EXTRACTING CRITICAL BEAMLINE ELEMENT MISALIGNMENTS FROM DATA USING A BEAM SIMULATION MODEL*

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Abstract

Successful implementation of AI/ML models for online tuning of accelerators highlights the need for accurate simulation of beamline elements. Deployment of such models requires the inclusion of realistic element misalignments during the simulation process. This paper presents an original method to determine misalignments across entire beamlines and apply them to the previously developed TRACK simulation model. Validation has been performed using experiment data in this study for a newly commissioned section of ATLAS called the Argonne Material Irradiation Station (AMIS) and an existing straight lattice known as the PII-BOOSTER. A preliminary study for the AMIS line shows the average difference in beam transmission between experiment and simulation for 28 tuning cases has dropped from ~46% without steering to ~16% after applying steering and further down to ~6% after accounting for 4 quadrupole misalignments in the simulation. Given these values and the well-established accuracy of the TRACK model, major deviations in element positions could be narrowed down enabling engineers to perform the necessary alignment corrections, and possibly eliminating the need for some steering elements. Predictability of the TRACK code has been shown to significantly improve after applying realistic alignment and steering corrections.

INTRODUCTION

Simulation of beamline elements is vital in the design of new lattices and making modifications to existing structures. However, even the most advanced models fail to accurately replicate experimentally measured data due to misalignment in lattice elements. Moreover, codes such as Methodical Accelerator Design software (MAD-X) that employ transfer matrices to simulate FODO lattices currently do not have the capability to account for such miscellaneous errors. The TRACK beam dynamics code developed at Argonne National Lab employs the particle tracking approach in which equations of motion are solved using Runge-Kutta based solvers. This approach is more amenable to account for misalignments. A recent update to the TRACK code has incorporated a separate misalignment function that can be setup along with the other elements when building up the lattice for simulation. Both rotational and translational misalignments in three dimensions can be accounted for via this function. Although currently used only for quadrupole misalignments, the tool supports simulating misalignments for most other types of elements.

Misalignment in accelerator components may lead to emittance growth, beam losses and breakup of the beam. Although misalignment in beam position monitors do not deflect the beam, they significantly compromise the effectiveness of any optimization that is implemented to tune the device. Ganesh Tiwari et al., [1] report on the effects of transverse spatial misalignment on the performance and stability of X-ray free electron oscillators. Given the current trend in development of smaller accelerators, Silva et al., [2] present a statistical method to determine the tolerances in misalignment of a set of lenses for such small machines. As part of this method, particle losses as a function of alignment accuracy of optical elements in a lattice is found. Marco Venturini et al., [3] present a method to model particle ray tracing through misaligned elements by sandwiching the transfer-map for aligned elements between two transformations, one applied at the entrance and one at the exit. Beam-based alignment methods account for misalignments without evaluating the values associated with each element of a lattice. The work presented in this research in contrast, offers an attractive alternative approach using the TRACK code to determine actual values of misalignment associated with quadrupoles. These values could then be used both in simulations to correct for error in predictions and during the design processes of new lattices by making suitable modifications. Two methods are proposed to this extent.

TRANSMISSION BASED MISALIGNMENT

This section provides a procedure to determine misalignment in quad elements along a single straight lattice solely employing experimentally measured values of transmission across the lattice. A straight lattice section known as the PII-BOOSTER line at the ATLAS LINAC was used to this extent (Fig. 1).

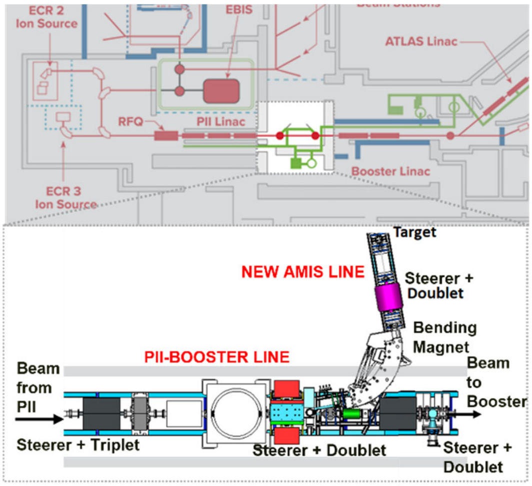

Figure 1: PII-BOOSTER lattice.

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Misalignment for the two doublet quadrupoles (QDP302 & 303) and the single triplet quadrupoles (QDP301+QSP301) is to be determined. The two-dimensional linear displacements in misalignment (x_d and y_d) along with rotational (x_r and y_r) misalignments are to be determined. In addition to controlling the strength of these quadrupoles, the three bidirectional steerers (STP) associated with each of these quadrupoles are also varied. By varying these control parameters, the transmission across this lattice is measured by one Faraday cup FCP301 at the beginning of the lattice and one FCP303 at the end of it. Figure 2 below shows the fitting and testing control/transmission data set to obtain the values of misalignment. Each set consists of data combined from two different runs.

