The Houghton College Cyclotron: Results and Modifications

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1. Abstract

The Houghton College Cyclotron consists of a 17 cm inner diameter, 2.8 cm thick evacuated aluminum chamber containing a "dee" shaped electrode and a grounded "dummy dee" placed between the poles of a 1.1 T electromagnet. Low pressure gas is introduced into the chamber where a filament, through electron collisions, ionizes the gas. The ions are accelerated in a spiral path by a constant magnetic and an alternating RF electric field. It is expected that the accelerated ions will reach energies of 280 keV, 140 keV, and 70 keV for protons, deuterons, and helium respectively, and may be used in small-scale nuclear experiments. The cyclotron successfully accelerated protons on one occasion, but after an hour of operation a discharge occurred which destroyed the filament and the surrounding insulation, and a leak in the vacuum chamber developed. To solve this problem, a new larger chamber was designed and is under construction.

2. What is a Cyclotron?

One of the earliest particle accelerators, the cyclotron, was originally devised by Earnest Lawrence at the University of California, Berkley in 1929. At this time, physicists were trying to find ways to accelerate particles for use in nuclear scattering experiments to gain a better understanding of nuclei. When Lawrence and his graduate student, M. Stanley Livingston, built the first cyclotron in 1931, it was considered to be the best method for accelerating particles. Unlike the electrostatic accelerator of the same time, the cyclotron requires relatively low voltages and, since it accelerates particles in a spiral pattern, it is relatively compact. Lawrence realized that he could use a magnetic field to alter the paths of the particles. When charged particles pass through a magnetic field perpendicular to the plane of motion, they will follow a circular path. Therefore, the particles can be accelerated over and over again in the same region of space (see Figure 1). Since magnetic fields do not do work, an alternating electric field is placed in the region of the particles to accelerate the ions. This electric field is created by two "dee" shaped electrodes (electrical conductors) with a potential difference between them. Ions are accelerated between the dees while traveling in a circular path. Once the ions have returned to the acceleration region, the potential on the dee is reversed causing the ions to accelerate again. With each cycle, the energy and radius of the particles' path increases allowing high energies to be reached with low potentials. The key to Lawrence's cyclotron was the discovery that the frequency required to accelerate the particles was constant, regardless of the radius of orbit.

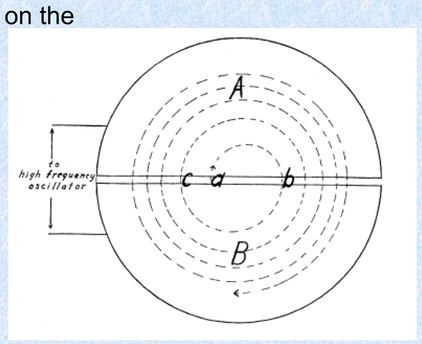

Figure 1 – The cyclotron. When a positive charge is placed at (a), it is accelerated between the dees (A and B) by an electric field. The magnetic field perpendicular to the particle's motion (not shown) causes its path to bend into a spiral represented by the dotted line. Figure taken from E. O. Lawrence and M. S. Livingston, Phys. Rev. 40, 19 (1932).

3. Cyclotron Frequency

Lawrence realized that the frequency required to accelerate the particle is constant regardless of the energy and radius. The reason for this is shown below. The force exerted on the particle by the magnetic field is given by the Lorentz force law.

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

For the particles traveling in a circular path, this force will be pointed centrally inward. Therefore,

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

where q is the charge of the particle, m is its mass, v is its speed, r is the radius of the path, and B is the external magnetic field. Therefore,

$$\frac{v}{r} = \frac{qB}{m}$$

The cyclotron frequency is the rate at which the potential on the dee oscillates, and is equal to the number of revolutions per unit time. For a circular trajectory, the frequency is the velocity of the particle divided by the circumference of its path. Thus,

$$f = \frac{v}{2\pi r} = \frac{qB}{2\pi m}$$

Therefore, the frequency only depends on the charge and mass of the particle, as well as the strength of the magnetic field. As the particle speeds up, the radius of its path gets larger as well. Thus, it always takes the same amount of time to complete a cycle.

