RUTGERS 12-INCH CYCLOTRON: DEDICATED TO TRAINING THROUGH RESEARCH AND DEVELOPMENT*

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Abstract

The Rutgers 12-Inch Cyclotron is a 1.2 MeV proton accelerator dedicated to beam physics instruction.[1] The 12-inch cyclotron project began as a personal pursuit for two Rutgers undergraduate students in 1995 and was incorporated into the Modern Physics Teaching Lab in 2001.[2] Since then, student projects have been contributing to the cyclotron's evolution through development of accelerator components. Most of the Rutgers 12-Inch Cyclotron components have been designed and built in house, thus giving its students a research and development introduction to the field of accelerator physics and associated hardware.

INTRODUCTION

With the exception of a few institutions, accelerator science and engineering is relegated to the national labs and is not commonly found at the universities. The development of a small educational cyclotron is well within the capabilities of a standard Modern (Senior) Physics Lab course and in doing so brings accelerator science to the pool of young students at that critical time when they are deciding their scientific paths.

To fulfil academic requirements, Rutgers undergraduate physics students take two semesters of a Modern Physics Lab course where they typically perform twelve standard lab experiments. Since 2001, one or two exceptional students are chosen from the fall semester's lab participants for an independent cyclotron project the follwing spring. The "cyclotron students" are assigned a single, semester-long project which provides them a real life experimental research experience in a modern physics context and introduces them to the field of accelerator physics. At the end of the semester, the cyclotron students compose one joint report and collaboratively present their work to their classmates and instructors during an oral session. The Rutgers 12-Inch Cyclotron has had, to date, eighteen students; six of them have redirected their career goals to pursue accelerator physics in both academia and industry.

The student projects continually contribute to the cyclotron's evolution and improved operation. For example, the first pair of students designed pole tips that would improve beam focusing.[3] They were followed by two students that had the pole tips machined, which they installed and characterized with a home-built magnetic field mapping system.[4] The resulting magnetic field provided the necessary focusing enabling an exceptional beam physics experience for subsequent students.[5] To further illustrate the impact of our educational program, this paper discusses two student-designed and -built components which have performed well and have general application to other accelerator facilities.

Due to the small size of the 12-inch cyclotron, standard components need to be miniaturized. We will describe our internal cold cathode Penning Ion Gauge (PIG) type ion source as well as the electrostatic deflector that measures the ion beam final energy.

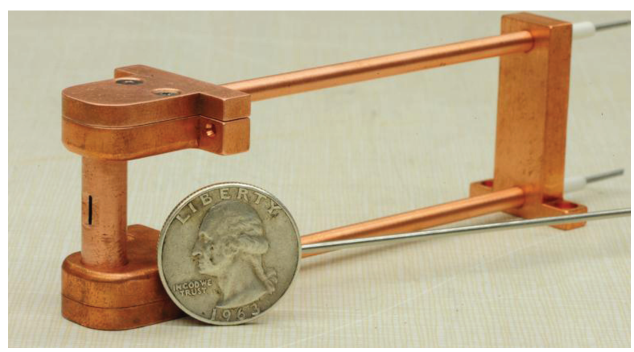

Figure 1: Miniature PIG ion source assembly with 0.7 x 4 mm slitted aperture.

ION SOURCE

The ion source has been our cyclotron's most challenging component to conquer. Early filament based designs generated mere nanoamps of protons and would only operate a few hours. With the promise of many hours of service, we set out to build a cold cathode Penning Ion Gauge (PIG) source, the results is shown in Fig. 1. Our Mark-III PIG has yielded a robust source of simple construction, outlined in Fig. 2. It uses two tantalum cathodes pinned to stainless steel leads that are seated in boron-nitride cups which are housed in copper bases. The chimney, chimney bases, and HV lead shields are also all copper. Cooling is through conduction to the upper and lower chamber lids.

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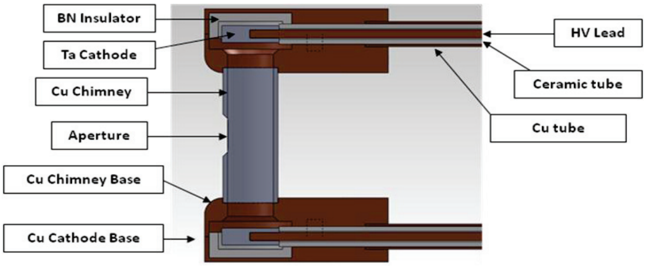

Figure 2: Cross sectional view of the PIG source.

