MEASUREMENT OF BEAM OPTICS DURING ACCELERATION IN THE RELATIVISTIC HEAVY ION COLLIDER

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Abstract

Measurements of the beam optics during acceleration have been performed at the Relativistic Heavy Ion Collider (RHIC). The results were used to obtain a measure of the maximum amplitude of the beta-beat envelope during acceleration which are of interest in the context of emittance and polarization preservation. The measured beta functions were then interpolated to locations of beam profile monitors for more accurate determination of the transverse beam emittances during the energy ramp. In this report we summarize recent improvements in the experimental methods, describe the measurement procedure and present experimental results.

INTRODUCTION

Optics measurements during acceleration are here based on excitation of the beam using pulsed kicker magnets (from the RHIC tune measurement system, ARTUS [1]) as opposed to driven excitations using AC dipoles [2], which are not well suited for measurements during the energy ramp. The response of the beam's change in centroid position was measured using beam position monitors (BPMs). Compared to measurements made previously [3] using the ARTUS kicker magnet [1], the measurement precision has been substantially improved by numerous enhancements made in the BPM and data delivery systems and by the application of continuously operating orbit and tune/coupling feedback [4] used to ensure reproducible and stable conditions during acceleration. For beam optics measurement during the energy ramp, a coherent beam oscillation was excited and single-bunch turn-by-turn (TBT) BPM measurements were acquired. These were carefully interleaved with average orbit measurements used by the orbit feedback. The TBT data were acquired at a selectable maximum rate possible (depending on whether acquisitions were desirable in both RHIC accelerators simultaneously) as limited by the data delivery times. The results were analyzed using slightly modified adaptations of existing frequency-based analyses [5-7] as described in Ref. [8].

In this report we summarize the improvements leading to reliable and robust measurements, describe the measurement procedure and present experimental results.

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TURN-BY-TURN BEAM POSITION MEASUREMENTS

Past beam optics measurements in RHIC were sometimes compromised by poor BPM performance [9]. During the early years of RHIC operation, modifications (e.g. electronics relocation, gain relay modifications) were made and automated timing scans were developed which contributed to substantially improved performance [10, 11]. Then several issues specific to the turn-by-turn BPM system were resolved: timestamp errors were eliminated (2008), FireWire (IEEE serial bus interface) error checking and staggering using software loop delays were implemented (2009), a RAM data corruption source was located in the integrated front end of the signal processing electronics and corrected (2009), changes were made to interrupt priorities (2009), and Sederta-card memory corruption was identified and eliminated (2010).

DETERMINISTIC DATA DELIVERY

During the shutdown before the RHIC FY11 run, a digital test mode was developed to ensure reliable and robust delivery of TBT BPM data and executed over many months. For each of the ~650 BPMs in RHIC, a test pattern was set at a 0.25 Hz rate in the TBT data array of the local signal processing unit. The received patterns, as logged by the RHIC control system, were subtracted from the expected patterns to detect data handling errors. While the symptoms of data delivery errors were varied (values missing, values repeated, etc.), it was found that they were primarily due to stale data being read back (if overloaded, the Sederta card lost a portion of data and delivered data previously saved in the circular buffer). The errors were solved by further staggering of data transmitted over FireWire using now the RHIC beam sync link turn counter to more precisely stagger the delays to prevent data transmission time overlaps between BPMs. After these modifications, error-free data delivery using the digital test mode was demonstrated: >100,000 acquisitions were performed, where 1 acquisition corresponds to readout of 1024 turns from all BPMs, or about 70 billion readings, with no errors.

ACQUISITION METHODOLOGY

Measurements of the beam optics were made reproducible by ensuring reproducible beam orbits and betatron tunes using the now standard beam feedback systems during acceleration. While orbit and tune feedback operate independently, the BPM measurements used by orbit feedback and the turn-by-turn BPM measurements share the same networks for data delivery. The timing of the delivery of beam position measurements for these two systems was therefore carefully staggered to avoid data corruption.

