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ERROR ANALYSIS AND COMMISSIONING SIMULATION FOR THE PETRA-IV STORAGE RING

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Abstract

The upgrade of the PETRA-III storage ring into a diffraction limited synchrotron radiation source is nearing the end of its detailed technical design phase. We present a preliminary commissioning simulation for PETRA-IV demonstrating that the final corrected machines meet the performance design goals.

INTRODUCTION

The PETRA-IV project [1] for upgrading the 2.3-km 6-GeV PETRA III storage ring to a diffraction-limited synchrotron radiation source is nearing the end of its detailed technical design phase.

Alignment errors and multipole errors in magnets are usual sources of machine imperfection. While the allowed multipole errors are not dissimilar to what has been specified and achieved at many accelerator facilities, i.e. at the $5 \cdot 10^{-4}$ level, the sensitivity to alignment is significantly increased due to the combined strong nonlinearities and focusing. This places emphasis on the need for realistic modeling of the relevant errors, the development of efficient beam orbit/optics correction schemes, with the goal to establish feasible error tolerance specifications and ensure rapid commissioning.

In this paper we present a preliminary commissioning simulation and performance results of a statistical ensemble of corrected machines for the current baseline error assumptions. This procedure follows the standard approach used in MBA simulated lattice commissioning [2–4].

SIMULATION SETUP AND ERRORS

The storage ring has a geometry inherited from the HEP programme of PETRA in the 1970s, which is unusual for a synchrotron radiation facility. It has eight arcs, four straight sections of approx. 108 m length, and four straight sections of approx 64 m length. Each arc is composed of nine hybrid six-bend achromat (H6BA) cells, of which a schematic can be seen in Figure 1. A selection of lattice parameters can be found in Table 1. A total of 643 CMs in both planes, 288 skew quadrupole correctors and 786 BPMs all suitable for turn-by-turn evaluations are available.

RMS machine-errors are assigned according to the values reported in Table 2, with each error source following a Gaussian distribution truncated at $\pm 2\sigma$.

Performance of the uncorrected lattice: To start to gain some insight into the lattice performance we studied the particle dynamics in the presence of all the errors included in our model (misalignments, calibration errors, etc.) but

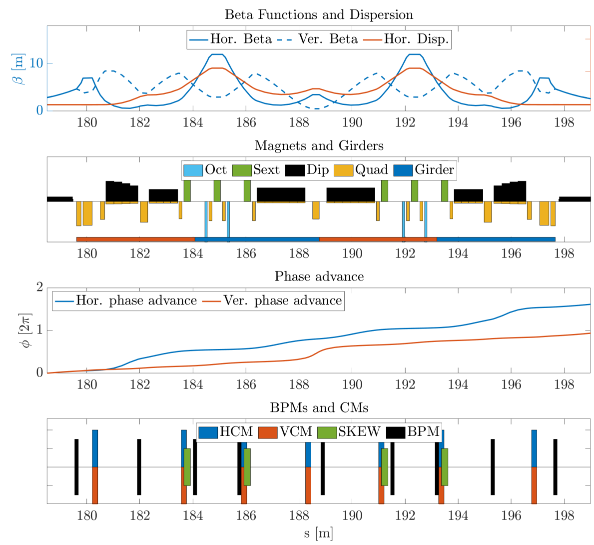

Figure 1: Lattice and magnet layout within one cell. Shown are (from top to bottom): the betatron and the dispersion functions, the the distribution of magnets and girders, the phase advance and the distribution of skew quadrupole and dipole corrector magnets and BPMs for orbit correction.

Table 1: Selected Lattice Parameters

Parameter	Value
Tunes ν_x/ν_y	135.18 / 86.27
Natural chromaticity ζ_x/ζ_y	-232 / -155
Corrected chromaticity ζ_x/ζ_y	6 / 6
Momentum compaction factor α_C	3.3 10^{-5}
Standard ID space	4.9 m
$\beta_{x,y}$ at ID, standard cell	2.2 m, 2.2 m
$\beta_{x,y}$ at ID, flagship IDs	4 m, 4 m
Nat. hor. emittance ε_x with IDs, zero current	19 pm rad

Table 2: Magnet and BPM Errors. Distributions applied in simulations are truncated 2σ Gaussians.

Error Type	rms value	Error Type	rms value
Girder rolls	200 µrad	BPM offset	30 µm
Girder trans. offset	100 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 %

before any correction to the orbit or linear optics. This provides an interesting way to draw comparisons with other machines [2–4]. The study scaled all the errors from Table 2 by the same multiplicative scaling factor; thus, an error scaling factor of 1 corresponds to the nominal errors.

