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# First demonstration of optics measurement and correction during acceleration with beta-squeeze in a high energy collider

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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.



## 1. Introduction

Measurement and correction of the optics during beam acceleration is desirable especially for large synchrotrons with acceleration duration on the order of minutes. Measurement of the optics during acceleration improves the understanding of the evolution of beam parameters (e.g. beam emittances). At RHIC, correction of the optics also provides improved beam control since model-dependent beam-based feedbacks are used during acceleration. Correction of the optics during acceleration could also improve the dynamic aperture for heavy ions and reduce the strengths of depolarization resonances for the polarized proton program by minimizing errors of the optics ($\beta$-functions and phase advances). However, it would be very time-consuming to pause at intermediate energies to allow measurement and correction of the optics during the simultaneous beam acceleration and beta-squeeze ramp. This motivated the development of a quasi-continuous, minimally invasive ramp optics measurement and subsequent implementation of optics corrections.

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

At RHIC, the optics have been measured quasi-continuously and corrections implemented during acceleration to the full beam energies. The methodology of the measurement and correction will be presented in the following sections. 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.

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## 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. Fig. 2 illustrates the beam rigidity and its derivative (the acceleration rate), and the $\beta$-functions at the interaction points ($\beta^*$) 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 $\beta^*$ at IP2, 4, 12 are the same as that for IP10 on the ramp, and stay at 5 m for the later part of the ramp. The horizontal and vertical $\beta^*$ 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 fundamental optical parameters such as the tune, the phase advance between beam position monitors, and with input from the accelerator model, the $\beta$-functions. At RHIC we use both the AC dipole [8,9] and the tune meter kicker [10] for optics measurements. For measurements during acceleration, only the tune meter kickers were used to excite betatron oscillations. The kickers produce a 140 ns full-width pulse with rise and fall times of ~10 ns [10]. With a 100 ns bunch spacing only a single bunch is excited leaving all other bunches unaffected. Free betatron oscillations in both planes are recorded using turn-by-turn BPMs after a bunch has been kicked multiple times. The number of kicks was adjusted to ensure a coherent oscillation amplitude in the range of 0.5–1 mm. Typically the number of kicks is ~4 at injection, ~19 at store energy and scales with beam energy during acceleration (rounded to an integer number). The turn-by-turn beam position measurement resolution is ~0.03 mm [11].

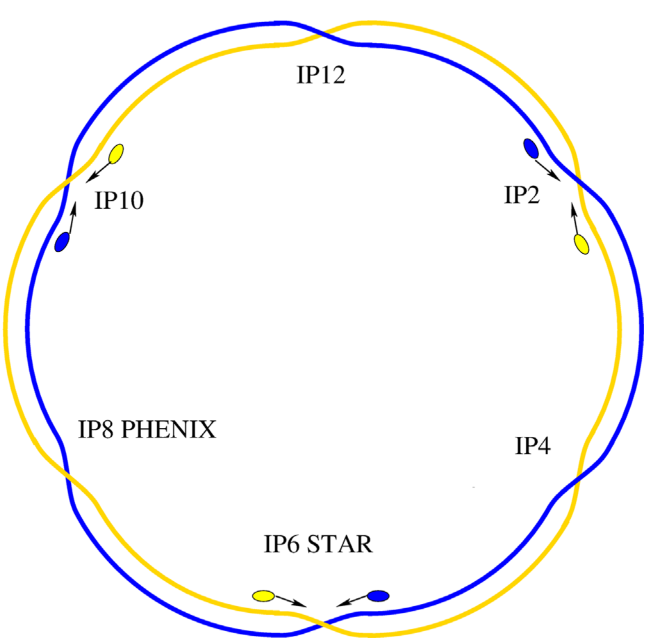


**Fig. 1.** Schematic of the Relativistic Heavy Ion Collider [6].

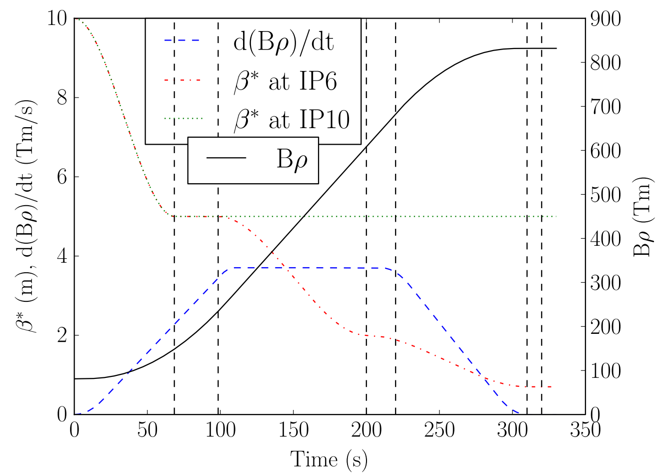


**Fig. 2.** The beam rigidity (black solid) and its corresponding derivative (blue dash), the $\beta$-functions at interaction points (green dot, red dash-dot) on the ramp for 100 GeV Au physics program in 2014. The horizontal axis is the time in seconds from the time that acceleration starts. Optics corrections were implemented at the times indicated by the vertical dashed lines. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

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

The measurement of the average beam position was delivered at rate of 1 Hz and used by orbit feedback to ensure reproducible conditions during beam acceleration. The turn-by-turn BPM data were acquired and delivered every 4 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 [17–21] 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,