BEAM BASED ALIGNMENT OF THE BEAM POSITION MONITORS AT J-PARC RCS

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Abstract

The J-PARC RCS is a Mega-Watt class rapid cycling synchrotron and it delivers an intensive beam to the neutron target and the MR. In order to handle large space charge, its physical aperture is designed to be more than 250mm. Even though its chamber size is very large, the BPM system gives precise data to determine the beam optics parameters of the ring. For this purpose, only relative positions and resolutions are important. However, for much higher intensity, absolute beam position measurements and accurate COD correction are indispensable. We have carefully installed all BPM detectors and measured the position with respect to the QM nearby. But it is also necessary to calibrate the BPM offset by using the beam. If each QM could be controlled independently, the simple beam based alignment technique can be utilized, but this is not the case for the RCS. There are seven families of QM, and only each whole family can be controlled at one time. We developed a new technique by expanding the simple method for the case of multiple QM focusing changed simultaneously, and applied it to the J-PARC RCS. The paper describes this method and presents about experimental results.

INTRODUCTION

The construction phase of the Japan Proton Research Complex (J-PARC) has been completed recently. It comprises three accelerators [1] and provides various intensive secondary particles for a variety of scientific programs. The RCS (3-GeV rapid-cycling synchrotron) is designed to provide 1 MW beam power for the MLF (Material and Life science experimental facility) and the MR (Main Ring) and its beam commissioning has been performed very successfully [2]. The BPM (Beam Position Monitor) system [3, 4] in the RCS is one of the important devices. The BPM has a good linearity due to its diagonal cut electrode shape and a resolution of 20∼30μm. However, its offset with respect to the nearest QM (quadrupole magnet) remains an uncertainty, in spite of careful and precise fabrication and installation. Those uncertainties have to be measured using the beam experimentally, namely by beam based alignment (BBA).

If an individual QM is controllable, it is rather simple and there are some examples of such analysis [5, 6]. However, in our case, it is more complicated, since several QMs are coupled together and only a group of QM can be controlled as family. This paper describes how to deal with this situation and discusses preliminary results.

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REVIEW OF SIMPLE BEAM BASED ALIGNMENT METHOD

The principle of BBA is that the orbit is not affected when one QM focusing is changed (ΔK), if the beam passes through the center of that QM. Otherwise, the beam is displaced by $x_1 \neq 0$ at that QM and the orbit is modified due to the dipole kick of $\Delta K x_1$.

BPM COD data for different initial orbits are taken with varying the QM field strength for BBA. An original orbit, $x_1(s)$, is described by following Hill's equation using a focusing function $K(s)$ of QM, and any field error $-\Delta B/B\rho$.

$$x_1''(s) + K(s)x_1(s) = -\frac{\Delta B}{B\rho} \tag{1}$$

Then, one of QM at $s = s_A$, has a changed field gradient by the amount ΔK, and the orbit is modified from x_1 to $x_1 + x_2$. This is expressed as,

$$(x_1 + x_2)'' + (K(s) + \Delta K)(x_1 + x_2) = -\frac{\Delta B}{B\rho}. \tag{2}$$

By taking the difference between eq.(2) and (1), it becomes

$$x_2'' + K(s)x_2 = -\Delta K[x_1(s_A) + x_2(s_A)] \simeq -\Delta K x_1(s_A), \tag{3}$$

by ignoring the term $\Delta K x_2(s_A)$. Now, the orbit change x_2 is described as a COD caused by a single kick $\Delta K x_1(s_A)$ and it is expressed by

$$x_2(s_n) = a_{nA}\Delta K x_1(s_A), \tag{4}$$

where

$$a_{nA} = \frac{\sqrt{\beta(s_n)\beta(s_A)}}{2\sin\pi\nu}\cos\left(\pi\nu - |\phi(s_n) - \phi(s_A)|\right). \tag{5}$$

$\beta(s_n)$, $\phi(s_n)$ are the beta function and the phase at s_n and ν is the tune.

In case, multiple QMs have been changed simultaneously, for example three QMs at $s = s_A$, s_B and s_C are coupled together, the equation of the orbit change x_2 becomes,

$$x_2'' + K(s)x_2 = -\Delta K[x_1(s_A) + x_1(s_B) + x_1(s_C)]. \tag{6}$$

For a model independent analysis, many orbits have to be measured with varying QM focusing [7]. On the other hand, a well measured optics model and one set of orbit data for all BPM by QM variation allow us to estimate the BPM offset. The solution of eq.(3) is eq.(4), and the solution of eq.(6) is similarly

$$x_2(s_n) = \Delta K[a_{nA}x_1(s_A) + a_{nB}x_1(s_B) + a_{nC}x_1(s_C)]. \quad (7)$$

Assuming virtual dipole elements at the varied QMs and using an optics model, the modified COD (x_2) could be fitted by using these dipole kicks $\Delta k x_1$ as free parameters. Dividing the determined dipole kick by the field gradient change ΔK, one can estimate the beam position inside these QMs, $x_1(s_A), x_1(s_B)$ and $x_1(s_C)$.

