MODEL BASED ORBIT CORRECTION IN A DIAGNOSTICS DEFICIENT REGION *

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Abstract

An orbit correction method is presented for a region where the number of beam position monitors is much less than the number of possible trajectory distortions points (quads). The method was developed for the Coupled Cavities Linac (CCL) part of the Spallation Neutron Source (SNS) linac. The orbit correction is very important in this region to minimize losses and activation, but a traditional orbit correction did not work here. The new method based on a realistic online model was developed. The procedure of a model parameters finding and results are discussed

MOTIVATION

In SNS's linac and ring the orbit correction is routinely performed by using the general XAL Orbit Correction application [1], but for the CCL the results were unsatisfactory in terms of beam losses and activation. The reason was a relatively small number of beam position monitors (BPMs) in this region (10 BPMs) compared to the number of possible orbit distortion points at CCL quads (47 quads). It is possible to provide zero BPMs' readings by using correctors and a conventional orbit correction algorithm, but it will not necessarily make the orbit flat between BPMs. A new approach to the orbit correction was needed.

SOLUTIONS

The only way to know the orbit without direct measurement is to use an adequate model to analyze available diagnostics data. There was a very strong indication that our XAL online model could be very accurate in the orbit predictions. Fig. 1 shows one common case of measured and calculated orbit differences in the CCL. The difference between BPMs readings and the online model predictions on average is less then 0.1 mm. The online model was synchronized with the live accelerator. This kind of agreement was seen for arbitrary combinations of CCL correctors and quads currents, but the absolute orbits could not be reproduced with the same accuracy.

A possible explanation for this situation could be that the model has the correct transfer matrices for beam line elements, but there are some unknown small (less or about 1 mm) non-zero offsets for quads and BPMs. Assuming this analysis is correct, two approaches to the CCL orbit correction were developed.

The first is a usual beam-based alignment. This approach was implemented in an XAL specialized application called "Quad Shaker" where the CCL quads were used as devices to measure the beam position. Then the usual orbit correction was used. The existing quad offsets were considered to have a negligible effect on loss reduction. The results from this approach were used to improve the online model improvement for the second orbit correction method.

The second approach consists of a modification of the online model to reproduce absolute CCL orbits and to correct the orbit using the model predictions rather than the BPM data. We call this approach a model based orbit correction. This solution is more convenient for a control room operation, because it does not need the lengthy beam-based aliment measurements and can be done even parasitically. Below we discuss both approaches.

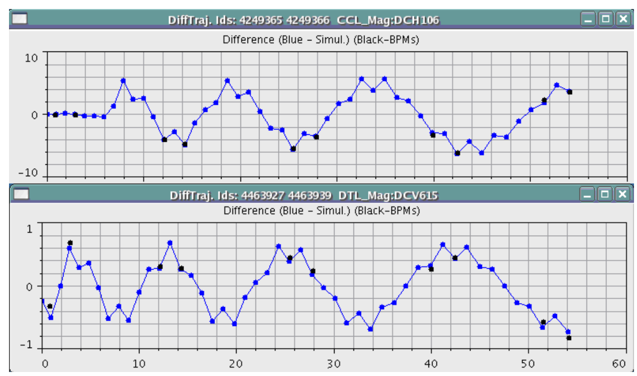

Figure 1: Horizontal (top) and vertical (bottom) orbit differences in CCL from the XAL online model (blue) and BPMs (black dots) live signals.

QUAD-SHAKER XAL APPLICATION

The Quad Shaker application scans the gradient of the field in the quads and measures the BPMs' responses on both transverse directions. The main goal is to get beam offsets inside quads and to correct the orbit by using available dipoles.

The responses of BPMs are defined by a formula

$$\begin{pmatrix} X_{BPM} \\ X'_{BPM} \end{pmatrix} = M \bullet \begin{pmatrix} \cos(K \cdot L) & \sin(K \cdot L)/K \\ -K \cdot \sin(K \cdot L) & \cos(K \cdot L) \end{pmatrix} \bullet \begin{pmatrix} X_q \\ X'_q \end{pmatrix} \quad (1)$$

$$M = \begin{pmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{pmatrix}$$

where M is a transport matrix between the exit from the quad and the BPM location, L is a length of the quad, X and X' are beam position and angle, and

$$K = \sqrt{G/(B \cdot \rho)} \quad (2)$$

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G is a quad field gradient and $B \cdot \rho$ is the magnetic rigidity.

