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OPTICS MEASUREMENT AND CORRECTION DURING ACCELERATION WITH BETA-SQUEEZE IN RHIC*

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Abstract

In the past, beam optics correction at RHIC has only taken place at injection and at final energy, with interpolation of corrections partially into the acceleration cycle. Recent measurements of the beam optics during acceleration and squeeze have evidenced significant beta-beats that, if corrected, could minimize undesirable emittance dilutions and maximize the spin polarization of polarized proton beams by avoiding the high-order multipole fields sampled by particles within the bunch. We recently demonstrated successful beam optics corrections during acceleration at RHIC. We verified conclusively the superior control of the beam realized via these corrections.

INTRODUCTION

It is desirable to minimize the machine optics (β-functions/phase advances) errors during beam acceleration to improve dynamic aperture for heavy ions and reduce depolarization resonance strengths for polarized proton program. However, it is not practical to pause at step-stones for optics measurement and correction in the simultaneous beam acceleration and beta-squeeze ramp. We demonstrated recently an on-the-fly beam optics measurement during beam acceleration and successfully implemented corrections which substantially suppressed beta-beats on the ramp in RHIC. The method of the measurement and correction is presented in the following sections.

BEAM OPTICS MEASUREMENT DURING BEAM ACCELERATION

Turn-by-turn measurements of the beam position with an applied excitation to the beam has been used at many accelerators to infer fundamental optical parameters such as the tune, the phase advance between BPMs, and with input from the accelerator model, the β-functions. Many different algorithms for data analysis have been successfully applied such as fitting in time domain [1], interpolated FFT technique in frequency domain [2, 3, 4] and statistical techniques (PCA, ICA) [5, 6] finding beam motions in a high dimension data. The interpolated FFT technique was adopted in this report to analyze the machine optics in RHIC.

The acquired turn-by-turn BPM data with the beam kicked by the tune meter kicker multiple times usually oscillates for less than 500 turns because of decoherence for a typical chromaticity setting (∼2 above transition, ∼-2 below transition). The application of interpolated FFT analysis on these BPM data yielded high precision tune, phase advances and β-functions measurement despite the limited data points acquired. This demonstration opens up the possibility of acquiring turn-by-turn BPM data with the tune meter on the ramp for optics measurement [7, 8].

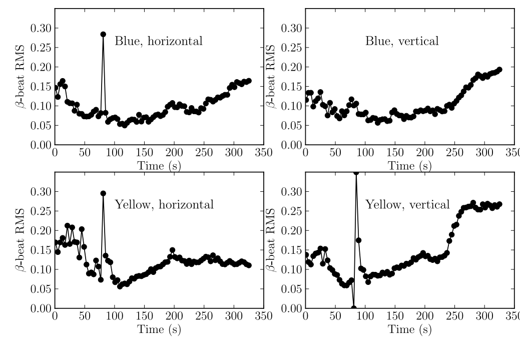

Figure 1: The measured beta-beats during beam acceleration (high energy Au-Au, 2014). Transition crossing occurs at ∼ 85 seconds after the start of acceleration.

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. 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 [9]. 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.

Since the volume of data being acquired is large, we present the deviation of the machine optics in the form of global beta-beat Root-Mean-Square (RMS) during beam acceleration. Figure 1 shows the RMS beta-beats at each time of optics measurement during beam acceleration for the Au-Au physics ramp in 2014.

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BEAM OPTICS CORRECTIONS DURING BEAM ACCELERATION

The optics errors manifest themselves as beta-beat or phase advance errors. Both errors can be corrected by adjusting quadrupoles strengths based on a linear system model because their responses to quadrupole gradient changes are linear in the range of our consideration [10, 11, 12, 13, 14, 15, 16]. Correction of global beta-beat and phase errors has been demonstrated successfully with implementation for accelerator operations at RHIC in 2013 [17]. The basics of the two corrections being applied in RHIC are similar. Suppose $(e_1, e_2, \ldots, e_m)'$ is the optics error (beta-beat or phase errors) being measured, M is the response of the optics errors to quadrupole strength variations in the form of a matrix. The correction can be obtained by solving the following equations:

$$-\begin{pmatrix} e_1 \\ e_2 \\ \vdots \\ e_m \end{pmatrix} = \begin{pmatrix} M_{11} & M_{12} & \cdots & M_{1n} \\ M_{21} & M_{22} & \cdots & M_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ M_{m1} & M_{m2} & \cdots & M_{mn} \end{pmatrix} * \begin{pmatrix} k_1 \\ k_2 \\ \vdots \\ k_n \end{pmatrix} \quad (1)$$

The optics errors on the left side are from both planes, on which proper weights can be applied based on the scale of the errors. The correction knobs in RHIC are the 72 quadrupoles with trim power supplies which all reside in the interaction regions [18].