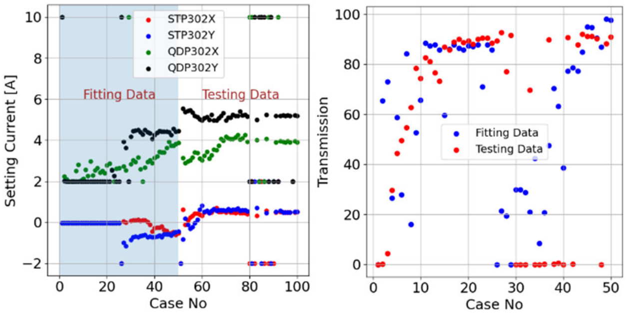

Figure 2: Control settings and transmission measurement.

Theoretically the maximum transmission should be 100%. Using a Bayesian Optimization algorithm fitting on input test parameters namely misalignment values on an objective function i.e., difference (error) between experiment and simulated transmission is used. The quad and steerer control settings corresponding to each case were used from experiment measurements. Table 1 shows the results of the evaluated/fitted misalignment values for all the quads. x_d and y_d are in units of mm; x_r and y_r are in units of mrad.

Table 1: Misalignment Values

	QDP 301X	QDP 301Y	QSP 301X	QDP 302X	QDP 302Y	QDP 303X	QDP 303Y
x_d mm	-0.14	0.44	0.66	2.00	1.28	1.31	0.45
y_d mm	-0.94	-0.93	-0.03	-1.53	-0.21	0.24	-0.45
x_r mr	0.17	0.53	0.39	0.211	-0.65	0.53	0.65
y_r mr	0.86	0.16	-0.01	0.607	-0.33	-0.08	0.31

Optimization bounds for displacement are ±2 mm and rotation are ±1 mrad. Based on this table it is clearly evident that no single quadrupole magnet is solely responsible for misalignment in all four parameters i.e. QDP301X has the highest rotational misalignment in y direction while QDP303Y is highest in X direction. However, QDP302X shows the highest translational misalignment in both x and y directions. Figure 3 below shows beam transmission results obtained using values of misalignment in simulations of test cases from two different experimental runs i.e., v5 and v4 each consisting of 50 data points.

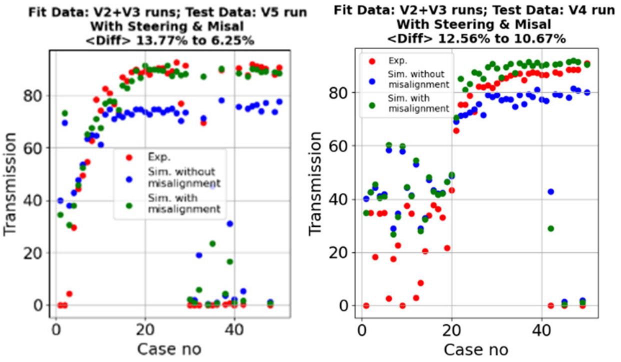

Figure 3: Comparison of simulated transmission with and without misalignment.

Applying misalignment mean transmission error in simulation for 50 cases drops from 13.8% to 6.3% for v5 run and from 12.6% to 10.7% for v4 run. A significant difference in simulated results is noticed for data 1-20 in the v4 run where transmission is below 50%. A look at beam center positions (Fig. 4) for these two runs shows that for the v4 run, beam center Y position is very close to the boundary region measurable by the beam profile monitor.

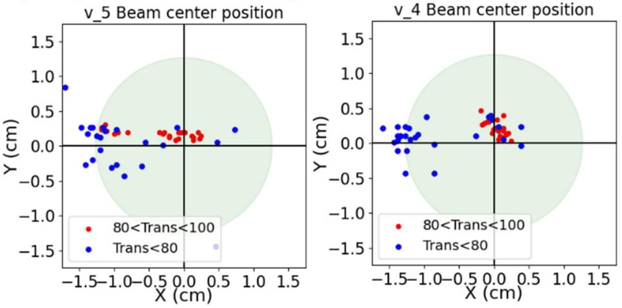

Figure 4: Beam-center position for test data.

Therefore, an updated method to evaluate misalignment values is proposed in the next section. This method is expected to be more appropriate in simulating results over a wider range of operating conditions that result in transmission less than 50% due to off centered beams.