In the general case the BPM response will be a function of the position and the angle of the beam at the entrance of the quad, but in the thin lens approximation we can get rid of the angle dependency and calculate BPM responses to the quad field change ("shaking") as follows

$$d(X_{BPM})/dG = -(L \cdot c \cdot m_{12})/(W_0 \cdot \beta \cdot \gamma) \cdot X_q \quad (3)$$

where β, γ are relativistic parameters, W_0 is a total energy, and c is a speed of light. The m_{12} transport matrix component for each quad-BPM pair are provided by the XAL online model. Usually it takes about 30-40 minutes to perform a scan on a field gradient for all 47 CCL quads. After the beam offsets for each quad are found, the orbit is corrected by using CCL dipole correctors and applying the standard XAL orbit correction.

The XAL Quad Shaker application successfully implemented the described orbit correction approach for the CCL part of the SNS linac, but the procedure takes too much time. The second approach looked more promising.

MODEL BASED ORBIT CORRECTION

To predict the trajectory in any part of the linac two components are needed: a correct model and initial conditions (positions and angles) at the entrance.

Model

It was said earlier that the discrepancy between model trajectories and measured by BPM positions was attributed to the transverse misalignment of quads. Based on this assumption the transformation of the coordinates after a passage through each quad will be defined by

$$\begin{pmatrix} X_{after} \\ X'_{after} \end{pmatrix} = \begin{pmatrix} \Delta \\ 0 \end{pmatrix} + M_{quad} \bullet \left(\begin{pmatrix} X_{before} \\ X'_{before} \end{pmatrix} - \begin{pmatrix} \Delta \\ 0 \end{pmatrix} \right) \quad (4)$$

where Δ is a quad offset parameter which is unknown, and M_{quad} is a linear transport matrix of the quad which is assumed to be known very well. The free parameters also include offsets for all BPMs. The total number of unknown model parameters for CCL was 114 (two offset directions for 47 quads and 10 BPMs). The procedure of finding these parameters consisted of two stages.

Model Parameters Finding I

In the beginning a set of seven Quad Shaker measurements were performed for different initial conditions at the CCL entrance. These conditions were created with upstream correctors in the Drift Tube Linac (DTL) preceding the CCL. The data were stored in external files (position of the beam inside quads) and in the XAL PV (process variable) Logger data base.

XAL PV Logger is a standard tool used to store a snapshot of an accelerator state in the data base. What the snapshot includes can be customized, and in our case it included the field and current in all magnets, BPM signals etc. Each snapshot has a unique index (ID), and the online model can be initialized at any time from the data base in accordance with this PV Logger ID.

During the fitting procedure we minimized the difference between model predictions and measured by Quad Shaker positions of the beam inside quads

$$\chi^2 = \sum_{i=(x,y)} \sum_{j=quads} (z_{i,j} - z_{i,j}^{model})^2 / \sigma_{i,j}^2 \quad (5)$$

The fitting parameters included the quad offsets and the four initial conditions per each Quad Shaker measurement. The total number of free parameters was 122 (horizontal and vertical offsets for each of 47 quads and initial parameters). The fitting procedure used an XAL inner optimization package with a simplex algorithm. At the end of this stage we found BPM offsets by comparing model data with the real BPM signals.

The test of the online model with the found quad and BPM offsets showed that there still was a significant disagreement between measurements and model predictions for an arbitrary state of the accelerator. The average difference was about 0.4-0.8 mm instead of 0.1 or less that we could expect from the orbit difference simulations (see Fig. 1). The typical quality of an agreement between measurements and the model is shown on Fig 2. At this point we decided to proceed with the fitting procedure and use a new set of data that has only BPM signals to reproduce. The process of collecting these data is much faster, because it does not include the time consuming quad shaking.

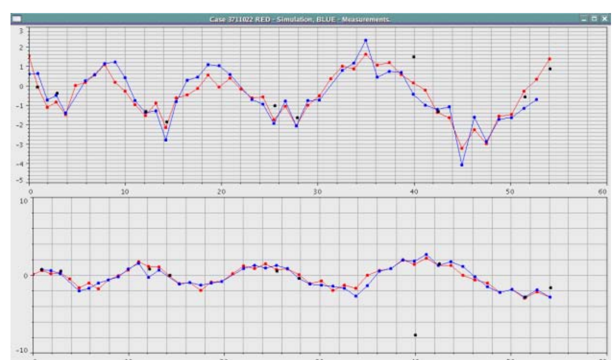

Figure 2: The horizontal (top) and vertical (bottom) CCL orbits measured by the Quad Shaker application (blue) and calculated by the online model (red).

