ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-THPA022

LATTICE-BASED SIMULATIONS FOR THE FAST ORBIT FEEDBACK SYSTEM OF PETRA IV

S. H. Mirza*, B. Dursun, H. T. Duhme, S. Pfeiffer, S. Jablonski, H. Schlarb
Deutsches Elektronen-Synchrotron DESY, Germany

Abstract

Modelling the fast orbit feedback (FOFB) system for the upcoming PETRA IV storage ring is in progress. The single-input-single-output (SISO) simulations provide an abstract insight into the FOFB system's performance and stability. Nevertheless, to investigate the orbit correctability in general and at spatial locations of interest, i.e. insertion devices, the simulations are extended to include the lattice model. The multiple-input-multiple-output (MIMO) numerical simulations are being carried out in Python-based cpymad and Matlab-based Simulation Commissioning (SC) toolkit, and initial results are presented.

INTRODUCTION

A fast orbit feedback system is currently being developed for the upcoming 6 GeV PETRA IV storage ring at DESY. The requirements for the transverse beam position and pointing angle of at least 10% of the electron beam size and divergence demand an RMS stability of 297 nm and 100 nrad in the vertical plane. Some of the beamlines are expected to have even tighter requirement e.g. 5% of the electron beam size and divergence. For that, a disturbance-rejection bandwidth of 1 kHz is targeted. The relevant beam parameters are shown in Table 1.

Table 1: Electron Beam Parameters at IDs

Parameter	Value
$\beta_{x,y}$ (m), standard cell	2.2
$\beta_{x,y}$ (m), flagship IDs	4
Nat. emittance $\epsilon_{x,y}$ (pm rad)	20, 4
Beam size $\sigma_{x,y}$ (μm), standard cell	6.6 , 2.97
Beam div. $\sigma'_{x,y}$ (μrad), standard cell	3.02 , 1.34
Beam size $\sigma_{x,y}$ (μm), flagship IDs	8.9, 3.98
Beam div. $\sigma'_{x,y}$ (μrad), flagship IDs	2.23 , 1.0

Orbit correction in a ring is a well known cross-direction problem having temporal and spatial dimensions. The temporal part helps to estimate the best case scenario of the disturbance-rejection bandwidth for the frequency response of the subsystems such as corrector magnet, vacuum chamber, power supply and cables. It can be be modelled as single-input-single-output (SISO) system which helps to optimize the subsystems against the FOFB bandwidth and stability requirements. On the other hand, the actual orbit correction at a specific location in the ring depends upon the lattice parameters (beta function β and phase advance μ) at that location as well as at the locations of correctors and BPMs and the machine tune Q. The response of each n^{th} corrector observed at a m^{th} BPM is described by the orbit response matrix elements given as

$$R_{mn} = \frac{\sqrt{\beta_m \beta_n}}{2\sin(\pi Q)} \cos\left(Q\pi - |\mu_m - \mu_n|\right). \quad (1)$$

The total system model is described as

$$\mathbf{G}(s) = G(s)\mathbf{R}, \quad (2)$$

where $G(s)$ is the total transfer function of all static and dynamic subsystems along signal chain. We assume that all corrector channels have identical frequency behavior. Therefore, the FOFB system is a multiple-input multiple-output (MIMO) system, and a full analysis requires the inclusion of the lattice model in the simulations for performance evaluation at the spatial locations of interest, i.e. at the insertion devices.

This proceeding presents the overall philosophy of the PETRA IV FOFB system, the modelling, simulation strategy, resources used, and the first results.

* sajjad.hussain.mirza@desy.de

SIMULATIONS FRAMEWORK

Simulation Resources

Two platforms are being used for lattice-based simulations i.e. Python module cpymad (MAD-X interpreter in python) and MATLAB-based Simulation Commissioning (SC). The reason for using the latter is to take into account the commissioning simulation, which provides corrected machines against strong non-linearities caused by larger misalignments. Initial simulations in [1] showed that the closed orbit exists only for 10% of the nominal errors (nominal Girder transverse offset of 150 µm rms and nominal magnet transverse offset of 30 µm rms) for 500 error seeds for PETRA IV. The 1^{st} turn threading, trajectory beam-based alignment (BBA), orbit and tune correction, beam-based alignment and LOCO-based optics corrections are performed in the commissioning simulations to apply the nominal errors and the final FOFB simulations are being performed over these corrected machines in SC toolkit. The simulations on linear machines are performed in cpymad as the PETRA IV lattice is primarily written in MAD-X.