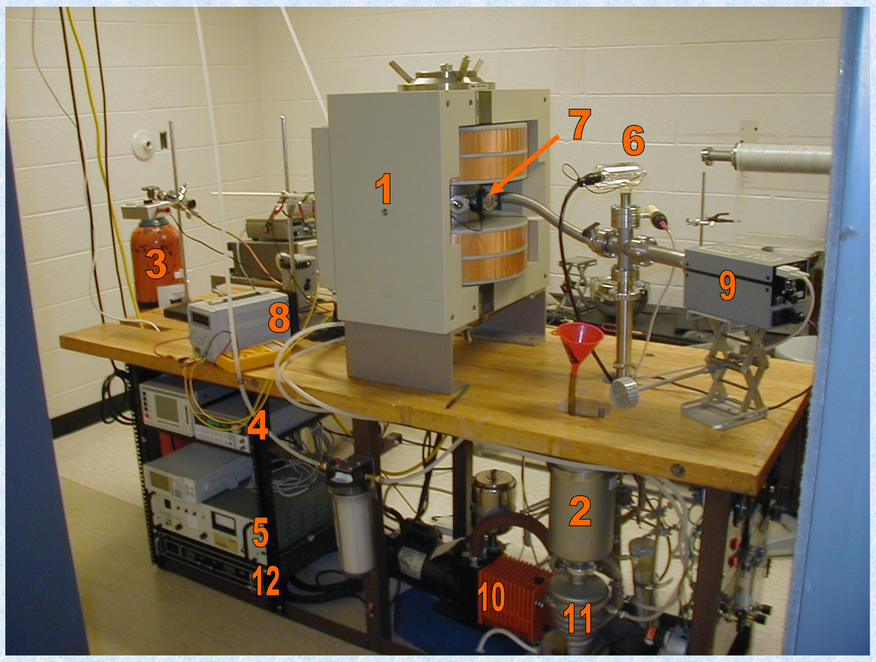

Figure 2 – The Houghton College Cyclotron, showing the (1) electromagnet (2) LN_2 cold trap (3) helium gas cylinder (4) RF generator (5) RF amplifier (6) ion gauge (7) chamber (8) filament supply (9) residual gas analyzer (10) forepump, (11) diffusion pump and magnet controller (12).

4. Design

4a. Vacuum System

The chamber is evacuated by a CIT-Alcatel 2012A rotary forepump, diffusion pump (Innovac R220), and an LN_2 cold trap. The forepump reduces the pressure to approximately 10^{-3} torr. At this pressure, the diffusion pump reduces the pressure to the desired pressure of approximately 10^{-6} torr. The cold trap prevents vaporized oil (from the diffusion pump) from entering the chamber. An ion gauge is used to measure the pressure inside the chamber. A SRS RGA-100 Residual Gas Analyzer monitors the composition and partial pressure of the gas in the chamber (see Figure 8). Valves placed throughout the system allow certain parts of the vacuum system to be isolated. Air can be allowed into the chamber without losing the vacuum in the rest of the system (see Figure 3).

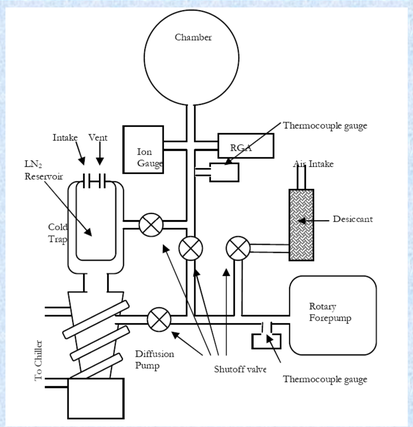

Figure 3 – Diagram of the vacuum system. The rotary pump lowers the pressure down to 10^{-3} torr before the diffusion pump reduces it to 10^{-6} torr. The shutoff valves allow certain parts of the system to be isolated without losing the vacuum. The ion gauge measures the pressure in the system.

4b. Electrical System

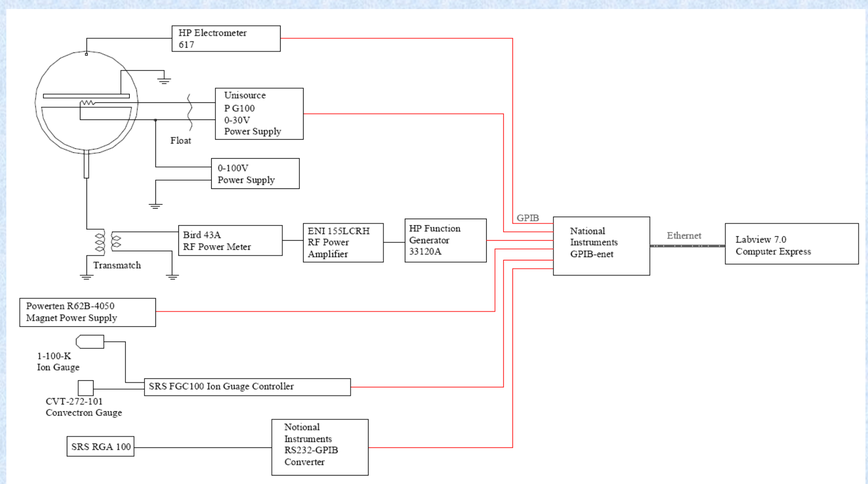

Figure 4 – Schematic diagram of the control system. All of the equipment may be controlled remotely via ethernet using Labview 7.0. A National Instruments GPIB-enet converter communicates with all GPIB devices, while the SRS RGA-100 Residual Gas analyzer RS-233 signals must first be converted to GPIB using a National Instruments GPIB-232CV-A converter.

4c. Magnet

The Houghton College Cyclotron uses a GMW Associates 3473-70 Electromagnet with 15 cm diameter poles. The maximum strength of the field at a pole separation 3.85 cm is 1.1 T while running at 50 A from a PowerTen R62B-4050 power supply. A water cooling system keeps the magnet from overheating by cycling 18°C water through the magnet at 0.8 gpm.

