BEAM ORBIT ANALYSIS AND CORRECTION OF THE FRIB SUPERCONDUCTING LINAC *

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Abstract

Beam based alignment (BBA) technique is an important tool for precise beam orbit correction of a high power linac, and it is supplement to a model based or an orbit response matrix (ORM) based orbit correction method. BBA could be applied to the beam orbit analysis and correction of the FRIB linac arcs where a beam orbit offset within 0.1 mm is required to tune the second order achromatic lattice. In this paper, we will first introduce the study of model based beam orbit correction of the linac arcs, and then a more precise orbit correction with BBA. Realistic misalignments of beam elements and beam position monitors (BPMs) are included in the simulation studies.

INTRODUCTION

Beam orbit analysis and corrections are one of the most essential processes applied for beam control in accelerators and beam transport lines, to significantly reduce beam loss and to preserve beam emittance, especially for high power machines. Various beam orbit correction techniques have been developed and demonstrated in particle accelerators including ring and linac, as the requirements to beam orbits for different machines can be substantially different.

We studied various beam manipulation methods in the beam commissioning plan of the FRIB superconducting linac and noted that orbit corrections are very important for the operations with multi charge state beams [1]. Although a beam orbit offset of 1 to 2 mm in the FRIB linac has no issues in simulation studies and likely in operations too, to precisely tune the second order achromat of all the folding segments, an orbit within 0.1 mm is needed. Different orbit correction methods are investigated in simulation studies with realistic misalignments of beam elements and BPMs.

Open XAL online model [2] is applied in the beam orbit analysis and correction. Both model based and beam based orbit correction techniques have been demonstrated in the SNS accelerator systems [3, 4], while different approaches are also planned for the FRIB linac system [5].

MODEL BASED ORBIT CORRECTION

An online model is usually applied to precisely predict beam orbit differences of the real machine, and a model based orbit correction could be conducted using a global optimization of the beam offsets of all the available BPMs, provided that misalignments of all the beam elements and BPMs are well within specifications. However, if errors, misalignments of beam elements or BPMs are outstanding, uncertainties of beam orbit after a model based correction could still be substantial, in which case, iterations of the orbit correction may become necessary, and measurements of the BPM misalignments will be important.

When needed, model based beam orbit correction can be easily extended to measure BPM misalignments. As model predicted beam orbit differences are mainly determined by the injection beam and misalignments of beam elements, series of measurements of beam orbit differences with the linac BPMs can be conducted to reconstruct the model.

The method is simple: different correctors fired in the linac and beam orbit differences measured with BPMs, the same beam steering is applied in the model and compared against model predicted orbit changes, the injection beam and misalignments of the beam elements optimized in the model to reproduce the BPM measurement results. Figure 1 shows an orbit difference exercise in simulation studies.

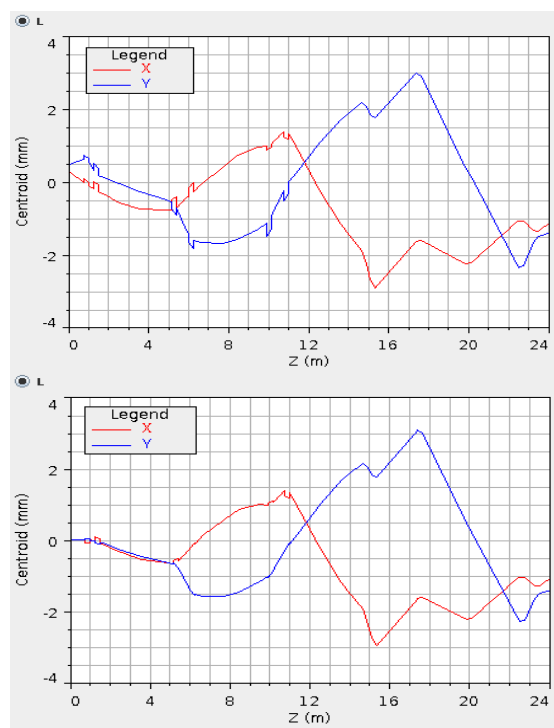

Figure 1: A model based beam orbit differences exercise. Upper: model with an inclined beam and misalignments of quadrupole magnets; Lower: reconstruction using BPMs.