Model Parameters Finding II

During the second stage we collected about 3000 accelerator state snapshots (by using XAL PV Logger) organized in 50 cases with 60 snapshots inside each case. Each case had a certain values of DTL dipole correctors and fixed initial conditions (position and angle of the beam) at the CCL entrance. The snapshots inside the case are characterized by different field values in correctors and quads. The fitting parameters in addition to the quad and BPM offsets included the initial conditions at the

CCL entrance for each case. In the beginning of the fitting procedure we used the offsets found on the previous stage.

The procedure included a filtering based on the initial conditions prediction. We fitted initial conditions for each snapshot inside each case first and removed snapshots that had more than three sigma deviation from the average initial conditions for this particular case. 48 snapshots from 3000 were marked as “bad” and were removed from the analysis.

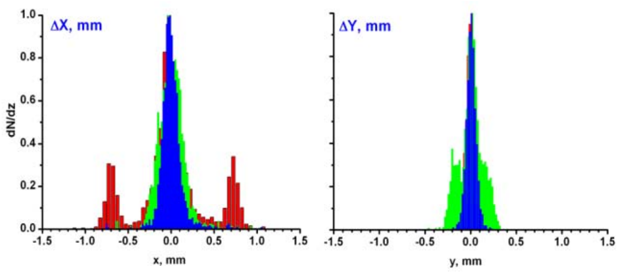

Figure 3: The distribution of the predicted initial beam position at CCL around average values for each case: red is for zero offsets; green is for offsets found during the stage one; and blue is for the final offsets values.

We could not include all 2952 snapshots in a fitting procedure because of a computer memory restriction, so we chose only 6 cases (about 360 snapshots) which cover practically the whole region of initial conditions for 50 cases. The rest of the cases were used for a quality control of the fitting.

Fig. 3 shows statistical distributions of the initial position predictions for the whole 2952 snapshots statistics on different stages of the fitting procedure. At the end of the fitting, the distribution had a good Gaussian shape without suspicious correlations found at early stages. We could say that the initial conditions at CCL can be determined with accuracy 0.15 mm and 0.2 mrad along both directions.

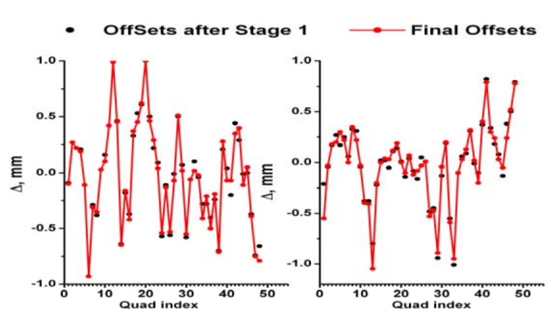

Figure 4: The horizontal (left) and vertical (right) quad offsets in CCL for two stages of the fitting procedure.

The final offsets for the quads in the CCL are shown on Fig. 4. The differences between offset values found during stages of the fitting procedure are very small, but they result in a big improvement in the agreement between model and measured data. The absolute values of the quad offsets are less that 1.2 mm, but they are still too big to be real geometrical offsets. We consider these offsets as integral correction parameters for all imperfections of a particular quad. At this time, a question about stability of these parameters is open. The orbit correction application based on them has been successfully used in the SNS control room for about a year without changes in the offset values.

Orbit Correction Algorithm

The model based orbit correction for CCL includes several steps:

- The online model of CCL with previously found quad and BPM offsets should be initialized from the live accelerator data including quad gradients, corrector fields, and BPM signals.
- The initial coordinates of the beam at the entrance of CCL should be found as a result of a fitting procedure where the model trajectory should reproduce the existing BPM readings.
- The new corrector fields should be found as results of another optimization procedure aimed to minimize the model orbit deviation from zero for fixed initial conditions found on the previous step.
- The found corrector field values are applied to the accelerator.

The time needed to perform these steps is about 10-15 second (spent mostly on fitting calculations), and it can be done parasitically. The average difference between the model and the live BPMs’ signals is usually less then 0.1 mm which is now corresponds to the orbit difference agreement.

CONCLUSIONS

Based on the results of these studies following conclusions can be made:

- The XAL online model can be very precise in predicting the trajectory of the beam.
- The BPMs in CCL part of SNS linac have linear response range at least +-6 mm with accuracy at least 0.1 mm.
- The usage of the developed algorithm for an automatic orbit correction reduced beam losses and activation in CCL.

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