The PIG's ion production was characterized in a 1 Tesla field by negatively DC biasing the DEE and measuring the collected current over a range of hydrogen pressures, arc discharge currents, and chimney aperture sizes, summarized in Fig. 3. The best arc stability was found for the smallest (0.031 inch) circular aperture. As expected, the collected ion current follows the arc current and extraction voltage. At arc currents greater than 40 mA thermal runaway causes a large increase in ion production; at these arc currents the chimney and bases are visually incandescent. Rapid sweeping operation of the cyclotron has shown simultaneous generation of protons and $^{+}H_2$ ions in a 5:1 ratio.

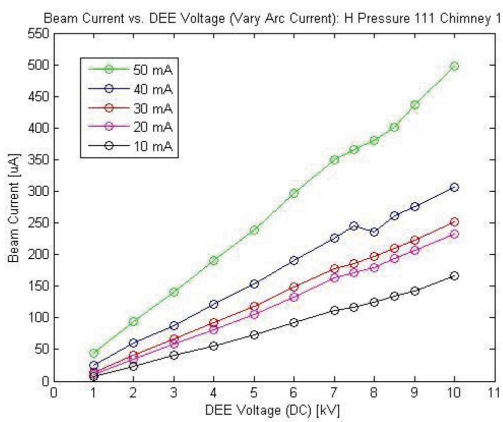

Figure 3: DC Characterization of proton beam current for a 1/32 inch diameter aperture for several arc currents.

Figure 4: Source disassembled showing erosion and buildup of Ta in the BN cup and chimney base.

Beam current from an arc current of 5 mA is sufficient for beam physics demonstrations, operating at greater currents quickly burns the phosphor screens. At 5 mA, the Mark-III PIG sources operate for greater than 40 hours without requiring servicing. Demanding greater arc currents reduces the source's lifetime. The most common failure is a build up of Ta flakes shorting a cathode to the copper base. Repair simply requires the PIG to be disassembled and scoured with acetone and methanol. After several hundred hours of operation at 5 mA the Ta cathodes need to be replaced due to erosion. Figure 4 displays an inspection after 10 hours of operation.

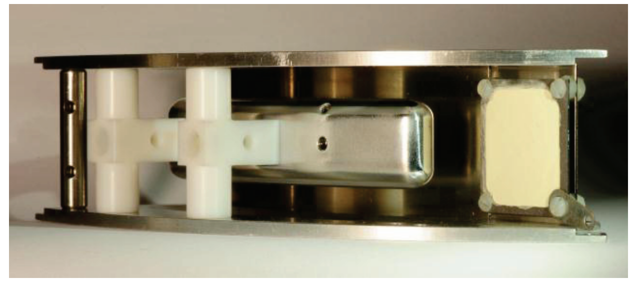

Figure 5: Electrostatic deflector assembly.

DEFLECTOR

Since various internal target experiments rely on radial intercept to select the incident beam energy, it was necessary to perform an absolute beam energy measurement at a large fixed radius. An electrostatic deflection channel was constructed to use as a Wien Filter variant. Ions of specific velocities, determined by the deflector's electric field E, are transported to a phosphor coated collector plate. Both beam images and currents can be quantified. The deflection channel has a nominal radius of curvature, ρ_1, of 7 inches and tangentially intercepts the cyclotron beam at a radius, ρ_o, of 4.0 inches and transports it to a radius of 4.5 inches over 43° of azimuth. For an ion, charge q, of kinetic energy T or equivalently mass m in an axial magnetic field of B at ρ_o, the required deflecting electric field, E, is found to be:

$$E = \frac{2T}{q}\left(\frac{1}{\rho_1} - \frac{1}{\rho_0}\right) = \frac{qB^2\rho_0^2}{m}\left(\frac{1}{\rho_1} - \frac{1}{\rho_0}\right)$$

In a 1 Tesla field, a potential of 33 kV is required to produce a transverse electric field of 4.2 MV/m to deflect the protons onto the viewing screen's center.

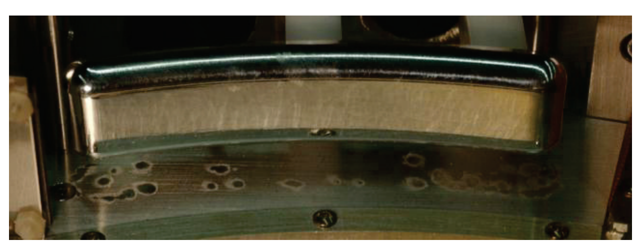

Figure 6: Partially disassembled deflector revealing pitting on bottom (and top) lids from internal arcing.