In the above exercises, reconstructed parameters of the injection beam and misalignments of the beam elements differ from those of the original model, mainly because of errors and multiple solutions with limited BPMs. However, misalignments of the BPMs can be identified and corrected with the measurements of beam orbit differences, and after the BPMs are marked a model based beam orbit correction is conducted. The results are shown in Figure 2.

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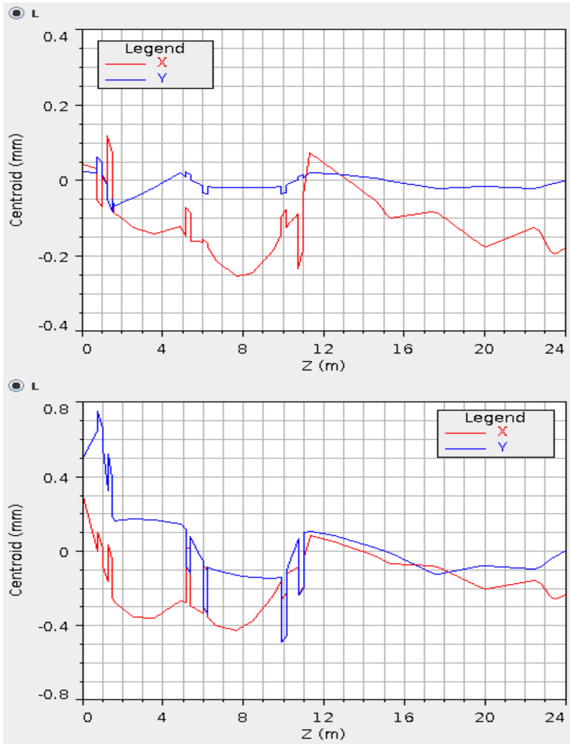

Figure 2: A model based beam orbit correction exercise. Upper: beam orbit correction with the reconstructed model; Lower: a verification using the original model.

As the reconstructed model differs from the original one, after beam orbit correction, beam offsets in the quadrupole magnets are still substantial - up to about 1 mm - which satisfies the general requirements of normal operation.

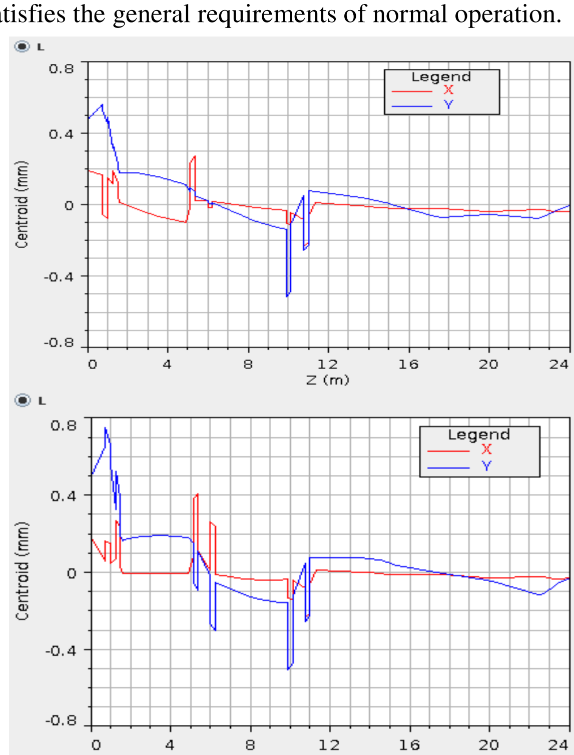

Figure 3: An orbit correction using high resolution BPMs. Upper: beam orbit correction with the reconstructed model; Lower: a verification using the original model.

