THE CYCLOTRON KIDS' 2 MeV PROTON CYCLOTRON

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Abstract

Over several summers, two high school students constructed a self-designed at Jefferson Lab. This paper describes the design of their 2 MeV proton cyclotron. The machine is now at Old Dominion University, where it will be used as an educational tool in the accelerator physics program.

INTRODUCTION

There has never been a better time for amateurs interested in science or engineering to find information online and to get in touch with others who share their interests. When Heidi Baumgartner and Peter Heuer (the "Cyclotron Kids"), met at an astronomy summer camp in their freshman year of high school, they decided that they wanted to take on the ambitious project of designing their own small cyclotron. Inspired by previous successful independently built cyclotron projects, they based their designs on information about other amateur particle accelerators that they found on the Internet.

There have been approximately a dozen previous amateur particle accelerator projects, including Fred Neill's 1999 winning submission to the Intel International Science and Engineering fair, in which he built a 4-inch diameter cyclotron at home. Dr. Timothy Koeth, then an undergraduate student at Rutgers University in 1995, built another cyclotron, which he continued to improve over the past decade, and has used to mentor many other Rutgers undergraduates. There are others, including the machine built at Knox College by Jeff Smith and by Mark Yuly at Houghton College.

The Cyclotron Kids drew basic designs for their machine inspired by those of other amateurs that had completed such an ambitious project, and then looked for a company to sponsor them to build their machine and enter it into a science fair. The donation of a diffusion pump from Capitol Vacuum Parts, a company in Chantilly, VA, further encouraged them. One of their funding request emails was forwarded to Andrew Hutton, the associate director of Jefferson Lab in Newport News, VA, at the time. Against their expectations, Dr. Hutton invited them to construct their cyclotron at the national lab, under the guidance of scientists and engineers there.

OVERVIEW OF CYCLOTRON DESIGN

Target Energy

When the project moved to Jefferson Lab, the project scaled up from what the Cyclotron Kids had planned on building in a basement. The target energy became 2MeV, with the goal of being able to produce electron-positron pairs from collisions of the protons with a stationary target [1].

Electromagnet

One of the most expensive parts of a cyclotron project is attaining a homogeneous magnetic field over a large cross-section. Jefferson Lab provided left over 1060 steel scrap, from which the 1.6 Tesla H-shaped electromagnet was designed. The Jefferson Lab machine shop then machined the pieces of the magnet and wound the coils of the magnet

The magnet (Fig. 1). has two excitation coils, each 360 turns of copper wire of 1/4 inch square cross-section, with an internal water cooling channel. Because of the difficulty of handling and winding such stiff wire, it was found easiest to assemble the magnet out of ten "double-pancakes," or coils of 18 turns of wire two layers thick, individually wrapped in insulating cloth and potted in epoxy. The ten double-pancakes were then all together cast in epoxy.

The magnetic field strength in the gap of the H-magnet is given by the following equation:

$$B = \frac{\mu_0 NI}{g} \quad (1)$$

The magnetic field is inversely proportional to the gap in the middle of the magnet, so it is advantageous to keep the gap between the magnet poles small. This tight spacing made the design of the vacuum chamber more difficult, but it was essential for achieving the target magnetic field strength of 1.6 Tesla.

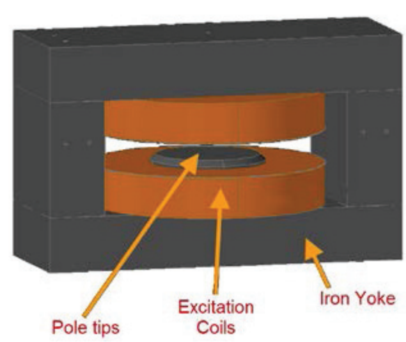

Figure 1: Overview of the electromagnet.

The design of the pole tips is also very important for particle beam focusing effects. A slight decreasing gradient along the radius of the magnet is necessary because the outward curving magnetic field lines provide a restoring force of the particle beam back to the midplane if it has some axial velocity. This gradient is achieved by a linear 0.02 inch taper from the center of the pole face outwards. POISSON Superfish, a magnetostatic modeling program from Los Alamos, was used to verify the design of the electromagnet, the portions of the

ISBN 978-3-95450-128-1

magnet that saturate first and the gradient of the magnetic field; the output of one simulation run is shown in Fig. 2. The electromagnet is show in Fig. 3.

