THE RUTGERS CYCLOTRON: PLACING STUDENT'S CAREERS ON TARGET*

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Abstract

The Rutgers 12" Cyclotron is an educational tool used to introduce students to the multifaceted field of accelerator physics. Since its inception, the cyclotron has been under continuous development and is currently incorporated into the modern physics lab course at Rutgers University, as a semester-long mentored project. Students who participate in the cyclotron project receive an introduction to topics such as beam physics, high voltage power, RF systems, vacuum systems and magnet operation. Student projects have led to three different focusing pole geometries, including, most recently, a spiral edged azimuthally varying field (AVF) configuration. The Rutgers Cyclotron is often a student's first encounter with an accelerator, and has inspired careers in accelerator physics.

INTRODUCTION

The Rutgers 12" Cyclotron (Fig. 1) is a 1.2 MeV particle accelerator dedicated to student education and exploration. Originally built as an extracurricular project by two Rutgers undergraduates, the majority of cyclotron development has been accomplished by current and former students.

Rutgers University, like many schools, does not offer any courses specific to accelerator physics. Even the number of graduate degree programs with accelerator research programs is limited. The Rutgers Cyclotron provides a unique opportunity for students to learn accelerator physics at the undergraduate level, and can serve as a model for other schools looking to develop an accelerator education program.

The cyclotron currently resides in a laboratory classroom at Rutgers University. Because of its low energy, the machine does not activate during operation and can safely be approached and incorporated into lab work. The 12-inch diameter H-frame iron core magnet provides a nominally 1 Tesla vertical field in the 2-inch magnetic gap. Interchangeable iron pole tips allow for application of various focusing schemes. The vacuum chamber, which operates at 10E-5 Torr, holds a 5-inch radius DEE and dummy DEE with a peak applied RF voltage of 10 kV and tunable frequency 2 - 30 MHz. Protons and $_2H^+$ are generated by an internal cold-cathode Penning Ion Gauge (PIG) source. Chamber diagnostics are a radial probe and a deflector, each equipped with a phosphor screen/current collector.[1]

In the first section, we will review the structure of student cyclotron projects and summarize the history of the cyclotron's development in a student-project timeline. Next we will motivate a specific project to implement edge focusing in the cyclotron. The third section will expand on the procedure of this project, while the fourth reviews results and conclusions. Finally, we comment on the Rutgers Cyclotron's contributions to the accelerator community.

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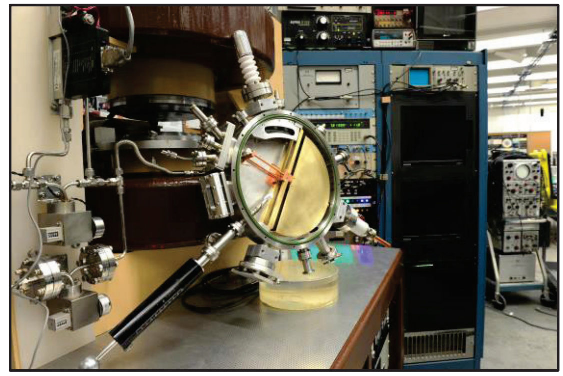

Figure 1: The Rutgers Cyclotron.

CYCLOTRON HISTORY

The cyclotron was originally conceived in 1995 by Rutgers undergraduates Timothy Koeth and Stuart Hanebuth. Koeth continues to play an important role as steward of the cyclotron system and mentor for student projects. Since 2001, cyclotron R&D has been driven and executed by undergraduate students, with significant contributions from both independent study students and participants in the Rutgers University Modern Physics Laboratory course.

Students enrolled in the Modern Physics course have the option of engaging in a semester-long cyclotron project as an alternative to the standard syllabus. In a typical cyclotron project, a small group of 1-3 students work closely with a mentor (typically a cyclotron staff member) in an independent study format, with well-defined goals that can reasonably be met within a semester.

