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AGS BOOSTER MODEL CALIBRATION AND DIGITAL-TWIN DEVELOPMENT*

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Abstract

An accurate physics simulation model is key to accelerator operation because all beam control and optimization algorithms require good understanding of the accelerator and its elements. For the AGS Booster, discrepancies between the real physical system and online simulation model have been a long-standing issue. Due to the lack of a reliable model, the current practice of beam control relies mainly on empirical tuning by experienced operators, which may be inefficient or sub-optimal. In this work, we investigate two main factors that can cause discrepancies between simulation and reality in the AGS Booster: magnet misalignments and magnet transfer functions. We developed a orbit response measurement script that collects real machine data in the Booster for model calibration. By matching simulated data with real data, we can develop a more accurate simulation model for future polarization optimizations, and build the foundation for a fully functional digital-twin.

INTRODUCTION

The Alternating Gradient Synchrotron (AGS) Booster is used to increase beam intensity in the AGS by pre-accelerating particles before they enter the AGS [1]. Accurate control of beam properties is indispensable to providing high quality beam to both the AGS, which serves as the injector for Relativistic Heavy Ion Collider (RHIC) and the future Electron Ion Collider (EIC).

Most of the beam optimization in the Booster is currently done by operators relying more on expert system knowledge and empirical tuning directly using engineering parameters (like magnet currents) rather than using an integrated physics model. In order to develop more streamlined control routines, we need to establish more accurate models for the Booster to better understand and predict how beam behaves in the machine. In this work, we present the progress on building a digital-twin model of the Booster. A baseline ideal physics simulation model is constructed using Bmad [2], and we aim to calibrate the model to better present the real machine using measured orbit response data.

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Two factors are studied for the calibration in this work: magnet misalignment and magnet transfer function. Magnet misalignments, which are the deviations of magnet locations from their designed locations, affects the raw orbit in the Booster. There has been trouble with making physics simulation with added misalignment agree with real orbit data. We present simulation studies on the effects of magnet misalignment based on misalignment data obtained in 2015. Magnet transfer function describes how the magnet field responds to change in power supply (PS) current. Traditionally, transfer functions are determined during magnet production measurements before installation, but how accurate they remain after the magnets are installed is unclear. We investigate the accuracy of quadrupole transfer functions by comparing orbit responses calculated in the model and measured in the real machine.

BOOSTER MAGNET MISALIGNMENT

Magnet location in the Booster is measured by the survey group using survey marker points, which are geometric points fixed with respect to the magnet structure. Cartesian position coordinates of these marker points with respect to the AGS geodetic grid give the precise locations of the Booster magnets [3]. The design magnet locations were measured after placement of magnets into the Booster tunnel. By remeasuring the marker points' coordinates, we can obtain alignment deviations of the Booster magnets. Figure 1 shows the survey data measured in 2015, and it contains misalignment data for dipoles and quadrupoles [4]. The results show a maximum alignment error of 3 mm vertically and 10 mm horizontally.

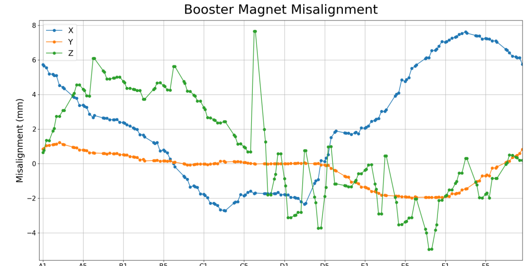

Figure 1: Booster magnet misalignment according to 2015 survey data.

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Simulation Studies in Bmad and Pytao

A Booster model is constructed in Bmad [2] to simulate how magnet misalignments affect the bare orbit. Survey misalignments from 2015 (Fig. 1) were used as the baseline values in the model. Bmad's simulation program Tao has a python interface PyTao, and we use it to run a sampling routine with different misalignment values.

The misalignment data includes dipole and quadrupole misalignments, so we studied three scenarios: only dipoles are misaligned, only quadrupoles are misaligned, and both are misaligned. Using survey data as mean, normal distributions of misalignment values with 5% standard deviation were simulated. The simulation results are shown in Fig. 2 for horizontal orbit and Fig. 3 for vertical orbit.

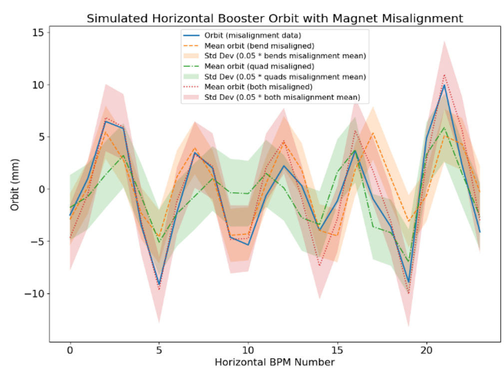

Figure 2: Simulated Booster horizontal orbit comparison with different magnet misalignments.