In further studies of the model based orbit correction we found that it offers little help to improve the resolution of BPMs and to provide some of the misalignment data to the model - except everything is known exactly. Under these conditions, a solution closer to the original model could be found, though the results of beam orbit corrections are not necessarily better. Because it centers a beam into the BPMs instead of magnets, while the number of BPMs is limited in the congested lattice. To achieve a better orbit correction for the purpose of achromat linac beam tuning, other orbit correction techniques should be developed.

In the simulation studies shown in Figure 3, resolution of the BPM is assumed to be 1 µm (100 times better than the design), and misalignments of a few magnets are given precisely in the model. However, after a model based orbit correction improvements of the arc magnets are not very significant compared against Figure 2, in which the BPM resolution is only about 0.1 mm.

BEAM BASED ORBIT CORRECTION

As limited by available BPMs in the compact lattice, we study BBA to center a beam into all the magnets instead. The principle of BBA is simple: a magnet is scanned and beam orbits measured with downstream BPMs, because variation of the measured beam orbit is proportional to the beam offset and the strength change of the magnet, beam orbit in the magnet can be measured accurately, and then the beam is corrected with an upstream corrector. E.g. in a quadrupole magnet assume beam offsets are x and y, then

$$\begin{aligned} \frac{dX_{BPM}}{dG} &= -\frac{QclM_{12}}{E\beta\gamma}\cdot x \\ \frac{dY_{BPM}}{dG} &= -\frac{QclM_{34}}{E\beta\gamma}\cdot y \end{aligned} \qquad (1)$$

where, Q, E, β, and γ are the charge, energy, and relativistic parameters of the beam particles respectively; c is speed of light, l is length of the quadrupole magnet, M_{12} and M_{34} are transfer matrix elements of the quadrupole-BPM pairs.

Using the simplest one-to-one BBA correction method: an upstream dipole corrector is fired and the beam centered into the scanning magnet, then proceed to the next magnet and until all the magnets are corrected. A beam orbit better than resolution of the linac BPMs could be achieved.

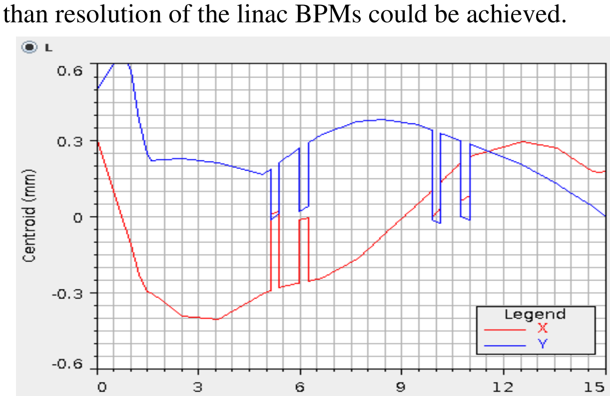

Figure 4: Beam orbit after a BBA correction in the arc of folding segment 1 (FS1) in the simulation studies.

Figure 4 shows a beam orbit after a BBA correction in the folding segment 1 (FS1) arc area, and it is better than

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0.1 mm of all the quadrupole magnets in the arc. To achieve that, resolution of the linac BPM is no worse than 0.1 mm, and the quadrupole doublets in the FS1 arc are installed and aligned precisely on girders.

In a BBA beam orbit tuning, the change of beam orbit is always concerned, therefore misalignment of the BPM is irrelevant. After the BBA orbit correction, residual beam offsets in a BPM could be considered as its misalignments, and e.g. used for future model based beam orbit correction. However, this misalignment is with respect to the center of magnet/magnets locally, and different to the measurements of BPM misalignments with model based orbit techniques discussed in the previous session. In the model based beam orbit correction, the BPM misalignment is with respect to the center of an ideal reference orbit.

HYBRID BEAM ORBIT CORRECTION

It can be extremely time consuming to apply BBA in a linac particularly when there is not a precise beam model and iterations of the beam orbit corrections are needed. For practical linac beam tuning and operation with high beam availability a precise model is critical, thus a hybrid beam orbit correction using both BBA and model techniques are investigated with simulation studies.

