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

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Abstract

The Rutgers cyclotron is a small 12-Inch, 1.2MeV 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 focus of this paper is on the experimental characterization of the transverse dynamics provided by these different focusing options. Magnetic field measurement results providing insight into the as-built properties of these magnetic poles configurations are reported. First measurements of the axial betatron tune as a function of the beam energy along the machine radius are discussed in detail and are shown to be in excellent agreement 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, 1.2MeV proton cyclotron built out of passion and with instructional use in mind. It has seen its first beam in 1999 [1]. It 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, 6, 7]. The spiral sectors poles feature Archimidean spirals with a four-fold symmetry [5], see Fig. 2 (left). The transverse betatron motion of the beam accelerated with the weak focusing pole configuration has been observed in the past [3] using the main diagnosis tool available at the cyclotron: a phosphor coated screen mounted on a radial probe instrument observed with a DSLR camera. A measurement campaign aiming at characterizing the transverse dynamics of these different focusing configurations has been carried out. It consists of 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. The magnetic data allowed to reconstruct the as-built focusing properties of the machine in the form of the axial tune as a function of the orbits radius. These were compared with direct betatron tune measurements extracted from the radial probe screen pictures.

To carry out the measurements discussed below, a special source chimney has been used. The design of the source, a cold cathode Penning Ion Gauge (PIC) source, is reported in Ref. [4]. The aperture is circular with a 0.8mm radius and it can sustain a current of 5mA. A modified source chimney featuring an aperture offset along the vertical axis was built in order to provide a beam with an initial axial offset. A picture of the modified aperture source is shown in Fig. 1 (left). The off-centered aperture is clearly identified.

The cyclotron magnet features flat poles with a maximum B-field of about 1T. 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 field gradient in turns provides axial focusing. The radial focusing comes from the usual dipole weak-focusing term. Given the low energy and low current of the cyclotron these pole-tips do not attempt nor achieve isochronicity. The radial and axial tunes are given by the

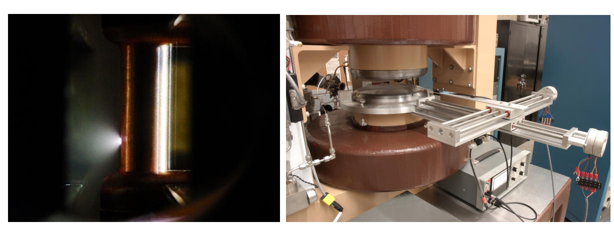

Figure 1: (left) Glow of the plasma out of the source chimney aperture. The symmetry plane of the cyclotron lies in the axial center of the chimney. The offset of the aperture with respect to that plane is directly visible. (right) Magnet setup with the azimuthally symmetric pole-tips. The magnetic measurement table is also visible.

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usual formulae

$$\nu_r = \sqrt{1-n}, \tag{1}$$

$$\nu_z = \sqrt{n}, \tag{2}$$

where n is the field index defined as $n = -\frac{\partial B}{\partial r}\frac{r}{B_0}$. The axial tune obtained from these magnetic measurements is compared with beam-based data in the next section. Radial sectors pole-tips providing the so-called Thomas focusing [2] have been built but the beam could not be accelerated up to the deflector radius due to poor isochronicity. The edge-focusing adds a term to ν_z^2 depending on the "flutter" (mean square deviation of $B(\theta)$:

$$F^2 = \left\langle \left(\frac{B(\theta) - \langle B \rangle}{\langle B \rangle} \right)^2 \right\rangle, \tag{3}$$

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 [5], at the same time providing additional focusing using a spiral sector design. The spiraling changes the edge crossing angles and the sector focusing contribution to the axial tune becomes

$$\nu_{sector}^2 = F^2 \left(1 + 2tan^2\epsilon\right) \tag{4}$$

where F is defined in Eq. 3 and ϵ is the spiral angle. An iterative design phase using a field solver and ion tracking lead to the machining of 270°spiral pole-tips 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.

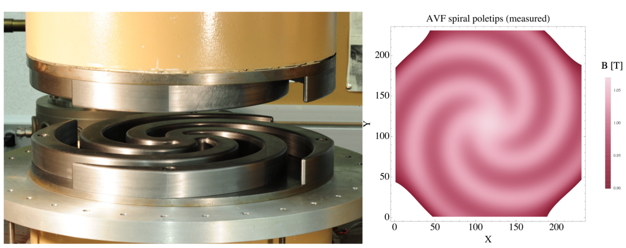

Figure 2: Spiral sectors pole-tips (left) and measured magnetic map (right.

BETATRON TUNE MEASUREMENTS

The aim of these beam based measurements is to characterize the as-built focusing properties of the different sets of the pole-tips. The instrumentation is based on a phosphor coated screen mounted on a radial probe system. The probe is manually displaced along the chamber's radius by the operator. A view port next to the radial probe allows to take images of the beam induced luminescence of the screen with a DSLR camera. The camera is set for long exposure shots (up to 5 seconds) while the operator maneuvers the radial probe. These beams images then feature a vertical and radial 2-dimensional picture of the beam. Figure 3 (left) displays a typical beam image obtained with the weak focusing pole-tips. The accelerating voltage is adjusted to find a balance between two characteristics of the beam image: if the voltage is not large enough the radial turn to turn separation is too small and one cannot distinguish between two consecutive turns in the beam image, if the voltage is too large then the length of the turn by turn signal is reduced. This measurement technique requires to calibrate the beam images to transform their pixel grid into coordinates in the usual frame of reference centered on the central axis of the magnet. To reach that goal, calibration pictures of the radial probe are taken each time a new set of data is taken. A careful calibration has been performed for each beam image used for this analysis. To induce vertical beam oscillations a modified source has been put in operation which features an offset chimney slit providing an initial axial offset allowing to observed the oscillations of the beam centroid as shown in Fig. 1 (left). A beam image obtained from an excellent setup for the spiral pole-tips is also shown in Fig. 3 (right).

