BEAM PHYSICS DEMONSTRATIONS WITH THE RUTGERS 12-INCH CYCLOTRON*

Timothy W. Koeth#, IREAP, University of Maryland, College Park, MD, 20742, U.S.A.

Abstract

The Rutgers 12-Inch Cyclotron is a research grade accelerator dedicated to undergraduate education.[1] From its inception, it has been intended for instruction and has been designed to demonstrate classic beam physics phenomena. The machine is easily reconfigured, allowing experiments to be designed and performed within one academic semester. Our cyclotron gives students a hands-on opportunity to operate an accelerator and directly observe many fundamental beam physics concepts, including axial and radial betatron motion, destructive resonances, weak and azimuthally varying field (AVF) focusing schemes, DEE voltage effects, and more.

INTRODUCTION

With the expanse of Proton Beam Radio Therapy, medical isotope and industrial facilities as well as numerous research labs, the demand for personnel trained in accelerator science and engineering is at an all time high. However, even upon graduation most undergraduate physics and engineering students are unaware of the option to pursue accelerator physics as a career. The Rutgers 12-Inch Cyclotron, Fig. 1, was built to introduce students to accelerator physics, let them explore many parameters of acceleration and focusing, and gain experience with standard accelerator hardware. Relative to other accelerator facilities, it is safe and accessible; reaching a maximum energy of 1.2 MeV protons, the Rutgers Cyclotron is not a radiological hazard and is easily approachable while operating.

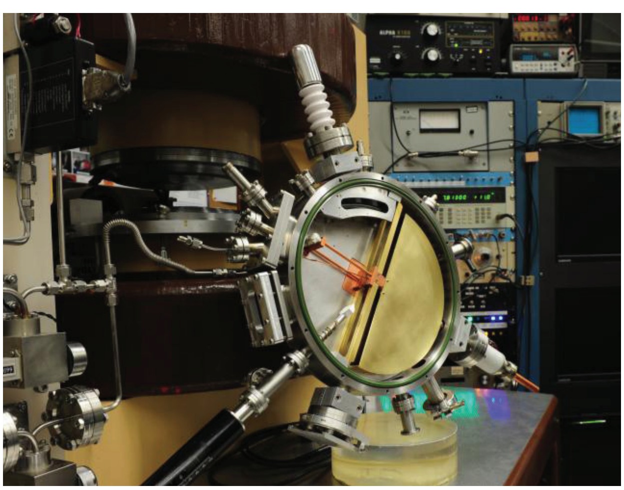

Figure 1: The Rutgers 12-Inch Cyclotron.

*This work privately supported by the Rutgers Cyclotroneers and a Rutgers Physics Department donor-funded Instructional Equipment Fund.

#:koeth@physics.rutgers.edu

Figure 2: Poletips for use on the Rutgers Cyclotron.

The H-frame cyclotron magnet has 12 inch diameter poles and approximately a 2-inch gap; the pole tips can be up to 1-inch thick and are easily removable – to date, we have four sets of pole tips and one of each set is shown in Fig. 2. They consist of two weak focusing (one “good” and one intentionally “bad” for educational purposes), a radial sector AVF and a spiral sector AVF, all with a maximum central axial field, $B_z(r=0)$, of 1.2 Tesla.[2,3] The magnet’s upper and lower coils are independently energized for intentional field imbalance so as to shift the median plane. The cyclotron has a single 5-inch radius DEE with a 0.9 inch vertical aperture and a matching dummy DEE. The Radio Frequency (RF) supply is tuneable from 2 to 30 MHz with power adjustable up to 1.5 kW; it can be operated in continuous or pulsed mode and is capable of achieving a peak DEE voltage of 10 kV.[4] The ion source is an internal cold cathode PIG source that operates in excess of 40 hours before requiring service.[5] Beam diagnostics include a radial probe carrying an electrically isolated phosphor plate, which provides transverse beam images as well as beam current measurements at all radii. A removable electrostatic deflection channel intercepts the ion beam at the 4-inch radius and is used as a velocity filter to measure ion energy.[6] The operating pressure of 1E-5 Torr is provided by a standard 4-inch diffusion pump stack. The cyclotron chamber’s position can be moved horizontally with respect to the magnet’s center. A full 3D SIMION model has been developed and extensively verified with every configuration of our cyclotron.[7]

