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BEAM-BASED GIRDER ALIGNMENT TO REDUCE CORRECTOR STRENGTHS: CONCEPTUAL SIMULATIONS FOR PETRA IV

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Abstract

DESY is currently planning an upgrade of PETRA III to a 4th generation light source. The upgrade involves pre-installing and aligning magnetic lattice components on girders before their installation in the tunnel. However, the long girders on the moving steps between concrete elements and the potential misalignment of the magnets present significant challenges for the PETRA IV lattice, particularly in maintaining beam storage within the ring. Previous commissioning simulations indicated the necessity for relatively high corrector strengths in the orbit correction system. To address this issue, a simulation study was conducted to explore the feasibility of beam-based girder alignment correction as a means to mitigate the need for high corrector strengths during machine operation. The results of this study are presented and discussed with an outlook towards future implementation.

INTRODUCTION

One key contributor to the relatively high corrector strength requirement for PETRA IV [1] is the girder misalignment, as inferred by the commissioning simulations [2]. The baseline error assumptions are given in Table 1. The maximum steering angle for the slow corrector magnets is 600 µrad. The overlap of fast correctors with some of the slow correctors in the lattice has led to a design with the high inductance of 23 mH [3] for combined slow/fast correctors. A study was performed to download the DC corrector strength of slow/fast correctors to all slow correctors in the lattice [4]. Here, we present a simulation study performed to demonstrate the relaxation of slow corrector strength using a global girder alignment correction calculated using a beam-based method.

Table 1: Girder, magnet and BPM errors. Gaussian distribution truncated in the simulations at 2σ for a given rms value.

Error type	rms	Error type	rms
Girder rolls	200 µrad	BPM offset	30 µm
Girder tran. offset	150 µm	BPM roll	0.4 mrad
Magnet trans. offset	30 µm	BPM noise (TBT)	20 µm
Magnet rolls	200 µrad	BPM noise (CO)	0.1 µm
Quad. calibration	0.5E-3	BPM calibration	2 %
Dip./Sext. calibration	1E-3	CM calibration	2 %

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The idea is to first commission the machine with the required corrector strength. In the second step, the orbit response matrix (ORM) is used to transform the corrector strengths into the corresponding orbit at BPMs. A modelled response matrix between the start and end misalignment of the girder and the orbit at BPMs (GRM) is used to calculate the corresponding girder misalignment by inverting this matrix. This misalignment is applied as a correction to the girders. The use of two separate RMs helps to regularize them independently, which is important as the GRM can only be modelled. This method can also be applied to compensate slow girder drifts over days and weeks.
For a given strength vector of m correctors $\theta_{m\times1}$, the corresponding girders start and end misalignment vector $g_{k\times1}$ for one plane, can be calculated as,

$$g_{k\times1} = (GRM^{+})_{k\times n} \cdot ORM_{n\times m} \cdot \theta_{m\times1},$$

where k is twice the number of girders, n is the number of BPMs and $^{+}$ is the pseudo-inverse. It is important to mention that the corrector strengths correspond not only to the girder-misalignment, but also to all other kinds of errors including girder rolls, magnet misalignment and rolls relative to the girder surface, and quadrupole and sextupole field errors. The efficiency and limitation of the method for PETRA IV are investigated with a large number of random machines.

SIMULATION SETUP

The simulations are performed in the Matlab-based SC toolkit [5, 6]. First, the simpler case is examined, where a subset of the errors given in Table 1 is investigated. This includes the misalignment of magnets and girders as well as BPM offsets and BPM and corrector calibration errors. The BPM offset of 30 µm should correspond to the offset that is achieved after trajectory and beam-based alignment of BPMs during the commissioning process. In the second step, the commissioned machines are used with all the errors specified in Table 1, and the reduction of the corrector strengths by the girder alignment is simulated. The required girder alignment correction is calculated only once and applied to the machines in small steps so that the stored beam is not lost for larger changes. The slow orbit feedback system is used at each step to correct the orbit, reducing the corrector strengths. Tune correction is also performed at each step. The singular values σ_i of the GRM are Tikhonov regularized as $\frac{1}{\sigma_i} \rightarrow \frac{\sigma_i}{\sigma_i^2+\mu}$, where an appropriate value of μ helps to reduce the effect of higher-order modes of the RM. In addition, a feedback scheme is implemented in which a

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new girder alignment correction is calculated at each iteration instead of a value calculated once.

