QUADRUPOLE BEAM-BASED ALIGNMENT IN THE RHIC INTERACTION REGIONS*

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Abstract

Continued beam-based alignment (BBA) efforts have provided significant benefit to both heavy ion and polarized proton operations at RHIC. Recent studies demonstrated previously unknown systematic beam position monitor (BPM) offset errors and produced accurate measurements of individual BPM offsets in the experiment interaction regions. Here we describe the algorithm used to collect and analyze data during the 2010 and early 2011 RHIC runs and the results of these measurements.

INTRODUCTION AND MOTIVATION

The objective of BBA at RHIC is to determine BPM readings at which beam goes through the center of a nearby quadrupole. Each reading is then used to null this offset in reported control system BPM data. The approach adopted by the authors focuses attention on BPM-quadrupole pairs that are in close proximity and are aligned with respect to each other. The standard technique [1, 2, 3] for storage rings involves calculating difference orbits between two states: nominal and slightly modified magnet strengths for the quadrupole nearest the BPM under investigation. This can be done for a number of different quadrupole-to-beam offsets that are varied by a local orbit bump centered on said quadrupole. It is then possible to calibrate the zero readings of the BPMs using the BPM offset reading for which varying quadrupole strengths result in a minimum (ideally zero) rms difference orbit i.e., when beam travels through the center of a quadrupole and receives no feed-down kick capable of disturbing the orbit.

Apart from measuring and correcting the BPM offsets as a part of instrumentation maintenance, the technique can be used for more specific applications. For example, as will be discussed shortly, the technique was used at RHIC to verify BPM offset reversals that previous BBA checks did not discover.

Our investigation is a follow-up to a similar study [4] performed at RHIC during both the copper and polarized proton portions of the 2005 run. That study, like this one, focused primarily on low-β IR BPMs. These additional efforts were undertaken in light of new information concerning the BPM offset reversals mentioned above.

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CQS Packages

It is advantageous for quadrupoles, correctors, sextupoles, and beam position monitors to be accurately located with respect to the beam and relative to each other. For this reason, RHIC was designed with many corrector-quadrupole-sextupole (CQS) "packages" that are comprised of the aforementioned magnetic devices, and optionally a BPM, in a rigid mechanical assembly. The CQS packages were surveyed "on the bench" before installation whereby any BPM-to-reference orbit and magnet-to-BPM offsets were recorded [5] . The latter of these measurements is used in the RHIC controls system to calibrate BPM offsets with respect to quadrupole centers and is known to change over time as work is completed and components settle. Installation tolerances for quadrupole-BPM misalignment were $\Delta x = \Delta y = 0.25$ mm rms.

The CQS packages are designed with leads for the magnets and instrumentation on only one end and are installed to minimize the amount of superconducting buswork and penetrations through the cryostat. This consideration is independent of beam direction, so the orientation of the packages varies throughout the ring depending on where the nearest cold cryostat is. The number of packages installed with each of the two possible orientations is approximately equal. Of the roughly 300 packages containing BPMs, 148

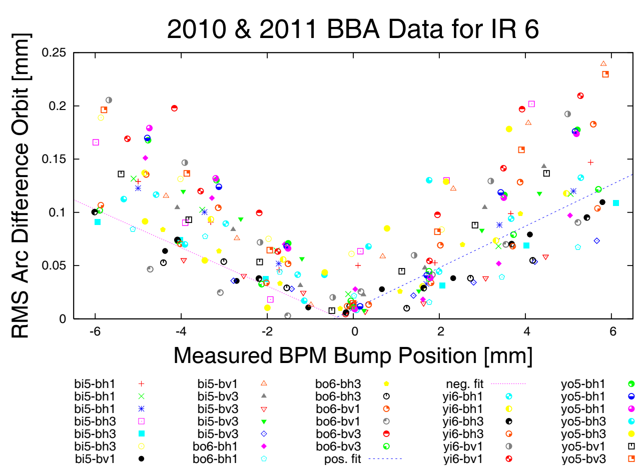


Figure 1: BBA data for all Q1 and Q3 BPMs at 6 o'clock in both Yellow and Blue. The resulting offsets for these BPMs are listed in table 1. Most BPMs are shown multiple times and only one fit (bo6-bv3 from March 09, 2010) is included. The RHIC BPM naming convention can be explained by way of an example: **Y**ellow **I**nside **2** o'clock **BPM H**orizontal **3** is abbreviated yi2-bh3.

Table 1: Parameters and BBA results for Blue and Yellow IR quadrupoles and corresponding BPMs. Listed are all the Q1 and Q3 triplet quadrupoles for STAR. The strengths listed here are nominal operational values at injection and quadrupole changes were made on top of them. Figure 1 is a plot of the latest BBA data for the same BPMs. Beta functions are listed for the gold portions of the specified runs, when most data was taken. Data marked † had 2010 BBA results installed prior to 2011 measurement and this was taken into account here. Those marked ‡ were only measured once.

