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BEAM-BASED ALIGNMENT SIMULATION ON TRANSPORT LINE OF CSNS

Yong Li, L.S.Huang, Z.P.Li, Y.W.An, X.H.Lu, W.B.Liu, S.Wang
Dongguan Campus, Institute of High Energy Physics，Dongguan 523803 China

Abstract

The China Spallation Neutron Source (CSNS) is a high beam power proton machine which needs high precise alignment. Compared to traditional optical alignment, the beam-based alignment (BBA) technique can implement higher precise alignment. This technique with two implementations is applied to the transport line of CSNS to get the transverse misalignments of beam position monitor (BPM) and quadrupole magnet by measuring BPM data under different conditions. The corresponding control system application programs were developed based on CSNS/XAL platform. The result shows the fitted result is consistent with the input result.

INTRODUCTION

CSNS is a high power proton machine which is composed of accelerator, target and spectrometer [1]. The accelerator mainly contained a linac with a modest but upgradable energy and a rapid cycling synchrotron (RCS) of the fixed energy at 1.6 GeV. The installation and beam commissioning of the front end of linac has been finished. The beam commissioning for MEBT is upcoming.

The control of beam loss is quite strict for the reason of high power proton. Orbit correction should be done to decreasing the beam loss. Besides, the orbit correction is normally the first and the most important work during beam commission. Other tasks can easily carry out with very small and smooth orbit. But unfortunately, the measured and the true orbit have difference for the error of alignment and resolution of the magnet and BPM. It can't reach the expected purpose with big errors. The calibration of BPM and quadrupole can be achieved through BBA method. In this paper, two kinds of methods and the detailed simulation based on XAL platform is presented.

REVIEW OF BEAM BASED ALIGNMENT METHOD

The study and application of BBA technique can be seen in many laboratories at home and abroad [2-4] and the way of implementation is diversity. Two kinds of implementations will be introduced in this section.

The principle of the first method is very easy. When the beam passes through the center of the magnet, the BPM data is the relative offset of BPM to the quadrupole. We can change the beam position at the entrance of the quadrupole and scan the gradient of the field in the quadrupole and measure the BPMs' responses on both transverse directions. In many situations, the error of alignment for quadrupole is very small; the measured offset can be approximately considered the offset of BPM. However, this method takes too much time.

The second approach looked more promising, which can get the quadrupole and BPM transverse misalignments simultaneously. This method also need to change orbit and scans the gradient of the field of quadrupole. Meanwhile, the liner optics between all beam line elements must be known.

Fig 1 is the beam orbit with misalignments. Based on the liner optics transmission theory, the beam position measurement (m_i) at BPM-i is assumed to be the sum of all upstream beam kicks from quadrupole offset, correctors, incoming launch conditions and BPM offset as in (1) and (2).

$$m_i = (\mathbf{x_i})_1 - \mathrm{b_i} \tag{1}$$

$$\boldsymbol{x_i} = \mathbf{R}^{(\mathrm{B_1}:\mathrm{i})}\boldsymbol{x_1} + \sum_{\mathrm{j}}^{\mathrm{N_{Ci}}} \mathbf{R}^{(\mathrm{C_j}:\mathrm{i})}\mathbf{c_j} + \sum_{\mathrm{j}}^{\mathrm{N_{Qi}}} \mathbf{R}^{(\mathrm{Q_j}:\mathrm{i})}\left(\mathbf{I} - \mathbf{R}^{(\mathrm{Q_j})}\right)\mathbf{q_j} \tag{2}$$

where x_1, $\mathrm{c_j}$ and $\mathrm{q_j}$ are, respectively, the incoming launch position/angle vector at the first BPM in the beam line, a corrector kick angle vector, and a quadrupole position offset vector defined as

$$\boldsymbol{x_1} = \begin{bmatrix} x_1 \\ x_1' \end{bmatrix}; \quad \boldsymbol{c_j} = \begin{bmatrix} 0 \\ \theta_\mathrm{j} \end{bmatrix}; \quad \boldsymbol{q_j} = \begin{bmatrix} \mathrm{q_j} \\ 0 \end{bmatrix}; \tag{3}$$

R is the 2x2 transfer matrix from the first BPM, or from corrector-j, or from quadrupole-j to the BPM-i, or simply the matrix across quadrupole-j.

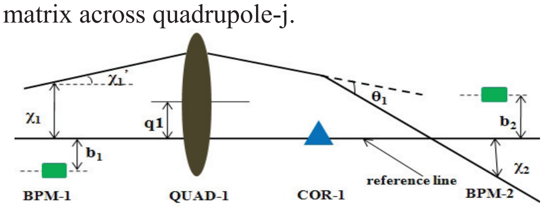

Figure 1: Beam based alignment scheme.

Based on Eq. 2, we can write a set of equations of each of BPM trajectory with different quadrupole strength settings and different incoming launch conditions. Quadrupole and BPM transverse misalignments can be calculated by the least square method.

