BEAM BASED ALIGNMENT OF SYNCHROTRON UNDER COUPLED QUADRUPOLE MAGNET ENVIRONMENT

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Abstract

The Beam Based Alignment (BBA) of the BPM is inevitable for precise and absolute beam position measurements. Even though careful fabrication and installation of the BPM detector, it has to be calibrated by using the beam. Usually, it requires that the individual quadrupole magnet is able to be controlled. However, it is not always that case. In addition, scanning over the all BPM is time consuming procedure. The BBA method under coupled QM environment would help to reduce time for calibration. It presents general formula and experiences at J-PARC RCS and parts of results are compared with the ordinal method at J-PARC MR.

INTRODUCTION

The Japan Proton Accelerator Research Complex (J-PARC) comprises three accelerators [1] and three experimental facilities by using various intensive secondary particles for a variety of scientific programs. Its construction phase has been completed and started user operation[2, 3]. The RCS (3-GeV rapid-cycling synchrotron) is a 25Hz cycle machine and designed to provide 1 MW beam power for the MLF (Material and Life science experimental facility) and the MR (Main Ring). The RCS beam power has been regularly 120kW (intensity of $1 \times 10^{13} ppp$) since November 2009. One hour 300kW operation, which intensity is about $2.6 \times 10^{13} ppp$, was also performed as a demonstration. This intensity is provided to the MR every $3.52s$, if the MR beam power is set to 100kW. The MR has been beam commissioned in May 2008, started from very low intensity, $4 \times 10^{11} ppp$. Before a summer shut down of 2010, it gives maximum beam power of $100kW$ (several $10kW$ in regularly) for Fast Extraction (FX) to the neutrino beam line.

The BPM (Beam Position Monitor) system of the RCS [4, 5] and that of the MR [6, 7] is one of the important devices. These BPM detectors have a good linear response due to its diagonal cut electrode and a resolution of 20∼30μm. However, its offset with respect to the nearest QM (quadrupole magnet) remains as uncertainties, 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 [8, 9, 10, 11]. However, in the RCS, it is more complicated, since several QMs are coupled together and only a group of QM can be controlled as family. For such a case, by extending the single QM sweep method to the multiple QM sweeping, and multiple BPM offset can be determined simultaneously and its preliminary results are presented [12].

In the MR, only some selected BPMs, which are in the slow or the fast extraction section, are corrected. Although determination of the offset and its correction is important, BBA is time consuming measurements. So far, it is not able to find such measurements during the limited accelerator machine study time. If the multiple BPM offsets are determined at once, it may help.

In this paper, in order to show this multiple QM sweeping method works generally, two analysis methods were applied to the MR for comparison. It is also presents further analysis, including higher order effect, on the RCS are presented.

REVIEW OF BEAM BASED ALIGNMENT METHOD AND ITS EXTENSION

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 $-\Delta B/B\rho$.

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

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

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

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

$$x_2''(s) + K(s)x_2(s) = -\Delta K \times [x_{1n} + x_{2n}] \simeq -\Delta K x_{1n} \quad (3)$$

by ignoring the term $\Delta K x_{2n}$. Here, $x_1(s_n) \equiv x_{1n}$, and $x_2(s_n) \equiv x_{2n}$. Since $\Delta K(s)$ is none-zero only at $s = s_n$, eq.(3) could be rewritten using this constant ΔK as,

$$x_2''(s) + K(s)x_2(s) = -\Delta K \delta(s - s_n)x_1(s) \quad (4)$$

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Now, the orbit change $x_2(s)$ is described as a COD caused by a single kick $\Delta K x_{1n}$ and it is expressed by

$$x_{2m} \equiv x_2(s_m) = a_{nm}\Delta K x_{1n}, \qquad (5)$$

where, m indicates an arbitrary location in the ring (s_m) and

$$a_{nm} = \frac{\sqrt{\beta_n\beta_m}}{2\sin\pi\nu}\cos\left(\pi\nu - |\phi_n - \phi_m|\right). \qquad (6)$$

$\beta_n \equiv \beta(s_n)$, $\phi_n \equiv \phi(s_n)$ are the beta function and the phase at $s = s_n$ and ν is the tune.

