RHIC INJECTION TRANSPORT BEAM EMITTANCE MEASUREMENTS*

J. Huang#, Duke University, Durham, North Carolina 27708, USA
D.M. Gassner, M. Minty, S. Tepikian, P. Thieberger, N. Tsoupas, C. Zimmer
Brookhaven National Laboratory, Upton, New York 11973, USA

Abstract

The Alternating Gradient Synchrotron (AGS)-to-Relativistic Heavy Ion Collider (RHIC) transfer line, abbreviated AtR, is an integral component for the transfer of proton and heavy ion bunches from the AGS to RHIC. In this study, using 23.8 GeV proton beams, we focused on factors that may affect the accuracy of emittance measurements that provide information on the quality of the beam injected into RHIC. The method of emittance measurement uses fluorescent screens in the AtR. The factors that may affect the measurement are: background noise, calibration, resolution, and dispersive corrections. Ideal video Offset (black level, brightness) and Gain (contrast) settings were determined for consistent initial conditions in the Flag Profile Monitor (FPM) application. Using this information, we also updated spatial calibrations for the FPM using corresponding fiducial markings and sketches. Resolution error was determined using the Modulation Transfer Function amplitude. To measure the contribution of the beam's dispersion, we conducted a scan of beam position and size at relevant Beam Position Monitors (BPMs) and Video Profile Monitors (VPMs, or "flags") by varying the extraction energy with a scan of the RF frequency in the AGS. The combined effects of these factors resulted in slight variations in emittance values, with further analysis suggesting potential discrepancies in the current model of the beam line's focusing properties. In the process of testing various contributing factors, a system of checks has been established for future studies, providing an efficient, standardized, and reproducible procedure that might encourage greater reliance on the transfer line's emittance and beam parameter measurements.

INTRODUCTION

The beam emittance measurements that were performed in various sections along the 580 m long AtR transfer line rely on a series of profile monitors equipped with mostly CCD cameras [1] to help determine the values of the beam parameters prior to injection into RHIC. Two sections of the AtR transfer line are being used to make beam emittance and beam parameter measurements between the machines that are of particular importance given that lower emittance allows for more frequent collisions, in turn producing a desirably higher luminosity.

The beam emittance and beam parameters' measurements are derived from measurements of the horizontal and vertical beam sizes at three separate locations together with the known strengths of the magnets in the AtR [2, 3].

By testing the sensitivity of emittance on factors such as calibrations, resolution, dispersion, and noise under uniform conditions, a straightforward method of measurement that can be applied to future studies was established.

OFFLINE EMITTANCE ANALYSIS

During the RHIC run we collected beam profile data from a variety of flags in the AtR line that were measured under different conditions. This beam profile information was logged for later use because a majority of our analysis was performed offline after the run cycle ended. In order to calculate and test the dependence of emittance to different parameters, we used the logged data and a script file that reads the saved input files and outputs the measurements in the form of the standard deviation (sigma) of the beam profiles. Given that emittance has a dependency on horizontal and vertical sigma values, we tested each potential factor by applying its impact, measured as a ratio or multiplier, to sigma. After editing a file of sigma's to adjust for the factor of interest, we ran the emittance script to determine the corrected measurements and re-evaluate the emittance.

INITIAL CONDITIONS

The beam emittance and beam parameter measurements in the AtR transfer line rely on VPMs which are plunged in and removed from the beam pipe through the FPM controls application which is an interface that allows users to alter configuration settings while viewing immediate results in one of four equally capable frame grabbers, or viewing windows. While inserted, the beam hits and illuminates the phosphor (Gd_2O_2S:Tb) screen; the image data is displayed and automatically logged. The 12 flags are distributed along the transfer line and separated into four sections named the U, W, X, and Y lines. Based on location, flags of interest for this study are UF3, UF4, UF5, WF1, WF2, and WF3 of the U and W-lines, corresponding to the transfer line between the AGS up to the switching magnet that deflects beams into either of the two RHIC accelerators.