Student Involvement

The following is a brief summary of student contributions to the cyclotron. In 2002, Chun and MacLynne designed a pair of weak focusing pole tips to replace the original perfectly parallel poles. The weak focusing tips were later installed and shown to dramatically increase deliverable beam current.[2] The weak focusing tips are pictured in Fig. 2a. The following year, Friedman and McClain measured the

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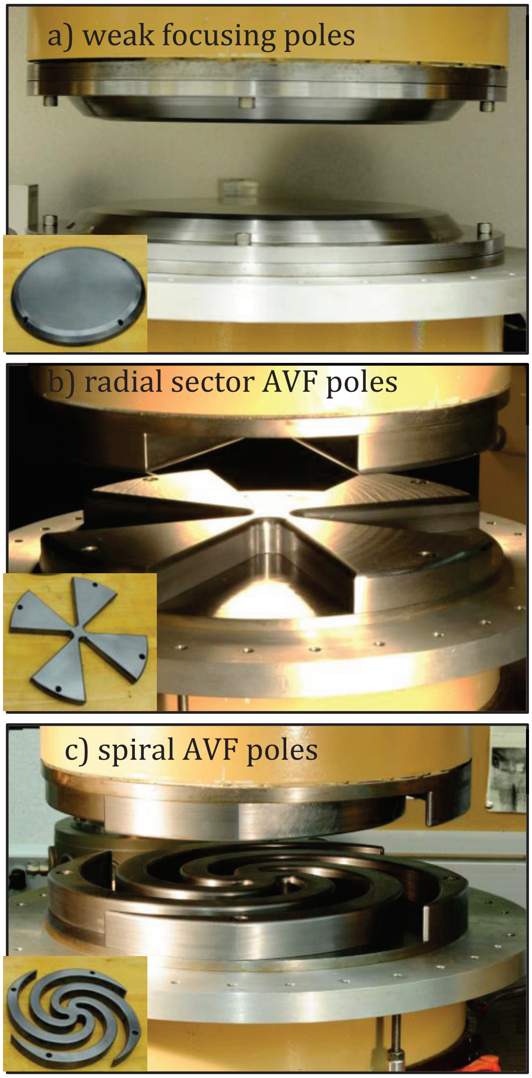

Figure 2: Rutgers cyclotron pole tips: a) weak focusing, b) radial sector, c) spiral AVF

1D field profile for comparison to simulations.[3] In anticipation of azimuthally varying fields, Shelley and Cahl designed and built an automated 2D Hall probe field mapper.

Several years afterwards, Barker worked on an auto-tuner for the RF power, and Ponter designed and installed the removable beam deflector.[4] Ponter continued to be involved in the design and commission of a Penning Ion Gauge (PIG) source, and characterization of the ion source was completed as an independent study by Rosenberg.[5] In 2011, a team of three students (Hine, Rosenberg and this author) designed and commissioned a set of azimuthally varying field (AVF) pole pieces for edge focusing in the cyclotron.[6] After the AVF project, Gonski, Burcher and Lazarov measured ion bunch length and demonstrated a radial phase probe using a novel optical technique, as preparation for a test of isochronicity in the spiral AVF tips.[7]

The cyclotron also served as a lab course experiment in the 2012 spring semester. In this trial run, a lab group spent 5 weeks learning cyclotron operation, tuning the system to find the resonant acceleration condition and

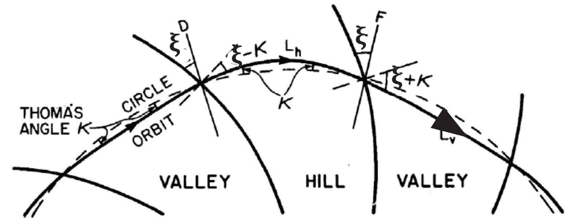

Figure 3: Schematic of edge focusing in a spiral-edged AVF field, with edge angle ξ and Thomas angle κ. Note that leading edge is focusing, while trailing edge is defocusing. Figure borrowed from [8].

measuring proton vs. $_2H^+$ production in the PIG source. Although productive, the independent study format was more successful in generating enthusiasm and catalyzing further interest in accelerator physics.

FOCUSING POLE TIPS

As mentioned above, a significant amount of cyclotron R&D was focused on improving and modifying magnet focusing. The original poles were precision ground parallel plates for purely vertical field. This solution only delivered a few nanoamps of current at the outer edge of the chamber.

