THE HOUGHTON COLLEGE CYCLOTRON: A TOOL FOR EDUCATING UNDERGRADUATES

M. Yuly, Houghton College, Houghton, NY 14744, USA

Abstract

The cyclotron is an ideal undergraduate research project because its operation and use involve so many of the principles covered in the undergraduate physics curriculum -- from resonant circuits to nuclear reactions. The physics program at Houghton College, as part of an emphasis on active learning, requires all majors to complete a multiyear research project culminating in an undergraduate thesis. Over the past ten years, seven students have constructed a working 1.2 T tabletop cyclotron theoretically capable of producing approximately 400 keV protons. The construction and performance of the cyclotron will be discussed, as well as its use as an educational tool.

THE SCIENCE CURRICULUM AT HOUGHTON COLLEGE

Houghton College is committed to providing a rigorous and practical curriculum to undergraduates majoring in science. In additional to the wide range of traditional coursework offered in the division, there is a strong emphasis on hands-on experiences that will develop the problem solving and applied skills needed by scientists in the real world. Traditional coursework usually focusses on the content of the discipline, but not on developing the traits needed to be a successful scientist. Today's science students need to become practical problem solvers able to apply their content knowledge to difficult problems, with the laboratory skills and character qualities needed to be successful. They need undergraduate experiences in analyzing real problems that do not have nice "textbook" solutions. Furthermore, these problems should develop more than intellectual problem solving skills, but also practical laboratory skills, as well as character qualities including patience, confidence and perseverance.

This applied emphasis led Houghton College to introduce the Summer Research Institute (SRI) [1] in 2007 and the Science Honors Program [2] in 2009. In the physics department, the emphasis is seen in the requirement that all physics majors complete an individualized research project that starts during their sophomore year and culminates in their senior year in a thesis and a presentation at a scientific meeting. Students receive course credit for working one-on-one with faculty members on their research projects, and the faculty receives teaching load credit. The long three-year project timeframe allows the students to make significant progress toward solving a difficult problem.