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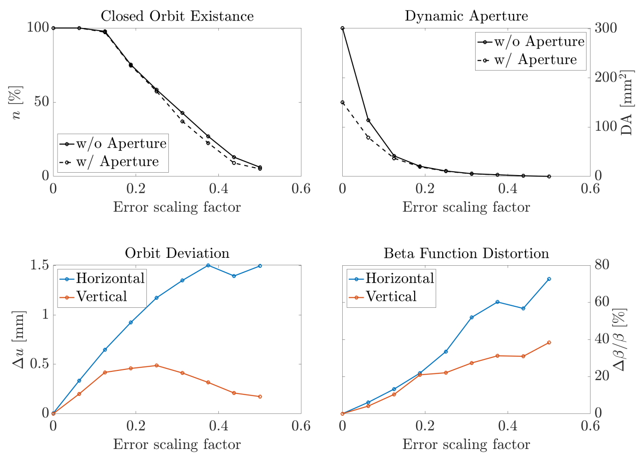

Figure 2: Lattice properties before correction for different scaling factors of the nominal error set. The plots are: the fraction of lattice realizations at which the closed orbit exists (upper left), the rms dynamic aperture (upper right), and the rms closed orbit deviation (lower left) and beta beat (lower right). The calculations in the top images were done with (dashed) and without (solid) physical apertures.

For each lattice realization we calculated the rms closed-orbit deviation (COD), the dynamic aperture, and the beta-function distortion $\Delta\beta/\beta$. The evaluation was performed with and without the physical aperture model. Results for 500 error realizations are shown in Fig. 2. At about 10 % of the nominal error amplitude the closed orbit exists in nearly 100 % of the cases (upper left plot) and drops to virtually zero at an error scaling-factor of 0.5. The closed orbit was deemed to exist if the AT `findorbit6()` function successfully converged to a solution.

COMMISSIONING SIMULATION

Commissioning simulations have two goals: to validate the lattice design and correction schemes informing the error-tolerance specifications, and to help prepare for the machine actual commissioning.

Our approach is to devise automated trajectory/orbit and optics corrections that can be applied to a statistically significant population of lattice-error realizations without ad hoc intervention. The lattice performance is evaluated by monitoring the dynamic- and local momentum aperture, typically representing the results in terms of cumulative distribution function (CDF) and range of likely outcomes.

On large machines like PETRA-IV with over 10000 elements in the lattice file, multi-turn, multi-particle tracking takes a considerable amount of time. In order to produce meaningful results for a variety of error assumptions in an ongoing lattice optimisation- and design process we decided to take short cuts at various stages, like for example not modeling stored beam BBA. Instead, we use conservative estimations on the expected results and assign them artificially at the corresponding correction step. A future version of the commissioning simulations will close the gaps and include a full start to finish tracking simulation.

1st turn threading: Initially the beam is expected to get lost within the first quarter of the ring. The first step in the correction chain is to establish transmission through one turn using a feedback-like iterative trajectory correction approach. At first we use a relatively large regularisation of the inverse 1-turn response matrix which gets decreased subsequently after establishing 1-turn transmission to further decrease the BPM readings.

Trajectory BBA: Storing beam with the assumed initial BPM offset of 500 µm is not possible for most error seeds. Thus, a turn-by-turn BBA procedure as described in [4] is applied. In dedicated studies we found that BPM offsets of 50-100 µm rms at this stage are achievable. However, in order to speed up the simulation we perform a pseudo-BBA routine by artificially realigning the BPMs w.r.t. to their neighbouring quadrupole magnet and conservatively assume 150 µm rms BBA accuracy.

Sextupole ramp up: At this point the large natural chromaticities are limiting the beam transmission and degrading the multi-turn BPM readings. Ramping up the sextupoles in steps of 1/10 of their nominal strength while applying the previously described trajectory feedback after each step works reliably and increases the overall beam transmission significantly.

Orbit- and tune correction: At this point the beam transmission is sufficient to allow for the reliable measurement of the closed orbit. Therefore, the simulation is switched from turn-by-turn to orbit mode and orbit feedback is applied.

The correction is performed in a loop successively decreasing the parameter α in the Tikhonov regularisation used to calculate the pseudo-inverse matrix. The loop is halted when the rms BPM reading stops decreasing. After each iteration of orbit feedback a tune correction is applied. Since there are more BPMs then CMs in the machine the final corrected BPM reading is about 50 µm rms.

