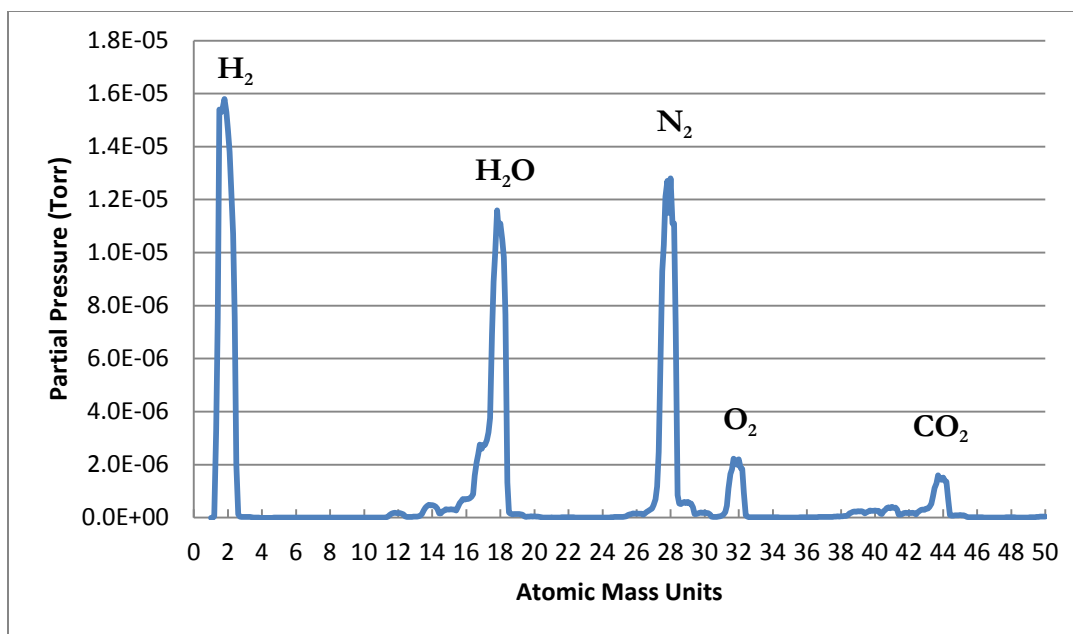


Figure 41. RGA scan prior to accelerating hydrogen ions. The hydrogen was present because of out-gassing from the chamber and dees. Air and water vapor were also present from outgassing, trapped water vapor, and air leaks.

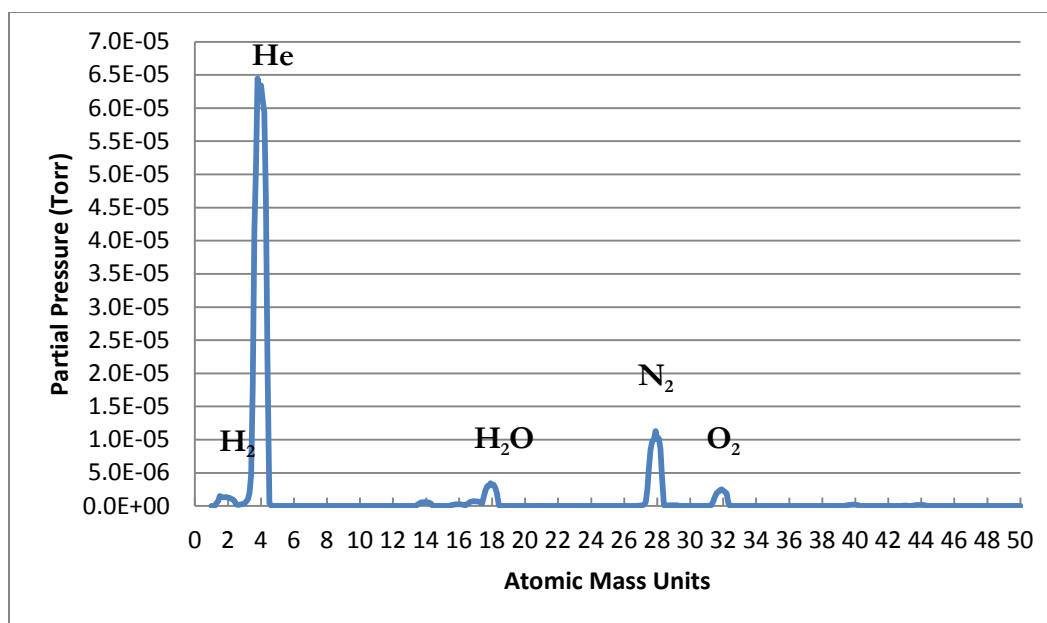


Figure 42. RGA scan for helium. Helium was released into the system through an Edwards LV10K leak valve. Hydrogen is present because of out-gassing from the aluminum chamber and dees.