In case, multiple QMs have been changed simultaneously, for example three QMs at $s = s_n$, s_l and s_s are coupled together, the equation of the orbit change $x_2(s)$ becomes,

$$x_2''(s) + K(s)x_2(s) = -\Delta K[x_{1n} + x_{1l} + x_{1s}]. \qquad (7)$$

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.(5), and the solution of eq.(7) is similarly,

$$x_{2m} = \Delta K[a_{mn}x_{1n} + a_{ml}x_{1l} + a_{ms}x_{1s}]. \qquad (8)$$

Assuming virtual dipole elements at the varied QMs and using an optics model, the modified COD (x_2(s)) could be fitted by using these dipole kicks $\Delta K x_{1n}$, $\Delta K x_{1l}$, $\Delta K x_{1s}$ as free parameters. Dividing the determined dipole kick by the field gradient change ΔK, one can estimate the beam position inside these QMs, x_{1n}, x_{1l} and x_{1s}.

Here, an effect due to neglecting $\Delta K x_2$ would be evaluated. The effect of higher order terms of (ΔK) in eq.(8) are calculated as follows. In case of one QM (at $s = s_n$), the modified orbit $x_2(s)$ at the location m is

$$x_{2m} = -a_{mn}\Delta K(x_{1n} + x_{2n}) \qquad (9)$$

and particularly the position at $m = n$, it becomes

$$x_{2n} = -a_{nn}\Delta K(x_{1n} + x_{2n}) \qquad (10)$$

and this constant x_{2n} can be determined as

$$x_{2n} = -\frac{a_{nn}\Delta K x_{1n}}{1 + a_{nn}\Delta K}. \qquad (11)$$

Then, at a location m, orbit change x_{2m} would be, [1]

$$\begin{aligned} x_{2m} &= -a_{mn}\Delta K(x_{1n} + x_{2n}) \\ &= -\frac{a_{mn}\Delta K(x_{1n})}{1 + a_{nn}\Delta K}. \end{aligned} \qquad (12)$$

In case of multiple QM (at $s = s_n, s_l, s_s$), it is similar as above. The equation of $x_2(s)$ is

$$\begin{aligned} x_2''(s) + K(s)x_2(s) + \Delta K(x_{1n} + x_{1l} + x_{1s}) \\ +\Delta K(x_{2n} + x_{2l} + x_{2s}) &= 0, \end{aligned} \qquad (13)$$

[1] Similar expression appears in ref.[9], but K in its denominator should be corrected by ΔK. And this is no more only lowest order expression, but includes higher order ΔK contributions.

and its solution at arbitrary location m is,

$$\begin{aligned} x_{2m} &= -\Delta K\left[a_{mn}(x_{1n} + x_{2n}) + \right. \\ &\left. a_{ml}(x_{1l} + x_{2l}) + a_{ms}(x_{1s} + x_{2s})\right]. \end{aligned} \qquad (14)$$

When m is equal to n, l or s, ($m = n, m = l$, or $m = s$), each cases are

$$\begin{aligned} x_{2n} &= -\Delta K\left[a_{nn}(x_{1n} + x_{2n}) + \right. \\ &\left. a_{nl}(x_{1l} + x_{2l}) + a_{ns}(x_{1s} + x_{2s})\right], \end{aligned} \qquad (15)$$

$$\begin{aligned} x_{2l} &= -\Delta K\left[a_{ln}(x_{1n} + x_{2n}) + \right. \\ &\left. a_{ll}(x_{1l} + x_{2l}) + a_{ls}(x_{1s} + x_{2s})\right], \end{aligned} \qquad (16)$$

and

$$\begin{aligned} x_{2s} &= -\Delta K\left[a_{sn}(x_{1n} + x_{2n}) + \right. \\ &\left. a_{sl}(x_{1l} + x_{2l}) + a_{ss}(x_{1s} + x_{2s})\right]. \end{aligned} \qquad (17)$$

Here, using $\vec{x_1} = \begin{pmatrix} x_{1n} \\ x_{1l} \\ x_{1s} \end{pmatrix}$, $\vec{x_2} = \begin{pmatrix} x_{2n} \\ x_{2l} \\ x_{2s} \end{pmatrix}$, $A = \begin{pmatrix} a_{nn} & a_{nl} & a_{ns} \\ a_{ln} & a_{ll} & a_{ls} \\ a_{sn} & a_{sl} & a_{ss} \end{pmatrix}$, and 3×3 unit matrix I, they are expressed as following.