ORBIT STABILITY DEMONSTRATIONS

Weak focusing (WF), empirically discovered in the first cyclotrons, and subsequently studied by R.R. Wilson, is an ideal introduction into orbit stability.[8,9] WF fields are, at some level, still present in all cyclotrons -

ISBN 978-3-95450-128-1

especially in the central region. WF was the orbit stability workhorse for early cyclotrons, synchrotrons, betatrons and synchrocyclotrons and has recently enjoyed a revival with the advent of compact superconducting cyclotrons and synchrocyclotrons for medical applications.[10]

A quick review reminds us that weak focusing employs an axial magnetic field, $B_z(r)$, that continuously decreases with increasing radius, r, which leads to an axial restoring force. A field index, n, is defined as:

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

with three possible cases for n; $n < 0$: B_z increases with r, $n = 0$: B_z is uniform, and $n > 0$: B_z decreases with r. It can be shown that for positive n, ions axially oscillate about the median plane with a frequency f_z:

$$f_z = \sqrt{n} f_o$$

Where f_0 is the orbit revolution [cyclotron] frequency. We then define the axial "tune" as ν_z:

$$\nu_z = \frac{f_z}{f_o} = \sqrt{n}$$

Similarly, the radial "tune" is can be shown to be:

$$\nu_x = \frac{f_x}{f_o} = \sqrt{1-n}$$

It follows that for axial stability, n must be greater than 0, and for radial stability n must be less than 1. Total transverse stability exists in the region of:

$$0 < n < 1$$

Coupling resonances between the transverse motions further limit the value of n. Values of n=0.2, 0.36, 0.5 (and others yet higher) need to be avoided. Since the ions begin their spiral journey at r=0 necessarily n also starts at 0, and will only climb as the radius increases; if n=0.2 is to be avoided (ν_x=2ν_z), then the rate at which B_z decreases must be moderated such that n=0.2 only near the final ion radius.

Despite Robert R. Wilson's rigorous 1938 study of an ion's oscillatory response to the cyclotron's fields, the motion has been coined "betatron motion" from Donald Kerst's similar 1941 analysis of electron orbits in his "betatron" accelerator.[9,11] To solidify these theoretical orbit concepts, our cyclotron students induce and measure betatron motion under differing conditions.

Axial Betatron Motion.

Small axial motion is initiated by a vertical electric field that imparts an upward kick to the ions immediately upon their exit of the chimney. Figure 3a is a SIMION simulation of ions crossing a radial reference plane in our "good" poletips' WF field, showing the beam coming to a focus near the DEE edge, where n=0.2. Figure 3b is the corresponding experimental observation in the Rutgers 12-Inch Cyclotron. The increased frequency of the axial oscillation with radius is a display of the growing field index, n. Both a) and b) exquisitely demonstrate adiabatic damping, and initiate a lecture on normalized emittance.

A standard cyclotron student exercise is to measure the tune (field index) as a function of radius. It is difficult to directly measure the axial frequency; however, the beam phase advance per revolution can beam measured by taking a long exposure photograph while slowly dragging a phosphor plate along a radial plane (Fig. 3b). From above, we can state that the axial betatron period of oscillation, T_z, relates to the ion revolution period, T_o:

$$T_z = \frac{1}{\sqrt{n}} T_0$$

Thus for a given n it takes $1/\sqrt{n}$ ion revolutions to complete one vertical betatron oscillation and it follows that the fraction which the betatron period advances at a given n per revolution is just $\sqrt{n}$.