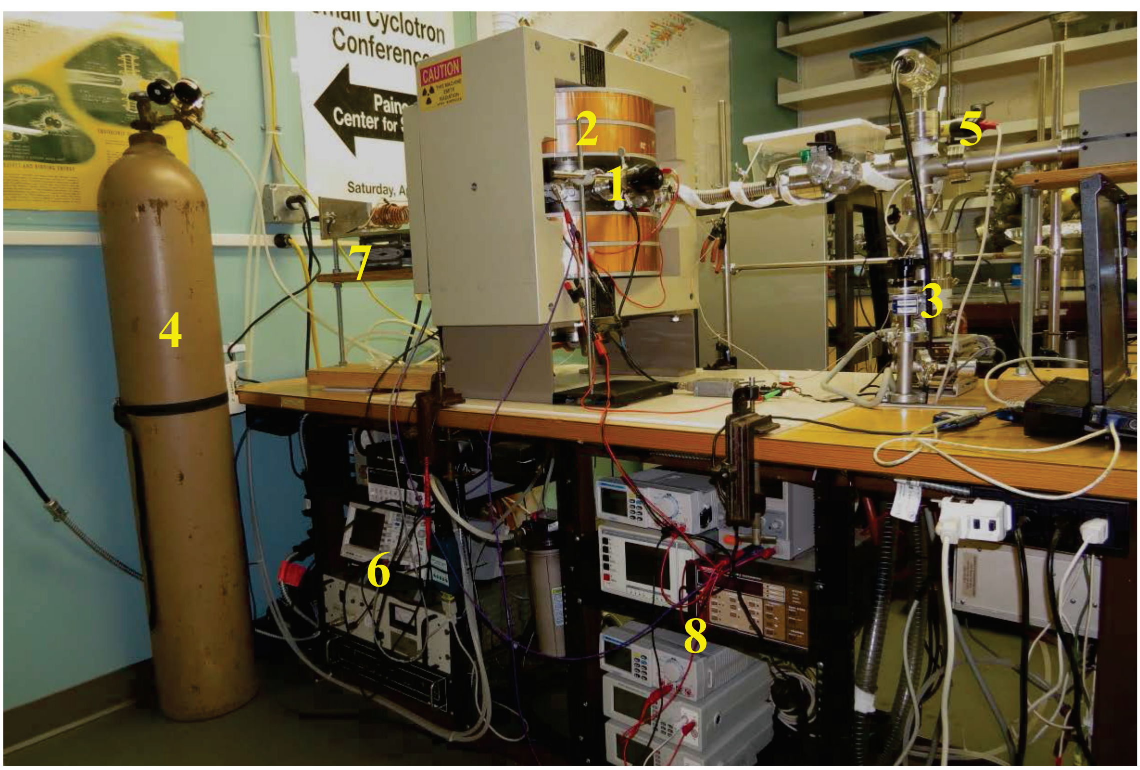

Figure 1: A photograph of the Houghton College Cyclotron, showing the (1) vacuum chamber and target linear motion feedthrough, (2) electromagnet, (3) turbopump, (4) hydrogen cylinder, (5) vacuum gauges and residual gas analyser, (6) RF system, (7) tuning coil, and (8) filament controls and beam current electrometer.

The cyclotron project at Houghton has been underway since about 2002, and has resulted in six undergraduate theses [3]. This project is in many ways the perfect culmination to the physics curriculum because it draws together so many of the topics the students have studied into one applied problem – students get practical experience with electric and magnetic fields, digital and analog electronics, nuclear physics, computer programming, machine shop, vacuum systems and even plumbing! In 2007, the first student to get the cyclotron working was hired immediately out of Houghton by the National Superconducting Cyclotron Laboratory. Today he is an engineer for ABT Molecular Imaging on their new "micro-cyclotron" for producing the positron emitting isotopes.

MINIATURE CYCLOTRONS

Several miniature cyclotrons have been built as educational projects by high school and undergraduate students [4]. One of the earliest examples was in 1947, when four high-school students in El Cerrito, California, teamed up to build a cyclotron, although it is not clear whether it worked [5]. More recently, in 2009, two high-school students, with help from engineers at the Thomas Jefferson National Accelerator Facility, built a small cyclotron [6] which has not yet successfully operated.

In 1954, undergraduates at Iowa State University successfully built and used a cyclotron in nuclear experiments [7]. Small cyclotrons were also built by undergraduates at Knox College [8] and MIT [9], which were abandoned before they became operational. Probably the most unique small cyclotron was the "cyclotrino" built at UC Berkeley for the purpose of carbon-dating artifacts [10]. Worldwide today there are only a few operating miniature cyclotrons similar to Houghton's. Probably the most famous is the Rutgers 12 inch cyclotron [11], which has been featured in many publications, including Physics Today [12].

THE HOUGHTON COLLEGE CYCLOTRON

The Houghton College cyclotron is a miniature cyclotron similar to M. S. Livingston's original design. The total cost of the machine over the ten year span of the project has been about $20,000, the largest portion of which was for the magnet. Many of the parts were either manufactured in the machine shop by students (such as the main vacuum chamber and Dee electrodes) or purchased used (such as the RF amplifier and turbo pump).

Figure 1 is a photograph of the cyclotron. The vacuum chamber (1), which is placed between the poles of a 1.2 T electromagnet (2), is evacuated by a turbo pump (3) and a rotary forepump below the table. Hydrogen or helium from a gas cylinder (4) is allowed to enter the chamber where it is ionized by electron bombardment from a hot filament at the center. The ions are accelerated by the oscillating voltage produced by the RF system (6) operating at the resonant frequency of the LC circuit formed by the Dee-electrodes and the tuning coil (7). The cyclotron has been designed so that it can be controlled remotely over ethernet

Vacuum Chamber

The vacuum chamber and Dee electrodes are shown in Figure 2. A 2.54 cm thick ring with an outer radius of 9.9 cm and an inner radius of 8.5 cm was milled from 6061 T6 aluminium to form the vacuum chamber wall. Ports were made in the chamber wall using ten KF-16 flanges, which were secured using Hysol Loctite 1C vacuum epoxy into holes drilled at equally spaced angles around the ring. Two 0.65 cm thick circular lids with radius of 9.9 cm were attached using aluminium screws to the top and bottom of the chamber wall, and included a gland for a Viton O-ring for the vacuum seal. A grove in the top of the lid allows a hall probe to be inserted for measuring the magnetic field, and an indentation to allow more room for the filament was cut on the inside of the top lid.