The first tips that demonstrated orbit stability were the weak focusing pole pieces described above. A slight radial taper introduces a field gradient, quantified by field index

$$n = -\frac{r}{B}\frac{dB}{dr},$$

where radial and axial stability exists for $0 < n < 1$. Coupling resonances further restrict $0 < n < 0.2$. In the existing tips, $n = 0.2$ occurs beyond the deflector radius. The vertical tune in a weak focusing field is shown to be $\nu_z = \sqrt{n}$. For a more complete explanation, see [9,10].

In 1938, Thomas demonstrated that azimuthal field variation in a cyclotron increases axial focusing and compensates for mass increase in relativistic cyclotrons.[8,11] In Thomas sector focusing, orbit scalloping introduces a radial velocity component that interacts with the azimuthal field B_θ between hill and valley sectors to provide axial focusing ($F = qv_rB_\theta$). This eliminates the need for a radial field gradient as in the weak focusing field. The vertical tune in a sector focusing field is

$$\nu_z^2 = -k + F$$

where F is the flutter, or mean field variation at fixed radius, and k is the average negative field index. A set of radial sector pole pieces of periodicity 4 were fabricated at the Rutgers cyclotron, as shown in Fig. 2b. As predicted via simulation, phase slippage at standard DEE voltage (8 kV) was so severe that ions were not delivered to the deflector.[7]

Experience with the radial sector pole tips motivated further work on AVF pole tips with the intention of implementing edge focusing. Spiraling pole sectors have curvature, defining edge angle ξ between the sector edge and the radial vector $\hat{r}$. A schematic is shown in Fig. 3. With the combination of sector and edge focusing, vertical tune is equal to:

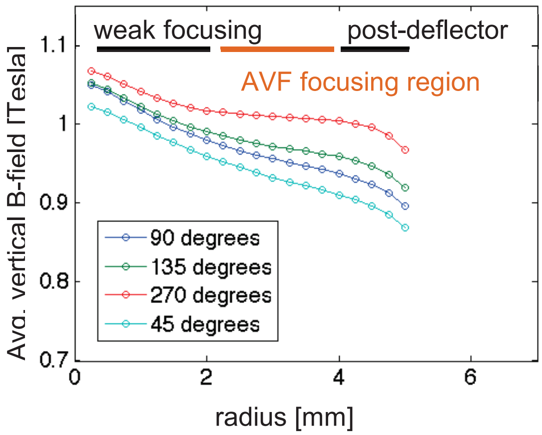

Figure 4: Average field profile over a circular path as a function of radius for several Archimedean spirals. Each spiral is defined by degrees swept from center to periphery. Note the weak focusing "bump" and flat isochronous region in the chosen design (270^{O}).

$$\nu_z^2 = -k + F(1 + \tan^2 \xi). [10]$$

This form is convenient for sectors defined by an Archimedean spiral, $r = a\theta^{1/n}$, for which $\tan \xi = d\theta/dr$. The AVF design project described below considers both Archimedean and non-Archimedean curves.

AVF POLE TIP PROJECT

The Spring 2011 cyclotron students (including this author) were tasked with designing a set of AVF pole tips capable of delivering beam to the chamber periphery with stronger focusing (higher vertical tune) than the existing weak-focusing field.

Design Procedure

The design process followed a methodical "trial and error" format. First, an informed design was drawn in a CAD program. Then, the pole piece geometry was imported directly to a 3D field solver. We inspected the average field profile and flutter as a function of radius. The ideal average field profile decreases with radial distance from the center before flattening out at larger radii, as shown in Fig. 4. This is necessary to provide weak focusing at the central region, where flutter is negligible. High flutter values were also desirable, to increase the vertical tune.

As an additional metric for pole piece performance, we modeled particle motion in the modeled fields with SIMION, an ion optics simulation software.[12] We tracked particles of various initial conditions and stationary energies to examine the region of stability in trace space. We also simulated particle motion with applied RF field in order to verify transport to the chamber wall and identify an RF operating point.

After examining field profiles and particle motion, the original design was adjusted or discarded, and a new design analyzed identically. Due to the short project duration (1 semester), each of the 3 students established competency in one program and worked as a team in interpreting results.

