USING THE ONLINE SINGLE PARTICLE MODEL FOR SNS ACCELERATOR TUNING

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Abstract

This paper describes the usage of the XAL online model for transverse and longitudinal tuning of the SNS linac. Most of the SNS control room physics applications are based on the XAL online model, which can be synchronized with an accelerator live state and used to tune the machine. Advantages of a simple and fast single particle model for orbit correction and longitudinal dynamics control in the SNS control room are discussed.

SIMULATION CODES AND THEIR APPLICATIONS

There are a variety of different codes for linear accelerator simulations. At the present level of average computational power we can divide them into two types, depending on convenience of their usage in an accelerator control room. Usually the multi-particle codes are too slow, need dedicated computers, and cannot be used in an interactive environment. They are usually used for off-line complex physical simulations. The codes from the other group are very simple, fast, and based on simulations of single-particle or envelope motion. They can be used for interactive tuning of the machine if they are contained in an infrastructure providing synchronization with the live accelerator. The XAL online model [1] is of this latter type of models, and we are going to discuss this model and two instances of its usage in the SNS central control room for linac tuning. The first instance is a model-based orbit correction application in the CCL part of the SNS linac, which is a region deficient in diagnostics. The second example is a longitudinal tuning control application for a warm part of the linac. Before we consider these applications we will describe the XAL structure and the place of the online model within it.

XAL AND ONLINE MODEL OVERVIEW

XAL is an application software environment for accelerator control systems implemented in Java [1]. Its development was started during the early days of the SNS project. The structure of XAL is shown in Fig. 1. It includes several utilities packages and applications. It has its own tool box with math, optimization, plotting packages, application framework, and services. The core of most applications is the XAL online model

The XAL online model simulates the motion of charged particles through specified accelerator sequences. It supports both linear sequences and rings. It uses six dimensional phase space propagation and linear transport matrices, calculates Twiss parameters, energy, and orbit distortions, and it includes space charge forces for envelope propagation. The machine optics can be input from design optics, the live machine, a memorized machine state, custom values, or a combination of these sources. The online model is fast enough to use interactively in optimization tasks.

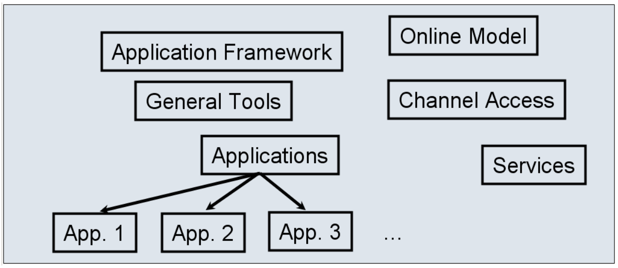

Figure 1: XAL structure

ORBIT CORRECTION IN A DIAGNOSTIC-DEFICIENT REGION

In the SNS linac and ring, orbit correction is routinely performed by using the general XAL Orbit Correction application [1]. This application minimizes the beam position monitor (BPM) readings by changing the vertical and horizontal corrector fields. For the CCL part of the SNS linac the results were unsatisfactory in terms of beam losses and activation. The reason was the relatively small number of BPMs in this region (10 BPMs) compared to the number of possible orbit distortion points at CCL quads (47 quads). Because of the small number of BPMs, it is possible to zero the BPM readings by using the available correctors and a conventional orbit correction algorithm, but it will not necessarily make the orbit flat between BPMs. A new approach to orbit correction was needed.

There is a well known beam-based alignment method of orbit correction for such situations. 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 use of this method reduced losses and activation in the CCL. The essential drawback of this approach was the long time needed to perform scans over the quad fields. Usually, 30-40 minutes were required to correct the orbit in the CCL.

To reduce this orbit correction time a new method called model-based orbit correction was suggested. The method includes the following steps:

- The online model of the CCL is initialized from the live accelerator data including quad gradients, corrector fields, and BPM signals.
- The initial coordinates of the beam at the entrance of

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CCL are found as a result of a fitting procedure where the model trajectory should reproduce the existing BPM readings.

- The new corrector fields are found as results of another optimization procedure aimed at minimizing the model orbit deviation from zero for the fixed initial conditions found on the previous step.
- The new corrector field values are applied to the accelerator.

The approach is shown in Fig. 2.

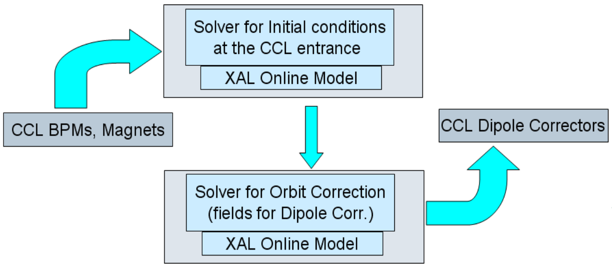

Figure 2: Model-based orbit correction algorithm

Unfortunately the application based on this algorithm did not reduce the losses and activation. This fact contradicted a very strong indication that our XAL online model could be very accurate in orbit predictions. Fig. 3 shows a typical case of measured and calculated orbit differences in the CCL. The difference between BPM 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 quad currents, but the absolute orbits could not be reproduced with the same accuracy.

