First Demonstration of Optics Measurement and Correction during Acceleration with Beta-squeeze in a High Energy Collider

C. Liu*, A. Marusic, M. Minty

Brookhaven National Laboratory, Upton, NY, U.S.A.

Abstract

Setting up collisions in high energy circular colliders requires beam acceleration and “beta-squeeze”. The latter produces small beam sizes, and hence, high luminosity by applying strong focusing with quadrupoles near the interaction points. At the Relativistic Heavy Ion Collider (RHIC), these two processes, beam acceleration and beta-squeeze, have been performed simultaneously during recent years. 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 beam optics corrections during acceleration at RHIC. As a valuable by-product, these corrections minimized the beta-beat at the profile monitors, so providing more accurate measurements of the evolution of the beam emittances during acceleration.

Keywords: linear optics, optics correction, beta-beat, emittance, dynamic aperture

1. Introduction

Measurement and correction of the optics during beam acceleration is desirable especially for large synchrotrons with acceleration duration on the or-

*Email: chunliu@bnl.gov
Preprint submitted to Elsevier

January 6, 2016

27 der of minutes. Measurement of the optics during acceleration improves the
 28 understanding of the evolution of beam parameters (e.g. beam emittances).
 29 At RHIC, correction of the optics also provides improved beam control since
 30 model-dependent beam-based feedbacks are used during acceleration. Correc-
 31 tion of the optics during acceleration could also improve the dynamic aperture
 32 for heavy ions and reduce the strengths of depolarization resonances for the
 33 polarized proton program by minimizing errors of the optics (β -functions and
 34 phase advances). However, it would be very time-consuming to pause at inter-
 35 mediate energies to allow measurement and correction of the optics during the
 36 simultaneous beam acceleration and beta-squeeze ramp. This motivated the de-
 37 velopment of a quasi-continuous, minimally invasive ramp optics measurement
 38 and subsequent implementation of optics corrections.

39 At the large hadron collider (LHC), optics measurements have been achieved
 40 at a limited number (six) of discrete energies during beam acceleration. These
 41 studies were motivated to better understand reported non-physical “growing”
 42 and “shrinking” emittances measured during beam acceleration [1]. Two data
 43 acquisition methods were employed. Turn-by-turn beam position measurements
 44 were acquired using a kicker to induce beam oscillations during acceleration,
 45 however, these data resulted in large uncertainties of the β -functions [2]. The
 46 optics measurements using an AC dipole driven excitation [2] produced better
 47 results which helped reduce the degree of reported emittance growth using the
 48 measured β -functions at the six energies and interpolation in-between for the
 49 emittance calculations. As reported in Ref. [2], the non-physical evolution of
 50 emittance was not understood completely due to the insufficient number (six) of
 51 β -function measurements during acceleration. Despite the large measured beta-
 52 beat amplitudes, optics corrections have not yet been applied during acceleration
 53 at the LHC [3].

54 At RHIC, the optics have been measured quasi-continuously and corrections
 55 implemented during acceleration to the full beam energies. The methodology
 56 of the measurement and correction will be presented in the following sections.
 57 In section 2, the measurement and analysis techniques for optics measurement

during beam acceleration will be introduced and measurement results will be presented. In section 3, beam optics correction during acceleration will be detailed for Au-Au lattice in 2014 [4]. In section 4, the improvements in ionization profile monitor (IPM) emittance measurements with optics corrections during beam acceleration will be presented. In section 5, the developments of optics measurement and correction during beam acceleration in RHIC will be summarized.

2. Beam Optics Measurement During Beam Acceleration

2.1. Overview of RHIC and its acceleration cycle

RHIC comprises two circular counter-rotating accelerators in a common horizontal plane, which are oriented to intersect one another at six interaction points with two colliding beam experiments (STAR and PHENIX) [5]. Each ring consists of three inner arcs and three outer arcs with six insertions joining them (Fig. 1).