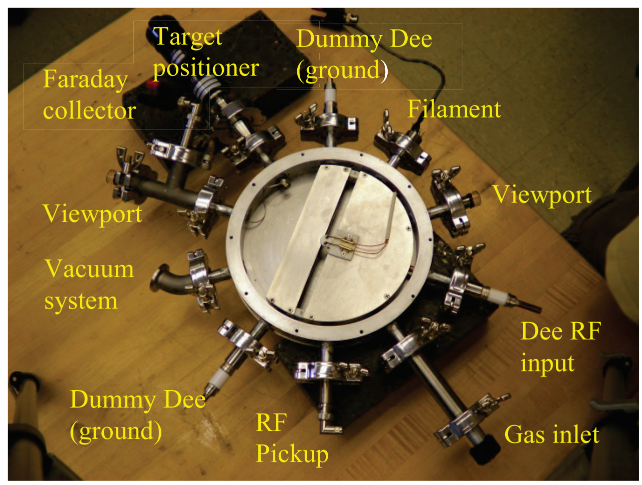

Figure 2: Vacuum chamber, ports, filament, and dee electrodes.

A circular ring of 6061 T6 aluminium, 1.27 cm thick, 0.6 cm wide, and 15.6 cm outside diameter, formed the walls for both the Dee and Dummy Dee. Two 5052 aluminium sheets, 0.13 cm thick, were fastened to the top and bottom of the ring with vented screws. The Dee was cut off the ring with a width of 7.8 cm and the Dummy Dee with a width of 3.2 cm. Ceramic spacers hold the Dee and Dummy Dee apart with a gap of 0.635 cm. The entire Dee electrode assembly is supported by three KF-16 electrical feedthroughs through ports at 120° from each other.

Magnet

The vacuum chamber was placed between the poles of a GMW Associates 3473-70 Electromagnet with 15-cm diameter flat pole faces. With the chamber in place, the separation between the pole tips is 3.81 cm, giving a maximum magnetic field of 1.28 T at 70 A. Currently, the magnet is powered by a PowerTen R62B-4050 power

ISBN 978-3-95450-128-1

supply which can only deliver 50 A, giving a maximum field of 1.16 T. The magnet is water cooled, requiring 18°C water flowing at 0.8 gallons per minute (at 50A), which is provided by a Haskris A5H chiller. A TEL-Atomic SMS 102 magnetic Hall Effect probe, which fits into a grove in the top chamber lid that allows it to be located at the center of the top pole face, is used to monitor the field strength.

Vacuum and Gas Handling System

The chamber can be evacuated down to a final pressure of approximately 2×10^{-6} Torr by a Pfeiffer Balzers TPU-062 Turbo Molecular Pump and a CIT-Alcatel 2012A rotary forepump. The foreline pressure is monitored using a CVG101 GA thermocouple gauge, while a KJL-6000 thermocouple and Granville Phillips 274 ion gauge are read out into a SRS IGC100 gauge controller to monitor the pressure in the chamber.

Two methods have been used to allow gas into the chamber: an Edwards LV10K leak valve and an MKS 1179A mass flow controller. These allow either pure hydrogen or helium, or a mixture, to flow into the chamber raising the pressure to up to 10^{-4} Torr. An SRS RGA-100 residual gas analyzer measures the partial pressures of the gasses in the chamber, including residual air and water.