SIMULATION RESULTS

This BBA application is developed based on the SNS/XAL [5], which is an open source development environment used for creating accelerator physics applications, scripts and services. There are many applications for beam commissioning like orbit correction, lattice calculation, lattice math and so on [6-7]. The result of XAL model for lattice calculation is consistent with the result used other accelerator code,

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such as mad, trace3D, parmila, etc. Additionally, XAL use JCA to realize interaction control with EPICS system interface, greatly simplifying the programs of the bottom work.

Analysis and Design of BBA Application

The specific implementation process for the first method is to change the magnetic field intensity of upstream corrector, gradually increase the field strength of the quadrupole for five times, and records the downstream auxiliary BPM readings simultaneously. Then we get the quadrupole response to auxiliary BPM by linear fitting of these five points. Then we back to the original quad field and record the measured BPM value. After we change to another strength of the corrector and repeat the process. The repeat number is more, the result is better. Finally, we fitted the measured BPM records and the quadrupole response for auxiliary BPM. The relative offset of BPM to quadrupole can be achieved from the fitting result when the quad response is zero.

For the second method, the least square method was not used in the Eq. 1. If the launch conditions were not changed during measurement, the matrix expression of Eq. 1 can be simply demonstrated as:

$$\begin{bmatrix} m_1 \\ m_2 \\ m_3 \end{bmatrix} = \begin{bmatrix} \mathrm{QR}_1 & -\mathrm{I} & \mathrm{LR}_1 \\ \mathrm{QR}_2 & -\mathrm{I} & \mathrm{LR}_2 \\ \mathrm{QR}_3 & -\mathrm{I} & \mathrm{LR}_3 \end{bmatrix} * \begin{bmatrix} \Delta q \\ \Delta b \\ x_{init} \end{bmatrix} \tag{4}$$

Where m is the BPM readings, the subscript number corresponds to different measurement conditions; QR is the response matrix which maps the quadrupole offset to the BPM readings downstream; LR is the response matrix of launch condition to each BPM. The Eq. 2 can be solved with the QR decomposition or singular value decomposition (SVD) method when we get all the BPM readings under different conditions. But unfortunately, Eq. 2 is ill-conditioned; the solution of the whole equation will be infinite. The reason in physics is that the reference line is unknown and the launch condition is so sensitive to the beam orbit. To stabilize the system and get the closest results, two ‘soft-constraints’ was added.

$$\textstyle\sum_i \Delta q_i = 0 \qquad \sum_i s_i . \Delta q_i = 0 \tag{5}$$

where s_i is the quadrupole location. After adding the two constraints, the input error is quite close to the fitted error by many tests.

Eq.4 didn’t reflect the contribution of the corrector to orbit directly. In fact it is included in the LR items. Beam distribution of XAL model is used in the form of a 7 x7 matrix like this:

$$x = \langle \mathrm{zz}^{\mathrm{T}} \rangle =$$

$$\begin{bmatrix} \langle x^2\rangle & \langle xx'\rangle & \langle xy\rangle & \langle xy'\rangle & \langle xz\rangle & \langle xz'\rangle & \langle x\rangle \\ \langle xx'\rangle & \langle x'^2\rangle & \langle x'y\rangle & \langle x'y'\rangle & \langle x'z\rangle & \langle x'z'\rangle & \langle x'\rangle \\ \langle xy\rangle & \langle x'y\rangle & \langle y^2\rangle & \langle yy'\rangle & \langle yz\rangle & \langle yz'\rangle & \langle y\rangle \\ \langle xy'\rangle & \langle x'y'\rangle & \langle yy'\rangle & \langle y'^2\rangle & \langle y'z\rangle & \langle y'z'\rangle & \langle y'\rangle \\ \langle xz\rangle & \langle x'z\rangle & \langle yz\rangle & \langle y'z\rangle & \langle z^2\rangle & \langle zz'\rangle & \langle z\rangle \\ \langle xz'\rangle & \langle x'z'\rangle & \langle yz'\rangle & \langle y'z'\rangle & \langle zz'\rangle & \langle z'z'\rangle & \langle z'\rangle \\ \langle x\rangle & \langle x'\rangle & \langle y\rangle & \langle y'\rangle & \langle z\rangle & \langle z'\rangle & 1 \end{bmatrix} \tag{6}$$

This matrix is called correlation matrix [8].This matrix considered the influence of the dipole component to trajectory compared to the 2×2（or 6×6）matrix.

Fig 2 is the operation interface of BBA application, which can give the results directly. In order to check or analysis data after measurement, this data were saved in MYSQL database. During the measurement, we need pay attention to the up limit and low limit of the field of magnet.

