A NOVEL OPTICAL METHOD FOR MEASURING BEAM PHASE AND WIDTH IN THE RUTGERS 12-INCH CYCLOTRON

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Abstract

We present an optical based measurement of beam bunch length and time of arrival (phase wandering) for protons accelerated in the Rutgers 12-inch Cyclotron. This technique is necessary to test the isochronicity of various magnetic field configurations, including radial and spiral azimuthal varying fields [1]. We discuss our inaugural measurements in a constant gradient weak focusing field and compare with simulation. Preliminary success with this method justifies continued exploration and refinement of this technique. By necessity, this method is insensitive to the DEE gap voltage and enables all cyclotron facilities to perform longitudinal measurements within their central region.

INTRODUCTION

The Rutgers 12-Inch Cyclotron is an educational accelerator dedicated to student training by experimental exploration of beam phenomena. Over a decade of experimentation has been focused on transverse beam measurements without any knowledge of the longitudinal behavior. This is because the large residual electric field of the radio frequency (RF) accelerating potential makes standard electronic beam phase and bunch length measurements impossible. RF filtering permits average beam current measurements, but removes any time structure within an RF cycle. We have developed an optical based measurement that is insensitive to DEE voltage using a fast (3 ns) phosphor screen viewed by a gated camera to create "time sliced" images which longitudinally profile the beam. The phosphor plate is located on the end of a radial positioner that can sweep the entire chamber radius and hence any ion revolution. Because a number of technical obstacles had to be mastered, we performed our first experiments in a weak focusing field, which is our simplest magnetic field configuration.

We recall that in a weak focusing field, the axial magnetic field decreseases with increasing radius so as to form axial-restoring radial field components above and below the median plane. As a consequence, the cyclotron condition can only be met at one point in the ion's flight from source to target; at all other locations, there is a mismatch between the cyclotron frequency and the RF accelerating frequency. When the two are not perfectly matched, each ion revolution acquires a phase error [2]. This error is acceptable, as long as the overall integrated phase slippage is less than 90°. The accelerating DEE voltage can be increased to reduce the number of turns and keep the phase slippage blow 90°. Alternatively, if one starts the ions in a magnetic field that is too high, they

can acrue a phase slippage in one direction that permits the cyclotron condition to be met midway. At this point, a reversal of the phase slippage leads to a net zero phase error, illustrating phase stability as displayed in Fig. 1. In contrast, in an isochronous field, ions return to the same azimuthal location every RF cycle. In this paper, we measure the bunch length and phase slippage under differing magnetic field strengths in the definitively non-isochronous weak focusing field.
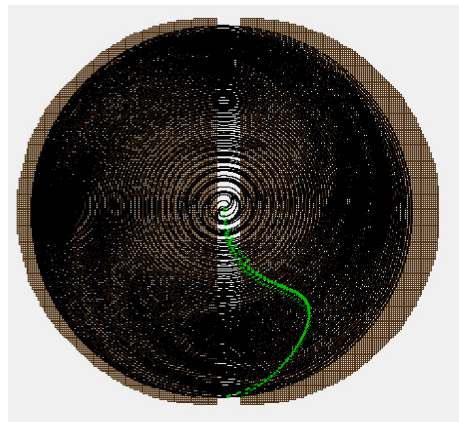

Figure 1: Simion demostration of phase slippage of proton in weak focusing field; green markers indicating ion location once per Radio Frequency Accelerating Voltage cycle.

SIMULATIONS

In order to anticipate the measurement's signature, the experiment was modelled in SIMION. A model of the weak focusing field generated by Poisson Superfish (PSF) was imported into SIMION. Flight time and ion paths were simulated in SIMION by tracking groups of ions through the cyclotron's 3D magnetic and RF electric fields [3]. Data such as ion position, time of flight (TOF), and energy were recorded for post processing. The fast phosphor target was modelled as a terminating plate with the same dimensions, and located at the corresponding experimental azimuth and radii position. The relative phase shift as a function of magnetic field was determined by the ion TOF, where flight termination occurred upon collision with the plate.

For each magnetic field value used in data acquisition, a separate PSF field was created and used in SIMION to generate ion flight simulations under experimental operating conditions. Comparison to measurements revealed a proportionality of relative phase shift between simulation and data. Precise definition of this relationship can be found in later sections. We expect a linear relationship between relative phase shift and magnetic

field, since cyclotron frequency is directly proportional to magnetic field strength. Simulations confirmed this expectation for various magnetic fields; such modelling can be seen in later sections.

