# **Characterizing the Houghton College Cyclotron**

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#### Abstract

The Houghton College Cyclotron consists of a 17 cm inner diameter evacuated aluminum chamber containing a "dee" shaped electrode and a grounded "dummy dee" placed between the poles of a 1.2 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 an alternating RF electric field in the constant magnetic field. It is expected that the accelerated ions will reach maximum energies of 400 keV, 200 keV, and 100 keV for protons, deuterons, and helium respectively. The cyclotron has successfully accelerated protons and helium ions. Currently, the performance of the cyclotron is being optimized for future small-scale nuclear experiments.



#### Results

The Houghton College Cyclotron is currently operational and its performance at varying frequencies, gas pressures, and filament voltages is being characterized in order to determine the optimal parameters. Figures 7-9 show the beam current as a function of magnetic field for representative magnet scans. The ions in resonance (as well as harmonics) can be seen. The colored lines identify the expected locations of the resonance peaks. The predicted resonance frequencies differ slightly from the measured frequencies, most likely because of problems with the magnetic field strength calibration. Recently, a slot was machined into the chamber lid to take a hall effect probe, allowing the magnetic field to be directly monitored.



When ions pass through a magnetic field perpendicular to their plane of motion, they will follow a circular path. This allows them to be accelerated by an electric field over and over again in the same region of space. In a cyclotron, two "dee" shaped electrodes accelerate the ions. With each cycle, the energy and radius of the particles' path increases allowing high

Figure 1 – Ion moving through a magnetic field.

energies to be reached with low potentials.

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 orthogonal to the magnetic field, this force will be pointed centrally inward. Therefore,

$$-mv^2$$
  $v aR$ 



Figure 3 – The Houghton College Cyclotron, showing the (1)  $H_2$  gas cylinder (2) Function Generator (3) RF Amplifier (4) Magnet Power Supply (5) Chamber (6) Programmable Power Supplies (7) Ion gauge (8) Turbopump (9) Residual gas analyzer (10) Pump control panel (11) Electromagnet (12) Electrometer (13) Variable inductor.

### Vacuum and Gas System

The chamber is evacuated by a Alcatel 2012A rotary forepump, and a Pfeiffer TPU062 turbopump. The forepump reduces the pressure to approximately 10<sup>-3</sup> Torr. The turbopump reduces the pressure to the desired pressure of approximately 10<sup>-6</sup> Torr. A water cooling system is used to prevent the turbopump from overheating. An SRS IGC-100 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. Valves placed throughout the system allow certain parts of the vacuum system to be isolated. A MKS 1179A mass flow controller (MFC) supplies gas to the chamber for ionization and acceleration.





Figure 7 – H scan at 3.485 MHz. The green and red vertical lines represent the predicted locations of the  $H_2^+$  and  $H^+$  peaks respectively. Harmonics of both H<sup>+</sup> and  $H_2^+$  are present.





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.

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,



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.

## **RF** System

The Houghton College Cyclotron uses an HP 33120A function generator to create the needed 0 – 20 MHz driving frequency. Since there is capacitance between the dee and the grounded chamber walls, a variable inductor is used in order to tune the RLC circuit to the desired frequency. An LDG AT-200PC antenna autotuner was used to match the 50  $\Omega$  output impedance of the ENI 155LCRH RF power amplifier. The RF amplifier drives the dee to typically 1300-1500 V<sub>pp</sub>, accelerating the gas ionized by the filament. The beam Figure 4 – Diagram of the vacuum system. The rotary forepump and the turbopump reduce the pressure to 10<sup>-6</sup> Torr. The MFC allows gas to flow into the chamber.

current (A)

Figure 5 – Measured (solid) and nominal (dashed)

magnetic field strength as a function of current.

Figure 8 – Plot of H and He run at 3.485 MHz. The blue, green, and red vertical lines represent the predicted locations of the He<sup>+</sup>,  $H_2^+$ , and H<sup>+</sup> peaks respectively.



Figure 9 –  $H_2$  full scan at 6.04 MHz. The green and red vertical lines mark the theoretical location of the  $H_2^+$  and  $H^+$  peaks respectively.

## Chamber

gpm.

The chamber (Figure 6) is a ring of inner diameter 17 cm made from 2.54 cm thick aluminum plate. The chamber wall is 1.2 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 stainless steel screws. Ten QF-16 flanges are glued with vacuum epoxy into holes drilled in the chamber wall and used for connecting the viewing ports , faraday cup, vacuum system, gas system, and RF circuit. Traditionally,

Ê<sub>0.6</sub> -

# Conclusion

The Houghton College Cyclotron is currently operational, and the performance of the cyclotron is being optimized. Beam current at varying frequencies and pressures are currently being monitored. Unfortunately, resonances are missing at high magnetic fields, corresponding to higher energies. To better understand this issue, beam current will be measured at varying radii. In the future, the shape of the magnetic field may be altered using iron rings in order to enhance focusing in order to produce the maximum beam current. Once the optimal parameters are obtained, the cyclotron can be used for small scale nuclear physics experiments. One such experiment could use deuterium gas and a collection plate within the chamber so that deuteron-deuteron reactions can occur. Such reactions release neutrons, which do not interact with the cyclotron's magnetic field and can penetrate the chamber walls – eliminating the need for a beam extraction method.

#### Electromagnet

a GMW Associates 3473-70

The Houghton College Cyclotron uses

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

magnet from overheating by cycling

water cooling system keeps the

PowerTen R62B-4050 power supply. A

18°C water through the magnet at 0.8

# current is measured using a Keithley 617 Electrometer. Typical beam currents at resonance are between 2 pA and 2nA.



Figure 2 – 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.

cyclotrons have two dees

of opposite polarity to accelerate the particles. The Houghton College Cyclotron has one dee and a "dummy dee". The dummy dee". The dummy dee is grounded, meaning the functional dee has to oscillate both above and below ground potential. The beam current is measured on a brass nut attached to a linear motion feedthrough so that current can be

measured at different radii. Figure 6 – A photograph of the cyclotron chamber, showing the (1) "dummy dee" (2) the brass charge collector (3) filament leads (4) filament and (5) the "dee"