Optics Correction at Injection and Store in RHIC

At nominal injection energy, $\sim 23GeV$ for proton and $\sim 10GeV$ for gold beam, the optics errors were constantly monitored to be moderate. It was considered as necessary to correct the optics only if the peak-to-peak beta-beat exceeded 20% at injection. The optics correction is not expected to alleviate the emittance growth in the heavy ion case which is dominated by the intra-beam scattering, nor improve the lifetime for any species at injection.

In low energy runs in which the beam energy is lower than the nominal injection energy, the sextupole components in the dipole magnets can have a significant effect on the optics [19]. The optics error can be substantial enough so that applications based on model optics would not work properly. Furthermore, the deviation of beta stars at the colliding IPs should be corrected for better luminosity. These two reasons justify the necessity of optics corrections for low energy runs, as well as the potential of better beam lifetime. The turn-by-turn BPM data from injection oscillation was used for optics analysis and correction [20]. The data acquisition was purely parasitic so that the optics was monitored for each physics store for the whole low energy run in 2014. This removed the burden of acquiring turn-by-turn BPM data by kicking the bunches whose intensity was on the low end limit for BPM monitoring. The corrections were applied in both rings. The beta-beat before and after the correction is shown in Fig. 2 for the Yellow ring only. The upper and lower plot show the horizontal and vertical beta-beat. The blue data points show the beta-beat before corrections and red points are from after corrections.

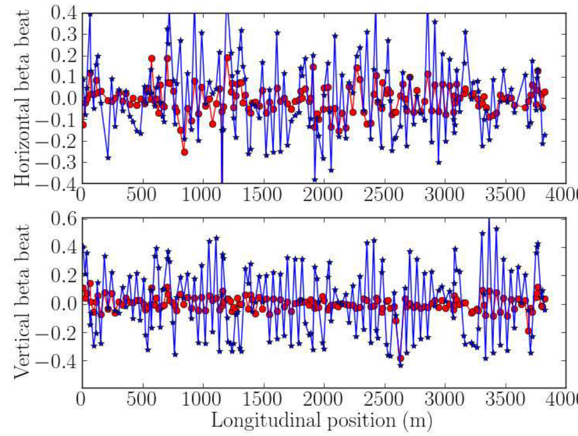

Figure 2: The beta-beats before and after optics correction in the Yellow ring for low energy run in 2014: the upper and lower plot show the horizontal and vertical beta-beats. The blue data point is the beta-beat before the corrections and red is after the corrections.

At store, BPM data for optics measurement was acquired by kicking the bunch with the tune meter kicker and recording the beam positions. The optics was usually measured when beams were not in collision to avoid beam-beam induced linear optics distortion. The principle of applying optics correction at store is the same as at injection. However, it is more desirable to have optics corrected at store for the direct benefit on the luminosity and luminosity lifetime. The results of optics correction at store will be presented in the following subsection together with the results of the optics correction during beam acceleration.

Optics Corrections during the Rotator Ramp

The first correction was applied during the fixed-energy rotator ramp for which the β-functions and phase advances are constant by design. This was motivated by large optical errors detected at the end of collision setup. The concerns about implementing the ramp optics correction related to potential beam loss and emittance dilution. As a test during the 2013 proton program [21], we applied corrections on a rotator ramp executed with fewer bunches (12 per accelerator) to study these effects. This test ramp had the same magnetic settings as a physics ramp. Optics corrections were applied to six intermediate points during the rotator ramp.

The results of the test negated concerns about adverse effects of ramp optics corrections; the beam loss on a subsequent ramp performed with only 12 bunches was actually less with optics correction implemented. Also, the IPM reported emittances for the test ramp was similar to those from a physics ramp with bunches filled fully in RHIC. In addition, the calculated beam emittance inferred from beam collision signals was similar as measured in physics stores. To avoid interference with other changes being

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made in the Blue ring, we implemented the correction for the rotator ramp for the physics program in the Yellow ring later. The rest of the 2013 run was executed without any complications with corrected optics during the rotator ramp in the Yellow ring.