Beam acceleration and beta-squeeze have been combined together in recent years for both the polarized proton program and the heavy ion program in RHIC as facilitated by the flexibility of the RHIC magnet ramping system [7]. There are two main advantages in combining acceleration and beta-squeeze; it improves time-efficiency and the insertion quadrupoles currents can be configured to be monotonically increasing on the way to top energy. Figure 2 illustrates the beam rigidity and its derivative (the acceleration rate), and the β -functions at the interaction points (β^*) on the ramp for the 100 GeV RHIC Au-Au physics program in 2014. The beta star at IP8 is the same as that for IP6 on the ramp, and reaches 0.7 m at store. The β^* at IP2, 4, 12 are the same as that for IP10 on the ramp, and stay at 5 m for the late part of the ramp. The horizontal and vertical β^* are equal at each IP.

2.2. Ramp optics measurement and analysis techniques

Turn-by-turn measurements of the beam position with an applied excitation to the beam is a technique that has been used at many accelerators to infer

87 fundamental optical parameters such as the tune, the phase advance between
 88 beam position monitors, and with input from the accelerator model, the β -
 89 functions. At RHIC we use both the AC dipole [8, 9] and the tune meter kicker
 90 [10] for optics measurements. For measurements during acceleration, only the
 91 tune meter kickers were used to excite betatron oscillations. The kickers produce
 92 a 140 ns full-width pulse with rise and fall times of ~ 10 ns [10]. With a 100 ns
 93 bunch spacing only a single bunch is excited leaving all other bunches unaffected.
 94 Free betatron oscillations in both planes are recorded using turn-by-turn BPMs
 95 after a bunch has been kicked multiple times. The number of kicks was adjusted
 96 to ensure a coherent oscillation amplitude in the range of 0.5 to 1 mm. Typically
 97 the number of kicks is ~ 4 at injection, ~ 19 at store energy and scales with beam
 98 energy during acceleration (rounded to an integer number). The turn-by-turn
 99 beam position measurement resolution is ~ 0.03 mm [11].

100 Due to the non-adiabatic excitation of the beam, the multiple kicks required
 101 for the optics measurements lead to emittance growth which can adversely affect
 102 the intensity of the kicked bunch. The expected emittance growth from applied
 103 excitations is discussed in Appendix A. The beam sizes at the final focusing
 104 quadrupoles on either side of each interaction point can become very large due
 105 to the beam emittance increase from the applied kicks and to the beta-squeeze
 106 towards the later part of the acceleration cycle. An automated procedure was
 107 applied which monitored the intensity of the bunch of interest and, if too low,
 108 switched to excite and detect a different bunch. Such dynamic bunch switch-
 109 ing allowed fully parasitic measurements executed periodically during machine
 110 setup periods. Comparison of emittance measurements with and without op-
 111 tics measurements showed no difference because the IPM averages over ~ 60
 112 bunches [12] and is therefore not very sensitive to emittance degradation of a
 113 single bunch.

114 The measurement of the average beam position was delivered at rate of 1
 115 Hz and used by orbit feedback to ensure reproducible conditions during beam
 116 acceleration. The turn-by-turn BPM data were acquired and delivered every 4
 117 s to generate a sufficient sampling of data for the optics measurements during

beam acceleration while maintaining tolerable beam loss on the kicked bunch. To avoid data corruption, the timing of the delivery of the measurements of average and turn-by-turn beam position was staggered carefully [13] thus allowing orbit feedback [14] to operate normally.

Many different analysis algorithms have been applied successfully on turn-by-turn BPM data such as fitting in the time domain [15, 16], the Fourier Analysis in the frequency domain [17, 18, 19, 20, 21] and statistical techniques (Principal Component Analysis, Independent Component Analysis) [22, 23] for characterizing beam motion. We adopted the interpolated FFT technique for this report to analyze the machine optics in RHIC. At RHIC, the coherent betatron oscillation usually loses coherence after 500 turns for a typical chromaticity ($\delta Q/(\delta p/p)$) setting (~ 2 above transition, ~ -2 below transition). Applying interpolated FFT analysis on these BPM data yielded high precision measurements of tune, phase advance and β -functions despite the presence of decoherence [24].