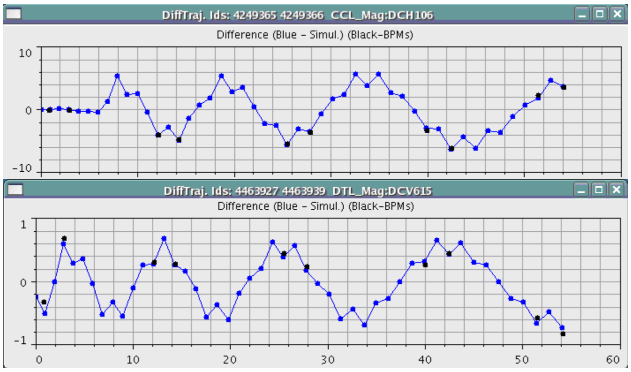

Figure 3: Horizontal (top) and vertical (bottom) orbit differences in CCL from the XAL online model (blue) and BPM (black dots) live signals.

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 (about 1 mm or less) non-zero offsets of the quads and BPMs. Based on this assumption the transformation of the coordinates after a passage through each quad will be defined by

$$\begin{pmatrix} X_{after} \\ X'_{after} \end{pmatrix} = \begin{pmatrix} \Delta \\ 0 \end{pmatrix} + M_{quad} \bullet \left(\begin{pmatrix} X_{before} \\ X'_{before} \end{pmatrix} - \begin{pmatrix} \Delta \\ 0 \end{pmatrix} \right) \qquad (1)$$

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 the CCL was 114 (two offset directions for 47 quads and 10 BPMs). The procedure to find these parameters consisted of two stages.

Finding Model Parameters: Stage I

Initially, 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. The contents of the snapshot can be customized, and in our case they included the fields and currents 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 positions (by Quad Shaker) of the beam inside the quads

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

The fitting parameters included the quad offsets and 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 new 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. 3). The typical quality of an agreement between measurements and the model is shown in Fig. 4. 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.

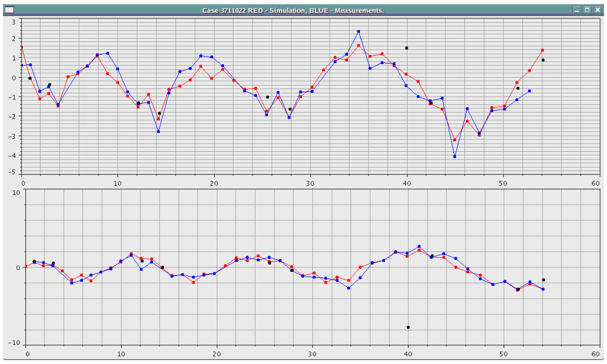

Figure 4: The horizontal (top) and vertical (bottom) CCL orbits measured by the Quad Shaker application (blue) and calculated by the online model (red).

Finding Model Parameters: Stage II

During the second stage we collected about 3000 accelerator state snapshots (by using XAL PV Logger) organized into 50 cases with 60 snapshots inside each case. Each case had 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. In addition to the quad and BPM offsets, the fitting parameters included the initial conditions at the CCL entrance for each case. In the beginning of the fitting procedure we used the offsets found in 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 larger than a three sigma deviation from the average initial conditions for the particular case. Of the 3000 snapshots, 48 snapshots were marked as "bad" and were removed from the analysis.

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 the 50 cases. The rest of the cases were used for quality control of the fitting.

Fig. 5 shows the statistical distributions of the initial position predictions for the whole 2952 snapshots at different stages of the fitting procedure. At the end of the fitting, the distribution had a good Gaussian shape without the suspicious correlations found at early stages. We could say that the initial conditions in the CCL can be determined with accuracy 0.15 mm and 0.2 mrad in both directions.

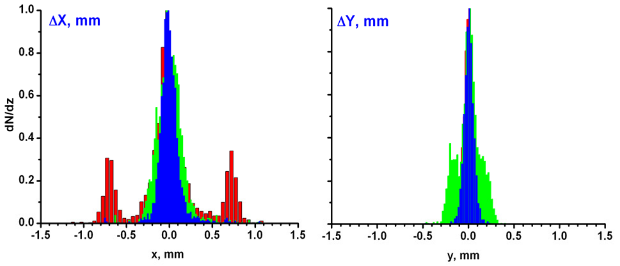

Figure 5: The distribution of the predicted initial beam position at the CCL around average values for each case: red is for zero offsets; green is for offsets found during the stage one; and blue is for the final offset values.