The pressures and amounts of each gas in the chamber were determined using an SRS RGA-100 as discussed in Chapter 3. A scan was typically performed immediately before running the cyclotron. An example of an RGA scan done prior to accelerating hydrogen ions is shown in Figure 41 and a scan prior to accelerating helium ions is shown in Figure 42. Helium was released into the system through a needle valve and hydrogen entered the system through naturally occurring out-gassing of the chamber and dees.

4.2 Acceleration Results

4.2.1 *Hydrogen Ions*

Although the ultimate goal for the cyclotron is to accelerate deuterons for scattering experiments, ion acceleration can be more easily tested using hydrogen ions because the aluminum chamber and dee naturally out-gassed considerable amounts of hydrogen. Thus, a gas handling system was avoided for the initial test. Furthermore, the hydrogen ions were of low enough energy (on the order of 10 keV) that radiation safety precautions were not necessary.

The procedure for the initial test of the cyclotron was as follows. First, the RF system was tuned to a resonant frequency of 3.55 MHz while the filament was set to 2.0 A and floated at -100 V relative to the chamber. At these settings, a SWR of 1:1 and forward power of 15.43 W were measured. When this test was performed, the pickup probe was not calibrated correctly so the actual dee voltage could not be determined. Finally, the amount of hydrogen in the chamber was measured producing the RGA scan shown in Figure 41. The current through the magnet was slowly ramped for fifteen minutes from 7 to 10 A, using a computer program written in Labview 7.0, while the beam current was read in from the Faraday cup (as discussed in Chapter 3). Based on Equation (2.1.4),

$$f = \frac{q}{2\pi m} B, \quad (2.1.4)$$

with a frequency of 3.55 MHz for protons (H^+), ion acceleration should occur at 0.233 T. As can be seen in Figure 43, there is a resonance peak with a magnitude of 1.5 pA at around 0.23 T. The exact location of the peak can not be determined because of the width of the peak. In other words, there was essentially zero current until the magnetic field reached the value necessary for accelerating protons. At this magnetic field, the current shot up indicating that protons were hitting the collector. Collection took place at a radius of roughly 5.95 cm corresponding to proton energies of 9.2 keV. The

difference between the theoretical and actual location of the peak may be due to an inaccurate calibration of the magnetic field as a function of current and hysteresis effects as discussed above. There are currently plans to avoid these calibration errors in the future by directly measuring the magnetic field. This system has not yet been implemented.

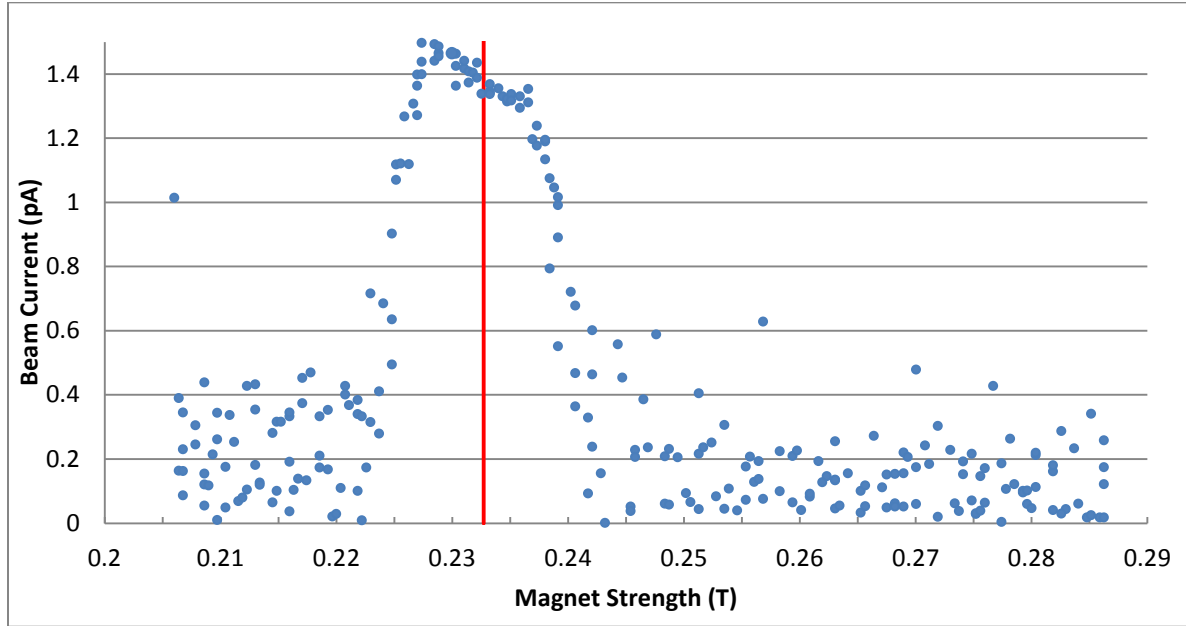


Figure 43. Plot of beam current as a function of magnetic field for accelerated H^+ at 3.55 MHz. Each data point represents the beam current measured by the Faraday cup at a given magnet current. The magnet current was converted to the magnetic field strength using Equation (4.1.6). The vertical line represents the theoretical location of 9.2 keV H^+ ions.