2.3. *Measurements of the optics during beam acceleration*

Acceptable signal-to-noise ratio of turn-by-turn beam position data was achieved by tuning of chromaticities during acceleration. The chromaticities during beam acceleration typically are optimized iteratively for improving beam transmission efficiency. Above transition for example, the chromaticities may be increased to enhance Landau damping, or lowered to reduce beam loss due to excessive tune spread. These adjustments usually result in acceptable signal-to-noise ratio of the turn-by-turn data, which prefers lower absolute chromaticities. Since the first ramp optics measurement occurred early during the initial beam setup, it was not obvious that the data would be of sufficient quality for extracting reliable optical information. Fortunately, the data collected under these non-optimal beam conditions could be used to infer corrections to the chromaticities, as had been applied for ramp tuning in earlier years [25]. After a few iterations of ramp optics measurements which were used to adjust chromaticities, we acquired measurements of beam positions for which the betatron oscillations lasted for the first ~ 200 out of 1024 turns following the excitation.

148 These data sets and the model machine optics were then used for the analysis
 149 of the linear optics. The optics model during beam acceleration was retrieved
 150 from the RHIC on-line model [26].

151 With turn-by-turn BPM data acquired every 4 s during beam acceleration
 152 in both rings, typically ~ 80 sets of data were collected during acceleration of
 153 beams to the full 100 GeV energy with total duration of ~ 5 minutes. Since
 154 the volume of data acquired is large, the deviation of the machine optics is pre-
 155 sented in the form of a global beta-beat Root-Mean-Square (RMS) [27] during
 156 beam acceleration. Figure 3 shows the RMS beta-beats at each time of optics
 157 measurement during beam acceleration. In all cases, the beta-beats at approx-
 158 imately $t = 100$ s into the acceleration cycle were near minimum and started
 159 to grow as the β -functions were squeezed at the interaction points starting at
 160 $t=200$ s. The relatively larger beta-beat in the vertical planes is due to the larger
 161 errors of the defocusing quadrupoles in the interaction region (IR) triplets based
 162 on the calculated correction strengths. Due to time limitations, only one data
 163 set was acquired before optics corrections were applied. Compared to the sta-
 164 tistical errors ($\sim 2\%$) presented in Ref. [24], the errors are expected to be larger
 165 ($\sim 5\%$) because the chromaticities had been set to high values to combat beam
 166 instabilities so ensuring high beam transmission efficiency during acceleration
 167 rather than optimized for measuring optics with high precision. The measure-
 168 ments around transition energy crossing at ~ 85 seconds were corrupted by poor
 169 signal-to-noise ratio in the beam position data due to faster decoherence from
 170 larger energy spread induced tune distribution.

171 *2.4. Interpolation of β -functions at intermediate locations*

172 The β -functions at locations of interest, for example at the ionization pro-
 173 file monitors (IPMs), were interpolated based on the measurements at nearby
 174 BPMs. Typically model β -functions are used for determining the beam emit-
 175 tances based on the measured beam sizes [28]. To assure better confidence in
 176 the emittance measurements it would be desirable to confirm whether these are
 177 consistent with the measured values. At RHIC, there are four IPMs, one for

each plane in both rings. The measured β -functions during acceleration at these IPMs are shown in Fig. 4 together with the model values. As the β -functions at interaction points were squeezed during acceleration, the deviation of the measured β -functions from the model values at the IPMs increased. The measured β -function reached $\sim$ twice that of the model value at the Yellow vertical IPM as shown in the lower right plot in Fig. 4.

A larger measured β -function implies a reported beam emittance larger than reality as the reported emittance used the model β -function. In 2013, new optics in support of the electron lens [29] was commissioned. The Yellow vertical IPM reported non-physical decreasing emittances during the final beta-squeeze. While the model β -function at that IPM increased during the final beta-squeeze, the measured beam size was more or less constant. The β -functions inferred from the ramp optics measurement revealed that the β -function at the IPM was actually flat, and decreasing in the later part of the ramp [13]. From these two examples, the knowledge of actual β -functions in the presence of model-to-accelerator errors was confirmed to be essential in understanding the evolution of beam emittance during acceleration.