The final offsets for the quads in the CCL are shown on Fig. 6. 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 regard these offsets as integral correction parameters for all imperfections of a particular quad. At this time, the question of stability of these parameters is open. However, 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.

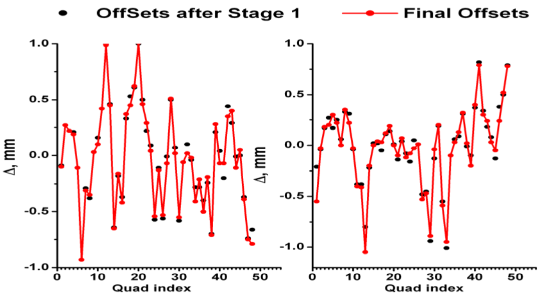

Figure 6: The horizontal (left) and vertical (right) quad offsets in the CCL for two stages of the fitting procedure.

LONGITUDINAL TUNING CONTROL

The longitudinal tuning control of the SNS warm linac is another example of a successful application of the XAL online model. The longitudinal tuning itself is based on the widely used Delta T phase scan technique developed by Crandall [2] or the "phase signature matching" method both implemented in XAL applications [3]. The tuning is a time consuming procedure, and it includes "switching off" cavities between the tuned cavity and BPMs. During SNS production runs, it is extremely undesirable to perform the tuning, but for various reasons, from time to time we have to check that cavity phases and amplitudes are tuned correctly. To check and to correct the longitudinal tuning without interruption of neutron production, the "longitudinal shaking" method with a small "phase shaking" amplitude was developed.

The "longitudinal shaking" method is based on comparison of simulated and measured responses to a simultaneous small phase (it really means time) shift of all RF cavities in a linac sequence. In the single-particle model these cavities' phase shifts are equivalent to a time shift of a particle entering the linac sequence. As the result of such a shift, the phases of the following BPMs (which are the times of a beam center arrival) change. Comparing simulated and measured BPM phase changes we can make conclusions about differences between design amplitudes of cavities and their real values.

Fig 7 shows a result of such a comparison for the case when an RF cavity between the second and third BPMs has its amplitude reduced from the design value. It is obvious that the wave described by the changes in the BPM phases is slower than one predicted by a simulated design case. The results for a well tuned linac are shown in Fig. 8.

This technique of the longitudinal tune check is convenient to use because it requires only a very small amplitude of cavity "phase shaking". Usually it is about 2-3 degrees. The trajectories, losses, beam size, and tunes in the SNS linac and ring downstream of this sequence are not affected by these small changes. There are some drawbacks to this method. First, it allows only the correction of the amplitudes of the cavities. The sensitivity to phase offsets of the cavities is low. Second, it is difficult to correct several cavities at once. The corrections should be performed sequentially. Despite these shortcomings, the method is very useful during production runs, and it is constantly used in the SNS control room.

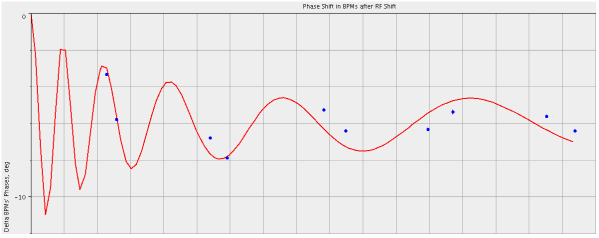

Figure 7: The BPM phase shifts in the SNS DTL and CCL linac as a function of distance from the beginning of the sequence. This is a fragment of the graph from an online application. Red color is for the simulated design settings, and the blue points are the live BPM readings.

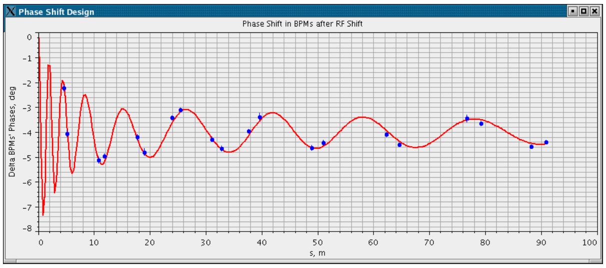

Figure 8: The same as Fig. 7. The data for a well tuned linac.

CONCLUSIONS

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

- The XAL online model can be very precise in predicting the trajectory of the beam.
- The linear response range of the BPMs in the CCL part of the SNS linac is at least +-6 mm and the accuracy is at least 0.1 mm.
- The algorithm developed for an automatic orbit correction reduces beam losses and activation in CCL.
- The longitudinal tuning control method is a very convenient method to check the agreement between design and real RF settings. The method is non-destructive, and can be used during the SNS neutron production runs.

ACKNOWLEDGMENT

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