The results seemed to indicate that the cyclotron was accelerating H^+ ions. An identical scan was performed and a resonance peak was found at the same magnet current. One thing to note is the small beam current that was actually produced; 1.5 pA. This value was barely above the noise. Current measurements at such small currents are sensitive enough to measure significant changes when people pass by the cable. One possible explanation for the small beam current may be that the gas pressure in the chamber was too high. As the pressure increases the ions collide with gas molecules and fall out of resonance.

In the above scan, the magnetic field was only scanned where resonance was expected for H^+ . In reality, resonance can occur at other values for the magnetic field. In an attempt to locate other peaks, a full scan of the magnetic field range (0 to 1.1 T) was conducted. Two peaks in particular were being searched for, those of H_2^+ and those pertaining to the harmonic frequencies of H^+ (see Section 2.1.2).

The hydrogen present in the chamber was H_2 , not H . When ionized, H_2 becomes either H^+ (if the molecule dissociates) or H_2^+ . Accelerated H^+ was detected in the previous scan. At the same frequency of 3.55 MHz, H_2^+ should be accelerated near 0.466 T.

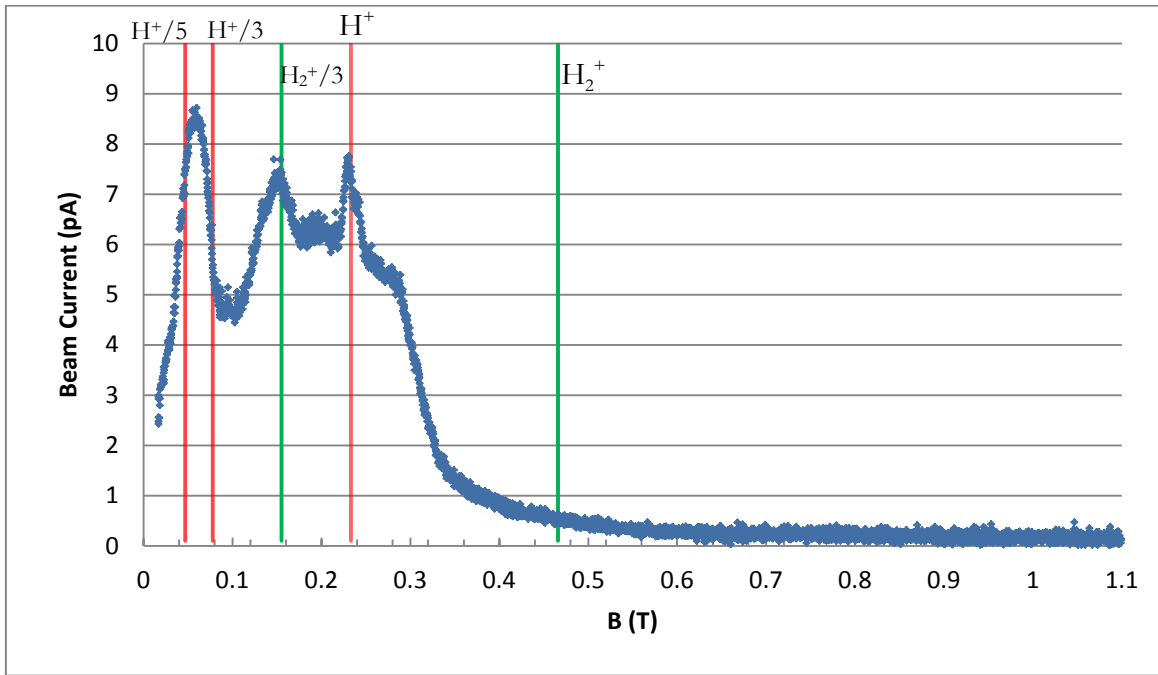


Figure 44. Hydrogen scan at 3.55 MHz. The green and red vertical lines represent the theoretical locations for the H_2^+ and H^+ respectively. The magnetic field was calibrated using Equation (4.1.6).