		2005 Run				2010/2011 Run			
Name	k[m^{-1}]	β_x[m]	β_y[m]	Hor.[mm]	Vert.[mm]	β_x[m]	β_y[m]	Hor.[mm]	Vert.[mm]
bi5-qf3	0.1148	144.47	62.06	-1.07±0.16	-0.24±0.00	127.92	66.59	-0.57±1.06	0.07±0.11†
bi5-qf1	0.0809	76.10	82.83	-1.78±0.34	0.08±0.13	62.52	121.82	0.49±0.46	-1.52±1.94
bo6-qd1	-0.0809	83.00	78.36	0.28±0.06	-1.46±0.62	84.82	61.39	1.27±0.28	0.06±0.23†
bo6-qd3	-0.1148	61.87	148.49	-0.33±0.19	-2.59±0.23	121.22	90.82	0.63±0.78	-0.06±0.02†
yo5-qd3	-0.1148	62.07	146.04	-2.87±0.15	0.56±0.25	69.81	136.42	-1.47±0.33	-0.12‡
yo5-qd1	-0.0809	83.22	77.11	0.38±0.22	0.04±0.14	130.30	67.98	0.70±0.14	-0.303‡
yi6-qf1	0.0809	76.40	82.24	0.56±0.47	-0.03±0.27	59.01	77.88	0.47±0.02	0.10±0.45
yi6-qf3	0.1148	145.09	61.48	-1.41±0.40	-0.16±0.18	89.40	113.85	-0.05±0.16	–

have an orientation of -1, defined here as the orientation with which the lead end of the package is the downstream end. This orientation must be used when applying offsets if accurate beam positions are to be reported.

When the BPM offsets were first introduced into the RHIC control system, the orientation of each CQS package was not properly taken into consideration. The result of this oversight was a systematic BPM offset error twice the magnitude of the survey value (the implemented offset being the opposite sign of, but equal in magnitude to, the correct setting) in the 148 packages installed with -1 polarity.

To further complicate the issue, the BPM survey offsets provided were incorrectly interpreted or implemented by a factor of -1. This was in addition to and independent of CQS orientation and therefore affected vertical plane BPMs as well as horizontal. The result of these two issues working in concert was a systematic offset error in all vertical and roughly half the horizontal BPMs.

DATA ACQUISITION AND ANALYSIS

BBA data was collected over several beam experiment sessions during the early parts of the 2010 gold and 2011 polarized proton RHIC runs. Thirty-five BPMs were analyzed spanning both rings (blue and yellow) and planes (vertical and horizontal) focusing primarily on BPMs in the 6- and 8-o'clock low-β IRs – the location of RHIC's two largest experiments, STAR and PHENIX.

One bunch was injected in each ring at injection energies of 9.8GeV/n and 23.8GeV/n and intensities of $\sim 1e9$ and $\sim 1e11$ for gold and polarized protons, respectively. Magnet control servers were separated to allow simultaneous and independent control and data acquisition in each ring. Beam parameters were tuned to avoid resonances and minimize beam losses. A local orbit three-bump was created using correctors centered on the quadrupole nearest the BPM under investigation and in the same plane. The bump was scanned in amplitude from -6 mm to $+6$ mm in 2 or 1.5 mm steps. At each bump amplitude, orbits were acquired for both the nominal quadrupole setting and an adjusted value of $\Delta k = \pm 10^{-3}\,\mathrm{m}^{-1}$ for focusing and defocusing quadrupoles, respectively.

This data was then used to produce plots of the arc (Q10 through Q10) rms difference orbit between baseline (pre quad change) and offset (post quad change) orbits as a function of average baseline BPM reading for each of the bump amplitudes. Least-squares fits to both positive and negative bump data were used to determine the location of rms minima. See figure 1. Perl and shell scripts were written to automate both data acquisition and analysis.