The gas in the chamber is ionized by bombardment with electrons coming from a hot filament at the center of the chamber. A standard AEI hairpin electron microscope filament floating at approximately -90 V is heated by 2 A of current. Stainless steel wires welded to the filament pins are attached to copper wires by inline barrel connectors which are vacuum epoxied to a ceramic insulator screwed to the top of the Dee. The filament leads are insulated with ceramic beads (not shown in Figure 2) as they travel over the top of the Dee to the feedthrough. RF pickup on each filament lead is shorted through a 0.001 μF capacitor to ground.

RF System

By using a tuned LC tank circuit, the Dee may be oscillated with voltage amplitudes of up to approximately 3000V relative to the grounded Dummy Dee. The Dee capacitance is approximately 76 pF. The secondary coil inductance of 0.87 µH or more in parallel with the Dee capacitance yields a resonance as high at 19.5 MHz, which is the maximum cyclotron frequency corresponding to 411 keV protons in the maximum magnetic field of 1.28 T. Energy can be injected into this resonant circuit by means of the primary inductor whose field couples to the secondary coil.

These inductors are ¼ inch copper tubing, wound coaxially, with the 6 cm diameter primary coil outside the 4 cm diameter secondary coil. The inductance of the primary coil can be changed by replacing the coil with one having a different number of turns, several of which have been constructed for this purpose. The impedance of the three-turn primary coil can be modified by making a connection at various places along the coil.

The secondary coil is driven by an RF signal from a HP 33120A function generator, with a magnitude of between 100 - 500 mV. This signal is amplified by an ENI 155LCRH RF power amplifier. An LDG AT-200PC antenna tuner is used to match the impedance of the amplifier and tuned circuit to eliminate reflected RF power. For normal operation, 10-40 W of RF power are required, which can be measured directly using a Bird 43A RF power meter or by the computer via the AT-200.

The voltage on the Dee was measured directly using an Elditest EN61010 high voltage oscilloscope probe. However, since this probe changed the capacitance of the circuit slightly, it was mainly used to calibrate the approximately 0-1 V signal from the RF pickup. The RF pickup was a small twist of copper wire located just inside one of the vacuum ports, a few millimeters from the Dee. Figure 3 is a typical cyclotron tune, showing the proportional relationship between the Dee voltage and the RF pickup voltage.

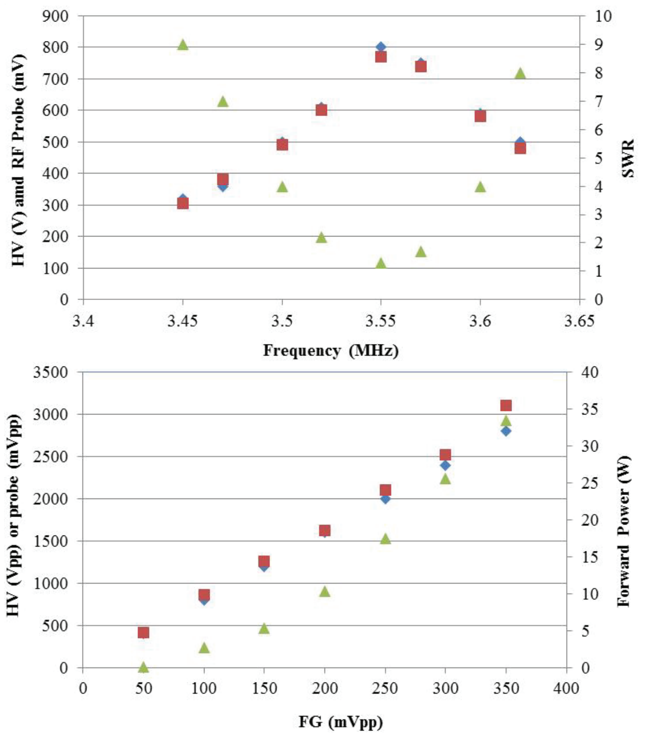

Figure 3: Tune at a frequency of 3.55 MHz. (Top) The peak-to-peak Dee voltage (blue diamond), RF pickup voltage (red square) and Standing-wave ratio (SWR) (green triangle) are plotted as a function of driving frequency. (Bottom) The peak-to-peak Dee and RF pickup voltages (symbols as above), and forward RF power (green triangles) are plotted as a function of peak-to-peak voltage from the function generator.