A full scan at 3.55 MHz for hydrogen is shown in Figure 44. A few things should be noted about this graph. First, there did not seem to be any peak at H_2^+ . This may be because of the number of ion orbits required at higher magnetic fields. At the gas pressure in the chamber, there may be too many molecules to collide with and the ions would fall out of resonance. Even though no H_2^+ peak was seen, there seems to be a legitimate $H_2^+/3$ peak. The lower magnetic field necessary for this peak reduces the number of rotations required, thereby reducing the probability of collisions. The first peak

on the graph lies directly between the two theoretical harmonic peaks for H^+ . The cause for this is currently unknown. One possible explanation may be that it is only one of the harmonics but because of inaccurate calibrations of the magnetic probe, it falls between the two harmonics. A second possible explanation is that it is a combination of the two peaks. Finally, the beam current was over 8 pA in this trial, nearly eight times greater than the previous trial. This result probably came about because the forward power was increased to 25.65 W from 15.43 W, which correlates to a higher dee voltage. Recall that as the dee voltage increases, the number of orbits necessary to reach the final energy decreases and the ion is less likely to fall out of resonance because of collisions with molecules.

Since the previous two trials were done at the same frequency, it was of interest to see what happens as the frequency is increased. Increasing the frequency should shift the peaks to higher magnetic fields and spread out the harmonic peaks so that they would be easier to distinguish. With this in mind, the function generator was set to 6.04 MHz at 300 mV (PP) resulting in a forward power of 26 W and a SWR of 1.14:1. Previously, the filament was floating at -100 V so that the electrons were given a significant amount of energy when they were emitted. With all of this energy, however, there was concern that most of the H_2 was being dissociated and accounted for the lack of H_2^+ resonance peaks. For this reason, the filament was run at 2.1 A while floating at -6 V relative to the chamber. A full 0 to 1 T scan was conducted at a hydrogen pressure of 2×10^{-6} torr. A plot of beam current as a function of magnetic field for this trial is shown in Figure 45.

As expected, the H^+ is now found at a B-field nearly twice as large as for 3.55 MHz. The other peaks present also shifted to the right and spread out from one another. Again, there are no resonance peaks above 0.5 T, a trend that continued through every scan. It is believed that the chamber and foreline setup does not allow the pressure to get low enough to produce the mean free path necessary for acceleration. In addition to the H^+ peak mentioned, there are also peaks near the expected locations for $H^+/3$, $H^+/5$, $H^+/7$, and $H^+/9$. Discrepancies between the theoretical and experimental peak locations may be from incorrect magnetic field calibration. The beam current in this trial reached over 20 pA for H^+ and nearly 60 pA for $H^+/9$. These numbers are larger than those recorded in the last trial and are most likely a result of lower pressures within the chamber. Note also, that the current decreases for larger magnetic fields. This may be the result of the greater number of ion orbits necessary at larger magnetic fields. With this setup, the H^+ ions accelerated near 0.4 T had an approximate energy of 26.6 keV.