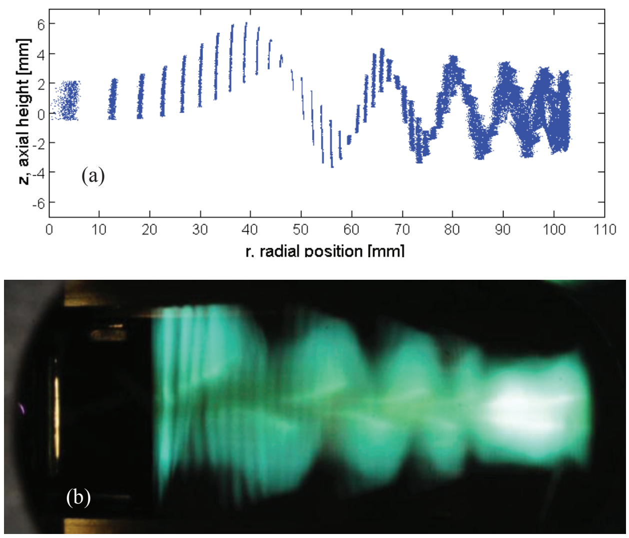

Figure 3: Simulated (a) and experimental (b) observation axial betatron motion in the Rutgers 12-Inch Cyclotron. Note turn-to-turn separation in early revolutions (left).

To estimate a local average tune, ν_z, the student notes the radial locations of two adjacent axial peaks and divides by the number of revolutions within that interval. When the radial beam spot is wider than the turn-to-turn spacing, overlap prevents a direct count of individual turns; peak DEE voltage is used to estimate the number of turns within the corresponding energy (radial) increment. By definition, the measured tune directly follows from the ratio of vertical oscillations to revolutions. The reader can estimate from Fig. 3a that ν_z≈0.09 at r=65 mm. A more precise method is described in reference [12].

Radial Betatron Motion.

Initial ion radial-position errors can be introduced by a horizontal offset of the chamber, and hence ion source, with respect to the magnet center. Since $\nu_x(r=0)$ begins at 1, any radial offset simply displaces the equilibrium orbit by the same. As the ions gain energy and spiral towards larger radii, $\nu_x(r)$ begins to drop, causing the location of maximum radial displacement to azimuthally process. This continues until a tight inter-turn bunching occurs on one side of the machine while large turn to turn spacing develops on the other, as shown in Fig. 4. Historically this has been exploited to increase extraction efficiency by placing the septum between turns. Radial displacements can be translated to axial when $\nu_x = 2\nu_z$ (n=0.2) is crossed and thus should be avoided.

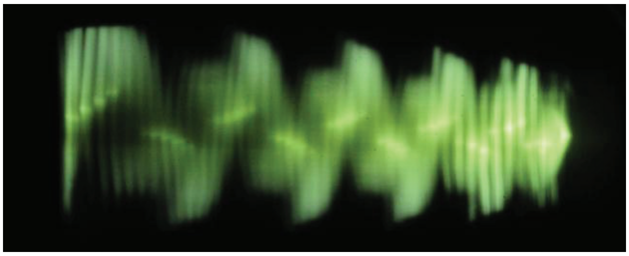

Figure 4: Increased turn-to-turn spacing at large radii.

Destructive Resonance.

We have built what may be the first set of poletips designed to intentionally drive a destructive axial resonance; we refer to these as the "bad" weak focusing poles tips. The n=0.2 point occurs at r=3.5 inches, well within the 5 inch DEE radius, so as to allow the ion displacement to grow. Since the n=0.2 is a difference resonance, the peak axial amplitude is bounded by the initial radial offset. A 3 mm displacement between the chamber and magnet centers was necessary to achieve the amplitudes simulated and observed in Fig. 5.

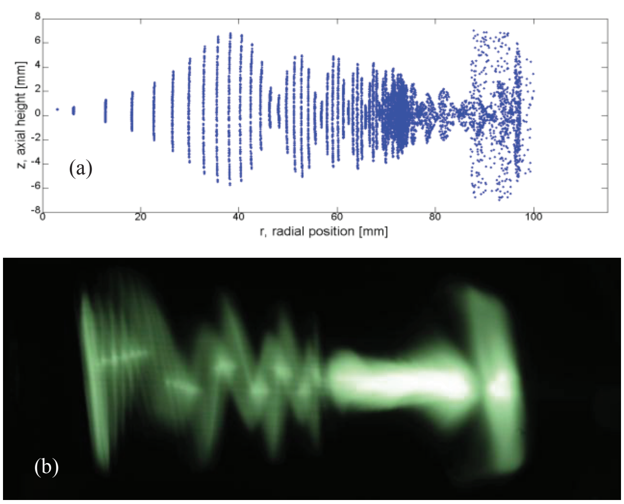

Figure 5: Simulation (a) and experimental observation (b) of axial beam blow up at the n=0.2 resonance.