A conceptual sketch showing the data acquisition methodology is shown in Fig. 1. Orbit feedback operated at its standard 1 Hz rate. We allowed 200 ms corresponding to an upper limit on the time to transmit all (4 planes from both accelerators) the average orbit BPM data well in excess of the 150 ms required based on previous measurements [12]. After delivery of the data for orbit feedback, the beam was excited in one plane followed a short time later by excitation in the other plane, where the spacing between applied excitations was set (~ 500 turns) to be longer than the decoherence time.

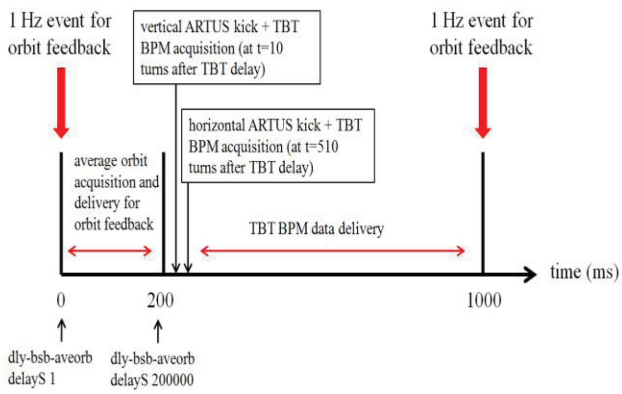

Figure 1: Conceptual sketch of carefully orchestrated timing to allow for turn-by-turn BPM acquisitions interleaved with BPM acquisitions required by orbit feedback during beam acceleration.

MEASUREMENT RESOLUTION

Following the above changes, the resolution of the turn-by-turn BPMs was first quantified using data acquired with continuous excitations provided by AC dipoles [13]. The resolution is here defined as the rms of the difference between the measurement and a sinusoidal fit to the measurement. In Fig. 2 is plotted in histogram format this rms for all BPMs for both transverse planes in both accelerators. Note that the resolution defined here represents an upper bound on the instrumental resolution; a correlation between poor resolution and large beta function (on either side of each interaction region) was determined by Fourier analysis to be due to residual oscillations of the beam (of about 10 Hz [11, 14], which for even higher precision analyses could be fit and removed from the data arrays).

APPLICATIONS

The Run-13 [15] ramp optics data were initially used [16] to determine the betatron tune spread along the energy ramp, which is important in the context of preservation of the proton beam polarization during acceleration. At that time a new beam optic designed for operation of new electron lenses [15,17] was being developed. An unexpected observation, namely reported shrinking beam emittances while establishing beams (i.e. “squeezing”) for collision was observed in the yellow ring which provided motivation for interpolation of the beta function measurements [18] to the locations of the ionization profile monitors (IPMs, [19]) which measure the transverse beam sizes.

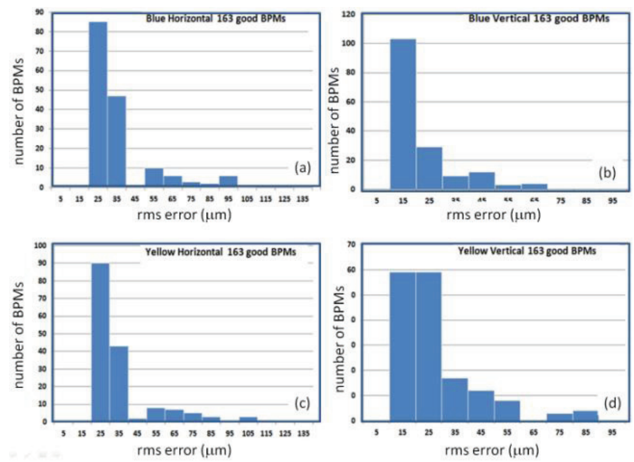

Figure 2: Resolution of turn-by-turn BPM measurements in histogram format for the blue/yellow ring horizontal plane (a)/(c) and vertical planes (b)/(d).

To investigate this further, ramp optics measurements were acquired. Shown in Fig. 3a/b are the model and measured beta functions at the IPMs in the two transverse planes. For reasons that are not yet understood the measured local beta function was observed to decrease while the model beta function, which is assumed for conversion of the beam size to emittance for online reporting, increased. The emittances (95%, normalized) derived using the model and measured beta functions are plotted in Figs. 3c/d. Using the measured beta functions, the emittances were constant - certainly not decreasing. These results are consistent with those acquired at the same time from the fluorescence monitor [20] which also indicated constant beam size while the model beta function increased.