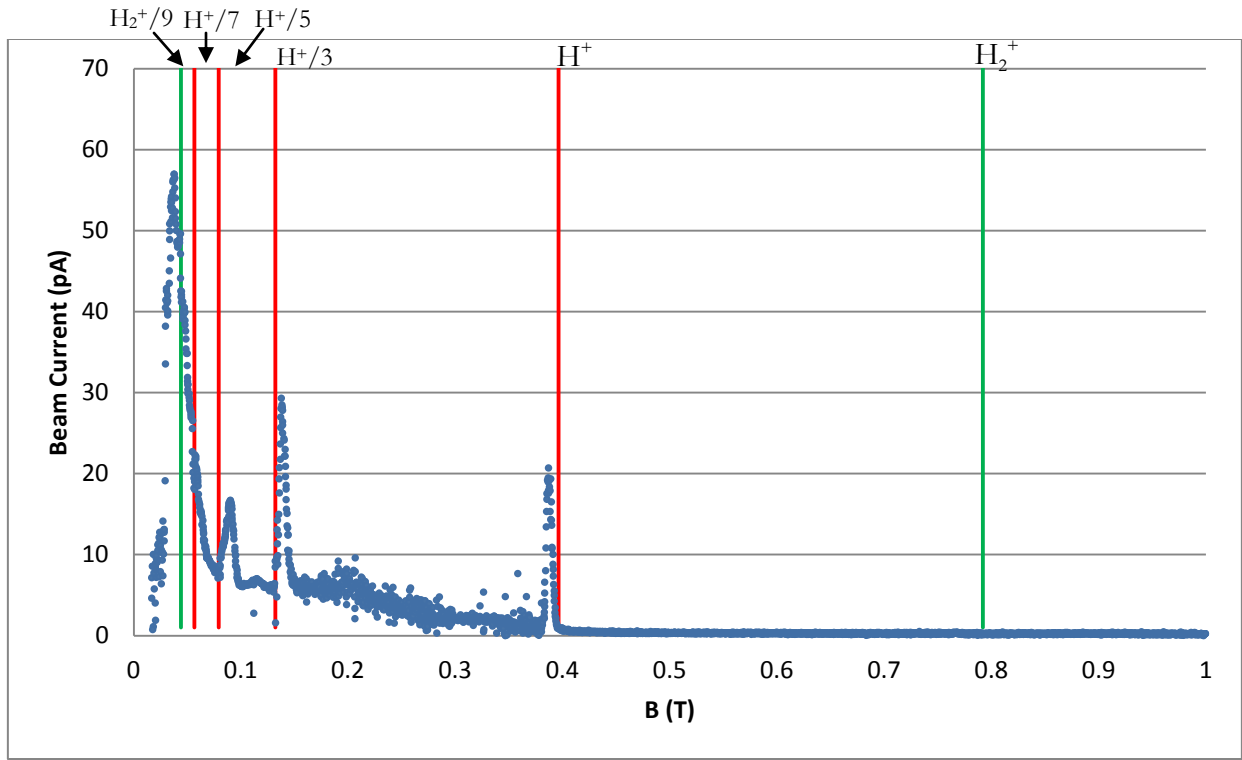


Figure 45. H_2 full scan at 6.04 MHz. The green and red vertical lines mark the theoretical location of the H_2^+ and H^+ peaks respectively. Differences between the theory and experiment are believed to be due to inaccurate magnetic field calibration.

4.2.2 Helium Ions

With several hydrogen scans completed, the helium gas system was connected to the chamber via one of the ports and helium was let into the chamber through an Edwards LV10K leak valve. The leak valve was sensitive and required a considerable amount of time to obtain roughly the pressure desired. When letting He into the system, the valve would open all at once and flood the system with the helium. The valve was then slowly closed while monitoring the pressure in the chamber until the desired pressure was roughly obtained. The RGA measured the amount of helium present in the chamber. As can be seen in Figure 42, the He pressure was approximately 6×10^{-6} torr and hydrogen was still present on the order of 2×10^{-6} torr. For He^+ and a driving frequency of 6.04 MHz, the expected magnetic field for resonance is 1.585 T. Since the electromagnet was only capable of fields up to 1.1 T, the driving frequency was reduced to 3.485 MHz which requires a magnetic field of 0.914 T for He^+ acceleration. At this frequency, a SWR of 1.04:1 and forward power of 10.44 W was

established. Finally, the filament was operated at 1.9 A and floated at -100 V relative to the grounded chamber. A full scan was conducted and its results are shown in Figure 46.

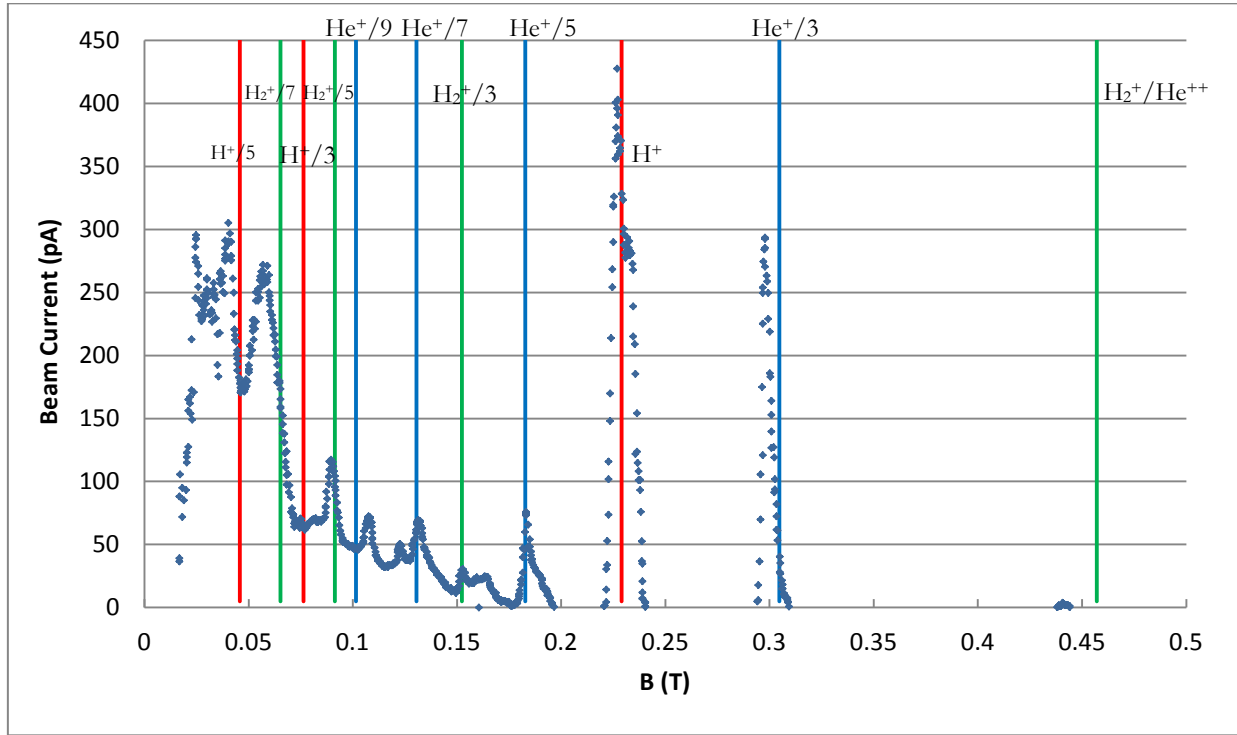


Figure 46. He scan at 3.485 MHz. The blue, green, and red vertical lines represent the theoretical location of the He^+ , H_2^+ , and H^+ peaks respectively. Though the scan was done through 1.1 T, there were no peaks above 0.5 T so these data were not plotted. Note that several of the peaks correlate well with the theoretical location for the harmonics of He^+ .