MORE DEMONSTRATIONS

We have only presented our introductory beam physics demonstrations. Many sophisticated experiments and measurements have been developed and more are continually being added to our repertoire. These include the radial and spiral sector AVF focusing poletips, a *floating wire loop* demonstration to visualize primary equilibrium and off-center AVF orbits, DEE voltage effects, ion source studies, phase stability, ion bunch length and phase measurements.[13,14,15] We conclude with a demonstration of vertical steering by shifting the median plane. While maintaining an average of the required ampere-turns in the upper/lower coils, the median plane can be shifted up or down by substantial current imbalances and still bring beam to the periphery. Figure 6 shows three standard radial-draw beam images: the left frame top/bottom coil at 17/12 amps, the middle frame at 14.5/14.5 amps, and the right frame at 12/17 amps.

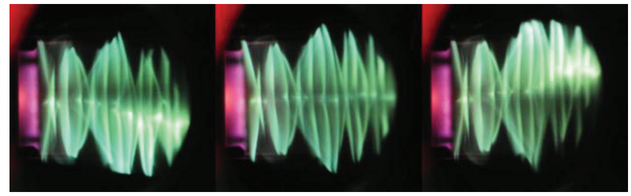

Figure 6: Axial steering by adjusting median plane.

CONCLUSIONS

The Rutgers 12-Inch cyclotron is a successful didactic tool to educate students in and recruit them to the field of accelerator physics. Its success can be measured by the, to-date, six undergraduate physics students that have re-directed their career goals into accelerator physics, in both academia and industry.

REFERENCES

[1] T. Feder, "Building a Cyclotron on a Shoe String," Physics Today, 30-31 (November 2004).
[2] T.W.Koeth, http://www.physics.rutgers.edu/cyclotron/papers/12_inch_magnet_studies_4.pdf
[3] T.W. Koeth, et al., http://www.physics.rutgers.edu/cyclotron/ papers/AVF_study_Dec_31_2011.pdf
[4] T.W. Koeth, et al., http://www.physics.rutgers.edu/cyclotron/papers/12_inch_dee_voltage.pdf
[5] T.W. Koeth, et al., "Rutgers 12-Inch Cyclotron: Dedicated to Training through R&D," these proceedings, WEPPT024.
[6] T.W. Koeth, et al., http://www.physics.rutgers.edu/cyclotron/papers/Deflector_Dec_31_2011.pdf
[7] www.simion.com
[8] J.L. Heilbron, Robert Seidel, and Bruce R. Wheaton, "Lawrence and His Laboratory," (1989).
[9] R.R. Wilson, "Magnetic and Electrostatic Focusing in the Cyclotron," Phys. Rev. 53:408-420 (1938).
[10] T. Antaya, "High-field Superconducting Synchro-cyclotron," Patent, PCT/US2007/001628 (USA, 2007) 26.
[11] D. W. Kerst and R. Serber, "Electronic Orbits in the Induction Accelerator," Phys. Rev. 60:53-58 (1941).
[12] T.W. Koeth, et al., http://www.physics.rutgers.edu/cyclotron/papers/Betatron_Studies.pdf
[13] K.J. Ruisard, et al., "The Rutgers Cyclotron: Placing Student's Careers on Target," Cyclotrons 2013, Vancouver, Canada, WE1PB02, these proceedings.
[14] T.W. Koeth, et al., http://www.physics.rutgers.edu/cyclotron/papers/IonSourceStudiesII_march_26_2008.pdf
[15] 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.

ISBN 978-3-95450-128-1