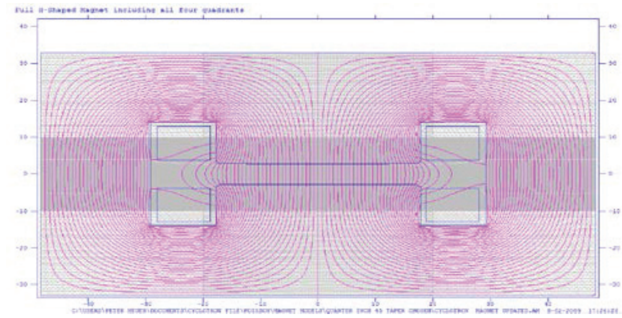

Figure 2: POISSON Superfish simulation of magnetic field in the iron electromagnet yoke.

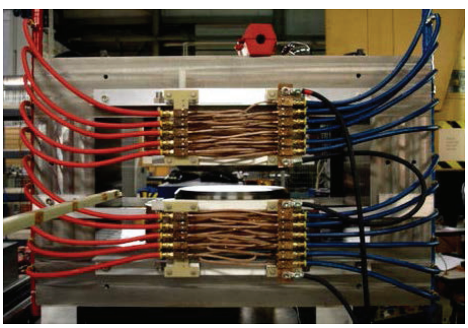

Figure 3: Completed electromagnet with water distribution manifold.

Vacuum Chamber and Component Layout

The vacuum chamber (Fig. 4) is 2 feet in width, 3 feet in length, and two inches in total height. The frame of the chamber is rolled 3/4 inch thick stainless steel, and the top and bottom lids are 3/16 thick stainless steel plates. The small height of the chamber and the thin nature of the plates caused the top and bottom of the chamber to bow in, which affected the capacitance of the dee and reduced the maximum voltage that the dee could withstand before flashing over. To alleviate this problem, posts were tack-welded to the bottom of the chamber to support the plates.

Half the chamber protrudes from the electromagnet so that a 3 inch diameter tube in the corner can extend directly downwards to a vacuum pump underneath. This design choicemaximizes vacuum conductance, which is particularly important when needing to keep a low vacuum pressure (10^{-7} torr) while injecting hydrogen into the chamber for a proton source. However, this design choice results in a very large, unwieldy chamber that is difficult to service due to its size and weight.

There is one semicircular dee 12 inches in diameter, and a "dummy dee," which is a grounded frame with an opening the same size as the opening of the other dee. The accelerating field is between the dee and the dummy dee, so aligning the openings precisely is important. Having only one dee rather than two doubles the voltage requirement, but reduces the cost and complexity of having two RF feedthroughs in the vacuum chamber.

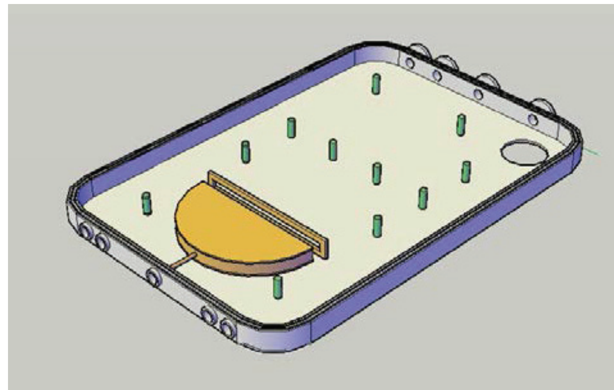

Figure 4: Layout of the vacuum chamber.

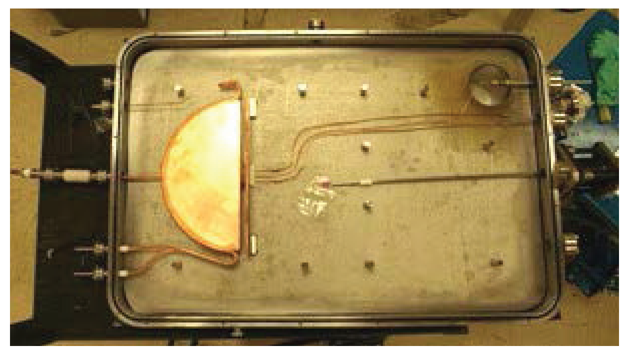

Figure 5: Completed vacuum chamber.

Figure 5 shows additional components in the chamber. The two feedthroughs in the lower left are for water cooling of the dee. On the top left, one feedthrough is an RF pickup that is used to sense the voltage on the dee for monitoring and feedback purposes. In the middle on the right side is a linear motion feedthrough with a rod extending into the chamber. The target is mounted at the end of this rod. On the top right there are feedthroughs to let in and out power to the ion source, as well as to let in hydrogen which is ionized to make protons.