Notice that the plot above only goes up to 0.5 T and the He^+ peak was expected to be at 0.914 T. As was the case in the previous trial, there were no signs of peaks in this region so it was not plotted. Although no He^+ resonance peaks were found, the data indicated that several harmonics of He^+ resonances were. Among these was $\text{He}^+/3$ which had a current of nearly 300 pA and energy 3.9 keV. Current readings were, in general, higher for this trial than previous ones. This is most likely due to the fact that the air pressure was lower than before, yet there were still sufficient amounts of He and H_2 for acceleration. A second type of peak to observe in this graph is that corresponding to He^{++} and H_2^+ . Since these two particles have the same charge-to-mass ratio, they require the same frequency to magnetic field ratio for acceleration. There seems to be several harmonic peaks for these ions, though

it can not be determined whether the peaks were from He^{++} , H_2^+ , or both. Finally, the H^+ peak is still present and reached a current of over 400 pA at an energy of 8.8 keV.

Another trial was performed using the same settings except that the He was removed from the chamber. Thus, it was a hydrogen scan but at a lower pressure (5×10^{-6} torr hydrogen pressure) than any of the previous trials. This was made possible because the pumps had been running for several days. This scan was performed because it could be directly compared to the previous He scan and could verify that the peaks seen in Figure 46 were actually from He ions. The results are shown in Figure 47.

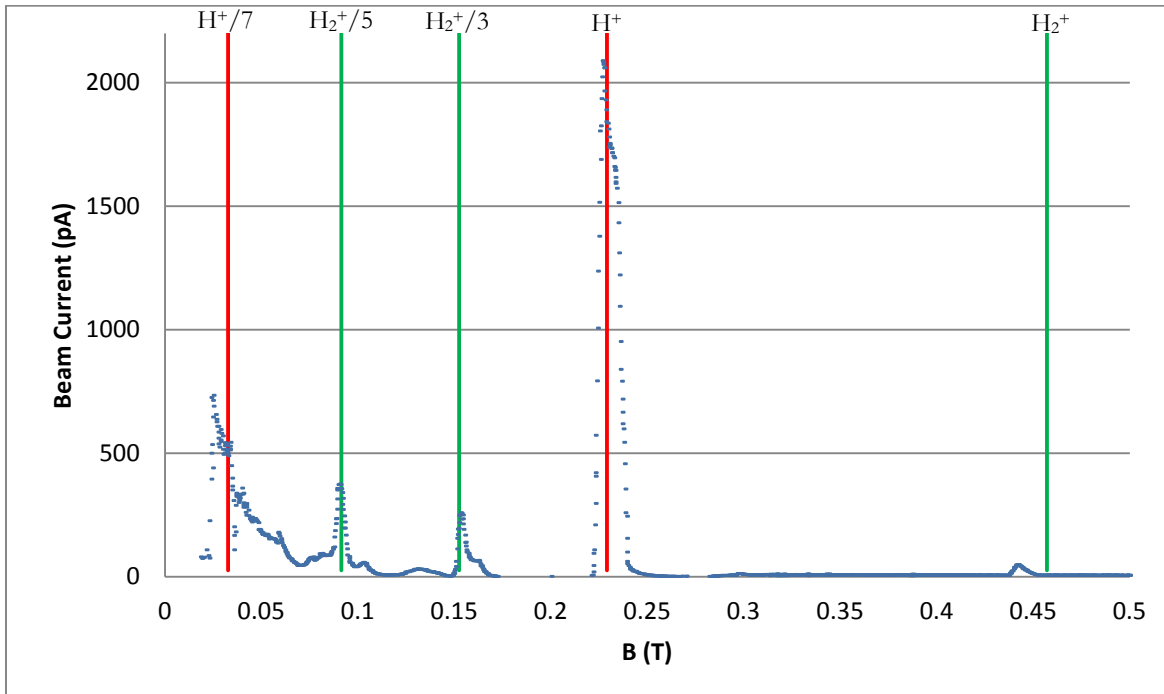


Figure 47. H scan at 3.485 MHz. The green and red vertical lines represent the theoretical locations of the H_2^+ and H^+ peaks respectively. Harmonics of both H^+ and H_2^+ are present.

