SCENARIO OF BEAM-BASED ALIGNMENT WITH NEW BPM SYSTEM FOR FUTURE BEAM COMMISSIONING OF 1.3-MW OPERATION AT THE J-PARC MAIN RING

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Abstract

In the main ring (MR) at the Japan proton accelerator research complex (J-PARC), beam-based alignment (BBA) is essential for precise calibration of beam position monitors relative to quadrupole magnet centers. With the upgrade of the beam position monitor (BPM) system for better precision scheduled in this summer, frequent and accurate BBA will become increasingly important to optics and orbit correction for realizing less beam loss and stable operation. In this study, a fast BBA method is experimentally investigated and compared with conventional approaches. The fast method uses orbit modulation within a single measurement to efficiently extract offset information. Experimental results show that the fast approach achieves alignment accuracy comparable to the conventional method while significantly reducing the required measurement time. These results demonstrate the feasibility of regular beam-based alignment measurements and provide a path toward more precise optics correction in the MR.

INTRODUCTION

Since new physics research requires a large number of particles, the MR at J-PARC aims to increase its beam intensity from the current value of 0.9 MW to 1.3 MW by JFY 2028 [1]. To achieve this goal, there is a strict limit of a particle loss rate of 1 % or less to suppress radiation. Previous researches have improved the 3-fold symmetry of optics parameters in MR with correction of the current to magnets, which is effective for decreasing the beam loss [2–4]. The observed residue error of the magnetic quadrupole field around 0.1 % has possibility to be caused by an orbit offset from the centers of sextupole magnets, which induces an effective quadrupole field error. After an ongoing upgrade of the beam position monitor (BPM) system, we will pursue further measurements of closed orbit distortion (COD) and correct the orbit error.

To fully utilize the upgraded BPM system whose accuracy is 10 µm [1] in the diameter of 130 mm, the relative positions of the magnetic centers of quadrupole and sextupole magnets with respect to the BPM electrical centers must be accurately determined. This calibration is performed by beam-based alignment (BBA), which evaluates the offset between the BPM origin and the magnet center using beam response measurements. In order to achieve and maintain the accuracy, the BBA procedure needs to be applied repeatedly. Therefore, reducing the measurement time while preserving the required accuracy is essential, and in this study we focus on experimental investigation toward faster BBA implementation for the quadrupole magnets.

OVERVIEW OF BEAM BASED ALIGNMENT

The goal of the BBA is to calibrate the BPM origin to the center of the BPM's adjacent quadrupole magnet(Q). The difference between the BPM electrode center and the Q center comes from those misalignment and the differences of the signal transmission gains. In this paper, y_{target} is defined as the BBA's target BPM value, y_i is defined as the value of another BPM i, and I_Q is defined as the current to the trim coil, attached on Q for correction.

The main idea of the BBA is that, if a closed orbit passes through a Q center, $y_{\text{target}} = y_0$, then changing I_Q does not change the orbit y_i. Therefore, in the BBA, linear fit searches the value of y_{target} where $dy_i/dI_Q(y_{\text{target}}) = 0$, which is why the BBA needs to change the orbit y_{target} and the value of I_Q. The change in the orbit y_i as a function of I_Q can be obtained from each available BPM i in the ring. Therefore, we obtain as many BBA results y_{0i} where $dy_i/dI_Q(y_{\text{target}} = y_{i0}) = 0$ as there are BPMs. You can apply statistical analysis to produce the result of y_0.

In the previous method [5], for each BPM, all combinations of the values of y_{target}, which was shifted by local bump, and I_Q were measured one by one. As a result, measurements for all 186 BPMs required a total of approximately 90 hours. Since the BBA is time-consuming, it had not been performed again after around 2014 until starting our study in 2025. The main limitation in speeding up the previous BBA procedure is that, within one cycle from injection and extraction, data were taken only at a single setting of y_{target}. If multiple y_{target} conditions are measured within one cycle, the total measurement time will be reduced.

This limitation is addressed by the Fast BBA method [6]. By modulating the orbit using an AC excitation of a correction magnet within a single cycle, the BBA measurement can be performed faster. In the Fast BBA, the 2-D graph of y_{target} and y_i is used. The line on the graph depends on I_Q, but there should be a fixed point crossing all the lines, which

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corresponds to the center of Q. An example of the measured 2-D graph is shown in Fig. 1. The five lines corresponds to the five settings of I_Q. The intersection point of the lines, precisely the point where the sum of the squared distance to the each line is minimum, shows an orbit passing through the Q center. Therefore, the BBA result from this data is the y_{target} value of the point.