EXPERIMENT

Bunch length and phase data were taken with the Rutgers 12-inch cyclotron operating at an RF frequency of 7.800 MHz and with magnetic fields around 0.5 Tesla. The 0.944-inch diameter ZnO:Ga doped "fast" phosphor deposit was layered between a 0.050 inch thick quartz substrate and a 1000 Å aluminium coating. The plate, mounted at the end of an adjustable radial probe, was electrically isolated for average beam current measurements. The fast phosphor screen has a 1/e relaxation time of 3 ns and was imaged through a vacuum view port using a Princeton Instruments PI-MAX 2 ICCD gated camera capable of 3 ns exposures. Operation at 7.8 MHz was a compromise between maximum achievable proton energy and extending the RF period so as to maximize the time resolution with the fixed 3 ns resolving time. At 7.8 MHz, 3 ns corresponds to 9° of RF phase. The cyclotron RF was operated in pulsed mode at a frequency of 20Hz to permit instantaneous high power (thus high DEE voltage) while maintaining a low average heat load. The PI-MAX gated camera trigger was synchronized to the RF trigger through a SRS DG535 digital delay generator which provided a coarse trigger delay adjustment; 100 ms to allow the RF tank circuit to "ring up" to steady state. The PI-MAX camera software automated the sub-RF period time incrementing. Due to the extreme sensitivity of the camera, and weak light of the phosphor, it was necessary to create a light-tight optical transport between the chamber viewport and the camera; the camera installation is shown in Fig. 2.

Figure 2: PI-MAX camera imaging fast phosphor screen.

An experimental run would consist of setting the PI-MAX camera software for a series of 3 ns time steps, of which 44 were needed to cover a single RF period, corresponding to a total range of 132 ns. At the operating frequency of 7.8 MHz, one RF period is 128ns, thus ensuring that our imaging process more than covered a full cycle. In our experiments, the light signal was weak and required 900 integrations per time step for a usable signal. At the RF pulse repetition rate of 20 Hz and 900

integrations per time step, a complete run of 44 time steps required over half an hour. Images from a single data set are shown in Fig. 3. Each frame in this set is a composite generated from the 900 integrations performed for each 3ns time step in the RF period. During data collection, the inner edge of the plate was at a radius of 91.0 ± 0.5mm, with the outer edge at 105.0 ± 0.5mm. This gave a proton termination energy of about 100 keV.
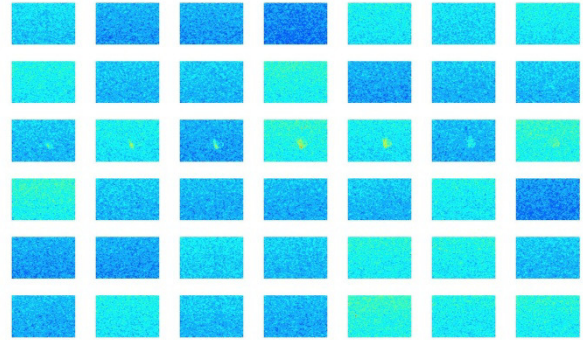

Figure 3: Sequence of 3 ns images (left to right, top to bottom), each made of 900 composite images at a radius of 90.81mm.

ANALYSIS AND RESULTS

The gated camera images were grayscale with an intensity range of 16 bits per pixel. The beam area was selected manually, and its brightness was normalized to the average intensity of each image. Due to the sensitivity of the camera, high noise levels were a constant challenge, so analysis based on relative intensity allowed for minimal image-to-image variation in noise intensity.

The data exhibited two temporally separated intensity peaks within one RF cycle, rather than the anticipated single Gaussian. We have concluded that we were imaging beam from two separate revolutions. Ions with sufficient radial extent in the nth turn terminated on the phosphor screen, while the remainder continued for another nth+1 revolution. This serendipitously provided a direct measure of the turn-to-turn (nth to nth+1) phase shift at a given radius. At the radial probe location of 91 mm, the turn-to-turn phase slippage was large, as seen in the upper plot of Fig. 4. We find that operating below the nominal magnetic field increased the turn-to-turn phase slippage.