$$\vec{x_2} = -\Delta K A(\vec{x_1} + \vec{x_2}). \qquad (18)$$

Explicit expressions of $\vec{x_2}$, and $\vec{x_1} + \vec{x_2}$ are

$$\vec{x_2} = (I + \Delta K A)^{-1}(-\Delta K A)\vec{x_1}, \qquad (19)$$

$$\begin{aligned} \vec{x_1} + \vec{x_2} &= (I + \Delta K A)^{-1}\{(I + \Delta K A) - \Delta K A\}\vec{x_1} \\ &= (I + \Delta K A)^{-1}\vec{x_1}. \end{aligned} \qquad (20)$$

Finally, the solution of equation (13) becomes,

$$x_{2m} = -\Delta K\left[\begin{array}{ccc} a_{mn} & a_{ml} & a_{ms} \end{array}\right](I + \Delta K A)^{-1}\vec{x_1}. \qquad (21)$$

This formula can be easily extended if the number of sweeping QM is increased.

BPM AND QM SYSTEM OF THE RCS AND THE MR

There are 54 BPM sensor heads around the ring for COD measurements at the J-PARC RCS [4]. 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, because they are connected to one power supply in series, 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.

In the MR, there are 186 BPM detectors and 216 QM with 11 families. Its insertion straight section, there are 7 families, QFS, QDS, QFT, QFP, QDT, QFR, QDR, which consist of 6 or 9 magnets. Rest of 4 families, QFN, QDN, QFX, QDX, are located around the arc section. For this measurement, one of QM family (QFS) was selected and it was compared with normal analysis and the new analysis method. All QMs are equipped with auxiliary coil, whose number of turns is 11 and whereas the main coil is 24 turns.

PROCEDURE OF MEASUREMENTS AND ANALYSIS

Measured Condition

RCS The data for BBA were taken with the following condition. The RCS was set to the DC storage mode, no acceleration mode. The initial operating tune was $(\nu_x, \nu_y) = (6.38, 6.45)$, 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. The BPM electronics gain was selected to be $\times 10$.

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.

MR As same as the RCS, the special measurements for BBA were taken with 3-GeV DC mode. BPMC (BPM signal processing units)[7] were operated with 'continuous COD mode'. The beam was kept about two seconds and the last half of the continuous data were taken with 1 ms sampling speed, namely 1000 points, and these are averaged for the analysis. The beam intensity is about $4.8 \times 10^{12} ppp$ with 6 bunches and the initial operating tune was $(\nu_x, \nu_y) = (22.40, 20.80)$.

When an individual QM was excited, the condition was following. The quadrupole magnets of the MR are equipped with the auxiliary coil winding and a remote controllable switcher selects one of the auxiliary coil and connects to a small DC power supply. The current from -4 to +4 Ampere were put on the auxiliary coil, which is correspond to about 2% of the main power supply. Initial orbits were defined by neighbor steering magnets to create local bump orbits, typically -8, 0, or +8 mm.

To excite a whole family of QFS, the main power supply of QFS were changed its output current from 0 to $\pm 2\%$ (via 5 to 9 points). This causes variation of tune $\nu \simeq \pm 0.36 \sim 0.4$. Nine steering magnets were used to define the initial orbits by adding $+0.2$mrad kick.

Analysis and Results

Results of MR An analysis procedure of BBA is as follows. The focusing force of one of QFS magnets located at $s = s_A$ were changed by varying the current of its auxiliary coil. As shown in Figure 1, orbit changes at $s = s_n$ (BPM003), $x_2(s_n)$, are plotted as a function of ΔK (namely the current of the auxiliary coil). Here, a term

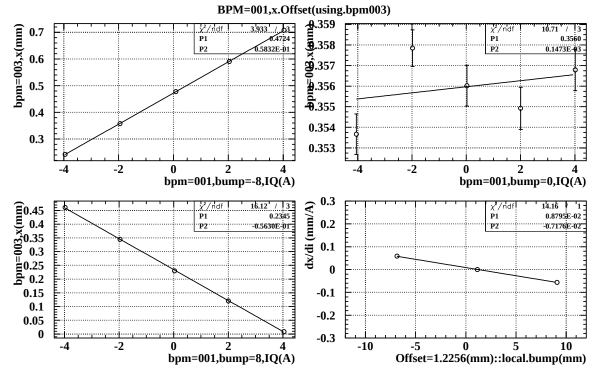

Figure 1: Example of MR BBA. Three plots show the position changes as a function of the auxiliary coil current. The right down graph indicates the determination of the BPM offset.