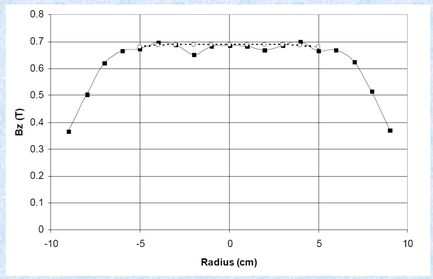

Figure 5 – Measured (solid) and nominal (dashed) magnetic field strength as a function of distance from the center of the magnet.

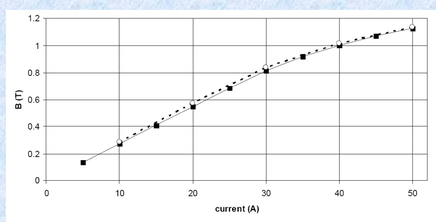

Figure 6 – Measured (solid) and nominal (dashed) magnetic field strength as a function of current.

4d. Chamber

The chamber (Figure 7) is a ring of inner diameter 17 cm made from 2.54 cm thick aluminum plate. The chamber wall is 2.8 cm thick. Two 0.65 cm thick, 19.8 cm diameter lids were also cut from aluminum plates and are fastened to either side of the chamber using ten ½ inch brass screws. Ten QF flanges will be glued with vacuum epoxy to holes drilled in the chamber wall and used for connecting the viewing ports, faraday cup, vacuum system, gas system, and RF circuit. Traditionally, cyclotrons have two dees of opposite polarity to accelerate the particles. The Houghton College Cyclotron has one dee and a "dummy dee" (these can be seen in Figure 4). The dummy dee is grounded, meaning the functional dee has to oscillate both above and below ground potential.

A Faraday cup is used to measure the beam current. A brass plate collector is placed perpendicular to the beam path at the end of an extendable bellows. This rod can be moved to position the collector at beam radii between 4.66 cm and 6.00 cm. The charge striking the collector is measured by an electrometer to record the beam current.

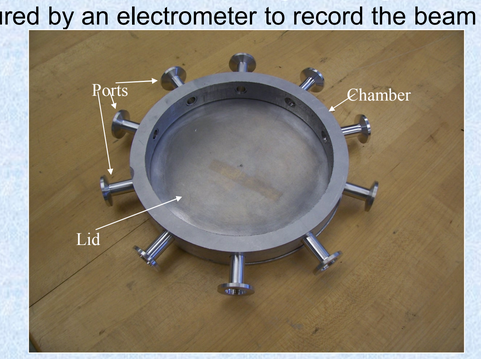

Figure 7 – Photograph of the chamber. The chamber, ports, and one of the lids are shown.

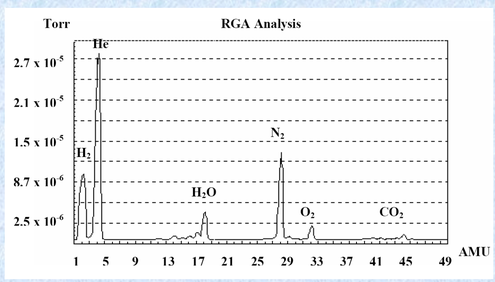

Figure 8 – A typical Residual Gas Analyzer (RGA) scan. The vertical axis represents the partial pressures of the respective gases present in the chamber. Helium was allowed in the system when the scan was taken.

5. Results

The Houghton College Cyclotron has operated successfully on one occasion. Although no helium was introduced to the system, an RGA scan indicated there was sufficient residual hydrogen in the chamber to accelerate protons. The RF generator was set to 3.65 MHz, corresponding to a magnetic field strength of 0.24 T. A distinct peak in current collected in the faraday cup can be seen in Figure 9 at a field strength of about 0.27 T. The discrepancy is believed to result from poor calibration of the magnetic field measurement.

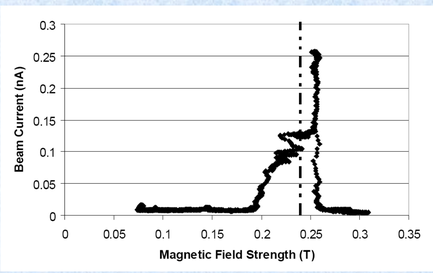

Figure 9 – Measured beam current as a function of magnetic field strength for hydrogen. A resonance peak is clearly visible.

6. Conclusion

The cyclotron ran for about one hour before a discharge from the dee to the chamber wall punctured the glass and epoxy insulation surrounding the filament. The chamber also developed a leak and can no longer reach pressures of 10^{-6} torr or below. Once the new, larger aluminum chamber is completed, the cyclotron should be ready for further testing. We hope in the future use the cyclotron to accelerate deuterium ions to induce deuteron-deuteron reactions, for the purpose of releasing neutrons to use in various neutron scattering experiments. Using a cyclotron to produce neutrons is advantageous because (1) neutrons do not interact with the magnetic field and can pass directly through the chamber wall, thereby requiring no extraction system, and (2) 140 keV deuterons would produce much higher energy 2.8 MeV neutrons.