The double peak data was deconvoluted by fitting to a dual Gaussian distribution, as seen in the upper plot of Fig. 4. The second peak was consistently of greater intensity than the first, and assumed to be the nth +1 revolution, which we take as the turn of interest. After removing the lower intensity peak (nth turn) from the dual-Gaussian fits, a comparison of several runs reveals a pronounced phase shift, as seen in Fig. 4, below.
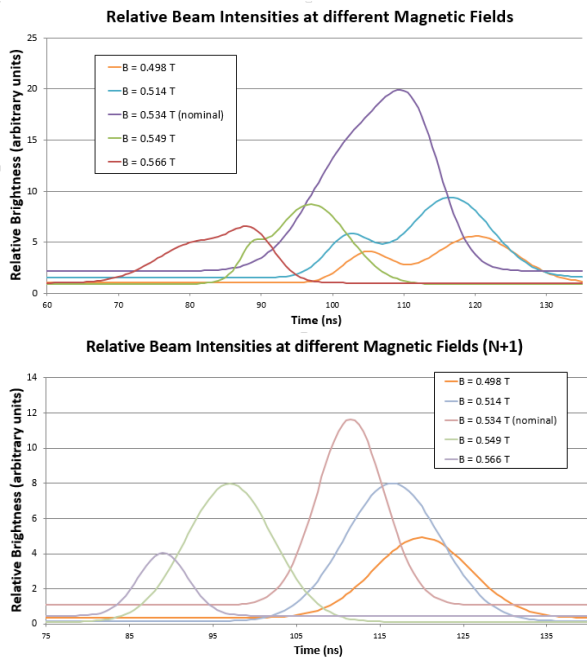
Figure 4: Double peak in brightness as a function of time, top. Second peak isolation, bottom.

The bunch length is reported as the FWHM of the primary (nth+1) Gaussian. As shown in Table 1, we observe a tendency for bunch length to decrease with a rising magnetic field.

Table 1: Bunch Length at Low, Nominal, and High B Field Values

Magnetic Field [T]	Bunch Length [°]
0.498 ± 0.03	38 ± 4.5
0.534 ± 0.03	26 ± 4.5
0.566 ± 0.03	20 ± 4.5

Relative phase shift was determined by the beam arrival time, which was taken to be the centroid of the Gaussian fit. We define a reference phase shift value of zero at the nominal magnetic field strength (0.534 T). As simulation predicted, the data exhibited a linear relationship between relative phase shift and magnetic field, which can be seen in Fig. 5. The error in the phase shift was taken to be the FWHM of the Gaussian fits in the analysis. Large errors can be attributed in part to high noise levels caused by background light in the gated camera. Additionally, during the experiment, current to the magnet was not continuously increased so as to follow the hysteresis loop. This practice came from the necessity of locating the nominal field first, then moving to higher and lower magnetic fields. Uncertainty in field strength is dominated by measuring the magnet current.
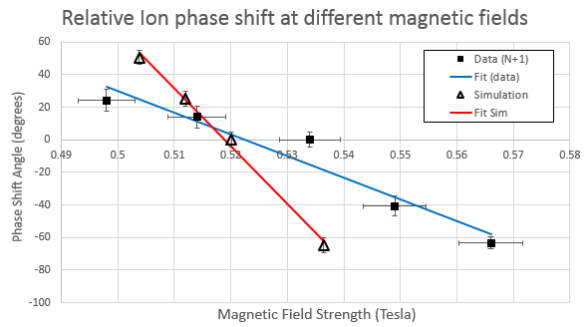

Figure 5: Relative phase shift with linear fit.

IMPROVEMENTS

Several improvements can be made to increase the precision of measurements using this technique. First, a larger "fast" phosphor plate could be made, which should stop the entire beam in one revolution and eliminate the need to separate nth and nth+1 turns in the data. Furthermore, we believe that the aluminium backing attenuated the proton beam and therefore reduced signal from the beam. This problem could be addressed by having the beam incident on the imaging side of the plate, or by reducing the thickness of the backing. Also, ideally the camera could be placed closer to the plate; however this was not possible with the lens used in this experiment. Finally, improved RF cooling would enable operation in continuous wave (CW) mode.

CONCLUSION

We have developed an optical method to measure ion beam bunch length and relative phase in the central region. This optical method mitigates measurement difficulties due to interfering RF fields near the accelerating gaps, and enables measurements to be made arbitrarily close to the ion source. Our phase shift observations agree qualitatively with simulation, but absolute agreement is yet to be achieved. To refine our simulations further, we are experimentally measuring the DEE voltage at 7.8 MHz.

REFERENCES

[1] K. Ruisard et al., "The Rutgers Cyclotron: Placing Student's Careers On Target," WE1PB02, these proceedings.

[2] T.W. Koeth, "Beam Physics Demonstrations with the Rutgers 12-Inch Cyclotron," Cyclotrons 2013, Vancouver, Canada, WEPPT025, these proceedings.

[3] *SIMION, simion.com.*