3. Beam optics corrections during beam acceleration

Global beta-beat and phase advance errors can be corrected by adjusting the strengths of the quadrupoles based on a linear system model because their responses to changes in quadrupole gradient are linear in the range of consideration [30, 31, 32, 33, 34, 35, 36]. Correction of global beta-beat and phase errors at fixed energy was demonstrated successfully with its implementation for accelerator operations at RHIC in 2013 [36, 37].

Compared to optics correction at a fixed energy, there are a number of unique challenges associated with correction of beam optics during beam acceleration. These include: (1) the ramping of the magnet power supplies can not be stopped and tuned, (2) a large volume of corrections (typically 72 quadrupole power supplies at over 30 different times during the energy ramp), so requiring a

207 time-efficient implementation method, and, (3) the consequences of the optics
208 correction, such as change of tunes and chromaticities must be predicted and
209 simultaneously compensated for.

210 We first tested ramp optics correction during acceleration in 2013 [38]. A
211 problem encountered was that the current curves for the magnet power supplies
212 would change dramatically with the corrections being applied, which caused
213 the power supplies to exceed their limits. These difficulties were circumvented
214 by applying a new strategy of implementation proposed after examining the
215 correction strengths along the acceleration cycle. The calculated correction
216 strength for all 72 trim quadrupoles in the Yellow ring on the energy ramp
217 are displayed in Fig. 5. With the exception of the strength changes around
218 transition crossing, the required correction strengths are linear between the
219 dashed lines. This finding prompted a strategy of implementing corrections
220 only at the dashed lines with linear interpolation of the correction strengths in-
221 between. The change of strategy helped in reducing the number of corrections,
222 therefore avoided the unnecessary constraints on the curvature of the quadrupole
223 strengths and the associated strength excursions.

224 This new scheme of ramp optics correction was tested successfully during
225 the high energy Au-Au program in 2014. Six intermediate points (vertical lines
226 in Fig. 2 and Fig. 5) were picked for implementing the corrections. They are
227 at time $t = 65$ s where β^* are all squeezed to 5 m, time $t = 95$ s where the
228 β -functions at colliding interaction points continue squeezing after transition,
229 $t = 200$ s and $t = 220$ s where β^* at colliding interaction points reach 2 m,
230 $t = 310$ s where beam energy acceleration finishes, and $t = 320$ s (Fig. 2). The
231 global beta-beats before and after two iterations of corrections are presented
232 in Fig. 6. For the first iteration, the corrections were applied at the time of
233 dashed vertical lines. For the second iteration, the corrections were also applied
234 at $t = 220$ s (solid vertical line) to eliminate a beta-beat bump at that location.
235 The global beta-beats not only were greatly reduced at the vertical lines where
236 the corrections were implemented, but the beta-beats were suppressed on the
237 same scale for any time on the ramp where the corrections were interpolated.

Even though the benefit of optics correction around transition was not clear from the linear optics measurement, the beam loss around crossing transition was lower after implementing the corrections.

4. Benefit on emittance measurement due to optics corrections during beam acceleration

4.1. Measured versus model β -functions at IPMs

The β -functions at the IPMs on the ramp are of particular interest since the IPMs are the crucial tool for monitoring emittances during beam acceleration. The β -functions before and after implementing optics correction on the ramp are shown in Fig. 7, together with the design values. The agreement between the measured β -functions and the design values was significantly improved with optics correction during acceleration. This facilitated a much more accurate characterization of the emittance on the ramp.

4.2. Improvement of IPM reported beam emittances

The emittances for two consecutive ramps, with no other changes other than ramp optics correction, are shown in Fig. 8. A $\sim 40\%$ reduction of reported emittance was observed in the vertical plane, and $\sim 15\%$ reduction in the horizontal plane because the β -functions were closer to the design values with corrected ramp optics. The remaining bumps in Fig. 8 are believed to be mostly due to residual beta-beat on the ramp, and partially due to the statistics of the emittance measurement.