The goal of our work was to test factors that affect emittance measurements as a means to produce an efficient method of acquiring accurate data during future run cycles. Before delving into these properties, however, ideal and uniform initial conditions were necessary. The FPM application offers a user-controlled environment for optimizing measurement conditions by way of optional background subtraction, intensity adjustment, and Range of Interest (ROI) selection. Previous research has elaborated on the potentially harmful effects of imperfect background subtraction and on the advantages of the ROI

*Work supported by the auspices of the US Department of Energy
julia.y.huang@duke.edu

ISBN 978-3-95450-141-0

function [4]. Background subtraction was therefore switched off for all scans.

Image intensity settings relate to gain and offset, or contrast and brightness, respectively. Using a python tape sequence, we acquired and plotted data sets to determine the effects of varying offset and gain settings on vertical and horizontal sigma and center of the beam profile. As an example, Fig. 1 illustrates the ideal offset range of 242-252 for which sigma remains constant. To avoid saturation, values on the lower end of this range were considered ideal. In the second scan, the gain was confirmed as having little effect on sigma while remaining in the viable range of 80-160. To confirm that accurate beam parameters were independent of beam intensity variations, we performed a scan of beam intensity and employed neutral density filters to conclude that there was no dependence of the beam profile for very low intensities and a maximum charge of 2 e11 protons per bunch.

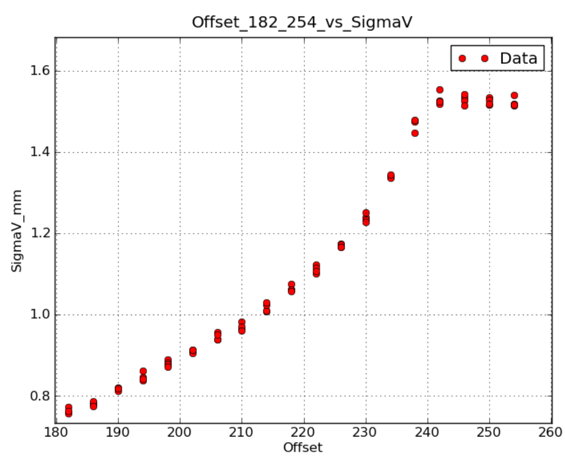


Figure 1: UF4 Flag with 1E11 protons per pulse, offset vs. vertical sigma intensity plot.

CALIBRATION

When discussing highly precise machinery and technology, it is reasonable to expect natural changes in positioning or accuracy of individual monitors and camera lenses. To counter this inevitable adjustment, we conducted a recalibration of flags in the U and W-lines using screen fiducial drawings from the commissioning of the transfer line. Marks on each drawing correspond to those on the phosphor screen of each flag and the comparison of theoretical and measured distances on these screens produced a corrective ratio.

Precise measurements of distance on flag screen images required a saved "bitmap" image from FPM. Since these images were Unix executable files, using an additional image processing software tool was necessary. ImageJ [5], a freeware available online, recognizes this file type, and offers the capability of viewing coordinate pixels on any imported image. Using the line tool and pixel display in ImageJ, we calculated the mm/pixel relationship to match existing calibrations using appropriate conversion factors.

By taking a ratio of the updated calibration over the existing value for each flag, we obtained corrective ratios. Since the measurement of interest in this study was emittance, we multiplied these ratios by measured sigma's from the initial scan to derive input data that demonstrated calibration effects on emittance measurements. These new values are shown in Fig 5.

PROFILE MONITOR RESOLUTION

The resolution of the AtR video profile monitor system is measured using a translation of the Modulation Transfer Function (MTF) for a bitmap under ideal intensity conditions with no suppression of the baseline. MTF is defined in equation 1.

$$MTF = \frac{(Peak - Valley)}{(Peak + Valley)} \tag{1}$$

Plot profiles of ruler sections on bitmaps in ImageJ provided average peak and valley values for each flag of interest. Resulting MTF amplitudes (contrast) ranged from 0.214 to 0.445, with four flags falling short of the ideal ratio 0.33, which corresponds to 200 micron resolution. As a result, we used a "PatternCalc" Excel program to generate a resolution coefficient, or Line Spread Function, from the contrast percentage. Using the adjusted input files, we corrected the emittance measurements based on the resolution of each flag.

