QUADRUPOLE BEAM-BASED ALIGNMENT AT RHIC*

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Abstract

Successful implementation of a beam-based alignment algorithm, tailored to different types of quadrupoles at RHIC, provides significant benefits to machine operations for heavy ions and polarized protons. This algorithm was used to calibrate beam position monitor centers relative to interaction region quadrupoles to maximize aperture. This approach was also used to determine the optimal orbit through transition jump quadrupoles to minimize orbit changes during the transition jump for heavy ion acceleration. This paper provides background discussion and results from first measurements during the RHIC 2005 run.

INTRODUCTION AND MOTIVATION

The heavy ion and polarized proton collider RHIC is currently in its fifth year of operation, and continuous improvement of delivered integrated luminosity is a significant challenge. One part of this effort is a focus to reduce the $\beta^\star$ at the interaction regions (IRs) [1]. Since the IR optics squeeze occurs during the acceleration ramp at RHIC, this leads to a desire to maximize aperture by reproducibly threading beams through the centers of the IR triplet quadrupoles. Beam-based alignment (BBA) is a now-standard technique [2, 3, 4] to calibrate beam position monitor (BPM) offsets so zero readings correspond to this optimal steering.

Though most appropriate for threading IR quadrupoles, where shunt power supplies permit the variation of single quadrupoles, BBA can also be performed for groups of transition jump quadrupoles. These quadrupoles are used to change the momentum compaction and transition energy of the RHIC lattice over a short time (30 ms) during acceleration. Position offsets in these quadrupoles at the time of this transition jump produce fast changes in orbit and tunes, leading to beam loss. BBA to determine offsets of BPMs near these quadrupoles will improve this steering for heavy ions.

For RHIC polarized proton operations, steering through transition-jump quadrupoles is not a concern, but polarization preservation through the full-energy 250 GeV acceleration ramp requires RMS orbit control relative to arc quadrupoles at the level of 400 μm, smaller than typical BPM survey and electronics offsets of 500–1000 μm. BBA of both IR and transition jump quadrupoles will permit accurate steering for high-energy polarization preservation and IR separation bumps with 110-bunch operations.

Operational experience at RHIC has also demonstrated that BPM readings can have large digital offsets, and these offsets can vary over time due to issues with aging gain and calibration relays [5]. BPMs in the 6– and 8-o'clock low-β IRs were modified to remove these relays during the 2004 shutdown period. Comparisons of BBA results between modified and unmodified BPMs over several months will help to determine large-scale BPM system modification plans for the next RHIC shutdown.

METHODS AND ANALYSIS

The objectives of BBA are to measure the beam offset x_q from the center of a given quadrupole, and to use this offset to zero the reading of a nearby BPM when beam is steered through the quadrupole center. When this quadrupole of strength k is changed by Δk, the beam offset x_q feeds down as a dipole error of kick θ located at this quadrupole. θ can be found with a global least-squares fit of a difference orbit between quadrupole settings k and $k + \Delta k$, giving [3]:

$$x_q = \frac{\theta}{\Delta k}\left(1 + \frac{k\,\beta}{2\tan(\pi Q)}\right) \tag{1}$$

where Q is the tune in the plane under consideration, β is the quadrupole beta function, and dispersive corrections of $o(1\%)$ are neglected. For all our measurements, $\Delta k = \pm 3 \times 10^{-3}\ \mathrm{m}^{-1}$ to avoid large optics, tune, and beam lifetime changes. This change is 2–3% of a typical

Table 1: Parameters for some RHIC IR quadrupoles used in injection BBA studies. Quadrupole names begin with a letter indicating ring color (blue or yellow), and include a letter designating whether they are horizontally focusing (f) or defocusing (d). Starred quadrupole names have unmodified BPM relay electronics.

Name	Length [m]	k [m^{-2}]	β_x [m]	β_y [m]
bi5-qf3	3.39	0.1148	144.47	62.06
bi5-qf1	1.44	0.0809	76.10	82.83
bo6-qd1	1.44	-0.0809	83.00	78.36
bo6-qd3	3.39	-0.1148	61.87	148.49
bo11-qd1*	1.44	-0.0809	80.91	76.45
bi12-qf1*	1.44	0.0809	76.95	80.95
yo5-qd3	3.39	-0.1148	62.07	146.04
yo5-qd1	1.44	-0.0809	83.22	77.11
yi6-qf1	1.44	0.0809	76.40	82.24
yi6-qf3	3.39	0.1148	145.09	61.48
yi11-qf1*	1.44	0.0809	76.04	82.40
yo12-qd1*	1.44	-0.0809	80.53	77.24