Fourteen pole piece conceptions were modeled during the semester long project. The most successful design, shown in Fig. 2c, was a four-sector Archimedean spiral (henceforth referred to as "spiral AVF") that sweeps 270^{O} from center to pole edge (12 inches). This configuration demonstrated a reasonably flat profile, with a variation of ~4% from 1.5 out to 4 inches, the final radius where the beam intercepts the deflector.

While the flutter is orders of magnitude smaller than less severe spirals, the SIMION traces show confinement comparable to the weak focusing pole tips, out to the deflector radius, as seen in Fig. 5. The stable region in the spiral AVF field is generally exceeded by the weak focusing tips except at low energies where AVF axial

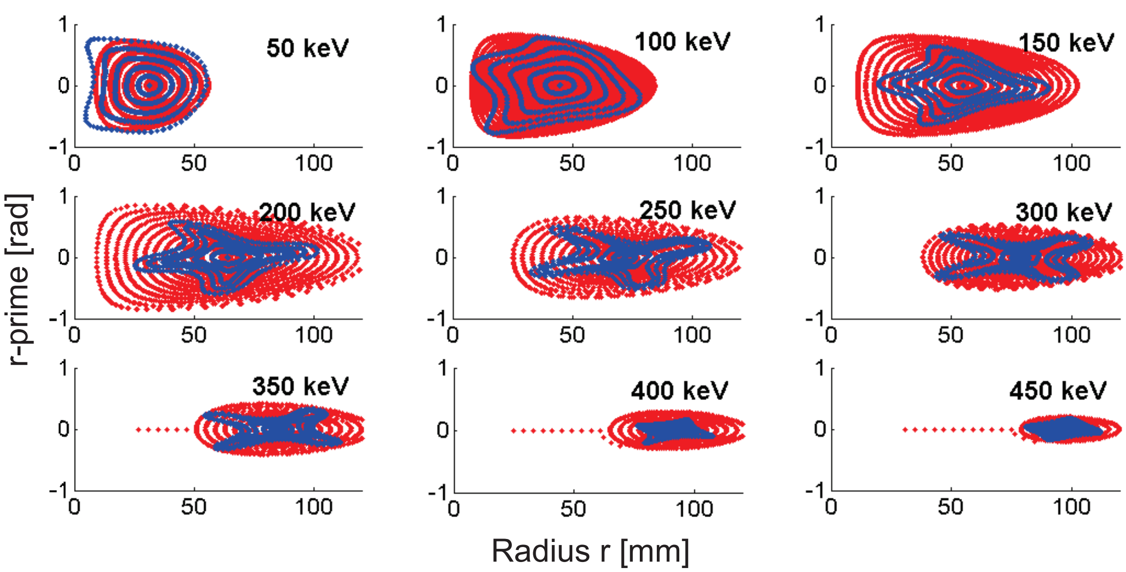

Figure 5: SIMION radial trace space plots for various (fixed) particle energies. Blue traces are Poincaré map in spiral AVF field, red traces in weak-focusing field. Note 4-lobed structure that reflects 4-sector geometry.

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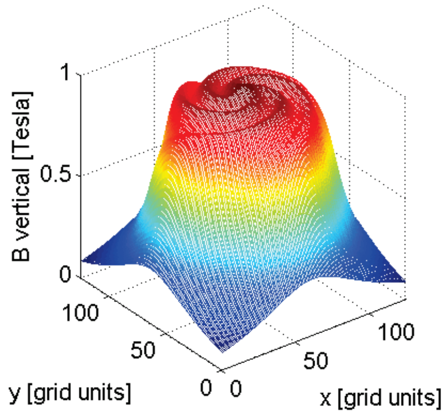

Figure 6: Spiral AVF measured field profile in midplane.

stability is greater, indicating a greater vertical acceptance near the ion source (plots not shown). Additional SIMION studies identified 6 kV peak voltage and 15.534 MHz frequency as the optimal working point for proton transport.

SPIRAL POLE TIP PERFORMANCE

The spiral AVF pole pieces were machined in-house, at the Rutgers physics department machine shop, and installed and tested on the cyclotron. We measured the vertical field in the median plane, shown in Fig. 6, using a custom-made 2D field mapper from a previous student project. The geometric center was identified using an FFT-based analysis that maximizes the fourth harmonic and minimizes all others. Difference analysis reveals a 14% variation between simulation and measurement. However, the discrepancy is <1% within the ion region.