A complete exercise of the hybrid beam orbit correction is as the following:

- Scan a quadrupole magnet in the arc and measure the beam orbit charges with downstream BPMs
- Use the online model to construct the beam offsets in the scanning magnet
- Proceed the same to the next magnet in the arc, and until all the arc magnets have been measured
- Fire dipole correctors upstream of the arc and in the arc, and measure beam orbit changes with BPMs
- Solve the injection beam and misalignments of all the arc magnets and BPMs based on the linac model and the above measurements
- Optimize beam orbit in the arc magnets using model based beam orbit correction technique

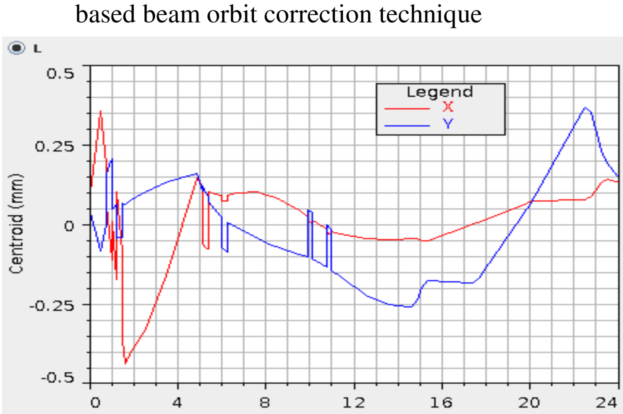

Figure 5: A hybrid orbit correction at the FS1 arc areas.

Shown in Figure 5 is an orbit of the reconstructed model of the FS1 arc after a hybrid orbit correction. As a precise model is built for the arc there is no more need for iterations of orbit correction. However, as limited by BPM resolution and magnet misalignments, errors can still be substantial.

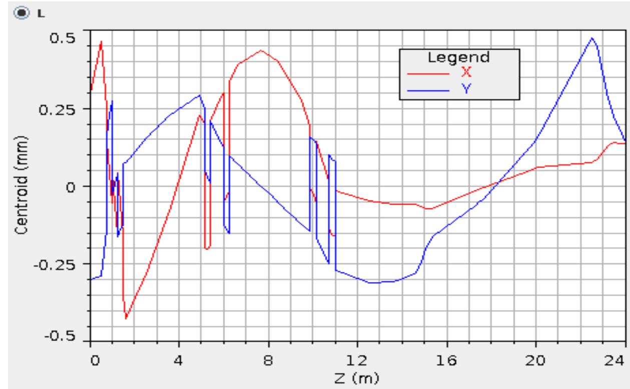

Figure 6: Beam orbit verification using the original model for the hybrid beam orbit correction at the FS1 arc areas.

Figure 6 shows the results of beam orbit verifications in the FS1 arc using the original model of the hybrid beam orbit correction exercise. The maximum beam offset in the arc quadrupole magnets is approximately 0.2 mm after an orbit correction based on the reconstructed model, and the errors are substantial mainly because of the limited BPM resolution and the significant magnet misalignments in the arc. To reduce the errors of the model and precisely correct beam orbit in the arc, resolution of the linac BPMs should be improved, misalignments of quadrupole magnets in the arc should be reduced, and other errors, such as errors of the dipole correctors and the quadrupole magnets, should be minimized.

It is difficult to achieve a 0.1 mm beam orbit in the FRIB linac based on a model, but fortunately, a beam orbit within 1 mm will be sufficient for high power operation, and the 0.1 mm beam orbit is only required for a precise achromat tuning, which could be achieved with the BBA beam orbit correction without any model.

CONCLUSIONS

Different orbit correction techniques are investigated for the FRIB superconducting linac using simulation studies, especially for the arc areas where a precise achromat beam tuning requires a beam orbit much better than that of the orbit needed for high power operation. Although the model based beam orbit correction technique satisfies the general requirements for operation, a beam based alignment (BBA) technique is developed for the linac arc areas as which is capable to achieve a beam orbit better than 0.1 mm, so that beam tuning of second order achromat could be conducted based on the BPM measurements.

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