DISPERSION

In the fall 1995 commissioning of the AtR transfer line, an early attempt to measure dispersion was made by adjusting magnet strengths to different extraction energies [6]. Unfortunately, too many influential variables were involved, thereby compromising the validity of results.

During the 2013 run cycle, we performed a dispersion scan at BPMs and flags by changing the AGS extraction frequency by 1 Hz steps for a range of -5 Hz to +5 Hz (Fig. 2). A correlation plot of this energy change ($G\gamma$) and BPM position (Fig. 3) provides a slope equal to the dispersive contribution [eq. 2a-2d]

$$x = a \cdot G\gamma + b \tag{2a}$$

$$a = \frac{\partial x}{\partial G\gamma} \tag{2b}$$

$$Dx = \frac{\frac{\partial x}{\partial G\gamma}}{G\gamma} \tag{2c}$$

$$Dx = a \cdot G\gamma \cdot 10^{-6} \tag{2d}$$

where $G\gamma$ is a convenient energy scale, G is the anomalous part of the proton magnetic moment (1.7928), γ=E/m with E as beam energy and m as proton mass. Equation 2d represents horizontal dispersion in meters.

Similarly, the dispersion at each flag was calculated with a correlation of $G\gamma$ at each flag plotted against position (horizontal center in pixels). This method required additional conversion factors to apply previously determined calibrations and convert units from pixels to meters. Dispersive contribution was measured using two methods at two locations for assurance, but this preferred method was applied to each flag location for additional corrective values.

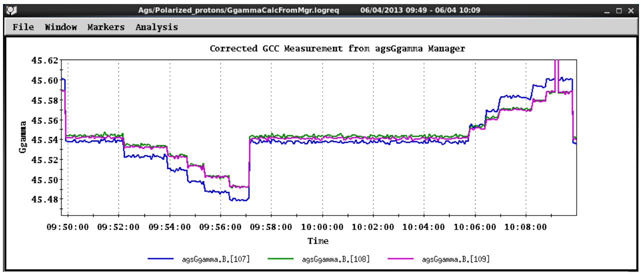


Figure 2: $G\gamma$ values for each time/frequency step.

Interestingly, the introduction of dispersive corrections had negligible effects on emittance, suggesting future studies can plausibly ignore this correction as shown in Fig 5.

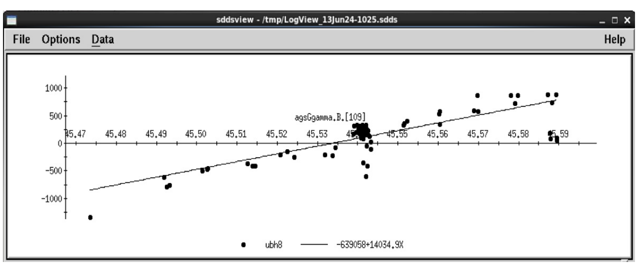


Figure 3: $G\gamma$ vs. BPM position fitted correlation plot.