BEAM CENTER BASED MISALIGNMENT

The objective function is now updated to minimize the difference (error) between the radial position of beam center predicted by the simulation and obtained from experiment. Figure 5 shows the comparison of beam center position with and without misalignment against experiment data for both fitting (top figure) and testing data (bottom figure). To avoid any biasing in input data used for fitting, random sampling is employed to pick 100 data points from v2 and v3 runs. This is to ensure that the input data used for fitting represents the entire space within the region measured by the beam profile monitor (light green circle) of diameter 2.75 mm. Despite this procedure, as could be seen from Figure 5, a bias in beam position is observed in experiment data used for fitting towards the axis and boundary regions of the measured space that translates to extreme values of transmission. As a result, the predicted values of misalignments are expected to be higher in magnitude than reality since these values are more representative of limiting extreme values of beam position. Despite this drawback, Fig. 5 shows the beam position predicted by the simulation with misalignment for test data (v4 and v5 runs) approaching experimental values. Without misalignment predicted values of beam center from simulation tend to be located close to the axis even for experiment data with very low transmission and beam located close to the boundary region.

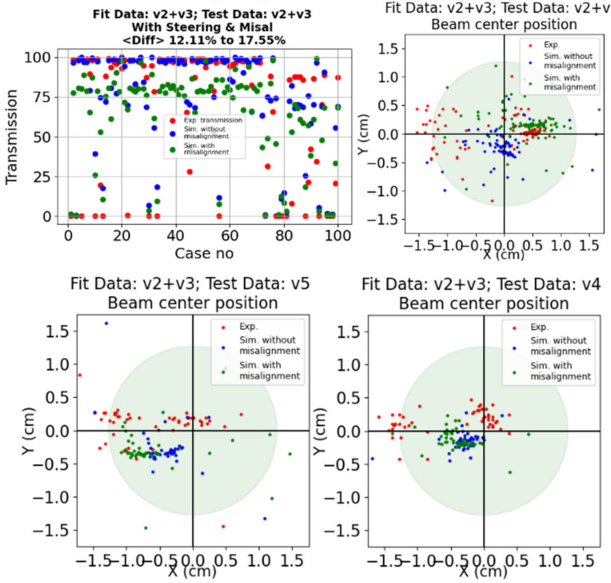

Figure 5: Comparison of simulated and experimentally measured beam-centers.

Figure 6 shows the comparison of transmission for this method. Using the obtained value of misalignments, a clear limit on simulated transmission is observed. By employing this method, the error in transmission considerably decreases for cases with transmission less than 50% in comparison to the previous method. However, in employing this new method, the same error noticeably increases for data with high transmission unlike the previous method. This is reflected in the drop in mean transmission error for this method which is not as high as the previous method.

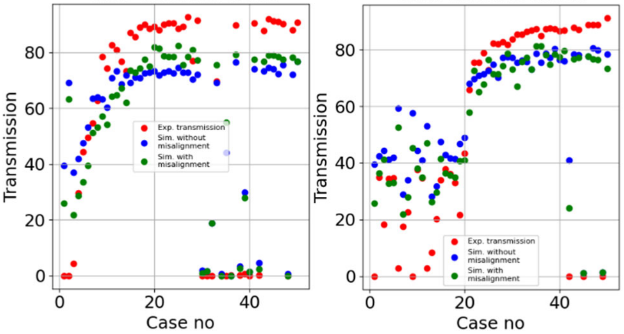

Figure 6: Comparison of transmission for beam-center based optimization.

Figure 7 shows convergence of error in both the transmission and beam center position.

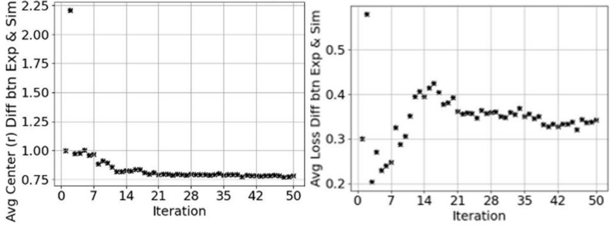

Figure 7: Variation of difference between experiment and simulated transmission and beam-center for fitting data.

As could be observed, convergence is reached at 20 iterations. The drop in beam center error although appreciable, is not significant. This can be associated with the non-uniform distribution of input data used for fitting. Overall mean error in transmission, however, does not decrease since it is indirectly dependent on beam position and any error in the latter directly translates to a higher error in transmission.

CONCLUSION

This research presents two contrasting approaches to find misalignment in quadrupole elements. When the error in simulated transmission is used as the objective function for the minimization problem, all cases with experimental transmission higher than 50% are accurately simulated with misalignment. When the error in beam center is used as the objective function for the minimization problem, cases corresponding to experimental data with transmission less than 50% are reasonably predicted. Therefore, a combined multi-objective function-based approach to minimize error in beam center as a first order effect and beam transmission as a second order effect with appropriate weights is proposed and to be carried out in future work. Beam size is another parameter that could be employed in this procedure to further improve the predictions.

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