BBA: After successfully storing beam a BBA procedure can be applied. We have not yet implemented this routine in the correction chain but reduce the BPM offset with respect to their neighbouring quadrupole magnet to 100 µm rms in the cells and 50 µm in the straight sections. Furthermore, we assume a BBA procedure can be performed on the skew quadrupole magnets in the sextupoles in order to align the BPMs adjacent to the sextupoles with 30 µm rms. Future iterations of the commissioning simulation will include these steps in full detail.

LOCO: LOCO-based linear optics correction [5, 6] is done in a sequence of steps. We found that a major reason for the correction to perform poorly is a significant orbit change between the response matrix measurement and the final correction. While orbit feedback is applied after each lattice correction step which keeps the BPM readings at their pre-LOCO values, if the phase advances change significantly the orbit itself might differ. Thus, the response matrix measurement is repeated multiple times within the optics correction scheme.

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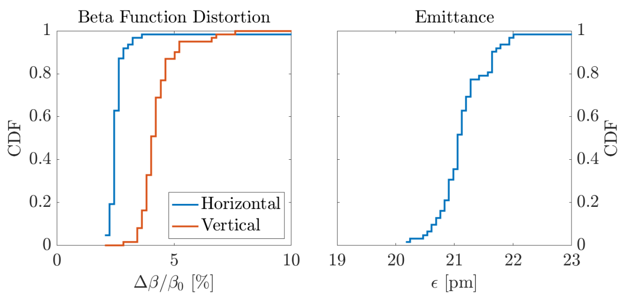

Figure 3: Cumulative distribution functions (CDF) of beta beat (left) and horizontal emittance (right) after performing linear optics correction.

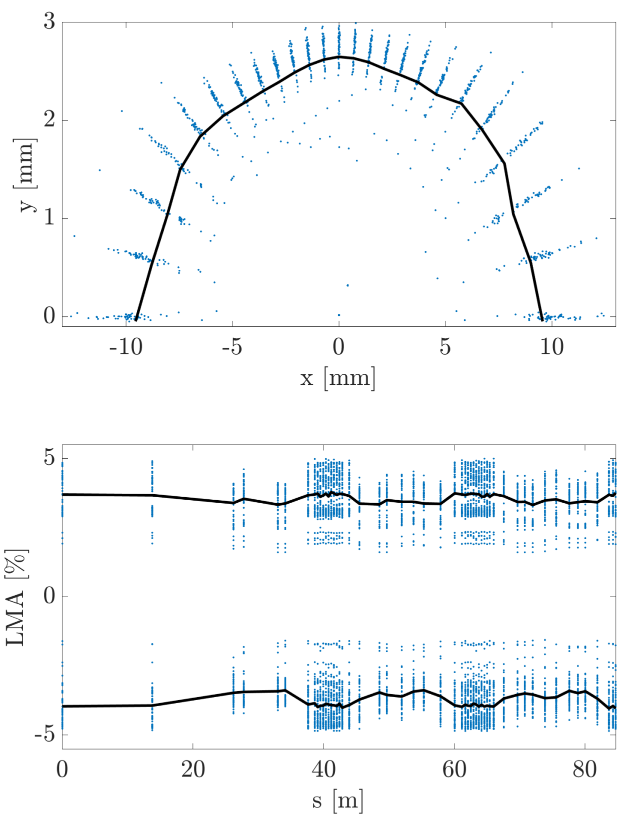

Figure 4: Dynamic aperture (top) and local momentum aperture (bottom) after performing linear optics correction. Plotted are the mean values (lines) and the results of individual error seeds (dots).

At first, we use only 17 out of 643 CMs in each plane to measure the response matrix and perform a coarse optics correction using the QF1 and QD4 quadrupole families. Thereafter, every 10th CM is used in both planes to measure a response matrix and 3 optics correction steps are performed with the initial QF1/QD4 quadrupoles, QF3/QD0 quadrupoles and all skew quadrupoles. Orbit feedback and chromaticity correction are applied after each step. This procedure of measuring a response matrix and applying 3 correction steps is repeated 3 times. The current optics correction is optimised for robustness as we routinely test different error specifications. At a later stage of the design process we will work on reducing the amount of required beam time.

Results of the final machines can be found in Figs. 3 and 4. The relatively large beta function error is due to the fact that the dispersion weight is set relatively high in order to minimise the emittance. Dynamic- and local momentum aperture are within the design goals to allow for off-axis injection [7] and sufficient life time.

CONCLUSION

A preliminary commissioning simulation for the PETRA-IV storage ring is presented, including first turn threading, BBA and optics correction. While not all correction steps are modelled with full realism yet, conservative assumptions on the correction results are used to determine that the final corrected machines meet the performance design goals.

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