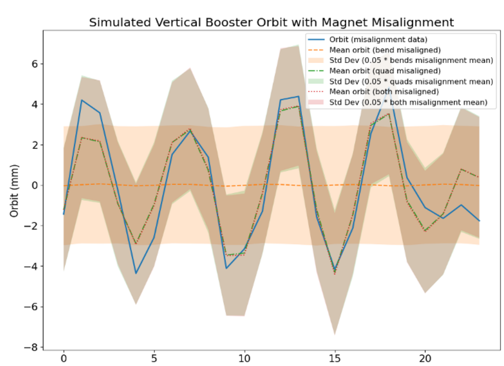

Figure 3: Simulated Booster vertical orbit comparison with different magnet misalignments.

We see that dipole misalignments have far less impact on the bare orbit than quadrupole misalignments, especially in the vertical plane. On the other hand, a 5% std in misalignment produces significant fluctuations in bare orbit, the difference between the extreme and the mean orbit can be as large as 4 mm.

QUADRUPOLE TRANSFER FUNCTION

There are 48 quadrupoles (24 horizontal, 24 vertical) in the Booster. They are powered in series with the main bending dipoles. Due to the intrinsic focusing component of the dipoles, the vertical quadrupoles are designed to be longer than the horizontal quadrupoles, in order to bring the vertical tune up closer to the horizontal tune.

The quadrupole transfer functions used in the physics simulation model are defined to match the two sets of tune measurement data taken in 1992 and 1993 [5]. The model uses a fifth order polynomial to model the gradient of a quadrupole based on its power supply current I_q:

$$\frac{\partial B}{\partial r} = a_0 + a_1 \cdot I_q + a_2 \cdot I_q^2 + a_3 \cdot I_q^3 + a_4 \cdot I_q^4 + a_5 \cdot I_q^5 \quad (1)$$

The polynomial coefficients used in the current Booster simulation model are derived from a least square linear regression fitting to the measured magnetic data [5].

ORBIT RESPONSE MEASUREMENT

In the RHIC complex at BNL, the Collider Accelerator Department (CAD) Controls Group uses various software tools to control and monitor accelerator elements. To collect orbit response data in the Booster, we developed a script [6] that sets each corrector to three settings: zero kick (baseline value), positive kick, and negative kick. The correctors are managed by FunctionEditor, a program that allows users to upload a time dependent current function to the power supply of the magnets. In order to set correctors to a constant kick, we define a trapezoid-shaped function whose flat top value is the desired current value in FunctionEditor, and send it to the machine (make live). After setting the corrector, live beam position monitor (BPM) data and all the magnet settings are saved. The script work flow is outlined in Fig. 4.

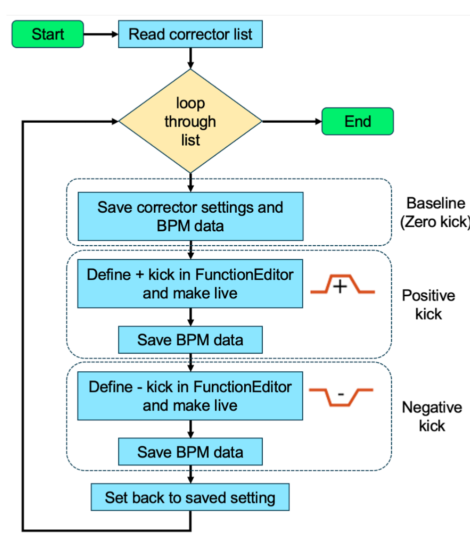

Figure 4: Work flow of orbit response measurement script.

The script was tested with both horizontal and vertical correctors in the Booster. Each corrector was set to ±22 Amp between 50 and 110 milliseconds during the Booster magnet cycle. The data collected includes both orbit data and all magnet settings in the Booster, including dipoles, quadrupoles, sextupoles, and all correctors. Saved magnet settings are

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then loaded into the Bmad model to produce simulated orbit data.

The comparison of the differential orbit (orbit difference between positive, zero, and negative corrector settings) for one corrector is shown in Fig. 5. For each corrector setting, three cycles of data was saved, and the error bars were calculated using those three rounds of data.

