ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-MOPOST033

BETATRON TUNE CHARACTERIZATION OF THE RUTGERS 12-INCH CYCLOTRON FOR DIFFERENT MAGNETIC POLES CONFIGURATIONS

Cédric Hernalsteens, CERN, 1211 Geneva 23, Switzerland
Michelle Miller, Brown University, Providence, Rhode Island, USA
Timothy S. Ponter, Ion Beam Applications, Louvain-la-neuve, Belgium
Brian Beaudoin, Timothy W. Koeth, University of Maryland, College Park, Maryland, USA
Kiersten Ruisard, Oak Ridge National Laboratory, Oak Ridge, TN, USA
Robin Tesse, ULB, Bruxelles, Belgium

Abstract

The Rutgers cyclotron is a small 12-Inch, 1.2 MeV proton cyclotron. Sets of magnet pole-tips were designed to demonstrate different cyclotron focusing options: weak focusing, radial sector focusing and spiral sector focusing. The purpose of this paper is to experimentally characterize the transverse dynamics provided by different types of focusing. Magnetic field measurements provide insight into the as-built properties of these magnetic poles configurations. First we discuss the axial betatron tune measurements as a function of the beam energy towards outer radii, which agree well with the values expected from measured magnetic data. Turn-by-turn betatron envelope oscillation measurements are also reported and compared with the tune measurements. Excellent agreement is once again found.

THE RUTGERS 12-INCH CYCLOTRON

The Rutgers cyclotron is a 12-Inch, 1.2 MeV proton cyclotron built out of passion and intended for instructional use. It saw first beam in 1999 [1] and since has been the host of multiple students projects, contributing to the improvement of the machine and its subsystems. In particular, different sets of magnet pole-tips have been designed and built. These different magnetic configuration illustrate the main aspects of the cyclotron focusing theory: weak focusing, radial sectors (Thomas focusing) and spiral sectors (Kerst and Laslett focusing effects) [2–4]. The transverse betatron motion of the beam accelerated with the weak focusing pole configuration has been observed in the past [5] using the main diagnosis tool available at the cyclotron: a phosphor coated screen mounted on a radial probe instrument observed with a DSLR camera.

We make two independent tune calculations based on two sets of measured data: a mapping of the magnetic field in the mid-plane of the magnet and transverse betatron centroid and envelope oscillations data extracted from beam images.

To carry out the measurements discussed below, we used a modified source chimney featuring an aperture offset along the vertical axis in order to provide a beam with an initial axial offset to drive large axial oscillations. The design of the source, a cold cathode Penning Ion Gauge (PIC) source, is reported in Ref. [6]. Additionally, the aperture is circular with a 0.8 mm radius, and it can sustain a current of 5 mA. A picture of the modified aperture source is shown in Fig. 1 (left). The off-centered aperture is clearly identified.

Magnetic Field Focusing

The cyclotron magnet features flat poles with a maximum B-field of about 1 T. The magnetic field can be shaped using pole-tips that are fixed on the flat poles. Magnetic maps have been measured using a home-made magnetic measurement table and stepper motors electronics with a digital Gaussmeter. The magnetic centers of the sector focusing pole-tips are identified using a field harmonic analysis on a set of circles with different radii; indeed the non-structure harmonics are minimal at the magnetic center.

The so-called weak-focusing poles have azimuthal symmetry (see Fig. 1 (right)). The axial magnetic field decreases with the radius, the gradient of which provides axial focusing. The radial focusing comes from the usual dipole

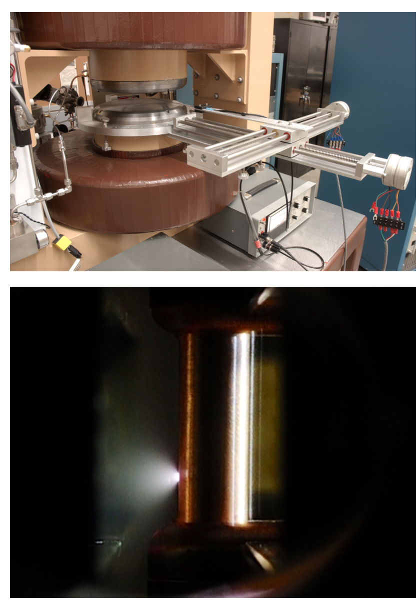

Figure 1: (top) Weak focusing pole-tips on magnet, with magnetic measurement stage. (bottom) Glow of the plasma out of the source chimney aperture. The symmetry plane of the cyclotron lies in the axial center of the chimney. The offset of the aperture with respect to that plane is directly visible.

ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-MOPOST033

weak-focusing term. Given the low energy and low current of the cyclotron these pole-tips do not attempt nor achieve isochronicity. The axial tunes is given by the usual formula

$$\nu_z = \sqrt{n}, \tag{1}$$

where n is the field index defined as $n = -\frac{\partial B}{\partial r}\frac{r}{B_0}$. Radial sectors pole-tips providing the so-called Thomas focusing [2] were built but the beam could not be accelerated up to the deflector radius due to poor isochronicity. Straight sector edge-focusing adds a term to ν_z^2 depending on the "flutter" (mean square deviation of $B(\theta)$:

$$F^2 = \left\langle \left(\frac{B(\theta) - \langle B \rangle}{\langle B \rangle} \right)^2 \right\rangle, \tag{2}$$

where $\langle B \rangle$ is the θ-averaged axial magnetic field. To successfully accelerate the beam up to the chamber's radius a new set of pole-tips was designed [7], at the same time providing additional focusing using a spiral sector design. The sector focusing contribution to the axial tune becomes

$$\nu_{sector}^2 = F^2 \left(1 + 2tan^2\epsilon\right) \tag{3}$$

where F is defined in Eq. (2) and ϵ is the spiral angle. The spiral pole tips are in the shape of Archimedean spirals that sweep 270°, as shown in Fig. 2 (right). A complete magnetic field map has been measured and is shown in Fig. 2 (left). In order to reconstruct the axial tune the field was integrated azimuthally (assuming circular orbits) to obtain the field gradient and the flutter F.

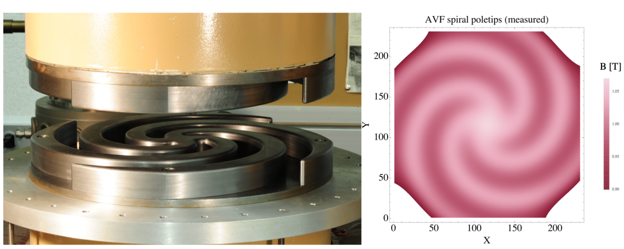

Figure 2: Spiral sectors pole-tips (left) and measured magnetic map (right.

BETATRON TUNE MEASUREMENTS

The aim of these beam based measurements is to characterize the focusing properties of the different sets of the pole-tip designs. Beam images are captured on a phosphor coated screen mounted on a manually actuated radial probe. A view port next to the radial probe provides line of sight to a DSLR camera. The camera is set for long exposure shots (up to 5 seconds) while the operator maneuvers the radial probe to capture an 2D image of the beam's axial and radial position. Figure 3 displays a typical beam image obtained with the weak focusing (left) and spiral pole-tips (right). The accelerating voltage is adjusted to find a balance between two characteristics of the beam image: if the voltage is too small the radial turn to turn separation is too small and one cannot distinguish between two consecutive turns in the beam image. However, if the voltage is too large then the length of the turn by turn signal is reduced. Beam-ff images are taken for each set of data to calibrate pixel grid to magnet center/midplane.

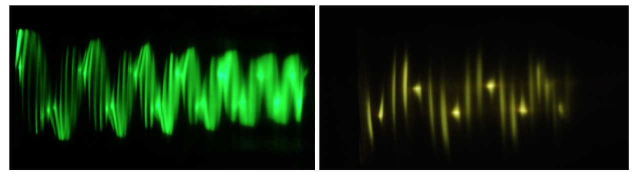

Figure 3: Beam image obtained from a long exposure shot of the moving radial probe screen for the weak focusing pole-tips (left) and for the spiral sectors pole-tips (right) where a good turn-by-turn separation is obtained. Note that both the beam centroid oscillation and beam envelope modulation are apparent.