of $a_{nA}x_1(s_A)$ is considered as a slope (see eq.(5)). Such measurements would be performed for three initial orbits $x_1^{[i]}(s)$ $(i = 1, 2, 3)$. In Figure 1, they are three local bump orbits, -8,0,8 mm at QFS001 (near BPM001). Then, previously obtained slope $a_{nA}x_1^{[i]}(s_A)$ is plotted versus measured position $x_1^{[i]}(s_A)_{measured}$ at the nearest BPM of the ΔK modified QM. Exactly speaking, the location of the magnet s_A and that of the nearest BPM is slightly different, but it is assumed that their beam positions are the same. The fitted line intersection with $x-$axis is determined as the offset of the BPM. If the measured beam position is that value, it does indicate no kick is given, namely where is considered as the center of the quadrupole magnet. The coefficient a_{nA} determined from an optics model does not appear during the analysis procedure. Hence, this is considered as a model independent analysis.

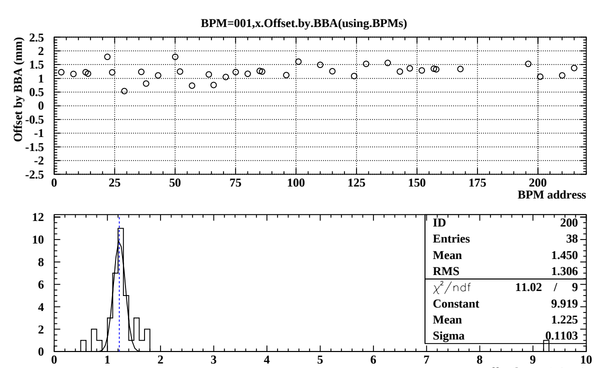

Figure 2: *BPM001* offset determination by whole BPM around the ring. Upper shows determined offset values by individual BPM. Lower shows statistics of all BPM results.

Beam orbit change x_2 due to ΔK can be measured anywhere around the whole ring, so above measurements can be applied for all the BPM as shown in Fig.2. Some BPM is very less sensitive, because its slope is very small and shows large error to determine the offset. Those data are eliminated.

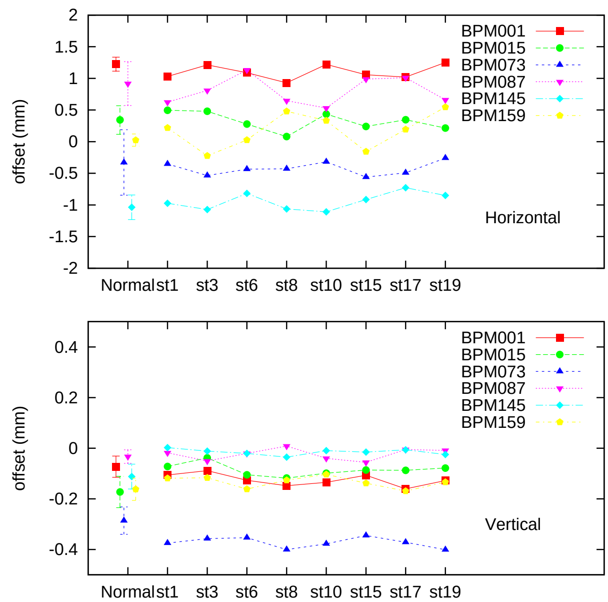

Figure 3: MR BBA offset estimation of BPM attached to QFS family magnets. Upper and lower are horizontal and vertical, respectively. Most left data is determined by single QM sweeping and reference. Eight data sets are independent measurements for different initial orbits defined by various steering magnets.

Now, it is considered the case of multiple coupled QM. As previously mentioned, QFS family magnets are controlled together. A procedure is similar to what is explained above. Firstly, the slopes at all BPM are determined as the QFS main current changed. Then, taking these slopes as COD, it is determined the COD source at all modified QFS $\Delta K x_1(s_A)$, where s_A corresponds to all QFS location. The optics model is used through a_{nm} in the module `CorrectionOrbit[]` of SAD [13]. 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".