Optics Corrections during the Energy Ramp

Ramp optics correction for the energy ramp was tested twice in 2013 [21]. Ramp optics measurement was performed on a 12 bunches per accelerator ramp first. Then the turn-by-turn BPM data near the step-stones were selected for analysis of linear optics and calculation of optics corrections. The correction strengths at those step-stones were implemented through the RampEditor application. The problem encountered in the first attempt was that each time a set of strengths were sent to a step-stone in RampEditor, the on-line model recalculated all relevant magnet strengths for the whole ramp which was too time-consuming. The solution was to send all correction strengths for a step-stone once, not separately. The other way around is to hold constant (anchor) the magnet strengths for the relevant step-stones so interpolation of magnet strengths will not occur after implementing corrections. The two ways are similar because changing strengths for a step-stone would anchor it as well. The problem encountered in the second attempt was that the current curves for the magnets would change dramatically with step-stones settings being anchored, which caused power supplies to exceed their limits.

The difficulties of applying optics correction on the energy ramp were circumvented by a new strategy of implementation, proposed after the correction strength for all step-stones are examined. The calculated correction strength for all 72 trim quadrupoles in the Yellow ring on the energy ramp are displayed in Fig. 3. With the exception of the strength changes around transition crossing at around 85 second in the ramp, the required correction strength are linear between the dashed lines, which represent the step-stones where the settings for quadrupoles (some or all) are fixed. This prompted a strategy of implementing corrections only for the step-stones at the dashed lines, with correction strengths for every stones in-between dashed lines automatically interpolated. The change of strategy helped on reducing the number of corrections and avoiding the unnecessary anchoring of the quadrupoles strengths.

The global beta-beats before and after two iterations of corrections are presented in Fig. 4.

SUMMARY

The optics measurement during beam acceleration in RHIC was first demonstrated and implemented during operations in 2013. The measurement results have been used to find abnormality of the ramp (for example, unphysical emittance change on the ramp), determine gradient errors and corrections, interpolate the measured optical functions to intermediate locations (e.g. at IPs, IPMs, polarimeters, Schottky detectors) and facilitate the tuning of the acceleration ramp. The difficulties encountered when implementing optics correction during beam acceleration in 2013 was overcome after measurements revealed that applying corrections for selected step-stones would be sufficient. The interpolated corrections for any point in-between those selected step-stones worked well for the ramp. The optics correction during beam acceleration was implemented operationally for high energy Au-Au and He3-Au physics programs in 2014. The beta-beats was reduced substantially on the ramp for the first time in a hadron collider by the optics correction during beam acceleration.

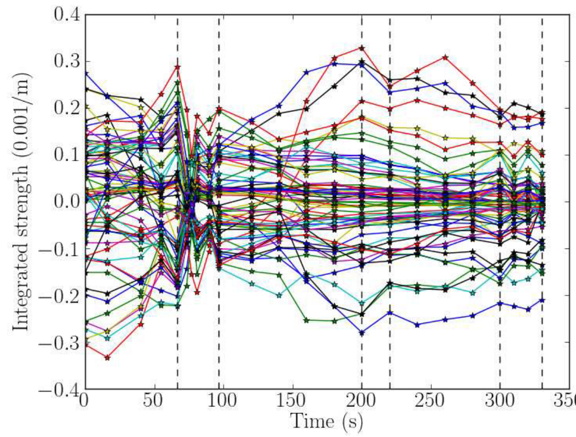

Figure 3: The calculated correction strength for the 72 trim quadrupoles in the Yellow ring on the energy ramp, the dashed lines are at the step-stones where settings for quadrupoles (some or all) are fixed. The horizontal axis is the time in seconds from the time the acceleration ramp starts.

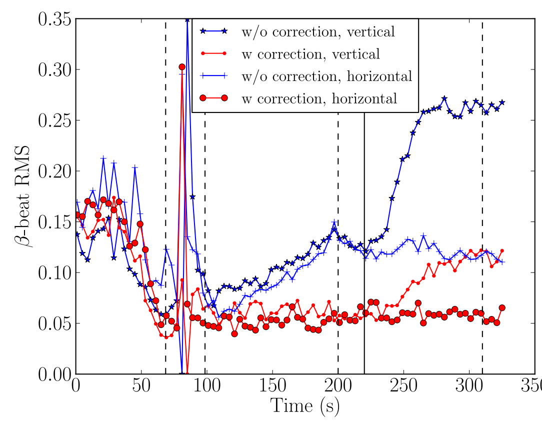

Figure 4: The measured global RMS beta-beats in the Yellow ring with (w) and without (w/o) ramp optics corrections. Optics corrections were implemented at 6 intermediate energies, at the times indicated by the vertical lines, with linear interpolation in-between.

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