The beam images were processed to extract the turn-by-turn signals corresponding to the axial beam centroid positions $\langle z \rangle_n$ and axial beam envelopes $\langle z^2 \rangle_n$. Although one might be concerned by the robustness of such data, multiple manual processing of each image turned out to provide data whose associated errors are well constrained. These data were in turn fitted with a harmonic signal using a moving window technique, weighted to measurement error. Image-by-image examination of the fit quality showed that the best results are obtained using a 5-point window. The low number of fit points allows us to resolve radial variations of the frequency, as the typical signal length is around 15 turns long.

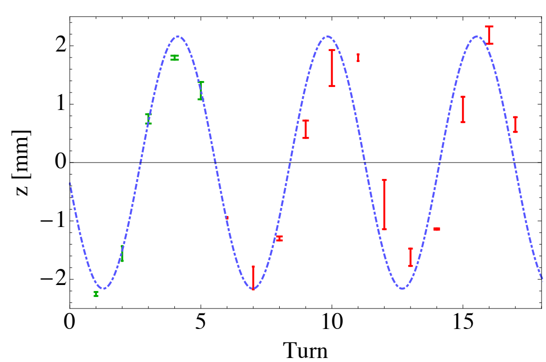

Figure 4: Axial centroid oscillation signal for the spiral sectors configuration. The best harmonic fit based on the first five points (green markers) is also shown.

Figure 4 displays the beam centroid oscillation signal for the spiral pole-tips. The fit is based on the first five points (green data points). One can observe the fitted harmonic motion shifted in phase relatively to the other data points (red data points). This is the effect of the axial tune variation along the machine radius.

ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-MOPOST033

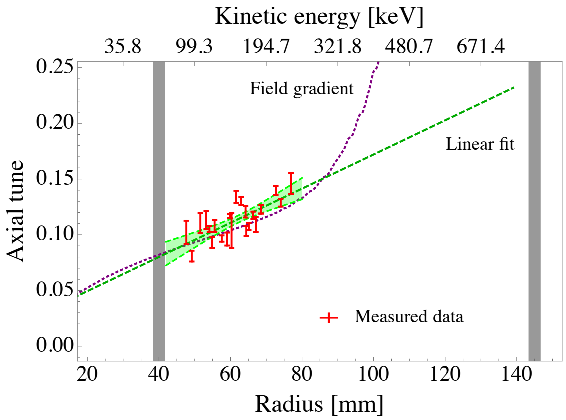

Figure 5: Results for the weak focusing pole-tips: tune from beam data (red), tune computed from measured magnetic field (purple), linear fit (green) with the 90% confidence intervals. The gray vertical bands symbolize the minimal and maximal radii reachable with the radial probe screen.

Our results for the measurement of the axial tune in the weak focusing configuration are shown in Fig. 5. Data points for the measured axial tune from the image processing are shown in red. The axial tune increases with the radius. The best linear fit in the measurement range[1] reads $\nu_a = (0.086 \pm 0.001) + (0.0012 \pm 0.001) \cdot (r - 45)$, where r is the radius expressed in millimeters in the range 45 to 80mm. The 90 % confidence interval is also shown revealing that the measurement resolution is sufficient to confirm the observed linear trend. The equation of the fit of the magnetic results (in the beam based measurement range) reads $\nu_a = (0.088 \pm 0.004) + (0.0015 \pm 0.0002) \cdot (r - 45)$. Fig. 5 also indicates the beam energy corresponding to a given radius. These represent the first direct tune measurements results (as a function of the radius or energy) obtained so far for the Rutgers cyclotron.

The analytic tune calculation based on the measured magnetic field, using Eq. (1), is shown in purple. The agreement between the two measurements is excellent and the radial dependence is clearly resolved.

Data obtained from the spiral pole-tips configuration of the cyclotron have also been analyzed to measure the axial tune as a function of the radius. Results are shown in Fig. 6. The measured tune is shown in red while the estimate from the magnetic measurements is shown in purple. Once again the agreement between the beam-based results and the results obtained from the analysis of the field map is excellent. The radial dependence is more complicated than in the weak-focusing case but nevertheless the overall shape is resolved. This result is the first beam-based measurement of this configuration and provides a last validation of the design process of these pole-tips [7].