Simulation Strategy

A time-domain simulation framework is laid down for the PETRA IV FOFB system in order to include the spatial domain for which the lattice model is called upon after each iteration of corrector-strength calculation. This leads to the generation of corresponding BPM values as well as closed

ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-THPA022

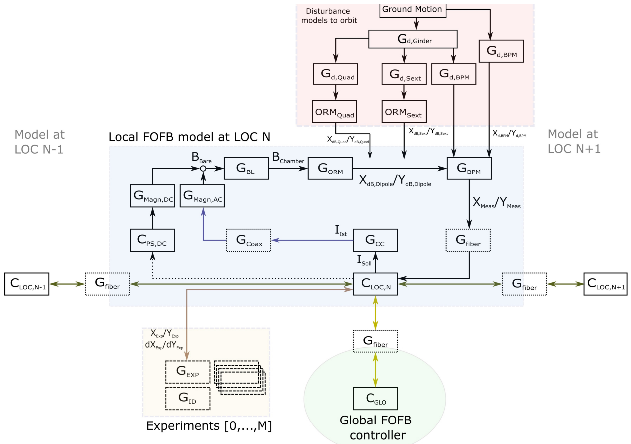

Figure 1: The global modelling of the FOFB system.

orbit at other locations (e.g. at insertion devices) including non-linear effects caused by larger static alignment errors of girders etc. It also helps to include all disturbances, and imperfections including BPM noise and corrector errors at each time step, directly in the lattice model. For only linear assumptions and for calculating orbit at BPMs, the lattice can be replaced with the ORM. For that, the disturbance needs to be modelled separately and added to the closed orbit at each iteration. Fig.1 shows a global view of the FOFB model including the disturbance block. The topology of the global system is also shown, where the global station interacts with local stations for BPM data aggregation and corrector strength distribution to a certain number of BPMs and correctors. A total of 16 local stations are distributed over the entire ring.

Dynamic disturbance modeling The disturbance to the closed orbit can be modelled for each source individually through its dynamic response to the ground vibrations as well as its spatial response to the closed orbit through corresponding response matrix. The major sources includes the oscillations of the misaligned quadrupoles while sextupoles and higher order magnets have an order of magnitude less effect. For initial simulations, worst-case scenario of zero-correlation length (random phase difference between each quadrupole's oscillations) is assumed and the pre-calculated magnet misalignments as function of time are updated at each time step of simulation.

Lattice model Lattice model is called upon at each iteration to update the corrector strengths and the misalignments of magnets and BPM noise and corrector errors. A total of 788 BPMs, 618 slow correctors per plane and 244 fast correctors in horizontal plane and 316 fast correctors in vertical plane are available for the orbit correction in PETRA IV. Figure 2 shows the distribution of BPMs and correctors in one cell. The top plot shows the lattice parameters and middle plot shows the locations of BPMs and slow correctors while the lowest plot shows the location of fast correctors only, in both planes. One can see that the locations of slow and fast magnets overlap in the lattice and due to space constraints,

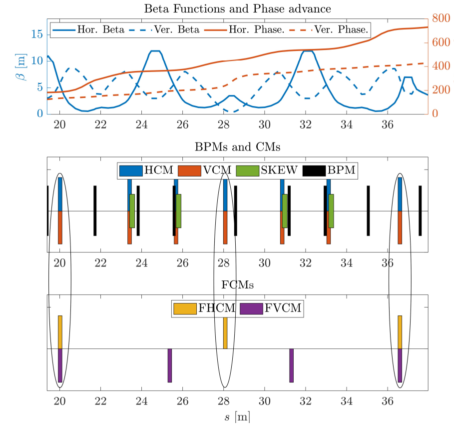

Figure 2: Location of BPMs and slow correctors (middle) and fast correctors (lowest) along with their lattice parameters (top).

they are combined in one physical magnet except for 2^{nd} and 3^{rd} vertical fast magnets where the slow magnets are extra winding on the skew quadrupoles. However, in order to keep same transfer function of corrector magnets at all locations of the cell in the vertical plane, identical magnet shall be used for two middle correctors. The combined AC/DC corrector magnet design is capable of 600 µrad DC deflection and 30 µrad integrated AC deflection up to 1 kHz.

System dynamics The dynamic transfer function is approximated as first-order system including an input/output delay and discretized with the sampling time T_s of FOFB system. Special focus is set to simulate the frequency response of corrector magnets along with vacuum chamber [2] and the current estimate (5 kHz) for the vacuum chamber is much smaller than previously assumed theoretical value of 17.8 kHz [3]. Upto now the dominant pole is given with 1.2 kHz (corrector PS bandwidth). The total estimated delay is 74 µs. Similarly, the PI controller is also discretized with zero-order hold approximation as

$$K(z) = \frac{K_p z + (-K_p + K_i T_s)}{z-1}, \qquad (3)$$

where K_p and K_i are proportional and integral gains and z is the z-transform.

ORBIT CORRECTION SCHEME

Any fast correction magnet can achieve DC deflection by design, so the FOFB system is used for orbit correction from quasi-DC to high frequency (1 kHz). The slow correctors are used to commission the machine and to correct large static orbit errors at the startup. Slow orbit drifts are later corrected by the FOFB system. In this way, only one feedback system may be in operation to avoid cross-talk between the slow and the fast system. In order to use the larger mode space of the slow correctors, a DC download from the fast correctors to the slow correctors is to be implemented.

ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-THPA022

DC Download

The slow corrector strengths can be calculated from the DC strength (average over certain time span) of the fast correctors using the corresponding ORMs as,

$$\theta_s = R_s^+ R_f \theta_f, \tag{4}$$

where θ_s is vector of strengths of slow correctors, θ_f is vector of strengths of fast correctors, and R_s and R_f are the orbit response matrices of slow and fast correctors to the BPMs, respectively. To demonstrate such a DC download, time-domain simulations are performed in cpymad where a perturbed orbit is generated over 5 seconds as a result of oscillations and drift of all quadrupole magnets. The perturbed orbit is plotted in Fig. 3 (top) at all BPMs at each time step. Although the update rate of PETRA IV FOFB simulation is planned to be 130 kHz, in order to run the simulations faster, the open loop system is discretized with 10 kHz to provide proof of principle. The fast system assumes an open-loop bandwidth of 1.2 kHz and a group delay of 84 µs (earlier estimate in [3]). The simulations show the orbit correction (second from top in Fig. 3) using fast correctors only for initial 0.5 s. The strength of the fast corrector is averaged over this time window for all correctors and transferred to the slow corrector magnets through Eq. (4) (second from bottom in Fig. 3), assuming a very slow dynamics with open-loop bandwidth of 1 kHz. As a result the DC part of the fast correctors (bottom plot in Fig. 3) does not follow the drift, while slow correctors take over the DC strength. A slow transition from fast to slow correctors ensures that the closed orbit does not notice anything of the transmission.

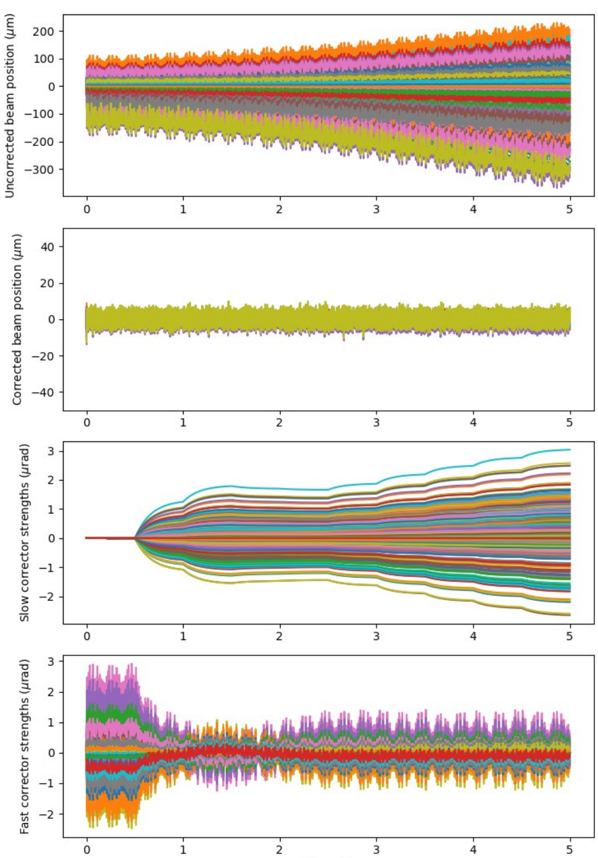

Figure 3: Download of DC current from fast correctors to slow correctors without disturbing the orbit.

SUMMARY AND OUTLOOK

This paper presents an introduction to the lattice-based modelling and simulations for the PETRA IV FOFB system. A time-domain simulation framework is established to consider the lattice model for investigating dynamic orbit correction at locations other than the BPMs. On the other hand, it offers the possibility to add local noise sources, e.g. to imitate the noise of the power supply unit for their technical specifications. In addition, non-linearities due to larger static misalignment errors were taken into account.

The Girder misalignment is the major source of orbit errors for PETRA IV that require larger strengths of the slow corrector magnets (600 µrad). In order to reduce the DC corrector strengths during operation, girder alignment correction is proposed for PETRA IV as an outlook, to be calculated based upon strengths of the slow correctors. A model-based Girder-to-BPM response matrix R_{GRD} can be used to predict the Girder alignment errors.

ACKNOWLEDGMENTS

We thank Thorsten Hellert (now back at Berkley LAB) for his help and support with the Simulation Commissioning Toolkit and Günther Rehm from HZB for fruitful discussions and suggestions.

REFERENCES

[1] T. Hellert *et al.*, “Error Analysis and Commissioning Simulation for the PETRA-IV Storage Ring”, in *Proc. IPAC’22*, Bangkok, Thailand, Jun. 2022, pp. 1442–1444. doi:10.18429/JACoW-IPAC2022-TUPOMS018

[2] J.-M. Christmann *et al.*, “Finite Element Simulation of Fast Corrector Magnets for PETRA IV”, presented at the IPAC’23, Venice, Italy, May 2023, paper WEPM049, this conference.

[3] S.H. Mirza, A. Aloev, H.T. Duhme, B. Dursun, A. Eichler, S. Jabłoński, *et al.*, “Requirements and Design for the PETRA IV Fast Orbit Feedback System”, in *Proc. 11th Int. Beam Instrum. Conf. (IBIC’22)*, Kraków, Poland, Sep. 2022, pp. 343–347. doi:10.18429/JACoW-IBIC2022-TUP43