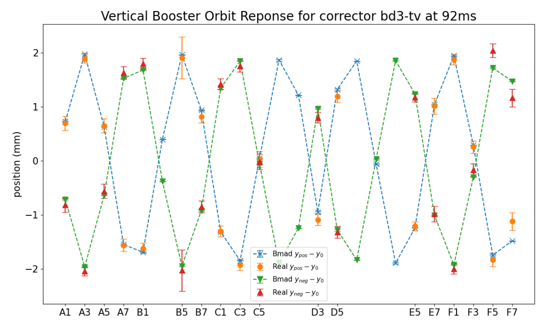

Figure 5: Comparison between measured and simulated vertical orbit responses with corrector bd3-tv set to ±22 A, data taken at 92 ms in the Booster cycle.

The difference between measured and simulated differential orbits are within 1 mm, but still larger than the error bars of the measurements. This means there are other factors impacting the differential orbit.

Dipole and quadrupole misalignments only affect raw orbit and not differential orbit, sextupoles were off during data collection so their misalignments would not matter. Therefore, we investigate how deviations from the quadrupole transfer functions affect the differential orbit, considering potential adjustments to the horizontal and vertical quadrupole strengths in our analysis:

$$k1_{h,v} = k1_{0_{h,v}} + dk_{h,v} \tag{2}$$

where $k1_{0_{h,v}}$ are the normalized gradients of the horizontal and vertical quadrupoles, calculated using the fifth order polynomial described in Eq. 1 with normalization factors. By adjusting the $dk_{h,v}$ values in the Bmad simulation, we aim to align the simulated differential orbits closely with those observed in actual experimental data.

In the simulation setup, there are 180 measurements (18 vertical BPM readings under 10 different corrector settings) represented by the vector $\vec{m}$. Bmad simulation gives predicted BPM readings based on the parameters dk_h and dk_v forming a vector $\vec{b}(d\vec{k})$. The goal is to find the parameter $d\vec{k}$ that minimizes the discrepancy between the observed $\vec{m}$ and predicted $\vec{b}(d\vec{k})$, considering the uncertainties in $\vec{m}$, which are repeated across all settings. This is quantified using a normalized chi-square statistic [7]:

$$\chi_n^2 = \frac{1}{f} \sum_{i=1}^{N} \frac{[m_i - b_i(d\vec{k})]^2}{\sigma_i^2} \tag{3}$$

where σ^2 is the variance of the measured BPM readings, N is the number of available measurements, and f is the degree of freedom which generally represent the number of values in the final calculation of a statistic that are free to vary. In our case, $N = 180$ and $f = 180 - 1$ (either horizontal or vertical). When χ_n^2 is minimized, the simulation differential orbit aligns more closely with actual data.

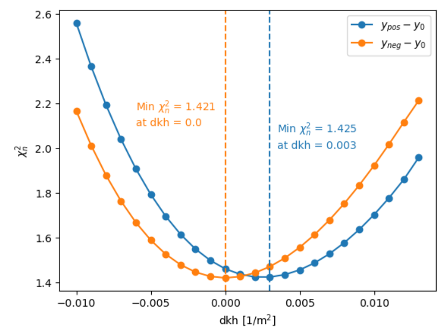

Figure 6: Variation of normalized chi-square values as a function of the parameter dk_h.

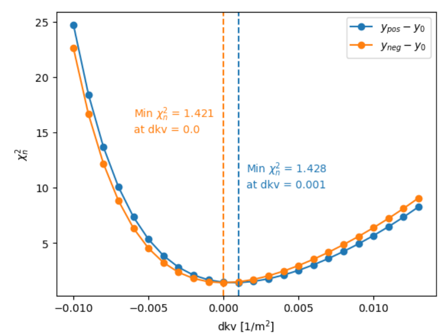

Figure 7: Variation of normalized chi-square values as a function of the parameter dk_v.

Figures 6 and 7 show the results of χ_n^2 with respect to dk_h and dk_v. The minimum χ_n^2 value is approximately 1.4 for all cases. For the differential orbit $y_{neg} - y_0$, the minimum χ_n^2 occurs at $dk = 0$ for both horizontal and vertical. For the differential orbit $y_{pos} - y_0$, the minimum χ_n^2 occurs at $dk_h = 0.003$ and $dk_v = 0.001$.

CONCLUSION

In this work, we constructed and calibrated a model for the AGS Booster that attempts to represent the real machine more accurately than the ideal physics simulation. Preliminary studies show that both magnet misalignment and magnet transfer function affects the orbits. An operational script is developed to take real orbit response data. Measured orbit responses agree pretty well with simulations, with small discrepancies within 1 mm. The investigation of quadrupole transfer function doesn't show obvious improvement of such discrepancies. Further studies are needed to find the exact calibration values to align the model with real machine.

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