5. Summary

The optics measurement and correction during beam acceleration with beta-squeeze was demonstrated for the first time. The measurement results were used to determine gradient errors and corrections, interpolate the measured optical functions to intermediate locations (e.g. at interaction points, ionization profile monitors and other devices), identify abnormalities in the ramp (for example,

265 non-physical changes in emittance on the ramp), and facilitate the tuning of
 266 the acceleration ramp. The optics correction during beam acceleration was
 267 implemented during the high energy Au-Au program and at the start of the He3-
 268 Au physics program in 2014. For the first time in a hadron collider, the beta-
 269 beats were reduced substantially during beam acceleration with beta-squeeze
 270 using an efficient algorithm for parasitic optics measurements and correction
 271 during beam acceleration. The errors in reported emittances by the IPMs due to
 272 use of imperfect model β -functions were significantly reduced with the corrected
 273 optics.

274 Ramp optics measurement and correction at RHIC resulted after several
 275 new developments. The interpolated FFT analysis enabled optics measurement
 276 with good precision based on turn-by-turn data with decoherence. Therefore the
 277 tune meter kicker was chosen to acquire turn-by-turn BPM data, which then
 278 allowed for the quasi-continuous measurements during beam acceleration. In
 279 addition, the carefully staggered timing of the delivery of the measurements of
 280 closed-orbit and turn-by-turn beam position allowed for continued use of orbit
 281 feedback during the optics measurements.

282 Measurement of the optics during acceleration will be used to validate mod-
 283 ification to the magnetic optics as applied to reduce the strength of depolarizing
 284 resonances [39] for higher polarization transmission efficiency in future high en-
 285 ergy polarized proton runs at RHIC. Necessary adjustments can be calculated
 286 and applied using the same method as ramp optics correction. The method
 287 developed in RHIC on optics measurement and correction during acceleration
 288 can be applied in any large scale synchrotron, for example, LHC and proposed
 289 super colliders for Higgs factory [40].

290 **6. Acknowledgments**

291 We would like to thank A. Drees, R. Michnoff, I. Blackler, and G. Marr for
 292 their contributions towards the development of optics measurement during beam
 293 acceleration. We also thank W. Fischer, M. Blaskiewicz, G. Robert-Demolaize

(run coordinator for high energy Au-Au program in 2014), V. Ranjbar (run coordinator for 250 GeV polarized proton program in 2013), and the operational crews for their encouragement and support of our work. Also, we are grateful to V. Schoefer, G. Marr and T. Shrey for their support of our work during the startup prior to the physics run. This work was performed under Contract No. DE-AC02-98CH10886 with the U.S. Department of Energy.

Appendix A. Emittance growth from optics measurements during acceleration

A beam kicked transversely from the closed orbit executes betatron oscillations which decoheres due to tune spread similarly to the case the beam is mismatched in position and/or angle during injection. The unnormalized RMS emittance would grow due to the mismatch [41] by $\delta\epsilon/\epsilon_0 = [(\delta x)^2 + (\alpha_x \delta x + \beta_x \delta x')^2]/(2\beta_x \epsilon_0)$. The α_x and β_x are the Twiss parameters at the location of the error. The δx and $\delta x'$ are the position and angle error respectively. The kicks introduced by the tune meter kicker during ramp optics measurements can be considered as equivalent to mismatch with angle error only. In the following, we treat the multiple kicks received by the beam as a single angle error equal to the total deflection of the kicks. Therefore, the emittance dilution in horizontal plane is

$$\begin{aligned}\delta\epsilon/\epsilon_0 &= (\beta_x \delta x')^2 / (2\beta_x \epsilon_0) \\ &= \beta_x \delta x'^2 / (2\epsilon_0) \\ \epsilon &= \epsilon_0 + \beta_x \delta x'^2 / 2\end{aligned}\tag{A.1}$$

As the unnormalized emittance shrinks due to adiabatic damping during acceleration, the relative effect of a constant kick angle increases.