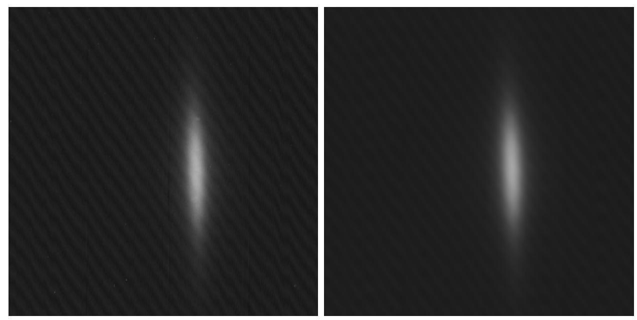
BACKGROUND NOISE

Figure 4a shows a high frequency noise pattern, or electromagnetic interference (EMI) drifting diagonally through the digitized image. This pattern is likely the result of upper harmonics in the switching power supply coupling to our analog video signal, but time has not yet been allocated to study this for confirmation. Background subtraction as a function in FPM was deemed overpowering in the 2011 study [4], but an alternative could be use of software filters like the Gaussian blur. This low pass filter blurs the EMI noise while maintaining integrity of the beam spot, in effect removing disruptive frequencies from raw data as shown in Fig 4b.

In this study, EMI noise suppression is performed on the bitmap of each flag with the most noticeable noise for optimal corrections in emittance. We use ImageJ to obtain initial standard deviations as well as new values after applying a Gaussian blur with a tested sigma (radius) of 3.0. A ratio of initial to final standard deviation produces the corrective ratio, which is then multiplied by sigma values already corrected for the previous three factors. Refer to Figure 5 for noise-corrected emittance results.

RESULTS/CONCLUSIONS

Beam emittances and beam parameters were measured at two different intensities along both horizontal and vertical planes to test the effects of calibration, resolution, dispersion, and EMI noise corrections. Both lower intensity and noise suppressed beams generally produced lower emittance measurements, whereas calibration and resolution corrections adjusted emittance on a case-by-case basis. Since our data collection method demonstrates no immediate problems, it is possible that the existing model of the magnetic optics of the transport line holds some inaccuracies. Future studies might then benefit from closer examination of actual magnet performance between the flags, together with the code used to evaluate emittance and the beam parameters.



Figures 4a-4b: WF2 bitmap with and without Gaussian blur of radius 3.0. Image at right is after the filter is applied.

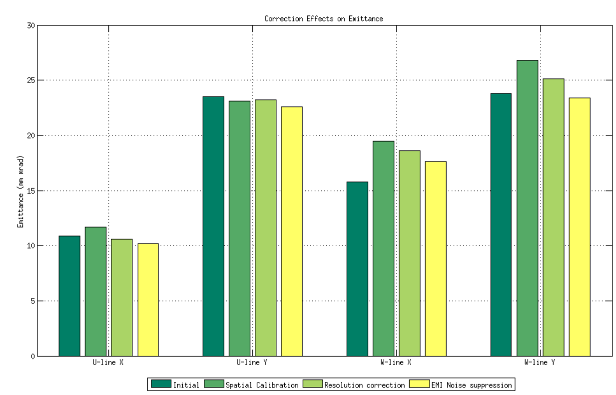


Figure 5: Average horizontal and vertical emittance measurements (in mm-mrad) for varying factors at U and W-lines. Dispersive corrections are not shown because they are negligible.

ACKNOWLEDGMENTS

Thanks to the operations staff in the Main Control Room for their cooperation and help with data acquisition during the 2013 run cycle.

ISBN 978-3-95450-141-0

REFERENCES

[1] R. L. Witkover, "Design of the Beam Profile Monitor System for the RHIC Injection Line", TPB26, PAC'95, Dallas, Texas, USA, (1995).

[2] N. Tsoupas et al., "A Computer Code to Measure the Beam Emittance and Beam Parameters of the ATR Line", BNL C-A/Accelerator Physics note 42, March 2001.

[3] M.C. Ross et al., "Automated Emittance Measurements in the SLC", p. 725, PAC'87, Washington DC, USA, (1987).

[4] P. Thieberger et al., "Baseline Suppression Problems for High Precision Measurements Using Optical Beam Profile Monitors", MOP208, PAC'11, New York, USA, (2011).

[5] http://imagej.nih.gov/ij/

[6] T. Satogata et al., "Physics of the AGS-to-RHIC Transfer Line Commissioning", MOP006G, EPAC'96, Sitges, Spain, (1996).