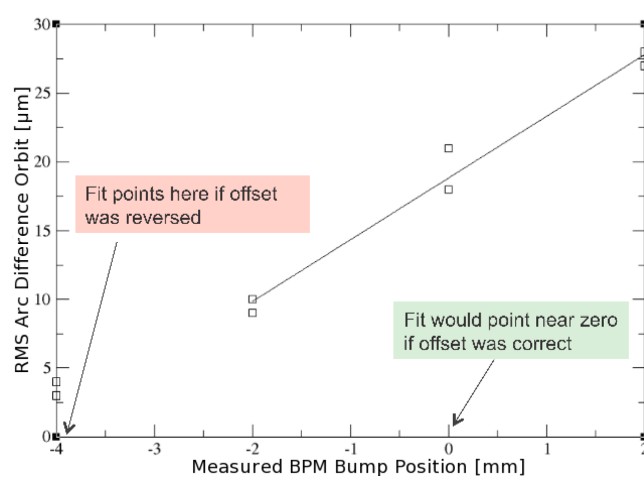
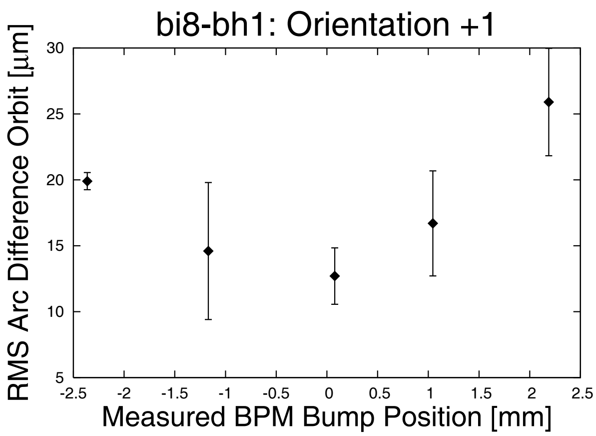
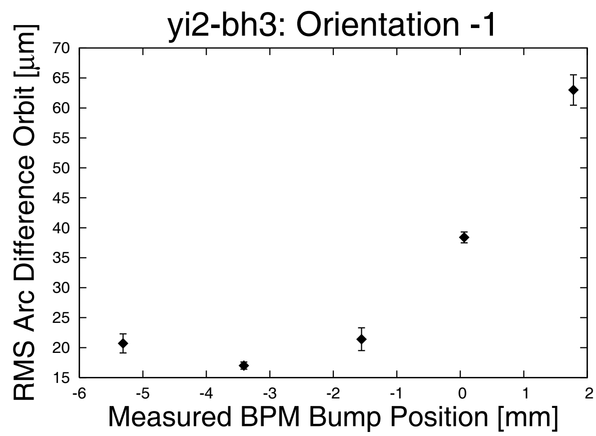


Figure 2: BBA plot for bo2-bv1 that was part of the confirmation of vertical BPM offset reversal. The controls system offset at the time of data taking was 1956μm. The BBA result above is twice the magnitude and the opposite sign of this value which is strong evidence for offset reversal.



(a) With a database offset of -1.36 mm, bi8-bh1 BBA would have given a result near +2.8 mm if its offset had been reversed.



(b) A result of -3.5 mm, roughly twice the magnitude and opposite sign of the database offset of 1.79 mm, suggests offset reversal for yi2-bh3.

Figure 3: A comparison of two horizontal BBA results contrasting correctly (figure a) and incorrectly (figure b) installed offsets. The quadrupole strength change used in producing the above data was $10^{-4}\,\mathrm{m}^{-1}$.

RESULTS

Confirmation of Offset Reversals

Over the past few runs, we had observed unphysical behavior of IR region orbit measurements. This was hypothesized to be due to systematic BPM errors. The confirmation of BBA offsets was a major step forward in understanding this anomaly.

Figure 3 contrasts two horizontal BBA results, one with each of the two orientations. The plot on the right shows yi2-bh3 (orientation -1) and on the left is bi8-bh1 (orientation +1) which, at the time of measurement, had database offsets of 1.79 mm and -1.36 mm, respectively. That the rms difference orbit reaches a minimum at a BPM reading of roughly twice the magnitude and opposite sign of the database offset for yi2-bh3 is strong evidence that this offset has been reversed. Results consistent with these were found for other horizontal BPMs with the same orientation and for all vertical BPMs, e.g., bo2-bv1 in figure 2.

IR Quadrupoles

Thirty-five IR BPMs have been analyzed since the database offsets were corrected. The average offset was $162 \pm 387\,\mu$m with reproducibility on many BPMs being $200\,\mu$m or less. This is a marked improvement over the 2005 results which had a standard deviation of $815\,\mu$m[4]. A number of BBA offsets near the 6-o'clock IR were installed. This reduced the average offset from $774\,\mu$m to $142\,\mu$m, a value comparable to the BBA accuracy for those BPMs. A sample of BBA results and corresponding quadrupole parameters is listed in table 1.

CONCLUSIONS

BBA data has been collected over the past two runs for all three of the active experimental IRs at RHIC, updating results from the 2005 run which were taken with incorrectly installed offsets. The technique was successfully applied to expose a systematic misuse of the BPM survey offsets in the control system. This is likely to benefit polarized proton operations as polarization transmission through acceleration ramps depends on RMS orbit control in the arcs, but a quantitative understanding of its impact is still under active investigation.

Data taking is ongoing as are refinements to the BBA technique aimed at reducing systematic errors and properly accounting for dispersive effects. Further development may focus on non-triplet BPMs such as those located near snakes, or arc quadrupoles that do not have individually shunted power supplies (a prerequisite for the current method) and as such, will require a modified procedure.

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