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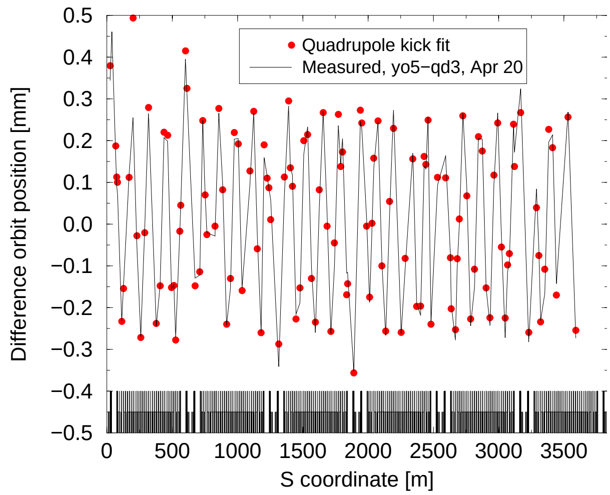

Figure 1: Typical BBA horizontal measured and fit difference orbits for a total quadrupole strength change of $\Delta k = 6 \times 10^{-3}\ \mathrm{m}^{-1}$ in yo5-qd3. This quadrupole is located at $s = 3800$ m.

IR quadrupole strength at RHIC injection, and produces an orbit change of 50–500 μm, above BPM reproducibility of 10-30 μm.

Eq. 1 can be used to calculate the quadrupole center offset (and therefore the BPM offset) even with a single Δk difference orbit. In practice this produces offset precisions of order 1 mm at RHIC. Improved measurements include statistics from quadrupole modulations with ± 5 mm IR four-bumps across the quadrupole, as well as slower runs of twenty separate bump positions to verify this method's accuracy. These bumps overlap triplet magnets on both sides of the IR, and residual bump leakage is removed with baseline orbit measurements for every bump setting.

RHIC transition jump quadrupoles are bussed together in both high-dispersion ($\eta_h = 1.7$ m) and low-dispersion ($\eta_h = 0.2$ m) families of four magnets in the RHIC arcs [6]. Variants of Eq. 1 with and without dispersive corrections are used to fit multiple kicks for various family excitations. Independent local three bumps are available at each transition quadrupole but were not used for these studies.

BBA data was acquired in several beam experiment sessions for quadrupoles in IRs 6, 8, 12, and 2 through the RHIC 2005 copper and polarized proton runs, evenly split between the independent blue and yellow rings. For each quadrupole measurement, orbits averaged over 10,000 turns were acquired at several different quadrupole settings (nominal and $\pm 3 \times 10^{-3}\ \mathrm{m}^{-1}$). These measurements were then repeated for several different orbit four-bumps spanning the quadrupole.

Perl and Tcl scripts written to automate data acquisition simultaneously in both RHIC rings allowed data collection for a full IR in about 30 minutes, dominated by quadrupole and bump ramping time. All data was acquired at injection energy, where $\beta^\star = 10$ m at all IRs and $\hat{\beta}$ is small in the IR quadrupoles. A C++ application was also commissioned to facilitate online and offline data analysis, and to permit routine BBA measurements during machine setup and beam experiments.

RESULTS

IR Quadrupoles

Fig. 1 shows a typical quadrupole strength kick fit for θ for a difference orbit taken between quadrupole strength changes of $\Delta k = \pm 3 \times 10^{-3}\ \mathrm{m}^{-1}$. These quadrupole fits use design optics and measured tunes, and have a residual difference RMS of 5–10% of the original difference orbit RMS. This scatter is mostly dominated by random BPM errors from 10 Hz orbit oscillations, which can reach 30 μm around the ring at injection.

Parameters for some RHIC IR quadrupoles are listed in Table 1, and BBA statistics based on several measurements are listed in Table 2. Accuracy of detailed scans of modified BPMs ranged from 100–200 μm, while BPMs with original relays have BBA error ranges that are an order of magnitude higher. These larger errors persisted in unmodified modules even after repeated recalibrations, since BPM on-board calibrations randomly change the seating and contact resistances of the relays. All 24 measured modified BPMs had reproducible offsets, with an average offset of 150$\pm$815 μm; these offsets have been applied to these BPMs for routine RHIC operations.

Some sample detailed scans of quadrupole kick vs BPM position at RHIC injection are shown in Fig. 2. These measurements are within 500 μm of faster BBA measurements made with only three position bumps. Only one BPM of these four, yo5-bh3, has a substantial offset, and this offset of -2.9 mm was reproducible over a timescale of weeks with no evidence of drift. Eq. 1 also predicts the response slopes in Fig. 2. Comparison is good to 10% for RHIC injection optics, though this technique could be used to confirm quadrupole linearity and optics in store conditions.

Table 2: BBA results for BPMs near RHIC IR quadrupoles listed in Table 1. Starred quadrupole names have unmodified BPM electronics.