Target and Beam Current

The internal target is a small L-shaped copper sheet attached to the end of a linear motion feedthrough by a ceramic spacer, allowing the target to be positioned anywhere inside the maximum radius of 7.2 cm determined by the wall of the Dee. The target is attached to a shielded coaxial cable which leads the signal out a BNC feedthrough to a Keithley 617 programmable electrometer, which is used to measure the beam current. A +9 V bias can be applied to the target using a battery to reduce the effect of secondary electrons on beam current measurements.

Control System

The cyclotron can be controlled remotely over Ethernet using Labview 7. A National Instruments GPIB-enet/10 controller is used to control and read out the GPIB devices used in the cyclotron, currently the magnet power supply, the function generator, the ion gauge controller, the filament bias voltage, the RF pickup oscilloscope, and the electrometer. The RS-232 output of the Teslameter is first converted to GPIB, and then read into the GPIB-enet controller. In the future, the option exists to also control the RGA and antenna tuner remotely.

RESULTS

The Houghton College cyclotron has been successfully used to accelerate hydrogen and helium ions. This past year, a series of measurements have been made to characterize the performance of the cyclotron as the energy was slowly increased.

A Labview code was used to slowly increase the magnet current, while simultaneously reading the magnetic field from the hall effect probe and the beam current from the electrometer. These "magnet scans" were performed each time a parameter was changed in order to study the behavior of the cyclotron.

Figure 4 shows a typical magnet scan, taken at a low frequency of 3.68 MHz with hydrogen and helium gas in the chamber. At this frequency, with a target radius of 68 mm, the H^+ ion energy is only about 13 keV. Resonance peaks are clearly visible at the expected magnetic fields for H^+, He^+ and H_2^+ ions.

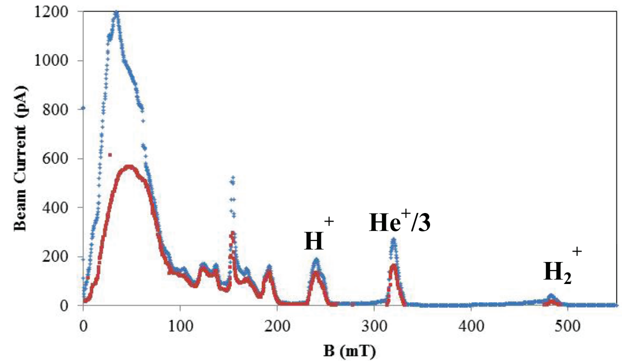

Figure 4: A typical spectrum for a mixture of hydrogen and helium at 3.68 MHz with the target at ground (blue) and +9 V on the target (red) to show the effect of secondary electrons.

In a cyclotron, the potential difference between the Dees reverses polarity each time the particle crosses the gap, causing the ion to accelerate. If the potential flips polarity any odd number of times before the ion reaches the gap, the configuration will still accelerate the ion.

For example, for a magnetic field with resonance frequency *f*, frequencies of 3*f* and 5*f* are also resonances. Equivalently, for a fixed frequency *f*, resonances will occur for lower magnetic fields, e.g. $B/3$ and $B/5$,