For calculation of the emittances during acceleration, it is helpful to normalize the emittances [42].

$$\begin{aligned}\epsilon_N &= \beta\gamma\epsilon = \beta\gamma(\epsilon_0 + \beta_x \delta x'^2 / 2) \\ \epsilon_N &= \epsilon_{N,0} + \beta_x \delta x'^2 / 2 * \beta\gamma\end{aligned}\tag{A.2}$$

Here the β is the Lorentz beta and γ is the relativistic factor. The normalized emittance after each optics measurement can be expressed in a recursive form

$$\epsilon_{N,i+1} = \epsilon_{N,i} + \beta_x \delta x'^2 / 2 * (\beta\gamma)_i \quad (\text{A.3})$$

i is the index of data acquisition for optics measurements. At location of the tune meter kicker, $\beta_x \sim 100$ m, for all energies during acceleration. The kick angles during acceleration is taken as a constant, $\delta x' = 0.008$ mrad. With mostly constant β -functions in the arc sections during acceleration, this kick strength excites an oscillation amplitude in the range of $0.5 - 1$ mm in the arc sections for all energies.

The evolution of the emittances during acceleration due to competing excitation and adiabatic damping are shown in Fig. A.9. The unnormalized emittances starts growing due to excitation at the beginning of the ramp since the adiabatic damping is weak with a slow acceleration. It then shrinks during the first half of the ramp due to acceleration with higher rate. It increases afterwards with further excitations and decoherence. The dilution of unnormalized emittance accelerates towards the end while ramp rate slows down. The beam will start to scrape at the final focusing quadrupoles when the β -function there reaches ~ 1000 m with 0.1 mm mrad unnormalized emittance. The evolution of emittances are consistent with the beam loss observed late in the ramp during ramp optics measurements. Excessive beam loss was avoided by switching to another bunch once in the middle of the ramp. The emittance of a single bunch can not be measured in RHIC by IPMs which were designed for multiple-bunch measurements.

References

- [1] M. Kuhn, G. Arduini, V. Kain, A. Langner, Y. Papaphilippou, M. Schaubmann, and R. Tomas. Origins of transverse emittance blow-up during the LHC energy ramp. *Proceedings of the IPAC 2014*.

- 328 [2] M. Kuhn, G. Arduini, V. Kain, A. Langner, Y. Papaphilippou, M. Schau-
329 mann, and R. Tomas. Emittance growth during the LHC ramp:
330 The true story. *Presented at Emittance working group, CERN, 2014*,
331 <http://indico.cern.ch/event/300042/contribution/1/material/slides/1.pdf>.
- 332 [3] See "Optics reconstruction from AC dipole measurements in the energy
333 ramp". <http://rtomas.web.cern.ch/rtomas/lhcoptics/>.
- 334 [4] G. Robert-Demolaize et al. RHIC performance for FY2014 heavy ion run.
335 *Proceedings of the IPAC 2015*.
- 336 [5] H. Hahn. RHIC design manual, October 2000.
- 337 [6] Courtesy W. Fischer.
- 338 [7] J. Van Zeijts and A. Marusic. Ramp design and implementation for
339 the RHIC Deuteron-Gold and polarized proton runs. *Proceedings of the*
340 *ICALEPCS 2003*.
- 341 [8] M. Bai, M. Meth, C. Pai, B. Parker, S. Peggs, T. Roser, R. Sanders, D. Tr-
342 bojevic, and A. Zaltsman. RHIC AC dipole design and construction. *Pro-*
343 *ceedings of the PAC 2001*.
- 344 [9] M. Bai, S. Peggs, T. Roser, T. Satogata, and D. Trbojevic. Measuring beta
345 function and phase advance in RHIC with an ac dipole. *Proceedings of the*
346 *PAC 2003*.
- 347 [10] A. Drees, M. Brennan, R. Connolly, R. Michnoff, and J. DeLong. ARTUS:
348 The tune measurement system at RHIC. *AIP Conference Proceedings*,
349 546(1):341–348, 2000.
- 350 [11] P. Thieberger. Private communication.
- 351 [12] R. Connolly, J. Fite, S. Jao, S. Tepikian, and C. Trabocchi. Residual-
352 Gas-Ionization beam profile monitors in RHIC. *Proceedings of the BIW*
353 *workshop 2010*.