Name	Horizontal [mm]	Vertical [mm]
bi5-qf3	-1.07 $\pm$ 0.16	-0.24 $\pm$ 0.00
bi5-qf1	-1.78 $\pm$ 0.34	0.08 $\pm$ 0.13
bo6-qd1	0.28 $\pm$ 0.06	-1.46 $\pm$ 0.62
bo6-qd3	-0.33 $\pm$ 0.19	-2.59 $\pm$ 0.23
bo11-qd1*	-0.39 $\pm$ 1.62	1.31 $\pm$ 1.10
bi12-qf1*	-0.87 $\pm$ 1.59	2.84 $\pm$ 2.85
yo5-qd3	-2.87 $\pm$ 0.15	0.56 $\pm$ 0.25
yo5-qd1	0.38 $\pm$ 0.22	0.04 $\pm$ 0.14
yi6-qf1	0.56 $\pm$ 0.47	-0.03 $\pm$ 0.27
yi6-qf3	-1.41 $\pm$ 0.40	-0.16 $\pm$ 0.18
yi11-qf1*	-8.31 $\pm$ 1.32	0.48 $\pm$ 0.26
yo12-qd1*	-0.38 $\pm$ 1.85	1.88 $\pm$ 1.50

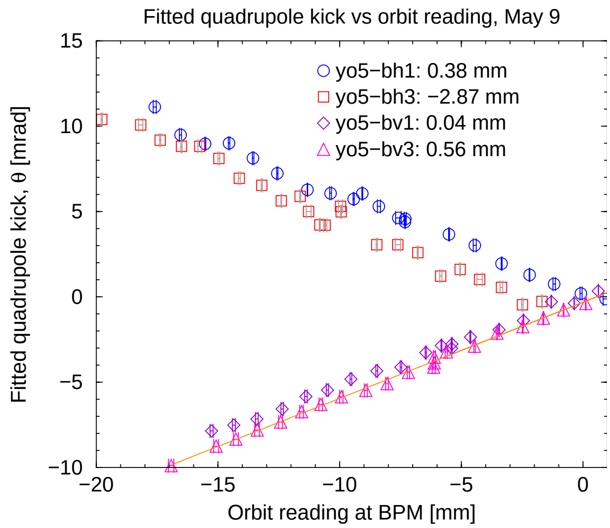

Figure 2: BBA scans for four IR quadrupoles in the yellow ring for 25 different bump positions, including one linear fit. The data is biased to negative BPM readings by RHIC injection separation bumps.

With random BPM errors from orbit jitter and noise, design optics were used for all quadrupole fits. Typical RHIC injection optics are good to the 5-10% level in arc quadrupoles, somewhat worse in triplet quadrupoles. Dispersion is quite low in these quadrupoles at injection, and contributes only a small systematic on the order of 1%.

Transition Jump Quadrupoles

To study the possibility of transition jump quadrupole BBA, we changed the strengths of several families by $\Delta k = \pm 3 - 5 \times 10^{-3}\ \mathrm{m}^{-1}$. The corresponding difference orbits were fit to four kicks located at the individual quadrupoles, and Eq. 1 was used to calculate BPM center offsets. Table 3 shows these measurements after removal of horizontal baseline orbit offsets in these BPMs. Reproducibility of these measurements is dominated by BPM relay issues as described in a previous section.

Transition jump quadrupole offsets will be improved with measurements including several settings of arc dipole correctors, effectively scanning the closed orbit through all transition jump quadrupoles simultaneously. Local three-bumps across single transition jump quadrupoles will also be used to measure both chromaticity sextupole and transition jump quadrupole BBA components from different order contributions to orbit response [7].

CONCLUSIONS

We have completed first measurements of beam-based alignment for RHIC interaction region and transition jump quadrupoles, demonstrating good consistency between detailed and cursory bump scans. Thirty IR BPMs in the RHIC blue and yellow rings were measured; modified BPM hardware with removed relays had reproducible offsets, with a total statistic of 150±815 μm. Unreproducible offset errors of over 1 mm were observed in unmodified modules after calibrations and gain changes. Initial measurements of transition jump quadrupole BBA require bumps through all quadrupoles to reduce errors to less than 100μm. Future plans for RHIC BBA include 1 Hz quadrupole modulation and million-turn BPM response to reduce signal to noise and improve resolution[8].

Table 3: BBA results for BPMs near bo6-qgt-ps and bo7-qgt-ps blue ring transition jump quadrupole families. All values are based on a single measurement and parenthesized measurements indicate malfunctioning BPMs.

Name	Horizontal [mm]	Vertical [mm]
bo6-b12	2.00	1.76
bo6-b14	-2.21	1.45
bo6-b16	3.45	-1.24
bo6-b18	(-16.32)	0.34
bo6-b6	-2.60	-2.47
bo6-b8	1.84	-0.10
bo7-b8	-0.42	(6.42)
bo7-b6	-3.33	5.27

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