Another example of beta function measurements at the RHIC IPMs is shown in Fig. 4 acquired with the lattice used for most of the FY13 run. The data shown here were acquired with a 1 Hz acquisition rate (ref. Fig. 1) in both accelerators. In all four planes the agreement between model and measured beta functions was observed to be best about midway during the acceleration cycle (which happens to be consistent with the tune errors seen by the tune feedback loops).

The evolution of the beta- and phase-beats during acceleration as measured by all BPMs was evaluated (and available in movie-style format). The amplitude of the envelope of the beta-beating in the accelerator arcs was consistent with those shown in Fig. 3.

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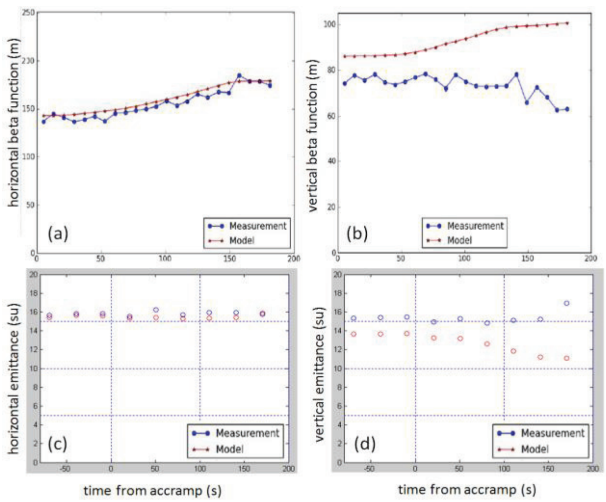

Figure 3: Model (red) and measured (blue) beta functions in the horizontal/vertical planes at 255 GeV during the final beta squeeze (a/b); IPM emittances (95%, normalized in mm-mrad) reported using the model (red) and measured (blue) beta functions in same planes (c/d).

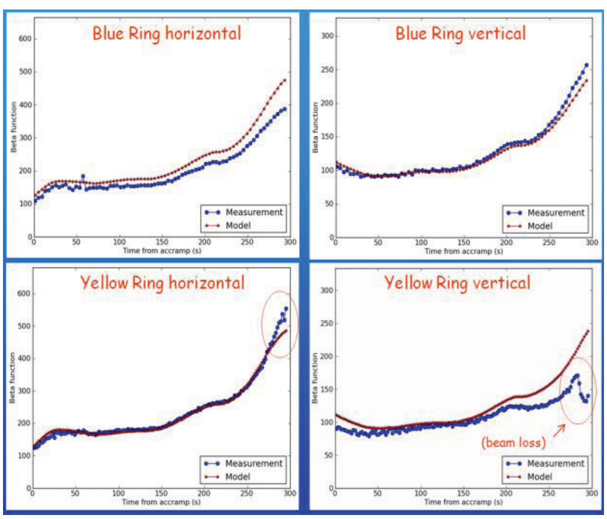

Figure 4: Model and measured beta functions at the 4 RHIC IPMs during acceleration of protons to 255 GeV.

SUMMARY

Numerous improvements in the BPM system have been completed over the years including most recently dedicated tests resulting in guaranteed error-free delivery of TBT data. The resulting resolution of the BPMs was measured and found to be excellent. This motivated further application of ARTUS-based beam optics measurements during beam acceleration in RHIC. With careful management of the transmission of BPM data used for orbit feedback and for TBT acquisitions, beta- and phase-beating were measured during the energy ramp and during the final beta squeeze in before collisions.

The results revealed that the presently used approach to optics correction based on fixed energy correction at injection and store with corrections propagated forward and backward, respectively, into the energy ramp [7,18] is appropriate. The measurements were also applied to better understand the beam emittances with measurement errors dominated by the uncertainty in the beta functions.

Efforts continue to utilize these ramp optics measurements for both validating corrections and for development of new methods for directly applying corrections during acceleration [21].

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