- [13] M. Minty, KA Drees, R. Hulsart, C. Liu, A. Marusic, R. Michnoff, and P. Thieberger. Measurement of beam optics during acceleration in the Relativistic Heavy Ion Collider. *Proceedings of the NA-PAC 2013*.
- [14] M. Minty, R. Hulsart, A. Marusic, R. Michnoff, V. Ptitsyn, G. Robert-Demolaize, and T. Satogata. Global orbit feedback at RHIC. *Proceedings of the IPAC 2010*.
- [15] P. Thieberger. Private communication.
- [16] G. Robert-Demolaize, M. Bai, and X. Shen. A graphic interface for full control of the RHIC optics. *Proceedings of the NA-PAC 2013*.
- [17] J. Laskar. Frequency analysis for multi-dimensional systems. Global dynamics and diffusion. *Physica D: Nonlinear Phenomena*, 67(1):257–281, 1993.
- [18] P. Zisopoulos, Y. Papaphilippou, and V. Ziemann. Beam optics measurements through turn by turn beam position data in the SLS. Technical report, CERN-ACC-2013-0175, 2013.
- [19] R. Bartolini, M. Giovannozzi, A. Bazzani, W. Scandale, and E. Todesco. Algorithms for a precise determination of the betatron tune. *Proceedings of the EPAC 1996*.
- [20] G. Vanbavinckhove, M. Aiba, A. Nadji, L. Nadolski, R. Tomás, and MA Tordeux. Linear and non-linear optics measurements at SOLEIL. *Proceedings of the PAC 2009*.
- [21] M. Aiba, S. Fartoukh, A. Franchi, M. Giovannozzi, V. Kain, M. Lamont, R. Tomás, G. Vanbavinckhove, J. Wenninger, F. Zimmermann, R. Calaga, and A. Morita. First β -beating measurement and optics analysis for the CERN Large Hadron Collider. *Physical Review Special Topics-Accelerators and Beams*, 12(8):081002, 2009.

- [22] YT Yan and Y. Cai. Precision PEP-II optics measurement with an SVD-enhanced Least-Square fitting. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 558(1):336–339, 2006.
- [23] X. Huang, SY Lee, E. Prebys, and R. Tomlin. Application of independent component analysis to Fermilab booster. *Physical Review Special Topics-Accelerators and Beams*, 8(6):064001, 2005.
- [24] C. Liu, R. Hulsart, A. Marusic, M. Minty, R. Michnoff, and P. Thieberger. Precision tune, phase and beta function measurement by frequency analysis in RHIC. *Proceedings of the IPAC 2013*.
- [25] D. Trbojevic, V. Ptitsyn, W. Fischer, L. Ahrens, M. Blaskiewicz, T. Hayes, F. Pilat, T. Roser, S. Tepikian, and P. Cameron. Improvements of the RHIC ramp efficiency. *Proceedings of EPAC 2002*.
- [26] N. Malitsky, K. Brown, N. D’Imperio, J. Kewisch, A. Fedotov, A. Luccio, F. Pilat, V. Ptitsyn, T. Satogata, S. Tepikian, J. Wei, and R. Talman. Joining the RHIC online and off-line models. *Proceedings of the PAC 2005*.
- [27] The global beta-beat RMS is defined here as $\sqrt{\frac{1}{n} \sum_{i=1}^n (\frac{\Delta\beta_i}{\beta_i})^2}$, where n is the number of BPMs, which is ~ 160 in each plane.
- [28] R. Connolly, R. Michnoff, T. Moore, T. Shea, and S. Tepikian. Beam profile measurements and transverse phase-space reconstruction on the relativistic heavy ion collider. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 443(2):215–222, 2000.
- [29] X. Gu, Z. Altinbas, M. Anerella, D. Bruno, M. Costanzo, WC Dawson, AK Drees, W. Fischer, M. Frak, and DM Gassner. Commissioning RHICs electron lens. *Proceedings of the NA-PAC 2013*.
- [30] R. Tomás, O. Brüning, M. Giovannozzi, P. Hagen, M. Lamont, F. Schmidt, G. Vanbavinckhove, M. Aiba, R. Calaga, and R. Miyamoto. CERN Large