[1] The measurement range does not reach the maximum range of the radial probe as the reduced turn-by-turn separation at higher energies does not allow to distinguish between the turns.

It is interesting to note that the measurement technique that we use readily provides a turn-by-turn envelope beating information. This is contrasting the usual case of synchrotrons where that kind of data is not as easily accessible. This provides a second and independent mean of measuring the betatron tune. Indeed it is well known that the envelope beating signal has a frequency which is two times the betatron tune. The envelope oscillation signal has been successfully reconstructed for spiral pole-tips beam images and the envelope tune is measured. The results are shown in Fig. 6 (light blue band). Within the measurement errors the envelope-based result matches very well the centroid-based tune values. The beam images that were analyzed did not allow to measure the envelope-based tune as a function of the radius however the measurement range is the same as for the other results.

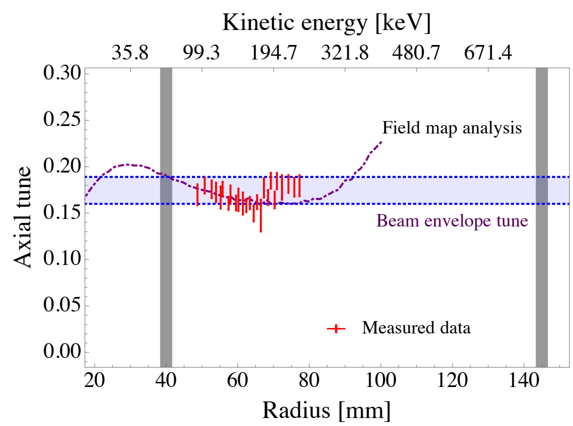

Figure 6: Axial tune measurement results. Experimental data points are shown in red. The tune function based on the measurement magnetic field is shown in purple. The tune reconstructed from the envelope modulation frequency is shown in blue.

CONCLUSION

The betatron motion of the Rutgers cyclotron has been analyzed in detail for different focusing configurations and the axial tune has been measured for the first time as a function of the beam energy for two pole-tips configurations: weak-focusing and spiral sectors. Each one of the flexible components of the cyclotron has been adjusted to provide high-quality beam profile images on the radial probe screen from which turn-by-turn centroid position has been reconstructed. The axial tunes obtained from these data have been compared from expectations from magnetic field mapping measurement done for the poles. The agreement between the two independent set of data is excellent. Additionally, envelope modulation frequencies have been obtained for the first time and once again the result agrees very well with the expected value. The results constitute the most detailed experimental characterization of the betatron motion at the Rutgers cyclotron.

ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-MOPOST033

REFERENCES

[1] http://www.physics.rutgers.edu/cyclotron

[2] L. H. Thomas, "The Paths of Ions in the Cyclotron I. Orbits in the Magnetic Field", *Phys. Rev.*, vol. 54, no. 8, p. 580, 1938. doi:10.1103/PhysRev.54.580

[3] K. R. Symon, D. W. Kerst, L. W. Jones, L. J. Laslett, and K. M. Terwilliger, "Fixed-Field Alternating-Gradient Particle Accelerators", *Phys. Rev.*, vol. 103, p. 1837, 1956. doi:10.1103/PhysRev.103.1837

[4] M.K. Craddock, "AG Focusing in the Thomas Cyclotron of 1938", in *Proceedings of the 23rd Particle Accelerator Conference*, Vancouver, British Columbia, Canada, 2009, paper FR5REP113, pp. 5041–5043.

[5] T.W. Koeth *et al.*, "Rutgers 12-Inch Cyclotron: Dedicated to Training Through Research and Development", in *Proc. of Cyclotrons2013*, Vancouver, Canada, 2013, paper WEPPT024, pp. 366–368.

[6] T.W. Koeth, unpublished, 2006.

[7] K.J. Ruisard *et al.*, "The Rutgers Cyclotron: Placing Student's Careers on Target", in *Proc. of Cyclotrons2013*, Vancouver, Canada, 2013, paper WE1PB02, pp. 291–295.