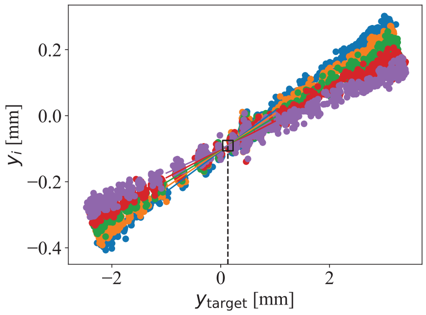

Figure 1: An example of the measured 2-D graph for the fast BBA.

EXPERIMENTAL SETUP

The information on MR is as below. The circumference is 1567.5 m. It has 186 BPMs. All of the quadrupole magnets contain trim coils, which can apply the magnetic field of around ±2 % of the main ones.

The setting of MR in the experiment is as below. The cycle is 780 ms, and the beam injected in 3 GeV is not accelerated until the beam dump. The sampling rate is 1 kHz. The number of bunches is 8, same as the daily operation, and the intensity is 1.2×10^{13} ppp, smaller than the operation. The tune is set as $(\nu_x, \nu_y) = (21.25, 21.30)$, which is different from that of operation for physics. The reason of changing the tune setting is as below. The hardware restricts the use of the trim coil of the sextupole magnets during BBA. Therefore, doing BBA with the usual tune causes beam loss because the third-order resonance cannot be suppressed by the sextupole magnets. Under such limitation, we changed the tune setting so that the beam loss is smaller.

In this experiment, we conducted three kinds of BBA for one BPM. Those are difference in how to change an orbit. BBA-1 is the previous way, where a local bump at Q shifts the orbit. It requires 15 cycles per single search, which consists of three orbit patterns combined with five current patterns applied to the trim Q coil. This was done for comparison. BBA-2 utilizes the COD induced by DC excitation of a single correction magnet rather than a local bump; as a result, the COD of the entire ring is displaced. It requires 15 cycles per single search, same as BBA-1. BBA-3, the Fast BBA, employs the same excitation scheme as BBA-2, but applies a sinusoidal modulation instead of a DC excitation. Therefore, it requires 5 cycles per single search, which consists of 1 pattern of the orbit combined with five current patterns applied to the trim Q coil. To check its reproducibility, BBA-3 is repeated four times. The orbits measured in the BBA-1 and 3 are shown in Figs. 2 and 3.

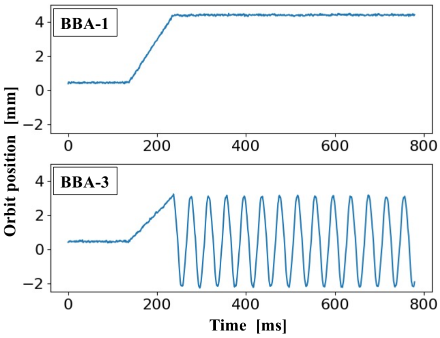

Figure 2: The orbits measured in the BBA-1 and 3.

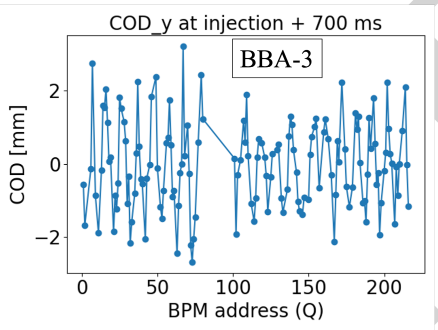

Figure 3: The COD over the entire ring at the moment in BBA-3.

The motivation for conducting BBA-2 is as follows. The COD over the entire ring, used in BBA-3, produces a larger slope of the beam position at Q than the local bump used in BBA-1. Since the target BPM for BBA is located 1 m from the center of Q, this difference in slope may affect the BBA result, which corresponds to the beam position at the BPM for an orbit passing through the Q center. If this effect is significant, the results of BBA-3 would differ from those of BBA-1 and it would need additional corrections. To evaluate the magnitude of this effect, BBA-2 is conducted.

The BPM to conduct BBA was chosen in the vertical direction, where the orbit deviation due to the dispersion is minimal, selecting the one with the maximum Twiss beta function of 29 m. The correction magnet for BBA-2 and 3 was selected based on the best orbit response at the selected BPM (orbit change per current). The frequency of the current to the correction magnet in BBA-3 is set as 25 Hz. Note that a pattern of the current to the correction magnet is set with intervals of 2 ms.