Off-Center Stable Orbits

Spiral AVF simulations revealed an unexpected feature of the pole tip geometry: Multiple off-center stable orbits were found at particle energy 250 keV (nominal r=2.75"). In Fig. 7, four stable fixed points can be seen surrounding the central fixed point. Higher amplitude particles encompass all five points, while some particles are trapped near the off-center points. This phenomenon is a nonlinear feature of the 4-sector design and reflects the 4-fold symmetry of the underlying geometry. These outer orbits are supported at regions where the average magnetic field, $\langle B \rangle = \frac{1}{C}\int B_z ds$, along a pseudo-circular (due to orbit scalloping) path of average radius $\langle r \rangle$ satisfies the cyclotron equation,

$$\langle r \rangle = \frac{mv}{q\langle B \rangle}$$

for a given particle energy. The off-center islands quickly disappear at higher energies, and seem to have little effect on particle motion/stability during acceleration.

The off-center equilibrium orbits were observed experimentally, using a wire-loop technique as shown in Fig. 8.[7] A 30 AWG 7 cm radius wire loop was energized with 2.5 amps and placed in the magnetic gap, separated from the pole face by a clear acrylic sheet. The loop aligns with the central stable orbit, but jumps to neighboring orbits if perturbed. Four additional orbits were found at higher radii, beyond the four seen in simulation. These are likely lower energy equilibria, as the wire loop technique does not strictly correlate circumference to ion orbit energy (due to an additional degree of freedom, tension).

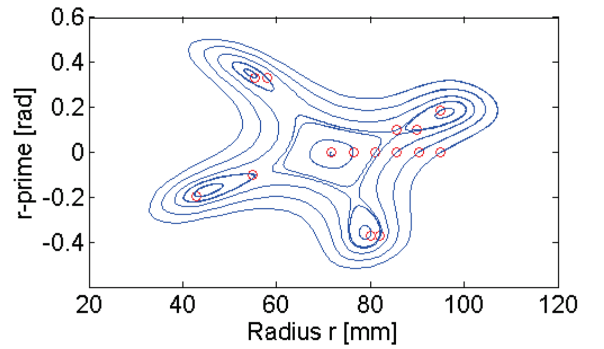

Figure 7: Spiral AVF radial trace space plot for 250 keV protons. Initial positions are marked in red. Note central orbit and 4 surrounding off-center fixed points.

Betatron Motion in Spiral AVF field

Following installation and characterization, the spiral AVF pole tips were tested with the PIG ion source. The spiral AVF tips have demonstrated successful transport of ions to the chamber periphery. Our SIMION model predicted that particle oscillations in the spiral AVF field would be less tightly bound than in the weak focusing field, but have a higher frequency (higher tune) near the central region. This was observed for several DEE voltage operating points. The photos shown in Fig. 9 demonstrate betatron motion of a proton beam in a ½ Tesla field, with f_{RF} = 7.8 MHz. All images were gathered using the radial P-22 Phosphor probe and a DSLR camera.

The comparison between weak and spiral pole tips can be seen in the relative onset of a tight focus. The weak focusing gradient gradually increases with radius, causing the betatron motion of the beam to adiabatically become more tightly bounded. In the spiral pole tips, the motion quickly reaches a focus, due to the comparatively stronger weak-focusing central region.

The spiral AVF tips met the goal of transporting ions to

Figure 8: Four predicted off-center stable orbits demonstrated with wire loop experiment.

their outer orbit and demonstrated use of edge focusing in the Rutgers Cyclotron. They produce stronger focusing in the central region when compared to the weak focusing poles. Future experiments will attempt to identify isochronous regions in the spiral AVF field.

CONCLUSIONS AND FUTURE PLANS

The Rutgers cyclotron project has fostered student exploration since 2001. Successful projects have both improved cyclotron operations and introduced basic accelerator physics concepts. The cyclotron, as a student's first experience in accelerator research, is helping inspire the next generation of accelerator physicists. To date, 18 junior- and senior-level undergraduate physics students have gained experience with this machine; six of them have gone on to pursue accelerator physics careers in both academia and industry.