Only Girder and Magnet Misalignments

A Gaussian distribution was applied to account for random misalignments of the girders, magnets on girders, BPM offsets, and BPM and corrector calibration errors, as detailed in Table 1. A total of 72 machines were prepared with the errors and used for corrector strength reduction by the girder alignment with identical Tikhonov parameter $\mu = 1$ for the GRMs for all machines. Figure 1 shows the results for one machine in the horizontal plane. The vertical plane also follows the same pattern. The top plot shows the girder start and end misalignment before (red) and after (blue) applying corrections and the middle plot shows the corresponding reduction in the corrector strengths. The lower plot shows the closed orbit before and after correction to illustrate that the reduction of the corrector strengths is not at the expense of an orbit distortion. A reduction of 25 % of girder misalignment rms results into 50 % reduction of the corrector strength rms. It is important to note that in this case the girder misalignment is the dominant error and therefore a significant reduction in corrector strengths occurs as a result of girder alignment correction. Furthermore, the cumulative distribution function (CFD) of girder alignment, corrector strengths and BPM values, for all 68 out of 72 machines is shown in Fig. 2. The remaining four machines were unstable due to beam losses, which have not been investigated further but most likely require a different regularization of the response matrices. The top row in Fig. 2 shows the girder's start and end misalignment, corrector strengths, and BPM values before and after correction in horizontal plane, while the lower row shows the same thing in the vertical plane.

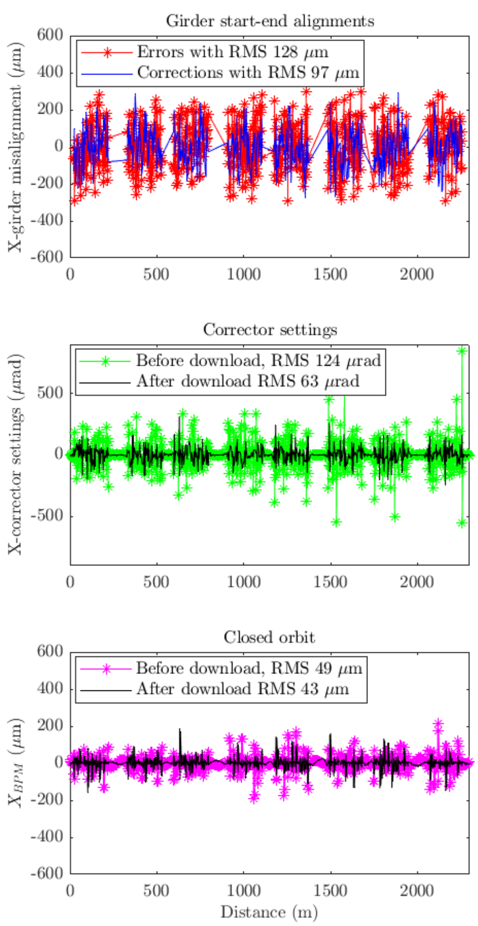

Figure 1: Reduction of corrector strengths by girder alignment. Top: Girder start and end misalignment. Middle: Corrector strengths. Bottom: Orbit at BPMs.

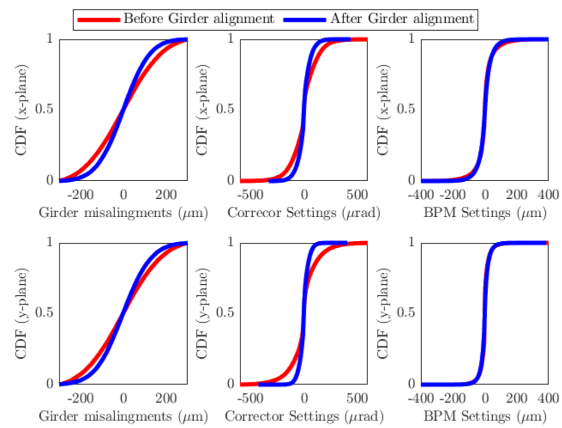

Figure 2: CDF of girder alignment, corrector strengths and orbit at BPMs for 68 random machines models of PETRA IV. Top: Horizontal plane. Bottom: Vertical plane. Before (red) and red (blue) after girder alignment correction.

Feedback Scheme for Girder Alignment Correction

As a next step, the girder alignment correction is calculated and applied in a feedback-like fashion at each iteration. The feedback is assumed to be slow such that no dynamics need to be modeled. Figure 3 shows the rms values of all girder start and end alignments as well as the corrector strength in both planes for one machine. Interestingly, a reduction of the Tikhonov parameter from 5 to 2, i.e. a more aggressive correction, led to a better correction of girder alignment in the beginning (as expected), but diverged over subsequent iterations, as can be seen from the red curve on top left of Fig. 3. A possible reason is that after few iterations, the girder misalignment are no more the dominant errors and further correction tries to correct the effect of magnet misalignments with the wrong actuator as girders. In order to confirm this, the magenta curve is simulated without any magnet misalignment, and one can correct the girder misalignment to a further minimum. This shows that the method has application to the extent when the dominant errors are girder misalignments.