Comparing this plot to that given in Figure 46, it becomes apparent that all of the harmonics of He^+ are gone. Furthermore, the current of the H^+ beam increased with the absence of the helium gas. This was expected because the overall pressure in the chamber decreased when the helium was removed. Notice also that the H_2^+ peaks are still present. Based on this, we know that the cyclotron was accelerating at least H_2^+ . It is still unknown, however, whether or not He^{++} had been accelerated.

Finally, no peaks were observed at magnetic fields greater than 0.5 T and this portion of the graph was omitted.

A final full scan was performed with helium once again in the chamber. This time, the He pressure was set at 1×10^{-5} torr (down from 6×10^{-5} torr in the previous He trial). Using the same frequency and voltage settings as those before, the results are shown in Figure 48.

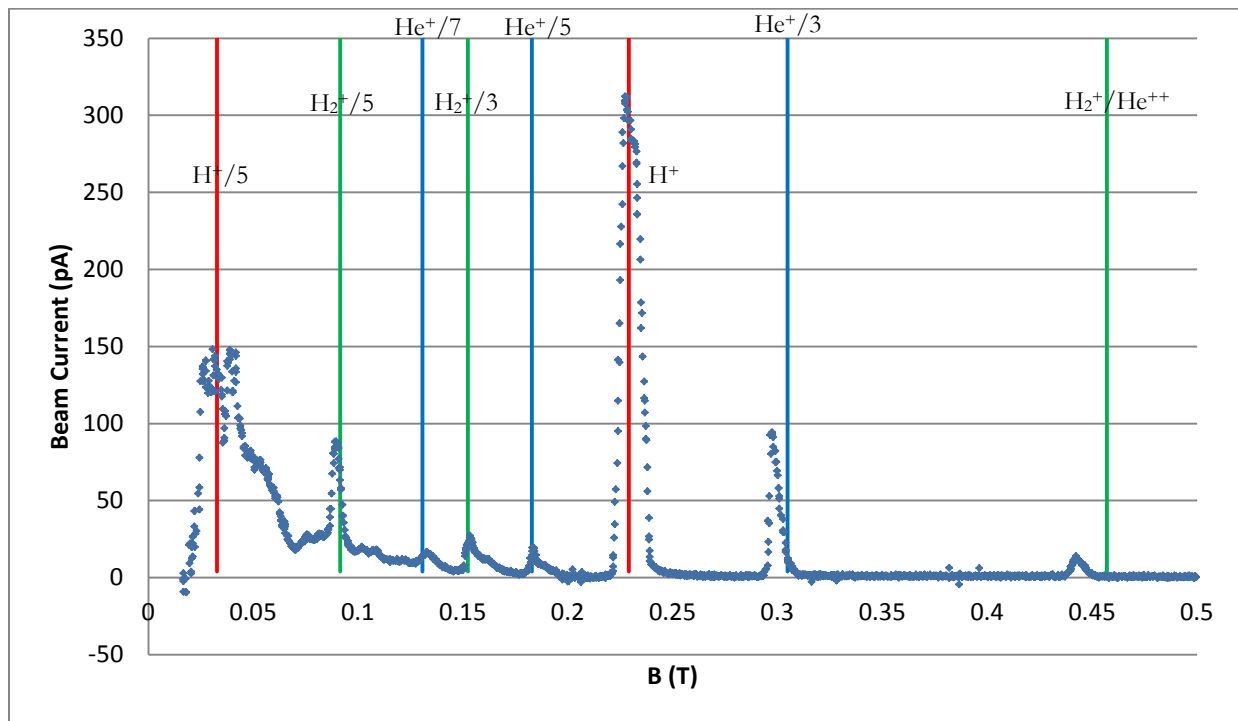


Figure 48. Scatter plot of second He run at 3.485 MHz. The blue, green, and red vertical lines represent the theoretical location of the He⁺, H₂⁺, and H⁺ peaks respectively.

Based on the last two plots, two things happened that were expected. First, the peak near 0.3 T reappeared. Though the theoretical line does not line up with the peak as well as it does for other peaks, the fact that it only appears when helium is present indicates that it is a helium peak. Furthermore, the other harmonic peaks of helium reappeared near 0.18 T and 0.13 T respectively after being absent in the previous trial. Finally, the beam current of each peak is lower than it was when no helium was present. Again, this is to be expected since the number of molecular collisions decreases with decreasing pressure.