BPM AND QM SYSTEM OF THE RCS

There are 54 BPM sensor heads around the ring for COD measurements at the J-PARC RCS [3]. Every half-cell, one BPM is located in front of a QM or behind. There are seven QM families, called QFL, QDL, QFM, QDX, QFX, QDN and QFN. The numbers of QM for these families are: 6, 6, 3, 9, 12, 12 and 12, and the total number is 60. QMs among each family are coupled and only a complete family can be controlled, not an individual QM. Most of QM have a corresponding BPM, except a half set of the QFX family.

PROCEDURE OF MEASUREMENTS AND ANALYSIS

Measured Condition

The data for BBA were taken with the following condition. The RCS was set to the DC storage mode, no acceleration mode. This was chosen, because, it is easier to change the QM focusing force in short time and it eliminated any ambiguities due to acceleration. The Sextupole magnets were switched off in order to minimize non-linear effects, although the intrinsic sextupole of the main bending magnet could not be eliminated. The effective RF voltage was lowered from 68kV to a few kV by using the "counter-phasing" technique in order to match linac beam energy and to suppress synchrotron oscillation at points of high dispersion along the ring. The operating tune was $(6.38, 6.45)$, the linac current was 5mA, the macro pulse was 0.1ms, the chopping was 560ns, the number of bunches is 1, and the beam intensity was about 8×10^{11}ppp.

Each QM family current had been changed by $0, \pm 2, \pm 4\%$ in principle, however, sometimes different set points were used to avoid the beam loss by resonance. Nine steering magnets, both horizontal and vertical each, had a kick of 0.5mrad to define the initial orbits.

Analysis and Results

The first data (@0ms) out of 20 COD data was excluded, because at this time the injection bump magnet is still on and small COD contribution leaks into the ring and the beta function shows beating due to the edge focus of the bump magnet. In spite of above conditions, some synchrotron oscillation remains at high dispersion points for horizontal data. In order to minimize such dispersion contribution to the COD data, only the data of 10ms after the injection are used for this analysis.

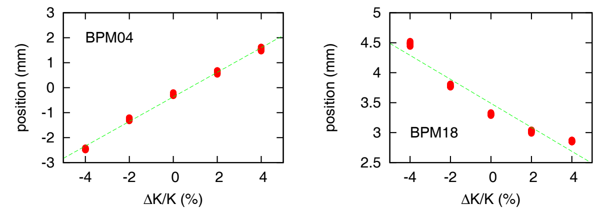

Figure 1: Examples of the position changes $x_1 + x_2$ (mm) versus $\Delta K/K$ at $BPM04$ (left) and $BPM18$ (right). Their positions are modified by varying the QDX focusing. A simple linear fit (green line) gives a slope of $\Delta K/K$.

The modified beam position ($x_1 + x_2$) at the BPMs are plotted versus $\Delta K/K$ and slope of $x_2/\frac{\Delta K}{K}$ is calculated (Fig.1). The calculated slopes of all BPM are considered as a new COD. Since it is assumed that coefficients a_{nm} are known, then one can determine the multi COD sources at the varied QM family by `CorrectionOrbit[]` of SAD [8]. From these COD sources $\Delta K x_1$, the original beam position x_1 is determined at the QM. Then, this absolute position at the QM and measured position at the nearest BPM are compared and the difference is defined as "the BPM offset with respect to the QM magnetic center".

The estimated BPM offsets for various initial orbits are plotted in Figure 2. One of the BPM offset is large (about -10mm). There is a large step between that BPM and its upstream chamber, and this causes such a large offset. This known problem is also corrected in the framework of BBA. The lower band shows the standard deviation for each BPM and these values are in the order of $\sigma \sim 0.5$mm. Relatively, larger σ parts are corresponding to the QFX, which is in a high dispersion section.

After applying these BBA results, the COD correction becomes much better compared with that before application as shown in Figure 3. Most of residual COD becomes less than 2mm except a few points, and one can get a more smooth orbit.