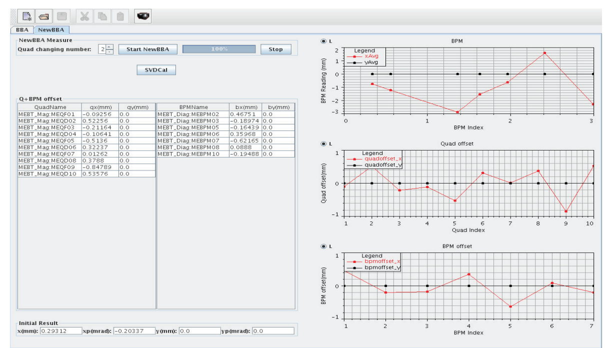

Figure 2: The operation interface of BBA application.

Testing of BBA Application

Software testing is also important for software develop. The application of virtual accelerator in XAL is specifically designed for the testing of other application. It is actually a soft IOC, which can provide the PV information of magnets, cavity, BPM, etc. It also can calculate the trajectory of beam line and beam size with arbitrary errors of BPM, magnet magnetic field. The original virtual accelerator didn’t consider the influence of quadrupole offset to beam orbit. In order to verify the correctness of the BBA program, the last component of Eq.2 is added to the virtual accelerator application.

The tolerance of the misalignment for magnets, diagnostic instruments in beam transfer lines of CSNS were shown in table 1. The simulation will refer to the data in the table.

Table 1: Alignment Requirement in Beam Transfer Lines

Device	Dipole	Quadrupole	Corrector	BPM
Δx(mm)	0.2	0.15	0.3	0.15
Δy(mm)	0.2	0.15	0.3	0.15
Δz(mm)	0.2	0.5	1.0	0.5
Δθx(mrad)	0.2	0.5	1.0	0.5
Δθy(mrad)	0.2	0.5	1.0	0.5
Δθz(mrad)	0.1	0.2	0.5	0.5

BBA application is firstly tested in MEBT sequence for the upcoming beam commissioning. Figure 3 is the layout of MEBT. There are totally 10 quadrupoles and 7 BPMs (8 BPMs are planned to be installed, 1 BPM was removed

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for the reason of difficult installation). The BPMs have the same position with the quads.

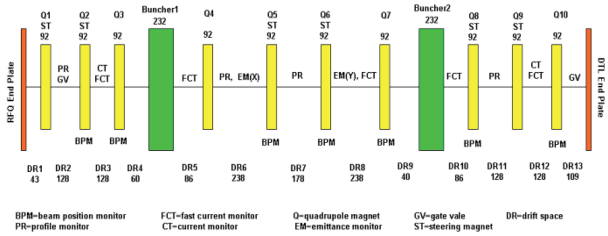

Figure 3: The layout of MEBT.

During simulation, we produce a non-zero orbit by giving proper initial beam parameters in virtual accelerator. Then we scan the quadrupole field strength one by one and record all the BPM readings. There are 142 equations (containing the added two constraints) in one transverse direction assuming each quadrupole changes magnetic field twice. The compared results are shown in figure 4 after SVD decomposition. It can be found the fitting results are consistent with input errors.

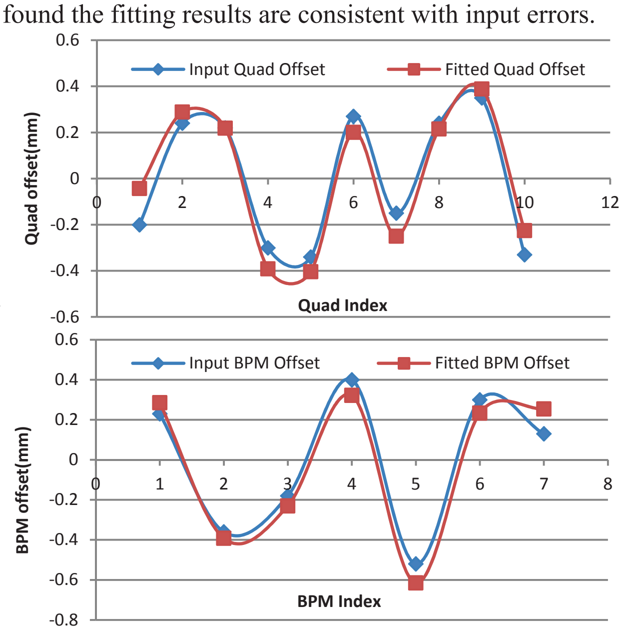

Figure 4: Input and fitted offsets.

After BBA measurement, the alignment results were provided to the diagnostic group. Applied physics group finished the orbit correction by applying the standard XAL orbit correction application with the final beam orbit after deducting alignment error. The other application for BBA is to improve the model to close to real machine.

CONCLUSION

This paper gives two methods to achieve BBA in the transport line of CSNS and design the simulation control program based on the XAL platform. The program has good results with little difference between input and fitted error and will get the best test in the upcoming commissioning on MEBT sequence.

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