The construction of the vacuum chamber presented a challenge. The bottom lid of the chamber was originally designed to be welded on, as maintaining high vacuum would be easier with one plate welded than two plates sealed with o-rings. A groove in the frame seats an o-ring that seals against the top plate of the chamber. However, after the welding, the bottom plate contracted so much that it bent the whole frame out of shape, as shown in Fig. 6. The solution to this problem was to grind off the bottom plate, straighten the frame in a press, and seal the bottom plate against the frame using a flat Viton ring.

ISBN 978-3-95450-128-1

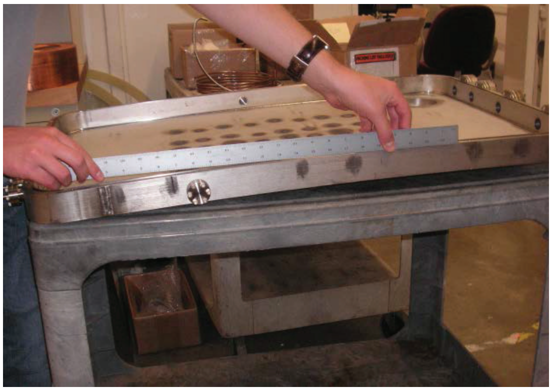

Figure 6: Warping of the vacuum chamber due to mechanical stresses after welding.

RF System

The cyclotron's radiofrequency system contains a 3kW tube-based PlasmaTherm power amplifier modified for operation at 24 MHz from its original operating frequency of 13.56 MHz. The dee forms a capacitive load, which is made to resonate at the cyclotron frequency with an inductor. The inductor and the dee form a high-Q circuit which rings up to a high voltage on the dee. Power from the amplifier is inductively coupled to the dee tank circuit. The matching network is shown in Fig. 7. L1 is a single turn of 3/8 inch copper tubing loosely coupled to L2, which resonates with the dee's 54pF capacitance and C2, a Jennings vacuum variable capacitor.

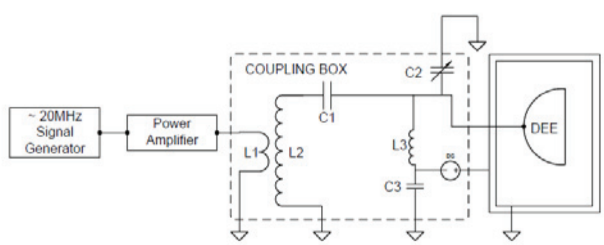

Figure 7: Front view of the dee, showing the placement of the ion source.

Ion Source

The ion source is a thermionic electron-emitting filament which is placed in a Macor base. A quarter-inch tube called a "chimney" sits on top of the filament, which shields it from the electric field of the dee. A hydrogen line leads into the base of the holder, right next to the filament. Ionized hydrogen is drawn out of a small hole in the side of the chimney by the electric field of the dee.

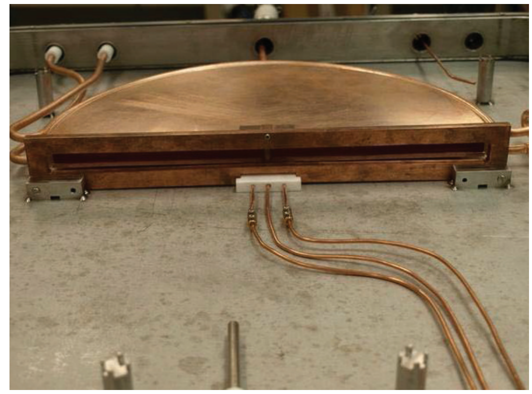

Figure 8: Front view of the dee, showing the placement of the ion source.

FUTURE IMPROVEMENTS

All the components of the cyclotron are currently finished. However, no system has been power tested due to safety restrictions at the national lab, particularly for students under 18. The cyclotron has been moved to Old Dominion University where it awaits the construction of supporting infrastructure and additional students to continue work on the project.

EDUCATIONAL IMPACT

The cyclotron project involved additional students, including German Diagama, another high school student from New York, was a team member in the first year of the project. At Jefferson Lab in the summer of 2010, three undergraduate students from Mexico studied the ion source filament in. Ambitious hands-on projects where students are given a lot of independence in the management and design of the project are invaluable learning experiences that teach skills that carry through their careers.

ACKNOWLEDGMENTS

The kind help of dozens of mentors ensured the success of the "Cyclotron Kids" project. In particular, we thank Jefferson Lab staff: Andrew Hutton, Philip Adderley, Marcy Stutzman, Carlos Hernandez-Garcia, Curt Hovater, Sam Holben and Evelyn Akers. Timothy Koeth has also been an inspiration and an invaluable mentor.

REFERENCES

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