DISCUSSION

The error of neglecting $\Delta K x_2$ should be estimated, and ΔK higher order terms of eq.(7) are calculated as follows

$$x_2(s_n) = -\Delta K \begin{pmatrix} a_{nA} & a_{nB} & a_{nC} \end{pmatrix} (I + \Delta K A)^{-1} \begin{pmatrix} x_1(s_A) \\ x_1(s_B) \\ x_1(s_c) \end{pmatrix} \quad (8)$$

where I is 3×3 unit matrix and matrix A is

$$A = \begin{pmatrix} a_{AA} & a_{AB} & a_{AC} \\ a_{BA} & a_{BB} & a_{BC} \\ a_{CA} & a_{CB} & a_{CC} \end{pmatrix}. \quad (9)$$

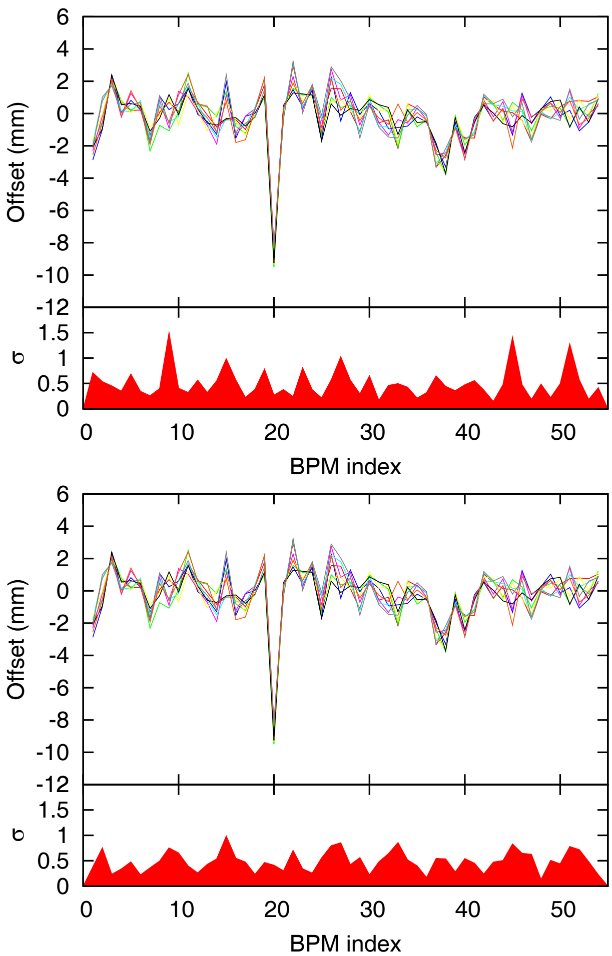

Figure 2: Results of estimated offset for all 54 BPMs. Nine different initial orbits are plotted with several colors. The upper plot contains results for horizontal and the lower plot is for the vertical offset. The bottom bands indicate the estimated error for each BPM.

This is the reason why some $x_1 + x_2$ plots [Fig.1 right is an example] show effects of higher ΔK terms, not only the linear term. In order to improve this BBA method, these effect should be included. The distance between the center of the QM and its neighbor BPM along the beam axis is about in the order of 1m. The transverse beam position between them might be slightly different and this needs to be addressed. As it is mentioned already, around high dispersive points horizontal uncertainties are relatively large. The dispersion function is significantly modified by changing the sensitive QFX. Since synchrotron oscillation is not eliminated completely, some dispersion contribution may interfere to the COD. The present COD data is averaged over 0.1ms, and it might be necessary to increase the averaging time to reduce these effects.

SUMMARY

We presented the model dependent Beam-Based-Alignment of the BPM with respect to the QM center. It is applicable even while multiple QMs arranged in a family have been changed. It is an advantage that it is not necessary to scan all QM, but a group of QM and it reduces the time consumed BBA process. As an example, the J-PARC RCS results are presented and the COD correction improvements would help for higher beam power operation. When higher order effects are calculated, this shows a possibility to further improve the accuracy of this method.

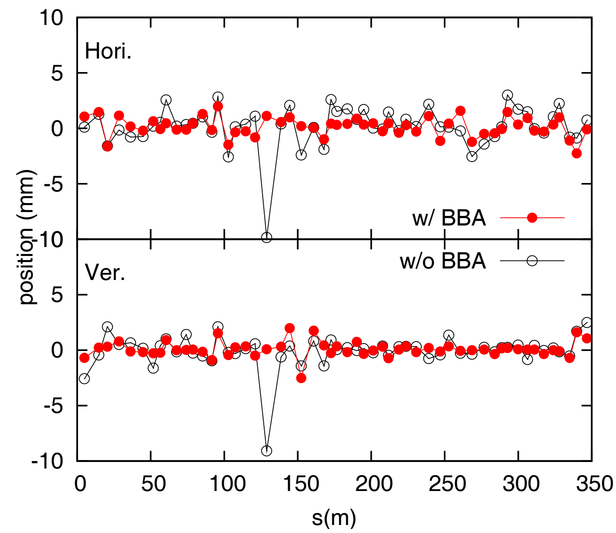

Figure 3: COD correction without (open circle) and with (closed circle) using BBA results. Upper is for horizontal and lower is vertical one.

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