Results of these two method are compared and shown in Fig.3. Results of two methods are consistent within error.

RCS results The estimated BPM offsets for various initial orbits are plotted in Figure 4 [12]. One of the BPM offset is large (about -10mm). There is a large pipe 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 around $\sigma \sim 0.5$mm, but some BPMs are larger.

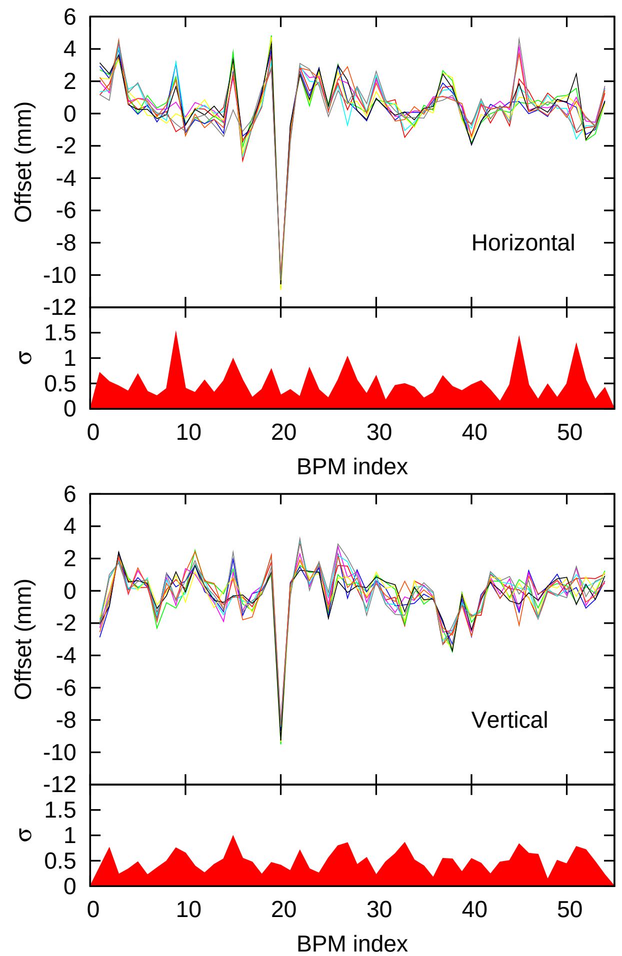

Figure 4: Results of estimated offset for all 54 BPMs. Nine different initial orbits are plotted with several colors. The upper plot contains results for horizontal and the lower plot is for the vertical offset. The bottom bands indicate the estimated error for each BPM.

Analysis including higher order term The essential difference between previous linear (ΔK) term analysis and higher order (ΔK) terms is embedded in an inverse matrix $(I + \Delta K A)^{-1}$ of eq.(21). Otherwise, eq.(21) and eq.(8) are the same. If (ΔK) is small, of course, it becomes close to the unit matrix. However, it is not practical to obtain analytical expansion of the matrix. Then, this inverse matrix is calculated numerically for each ΔK. It is turned out that sometimes none diagonal term would be as large as 20% or more for $\Delta K/K = -4\%$. It has to be taking into account absolutely.

For example, QFL family has 6 unknown $x_1(s_i)$ $(i = 1, ..., 6)$. Using measured orbit difference at all 54 BPM $x_2(s_j)$ $(j = 1, ..., 54)$ for every ΔK and above inverse matrix, six unknown were obtained. Again these beam position at QFL magnets were compared with neighbor BPM and those offsets were determined.

Figure 5 is as same as Figure 4, but it is taking into account the higher order (ΔK) terms contributions. Its un-