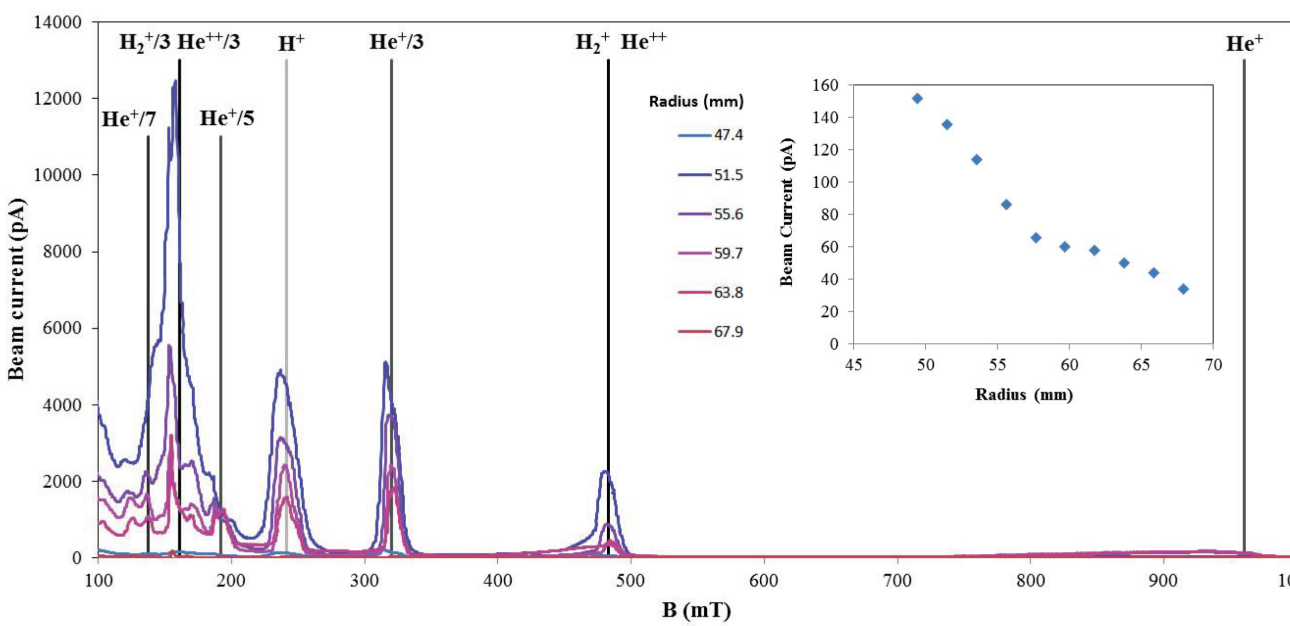

Figure 5: Beam current as a function of magnetic field for various target radii at 3.68 MHz. The Dee voltage was about 2100 Vpp, and the chamber was filled with about 2×10^{-5} Torr of a gas mixture of approximately equal partial pressures of hydrogen and helium. (Inset) A plot of the beam current as a function of target radius for the $He^{+}/3$ peak at 320 mT.

ISBN 978-3-95450-128-1

corresponding to an odd multiple of a lower frequency, f', since

$$f = nf' = n\frac{e}{2\pi m}\left(\frac{B}{n}\right)$$

where n is an odd integer.

The peaks at lower magnetic fields seen in Figure 4 are due to this effect. By measuring the current with the beam collector at ground and at +9 V, it can be seen that the secondary electrons are created in significant numbers on the target.

Figure 5 shows a series of magnet scans with the beam collector at different radii. As expected, the beam current falls as the distance from the center is increased. Interestingly, a series of measurements (Figure 5 inset) made at different radii with the magnetic field fixed at 320 mT, which corresponds to the resonance at B/3 for He^+ ions, shows a "kink" near a radius of 57 mm.

The pressure in the chamber has a large effect on the beam current obtained, and typically needs to be in the range from 10^{-6} to 10^{-4} Torr for the cyclotron to operate. If the pressure is too low, the current is reduced because there are not enough gas molecules in the chamber to ionize; if the pressure is too high, collisions with neutral gas molecules reduce the mean free path of the ions, and cause the resonance peaks to become broad and shift. The largest beam current recorded, shown in Figure 6, was about 0.1 μA for the B/3 resonance for H^+ ions with a pressure of about 1×10^{-4} Torr. Notice how the width of the H_2^+ peak has increased.

The highest proton energy obtained so far is about 160 keV, with a 3 pA peak near the correct magnetic field of 796 mT for 12.1 MHz.