Chapter 5

CONCLUSION

After the cyclotron dee and chamber were damaged in the spring of 2007, a new design for a chamber and dee was developed and the parts were constructed. Using these, the Houghton College cyclotron successfully accelerated He^+ , H_2^+ , and H^+ ions. Currents of up to 2 nA were obtained with energies up to 9.2 keV for protons. Though ions were accelerated, resonance peaks were never detected at magnetic fields greater than 0.5 T. This may be because at large magnetic fields, ions travel through a greater number of orbits and are more likely to collide with gas molecules. In the immediate future, the cyclotron will be systematically tested by varying parameters such as the gas pressure, filament current, and dee voltage in order to maximize the beam current produced as well as to obtain resonance peaks at higher magnetic fields. It is possible, that the gas pressure needs to decrease in order for this to happen. This would require a better method for sealing the chamber to prevent air leaks and a more precise helium leak valve to get lower helium pressures in the chamber. Another future consideration is to shape the magnetic field with iron shims to either radially decrease or azimuthally vary the field to improve beam focusing. A more focused beam should improve the amount of beam current collected. Ultimately, the cyclotron will be used to accelerate deuterium ions to setup neutron emitting, deuteron-deuteron interactions within the chamber. These neutrons pass through the wall of the chamber where they will be used for low-energy scattering experiments.

References

-
- [1] P.P. O'Shea. *Notes and Records of the Royal Society of London*, **27**, 67 (1972).
 - [2] M. Stanley Livingston and John P. Blewett, *Particle Accelerators* (McGraw-Hill Book Company, New York, 1962).
 - [3] E. Rutherford, Proc. Roy. Soc (London), **117**,300 (1927).
 - [4] J.D. Cockroft and E.T.S. Walton, Proc. R. Soc (London), **A136**, 619 (1932).
 - [5] J.D. Cockroft and E.T.S. Walton, Proc. R. Soc (London), **A137**, 229 (1932).
 - [6] D.H. Sloan and E.O. Lawrence, Phys. Rev. **38**, 2021 (1931).
 - [7] W.S. Mann, "The Cyclotron," rev. ed., Methven's Monographs, Wiley (1953).
 - [8] E.O. Lawrence and N.E. Edlefsen, Science, **72**, 376 (1930).
 - [9] E.O. Lawrence and M.S. Livingston, Phys. Rev. **40**, 19 (1932).
 - [10] M.S. Livingston, Ph.D. Thesis, University of California, Berkeley, 1931.
 - [11] E.O. Lawrence and M.S. Livingston. Phys. Rev. **45**, 608 (1934).
 - [12] E.O. Lawrence and D. Cooksey, Phys. Rev. **50**, 1131 (1936).
 - [13] Triumf Cyclotron
<http://www.triumf.info/public/about/background.php>. (Viewed February 8, 2009)
 (Author Unlisted).
 - [14] D.J. McGuire. *The Proceedings of the Iowa Academy of Science*. **68**, 474 (1961).
 - [15] J. Smith. undergraduate thesis, Knox College, 2001.
 - [16] A. R. Boone. *Popular Science*. **11**, 102 (1947).
 - [17] F. Niell. "Cyclotron Notes." (2002).
 - [18] K.J. Bertsche. Ph.D. Thesis, University of California, Berkeley, 1989.
 - [19] B.T. King. undergraduate thesis, Houghton College, New York, 2003.
 - [20] S.C. Tuminaro. undergraduate thesis, Houghton College, New York, 2003.
 - [21] M.J. Cressman. undergraduate thesis, Houghton College, New York, 2006.
 - [22] A.J. Loucks. undergraduate thesis, Houghton College, New York, 2007.
 - [23] M.S. Livingston, Rev. Sci. Instrum. **7**, 55 (1936).
 - [24] M.A. Tuve, O. Dahl, and L.R. Hafstad, Phys. Rev. **48**, 241 (1935).
 - [25] M.E. Rose Phys. Rev. **53**, 392 (1938).
 - [26] R.R. Wilson, Phys. Rev. **53**, 408 (1938).
 - [27] J. Rosenblatt. *Particle Acceleration* (Nederlandse Boekdruk Industrie, Netherlands, 1968).
 - [28] B.L. Cohen, Rev. Sci. Instrum. **24**, 589 (1953).

-
- [29] T. W. Koeth (unpublished).
http://www.physics.rutgers.edu/cyclotron/papers/12_inch_dee_voltage.pdf (2005)
(Viewed on February 2, 2009).
- [30] H.A. Bethe and M.E. Rose, Phys. Rev. **52**, 1254 (1937).
- [31] P.A. Tipler, Ralph A. Llewellyn. *Modern Physics 5th Edition* (W.H. Freeman and Company, New York, 2008)
- [32] D. Bohm and L. Foldy, Phys. Rev. **70**, 249 (1946).
- [33] J. Richardson, B.T. Wright, E.J. Lofgren, and Bernard Peters. Phys. Rev. **73**, 424 (1948).
- [34] L.H. Thomas, Phys. Rev. **54**, 580 (1938).
- [35] R. A. Serway and J.W. Jewett. *Physics: for Scientists and Engineers with Modern Physics*. (Thomson – Brooks/Cole, California, 2008)