The deflection channel, Fig. 5, was constructed as a modular assembly that could easily be removed and replaced as needed. A 0.005 inch thick, curved, grounded stainless steel sheet forms the septum and separates the main accelerating volume and the deflection channel. A slightly greater curved high voltage (HV) electrode was concentrically arranged to complete the deflection

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channel with an average 0.31 inch gap spacing. In order to safely hold voltage, the HV electrode's corners were rounded so as to limit the maximum *E* field to a conservative 170 kV/inch. In addition, the electrode was highly polished. Electrical connection is made to the HV electrode by directly seating a HV ceramic vacuum feed-through conductor into the electrode. To limit current in the event of a short or arc, a 75 MΩ series resistor was installed in the HV coaxial line between the power supply and deflecting electrode.

During commissioning, at sufficiently high voltages (~ 30kV) arcing occurred inside the chamber – both light and audible snapping were observed. Coincident with the internal arcing, a mysterious external arcing was observed between the grounded shield of the HV supply's coaxial cable and various grounded surfaces, such as the magnet frame. One such arc terminated on the upper magnet coil, causing costly damage to the magnet power supply. Evidence suggested the internal arcing was initiated by secondary electron emission. Pitting, Fig. 6, on the internal surfaces of the top and bottom lids only occurred directly above and below the perimeter of the electrode; however, locations of highest E-field, such as directly below the electrode's centerline did not show pitting, exonerating field emission based brake-down. Further, no damage was observed on the deflector electrode. To mitigate the arcing, the polished HV electrode was coated with Aerodag-G graphite lubricant in order to reduce the coefficient of secondary electron emission, Fig. 7. It was determined that due to the rapid formation of the internal arc, the segment of HV cable between the series resistor and chamber formed a Blumlein HV pulse generator explaining the apparent ground-to-ground arcing. A 5 MΩ HV resistor was also installed in series with the coaxial center conductor and the chamber just prior to the HV vacuum chamber bushing. This suppressed all arcing and deflector operation at full potential is routine.

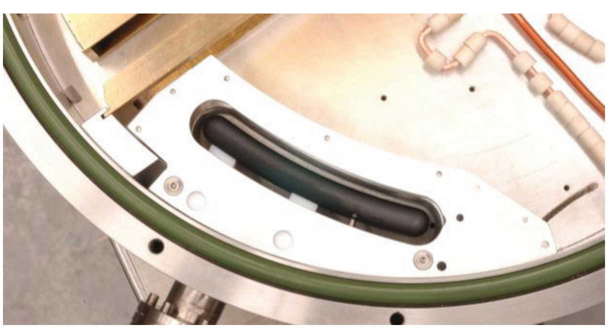

Figure 7: Deflector assembly, with clearance slot exposing electrode, now coated with Aerodag-G.

Beam transported to the end of the deflection channel is viewed on a P-22 phosphor screen which is mounted at a 45° angle with respect to the incident beam and to the axis of a vacuum view port, Fig. 8a. Several features are immediately noticed: first, the upper and lower portions of the beam are horizontally distorted and secondly the imaged beam displays bands. A full 3D SIMION simulation of the deflector assembly has been created to understand both.[6] The 'smearing' is caused by the fringing electric field. The bands are compilations of revolutions. Ions with sufficient radial extent in the n^{th} turn are captured by the channel and form the outer (right most) band in Fig. 8. Those not intercepted continue on for another revolution, $n^{th}+1$, of acceleration, and thus have a greater rigidity and hence are deflected less forming the second band, and so it goes for the third band, or $n^{th}+2$ turn. This was verified by simulation: 385, 405, and 425 keV ions were admitted to the deflector resulting in a comparable target image, Fig. 8b. Considering the finite width of the deflector entrance slit and channel, the resolution has been calculated to be 10% at 500 keV.

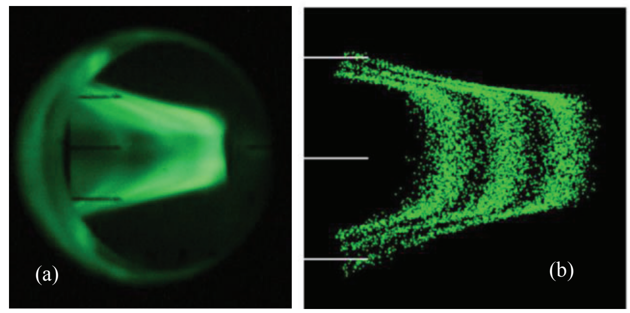

Figure 8: (a) Beam transported though the deflection channel and onto a phosphor screen, (b) SIMION simulation of the observed n, $n^{th}+1$, $n^{th}+2$ turns.

CONCLUSIONS

Rutgers physics students have been successful in producing miniature accelerator components, such as the ion source and deflector, and in return the Rutgers Cyclotron has been successful in producing accelerator physicists. To-date, our program has recruited six undergraduate physics students to pursue accelerator science and engineering in both industry and academia.

ACKNOWLEDGEMENTS

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