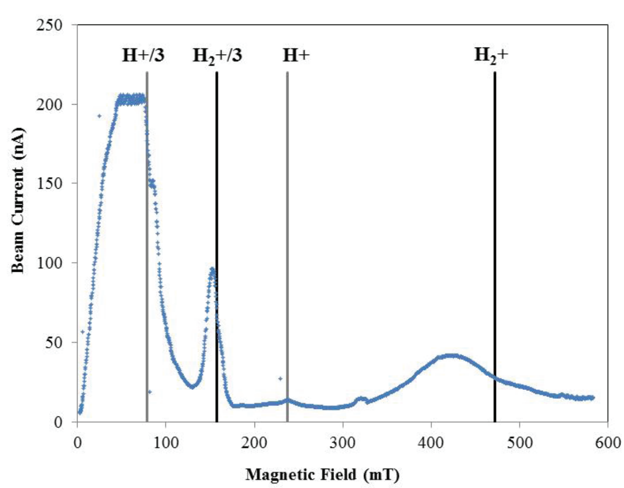

Figure 6: Highest current peak recorded, nearly 0.1 A, at 3.62 MHz, for hydrogen at approximately 1×10^4 Torr.

FUTURE PLANS AND CONCLUSION

Future student projects involving the cyclotron will focus on two areas: improving the cyclotron performance and nuclear physics. A current student project is to create a computer model the cyclotron using to the Poisson Superfish and Simion codes. This model will assist in shaping the magnetic field to improve focussing and thereby increase the current. In order to reach maximum theoretical proton energy of 400 keV, the magnet will need more current and cooling than is currently available, and the RF system will need to operate at higher frequencies than can be provided at present.

Since the cyclotron has no means to extract the beam, targets must be placed inside the chamber, and thus the study of nuclear reactions is limited by the ability to extract the reaction products. Highly penetrating gamma rays and neutrons can penetrate the walls and be detected outside the chamber. To detect ions recoiling at 90° the target could be placed directly in front of a port, to which a surface barrier detector is attached. Using these techniques, low-energy fusion reactions such as ^{2}H(d, n)^{3}H, ^{2}H(d, p)^{3}He and ^{2}H(^{3}He, p)^{4}He and gamma resonances like ^{19}F(p,γ)^{16}O and ^{31}P(p,γ)^{32}S could be studied with beams in the nA range.

The cyclotron has been a very effective tool in teaching students to solve practical research problems and "think like a physicist". Building and using the cyclotron requires knowledge drawn from almost every area of physics, in combination with the ability to synthesize this knowledge into workable, practical solutions. The cyclotron offers innumerable quantities to measure, and an unlimited supply of unexpected behaviors that can be studied and understood. And, of course, because it's a cyclotron, it requires students to develop the character qualities of patience and perseverance.

REFERENCES

[1] http://www.houghton.edu/academics/majors-programs/summer-research-institute/
[2] http://www.houghton.edu/academics/majors-programs/honors-program/science-honors/
[3] N.A. Fuller (2013), D. Haas (2009), A.J. Loucks, (2007), M.J. Cressman (2006), S.C. Tuminaro (2003); B.T. King (2003); http://www.houghton.edu/physics/student-research/theses/
[4] C. Cofield, *Symmetry* **4**, 24 (2010).
[5] A. R. Boone. *Popular Science* **11**, 102 (1947); B. V. Siegel and R. C. Sinnott, *Phys. Today* **1**, 4, 10 (1948); A. G. Ingalls. *Scientific American* Sept. 154 (1953).
[6] K. Carter. "Cyclotron Kids Build Accelerator at JLab," *On Target*, Thomas Jefferson National Accelerator Facility newsletter (2009); (http://www.jlab.org/news/ontarget/target-september-2009)
[7] J. McGuire. *Proc. Iowa Academy of Sci.* **68**, 474 (1961).
[8] J.C. Smith, Undergraduate Thesis, Knox College (2001).
[9] L. Dewan, Undergraduate Thesis, MIT (2007).
[10] K.J. Bertsche. Ph.D. Thesis, University of California, Berkeley (1989).
[11] http://www.physics.rutgers.edu/cyclotron/
[12] T. Feder. *Phys. Today* **57**, 30 (2004).