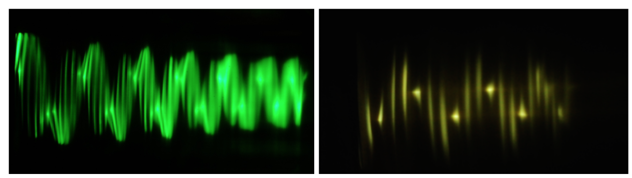

Figure 3: Beam image obtained from a long exposure shot of the moving radial probe screen for the weak focusing pole-tips (left) and for the spiral sectors pole-tips (right) where a good turn-by-turn separation is obtained. Note that both the beam centroid oscillation and beam envelope modulation are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

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 images turned out to provide data whose associated errors are well constrained. These data were in turn fitted with an harmonic signal using a moving window technique. The fitting technique takes the measurement errors into account: lower weights were associated with the data points corresponding to large beam envelopes, as the determination of the centroid of these data points are not as precise as those were the beam is at a focus. Image-by-image examination of the fit quality showed that the best results are obtained using a 5-point window. That relatively low number of data points allowed to extract frequency information for many radial position as the typical signal length is around 15 turns long.

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.

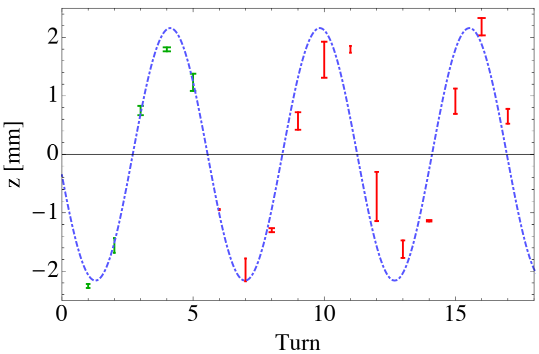

Figure 4: Axial centroid oscillation signal for the spiral sectors configuration. The best harmonic fit based on the first five points (green markers) is also shown.

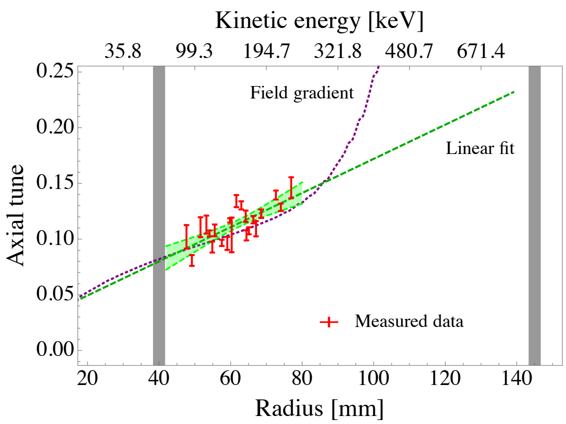

Figure 5: Results for the weak focusing pole-tips: tune from beam data (red), tune computed from measured magnetic field (purple), linear fit (green) with the 90% confidence intervals. The gray vertical bands symbolize the minimal and maximal radii reachable with the radial probe screen.

Our results for the measurement of the axial tune in the weak focusing configuration are presented in Fig. 5. The data point for the measured axial tune are shown in red. The result is very interesting as it reveals a trend on the increase 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 tune function based on the measured magnetic field, using Eq. 1, is shown in purple. The equation of the fit of the magnetic results (in the beam based measurement range) reads $\nu_a = (0.088 \pm 0.004) + (0.0015 \pm 0.0002) \cdot (r - 45)$. The agreement between these values and the values obtained from the beam based measurement is excellent and the radial dependence is clearly resolved. Fig. 5 also indicates the beam energy corresponding to a given radius. These represent the first tune measurements results (as a function of the radius or energy) obtained so far for the Rutgers cyclotron.

[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.

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 [5].

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.

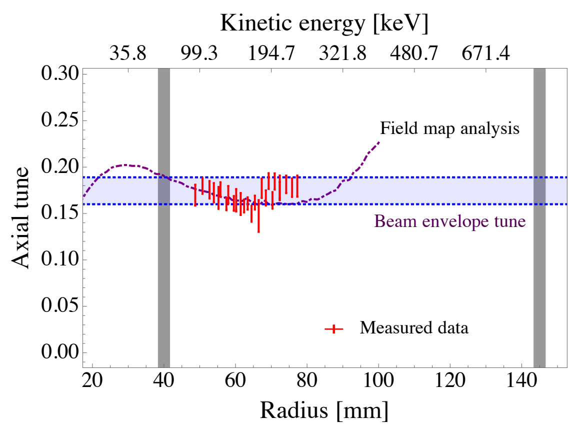

Figure 6: Axial tune measurement results. Experimental data points are shown in red. The tune function based on the measurement magnetic field is shown in purple. The tune reconstructed from the envelope modulation frequency is shown in blue.

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 cyclotrons have been adjusted to provide high-quality beam profile images on the radial probe screen from which turn-by-turn centroid position and envelope signals have been reconstructed. The axial tunes obtained from these data have been compared from expectations from magnetic field mapping measurement done for the poles, including the newly designed spiral sector pole-tips. 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.

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