The Rutgers cyclotron was the inspiration for a 1 week course at the United States Particle Accelerator School (USPAS) in January 2013. A second course (2 weeks) is in preparation for January 2015.

Future plans include the assembly of a second generation 19-inch educational cyclotron. The cyclotron facility has already secured an H-frame 19-inch magnet, a special General Electric magnet delivered to Rutgers in 1947 and operated for 35 years for NMR research before retirement to storage.[13] Upon acquisition, the venerable magnet coils were in need of refurbishing and are currently awaiting new copper windings. As the 19-inch project evolves, physics students will participate in the design and commissioning of the new vacuum chamber, diagnostics, pole tips and support systems.

Although primarily an educational tool, the Rutgers Cyclotron is a relevant research facility, enabling novel measurements and diagnostic techniques. The cyclotron will remain an accessible but modern facility dedicated to student research, and we anticipate the launch of many more accelerator careers.

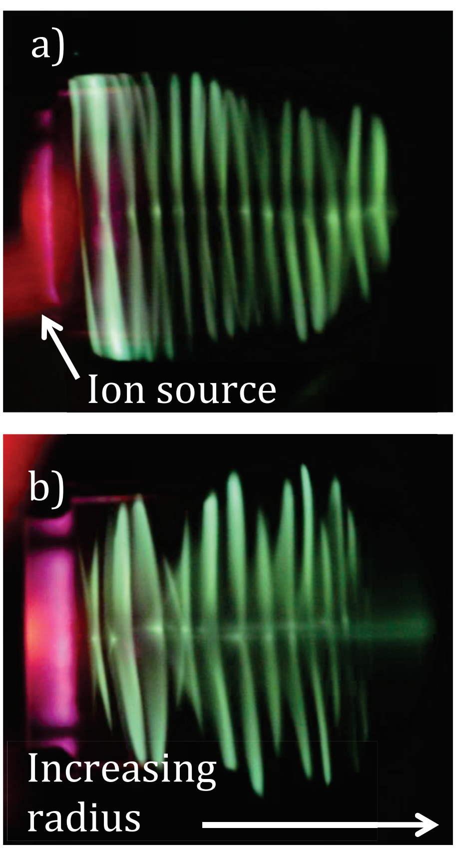

Figure 9: Betatron motion observed with radial Phosphor probe. a) weak focusing field, b) spiral AVF field, for DEE powered at 100 Watts.

REFERENCES

[1] www.physics.rutgers.edu/cyclotron
[2] C. Chun and L. Mac Lynne, http://www.physics.rutgers.edu/cyclotron/papers/The_Cyclotron_Magnet_and_RF_Oscillator-low-quality.pdf
[3] R. Friedman and J. McClain, http://www.physics.rutgers.edu/cyclotron/papers/Profiling_the_Magnetic_Field_of_the_New_Pole_Tips.pdf
[4] T.W. Koeth, T. Ponter et. al, http://www.physics.rutgers.edu/cyclotron/papers/Deflector_Dec_31_2011.pdf
[5] T.W. Koeth et. al, "Rutgers 12-inch cyclotron: dedicated to training through research and development," Cyclotrons 2013, Vancouver, Canada, WEPPT024, these proceedings.
[6] T. W. Koeth et. al, http://www.physics.rutgers.edu/cyclotron/papers/AVF_study_Dec_31_2011.pdf
[7] J.L. Gonski, et al, "A Novel Optical Method for Measuring Beam Phase and Width in the Rutgers 12-Inch Cyclotron," Cyclotrons 2013, Vancouver, Canada, WE1PB04, these proceedings.
[8] M. Craddock, "AG focusing in the Thomas Cyclotron," Proceedings of the 2009 PAC, Vancouver, BC, Canada.
[9] T.W. Koeth, "Beam Physics Demonstrations with the Rutgers 12-Inch Cyclotron," Cyclotrons 2013, Vancouver, Canada, WEPPT025, these proceedings.
[10] J.J. Livingood, "Principles of Cyclic Particle Accelerators," D. Van Nostrand, 1961
[11] L.H. Thomas, Phys. Rev. 54, 580 (1938)
[12] www.SIMION.com
[13] A. B. Robbins, History of Physics and Astronomy at Rutgers (Gateway Press, Baltimore, MD, 2001).

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