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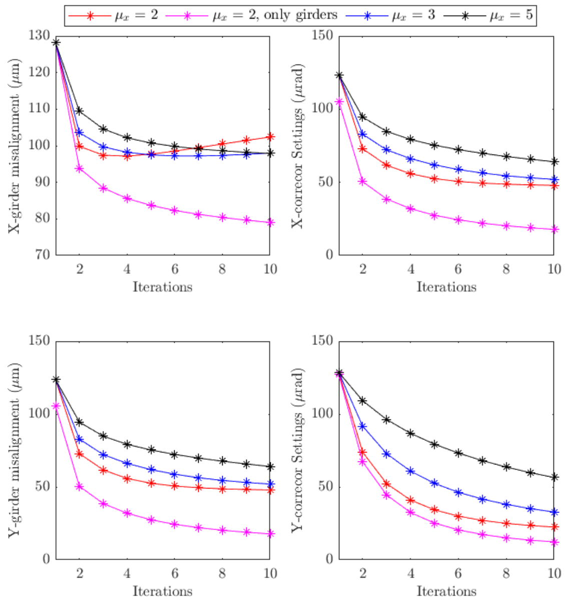

Figure 3: Girder alignment rms and corrector strength rms over many iterations of feedback as a function of Tikhonov parameter. Top: Horizontal plane. Bottom: Vertical plane.

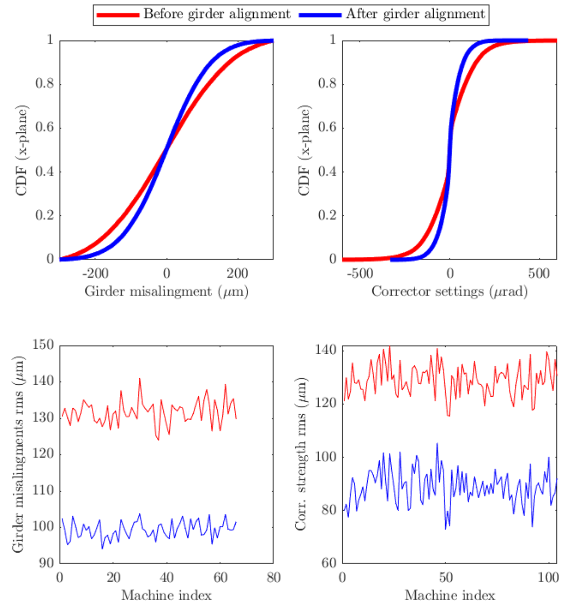

Figure 4: Data for commissioned machines before (red) and after (blue) girder alignment correction. Top: CDF of girder alignment and corrector strength of 104 random machines. Bottom: rms of girder alignment and corrector strength.

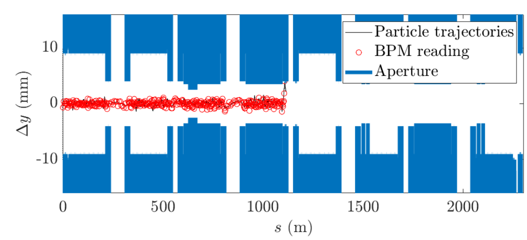

Figure 5: An example of beam threading using girders as actuators.

Commissioned Machines

The simulations were expanded to include more realistic error models, including all errors from Table 1. To achieve a closed orbit, commissioning simulations were conducted [2]. The simulations were performed for 124 random machines and the reduction of corrector strengths was successful for 104 machines for identical regularization of the GRMs. In Fig. 4, the CDF is plotted for the horizontal plane (top row), and bottom row shows the rms values for the girder misalignment and corresponding corrector strength for each machine before and after correction. An average reduction of girder misalignment rms of 25 % results in an average reduction of corrector strength rms of 30 % for all machines.

CONCLUSION

This contribution presents a perspective of a three-feedback scheme for PETRA IV, where slow and fast orbit correction can be accompanied by a very slow (days to weeks) correction of girder misalignment to reduce the corrector strengths during machine operation. The simulations show that the method can be successfully applied if girder misalignment are the dominant source of error.

OUTLOOK

Another possibility is to include the girders as actuators in the machine's commissioning. Using the GRM, a preliminary simulation is performed for achieving the beam threading as shown in Fig. 5 for the vertical plane, as a future (research) direction. Here, the BPM offset rms is 500 µm before beam-based alignment.

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