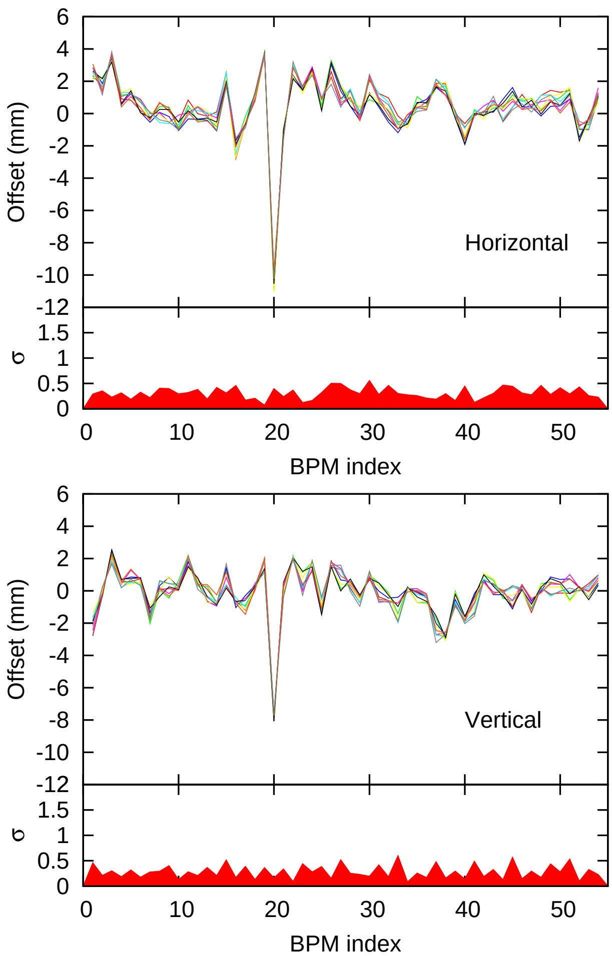

Figure 5: As same as Figure 4, but it is taking into account effect of higher order (ΔK) terms included.

certainties σ becomes less than 0.5mm for all BPM.

DISCUSSION

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, but in the present analysis these are not considered and this needs to be addressed. Initial orbits were defined by adding single kick at one of steering magnet. Most of the cases, positive or negative kick are given and a comparison with these data might indicate sizes of this systematic error. Model accuracy is also important and it needs to be evaluated.

SUMMARY

We presented an analysis of the BPM Beam-Based-Alignment at the J-PARC RCS and MR. It shows that new BBA method under multi-coupled quadrupole magnets and the normal ordinary method are consistent within error. For the RCS, the higher order term contribution were taking into account and it improves the offset estimation. We are going to apply these new results for the RCS COD correction after 2010 summer shut down.

REFERENCES

[1] Y. Yamazaki eds., Accelerator Technical Design Report for High-Intensity Proton Accelerator Facility Project, J-PARC, KEK-Report 2002-13; JAERI-Tech 2003-044.

[2] H. Hotchi, in this proceedings.

[3] T. Koseki, in this proceedings.

[4] N. Hayashi, et al., "The Beam Position Monitor System of the J-PARC RCS", Proceedings of EPAC 2008, Genoa, Italy (2008) TUPC035, p.1128-1130.

[5] H. Takahashi, N. Hayashi and M. Sugimoto, "Synchronized Data Distribution and Acquisition System Using Reflective Memory for J-PARC 3GeV RCS" *Proceedings of EPAC 2008*, p.1553-1555., Genova, Italy (2008)

[6] T. Toyama, et. al., "Performance of the Main Ring BPM during the Beam Commissioning at J-PARC" *Proceedings of IPAC'10*, p.981-983., Kyoto, Japan (2010)

[7] S. Hatakeyama, et al., "The Data Acquisition System of Beam Position Monitors in J-PARC Main Ring" *Proceedings of IPAC'10*, p.2698-2700., Kyoto, Japan (2010)

[8] R. Brinkmann, M. Böge, "Beam-Based Alignment and Polarization Optimization in the HERA Electron Ring", *Proceedings of EPAC'94*, p.938-940., London (1994)

[9] D. Robin, G. Portmann, L. Schachinger, "Automated Beam Based Alignment of ALS Quadrupoles." NLC-Note **18** (1995)

[10] M. Masuzawa et al., "Beam-based Calibration of Beam Position Monitors and Measurements of the Sextupole Magnet Offsets at KEKB", Proceedings of EPAC2000, Vienna, Austria (2000) WEP5A16, p1780-1782.

[11] N. Hiramatsu, "Beam Instrumentation for Accelerators", KEK Internal 2004-4 (Japanese) p.108-115.

[12] N. Hayashi, et al., "Beam Based Alignment of the Beam Position Monitor at J-PARC RCS" *Proceedings of IPAC'10*, p.1005-1007., Kyoto, Japan (2010)

[13] K. Oide et al., SAD (Strategic Accelerator Design) `http://acc-physics.kek.jp/SAD/sad.html`.