- 408 Hadron Collider optics model, measurements, and corrections. *Physical*
409 *Review Special Topics-Accelerators And Beams*, 13(12):121004, 2010.
- 410 [31] V. Lebedev, V. Nagaslaev, A. Valishev, and V. Sajaev. Measurement and
411 correction of linear optics and coupling at Tevatron complex. *Nuclear In-*
412 *struments and Methods in Physics Research Section A: Accelerators, Spec-*
413 *trometers, Detectors and Associated Equipment*, 558(1):299–302, 2006.
- 414 [32] G. Vanbavinckhove, M. Bai, and G. Robert-Demolaize. Optics corrections
415 at RHIC. *Proceedings of the IPAC 2011*.
- 416 [33] G. Wang, M. Bai, and L. Yang. Linear optics measurements and corrections
417 using AC dipole in RHIC. *Proceedings of the IPAC 2010*.
- 418 [34] M. Bai, J. Aronson, M. Blaskiewicz, Y. Luo, G. Robert-Demolaize,
419 S. White, and G. Vanbavinckhove. Optics measurements and corrections
420 at RHIC. *Proceedings of the IPAC 2012*.
- 421 [35] R. Calaga. *Linear beam dynamics and ampere class superconducting RF*
422 *cavities at RHIC*. PhD thesis, Stony Brook University, 2006.
- 423 [36] X. Shen, G. Robert-Domolaize, S. White, Y. Luo, A. Marusic, M. Bai,
424 SY Lee, and R. Tomás. AC dipole based optics measurement and correction
425 at RHIC. *Proceedings of the NA-PAC 2013*.
- 426 [37] C. Liu, M. Blaskiewicz, KA Drees, A. Marusic, and M. Minty. Global
427 optics correction in RHIC based on turn-by-turn data from the ARTUS
428 tune meter. *Proceedings of the NA-PAC 2013*.
- 429 [38] C. Liu, A. Marusic, and M. Minty. Implementation of optics correction on
430 the ramp in RHIC. *Proceedings of the NA-PAC 2013*.
- 431 [39] V. Ranjbar. Approximations for crossing two nearby spin resonances. *Phys.*
432 *Rev. ST Accel. Beams*, 18:014001, Jan 2015.

- 433 [40] A. Blondel, A. Chao, W. Chou, J. Gao, D. Schulte, and K. Yokoya. Accel-
434 erators for a Higgs Factory: Linear vs. Circular. *Report of the ICFA Beam*
435 *Dynamics Workshop, arXiv preprint arXiv:1302.3318*, 2013.
- 436 [41] D. Edwards and M. Syphers. *An introduction to the physics of high energy*
437 *accelerators*. John Wiley & Sons, 2008.
- 438 [42] A. Chao and M. Tigner. *Handbook of accelerator physics and engineering*.
439 World scientific, 1999.

Figure 1: Schematic of the Relativistic Heavy Ion Collider [6].

Figure 2: The beam rigidity (black solid) and its corresponding derivative (blue dash), the β -functions at interaction points (green dot, red dash-dot) on the ramp for 100 GeV Au physics program in 2014. The horizontal axis is the time in seconds from the time that acceleration starts. Optics corrections were implemented at the times indicated by the vertical dashed lines.

Figure 3: The measured RMS beta-beats during beam acceleration. Transition crossing occurs at ~ 85 seconds after the start of acceleration.

Figure 4: The measured and design β -functions at the ionization profile monitors.

Figure 5: The calculated correction strengths for the 72 trim quadrupoles in the Yellow ring on the energy ramp; the correction strengths are linear between dashed lines. Optics corrections were implemented later at the times indicated by these vertical dashed lines.

Figure 6: 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.

Figure 7: The model and measured β -functions on the ramp at the ionization profile monitors in the Yellow ring with and without ramp optics corrections.

Figure 8: The reported RMS normalized beam emittances based on ionization profile monitor measurements in the Yellow ring with and without ramp optics correction.

Figure A.9: The calculated emittances growth due to kicks from the tune meter kicker during ramp optics measurements.