RESULTS

The results of the three BBAs are shown in Fig. 4. The main assumption of the analysis is that the deviations of the measurement data follow a Gaussian distribution. The procedure used to obtain the results is as follows. For BBA-1 and BBA-2, the BPM signals $y_i(t)$ from 400 ms to 780 ms after the start of the injection in each cycle are averaged, and the standard error is adopted. The COD at the target quadrupole is varied, and the resulting change in COD is evaluated as a linear function of the current I_Q, from which the slope dy_i/dI_Q is obtained. The standard error differs for

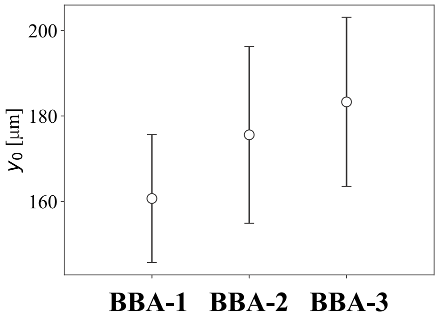

Figure 4: Results of the three BBA experiments.

each BPM location (index i). This variation arises not from noise of the measurement system, but rather from the optics-dependent sensitivity of dy_i/dI_Q at each location, which affects the signal-to-noise ratio. Consequently, the offset y_{0i} at the target BPM and its associated error σ_i are evaluated using all available BPM data. Each BPM is weighted by the standard error, and a total of 155 BPMs are included in the analysis, including the target BPM itself. Then the offset y_0 and its standard error σ is as below,

$$y_0 = \frac{\sum_i y_{0i}/\sigma_i^2}{\sum_i 1/\sigma_i^2}, \quad \sigma = \sqrt{\frac{\sum_i (y_{0i} - y_0)^2/\sigma_i^2}{\sum_i 1/\sigma_i^2}},$$

which is shown in Fig. 4. For the BBA-3, the offset y_{0i} obtained by BPM i is defined as the result of linear fittings in the first measurement of BBA-3, and its error σ_i is defined as the standard deviation of the results in all the four measurements. Then, the offset y_0 and its standard error σ is calculated in the same way as the other BBAs. Note that the BBA-3 uses 154 offsets y_{0i} since the 2-D map of $(y_{\text{target}}, y_i = y_{\text{target}})$ does not provide useful information and is therefore excluded. In contrast, the other BBAs can still evaluate the shift at the target BPM as a function of I_Q. The used data in BBA-3 are from all the cycle.

DISCUSSION

The results from the three BBAs are consistent, which means there is no difference larger than the error. The difference in the results due to the slope of the beam position was not observed. The measurement time for BBA-3 is 6 min, while that for BBA-1 is 23 min. Here, the time means the duration from the first cycle to the last one in the BBA measurement, including the time to change the settings and save the data. Therefore, the Fast BBA in MR can shorten the total time into one fourth for BBA with maintaining the accuracy.

Comparison of the results obtained in the most recent BBA prior to this study with the value of 376±16 μm indicates that a change has occurred over the past decade. Therefore, it is concluded that performing BBA only once is not sufficient to maintain the accuracy of the calibrated offset.

Figure 5 shows the root mean square of the spectra of the COD at BBA's target BPM obtained by FFT (fast Fourier transform) for each BBA. The left panel of Fig. 5 shows that the spectrum of BBA-2 has a sharp peak at 20 Hz and a broad peak around 300 Hz. BBA-2 uses orbits with larger COD than BBA-1, which seems to cause the peaks. BBA-2 has fewer settings of the correction magnets for all the BPMs, but it shows larger deviations than BBA-1. The right panel of Fig. 5 shows that the spectrum of BBA-3 has a peak at 25 Hz, corresponding to the AC excitation frequency, along with its harmonics. All spectra have a peak at 490 Hz. This frequency differs from the synchrotron frequency of 346 Hz and from the switching frequencies of the correction magnets. Therefore, its origin is still under investigation.

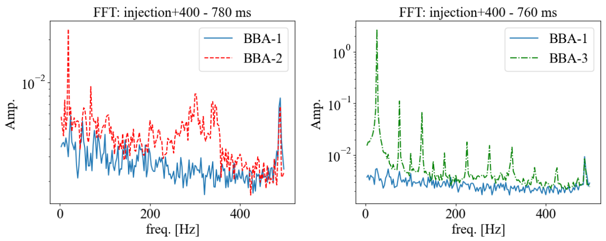

Figure 5: Results of the FFT analysis.

SUMMARY AND OUTLOOK

This experiment shows the possibility that the idea of the fast BBA shortens the time length for BBA into half in the generally same accuracy. Furthermore, it is revealed that conducting BBA regularly is necessary to keep an accuracy of the BPM system.

To realize repeating BBA, the total time length for BBA needs to be smaller than 8 hours, less than one tenth as the previous one because MR needs to stop an operation for physics experiment during BBA. To make the BBA faster, it seems to be applicable to develop a technique for doing BBA simultaneously based on ideas of exciting different frequencies, as described in [6], or fitting the offsets with the model-based calculation [7, 8].

The analysis so far neglects the error due to the distance between the BPM and Q. To achieve a COD precision of less than 10 μm, we need to minimize this error [9]. When it comes to BBA for a horizontal BPM at large dispersion, it is important to address the orbit deviation caused by synchrotron oscillation and the power supply ripple of the main bending magnets [5].

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