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SENSITIVITY STUDIES OF THE PETRA IV LATTICE

I. Agapov *
Deutsches Elektronen Synchrotron, Notkestrasse 85, 22607, Hamburg, Germany

Abstract

As the machine with the smallest emittance among the planned fourth-generation hard x-ray synchrotron light sources, PETRA IV will have very demanding requirements on magnet alignment and stability. Several developments to address mechanical and beam-based stabilization have been started in connection to that. Here we summarize the alignment and field error tolerances resulting from startup and commissioning simulations of the main ring.

INTRODUCTION

PETRA IV is 6 GeV synchrotron light source facility currently being designed at DESY Hamburg. The project is described in more detail in these proceedings [1]. Early on it became clear that all candidate lattices become unstable when alignment errors of 5 to 10 µm (rms) are introduced. This alignment level is technically possible in principle, but not feasible for large-scale accelerator installations. So, as other fourth generation synchrotron light sources, PETRA IV will have to rely extensively on "machine bootstrapping", i.e. a set of procedures geared to start up the machine, accumulate beam, and tune the optics to design parameters. The approach taken for PETRA IV at present was to delay detailed commissioning simulations to the point in time where both the technical layout is more mature and the high level control tools featuring a flight simulator mode are established, which would allow to both establish the commissioning procedures and debug the commissioning tools at the same time. At this stage we concentrated on understanding if the required diagnostics resolution, tunnel stability etc. can be achieved. The simulations performed back up our conclusion that ambitious but realistic alignment goals are required to guarantee smooth machine operation.

ALIGNMENT REQUIREMENTS

The simplified startup simulations comprises following steps. A misalignment is applied to the lattice based on the model described later. Then open trajectory is corrected with all nonlinear elements switched off. Nonlinear elements are then ramped in 10% steps, and at each step open trajectory is corrected with SVD algorithms keeping a small number of singular values. After that, closed orbit and tune are corrected in several steps with increased number of singular values. The resulting chromaticity is not far away from the design value and is not corrected.

The alignment model is based on the following expression for individual element offsets

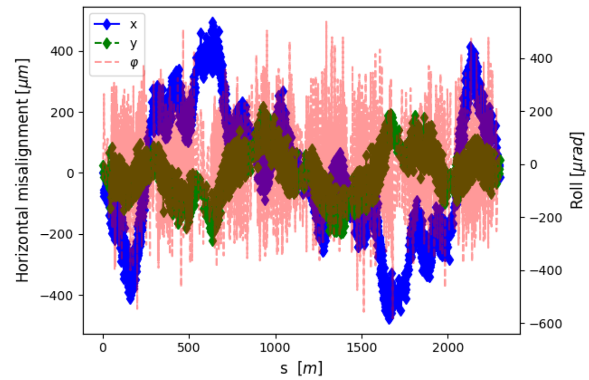

Figure 1: A realization of misalignment based on model based on Eq. 1. Here σ_X=30 µm, σ_Y=30 µm, Σ_{XG}=50 µm, Σ_{YG}=50 µm, Σ_X=400 µm, Σ_Y=100 µm, N_h=20 and α=1.

$$\Delta_{X,Y} = \xi_{X,Y}(s) + \zeta_{X,Y}(s) + \sum_{k=1}^{N_h} \frac{A_{X,Y,k}}{k^\alpha} \sin\left(\frac{2\pi k s}{L}\right) \quad (1)$$

Here $\xi_{X,Y}$ are normally distributed variables with standard deviations σ_X and σ_Y, independently distributed for each s (incoherent), $\zeta_{X,Y}$ are normally distributed variables with standard deviations σ_{XG} and σ_{YG}, independently distributed for each girder, and $A_{X,Y,,k}$ are the random amplitudes of harmonics with standard deviations Σ_X and Σ_Y. Simulations showed that the results are not too sensitive wrt. the exact model as long as element offset variation on short length scales (up to 100 m) is similar, and moderately sensitive wrt. values of girder alignment, with magnet-to-magnet alignment being the most critical parameter. An example of results based on the model described in the caption to Figure 1 are shown in Figures 2 and 3. The alignment specifications resulting from these simulations are presented in Table 1

The degradation of dynamics aperture and momentum acceptance have roots in the shape of the tune diagram: for large momentum offsets (about 1.5%) the tune encounters a half-integer resonance, while for large amplitude offsets a fold in the frequency map exists (see Figures 4 and 5). While the half-integer resonance crossing is expected to be popssible (see below), it is not yet clear if the DA limitation by the fold can be overcome. The latter issue is however less critical in comparison to MA degradation.

BEAM SIZE STABILITY

The residual orbit, dispersion, and beta beating have two effects on the machine performance: the effective beam size is increased and the beam dynamics characteristics such

* ilya.agapov@desy.de

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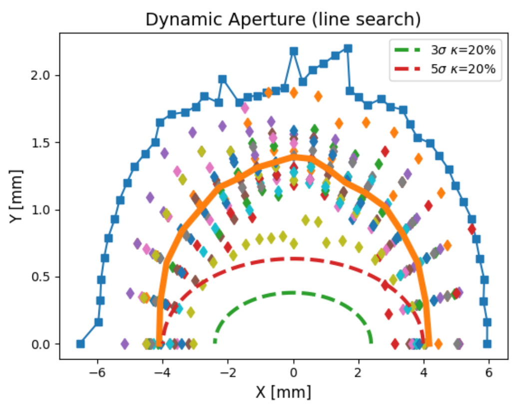

Figure 2: Dynamic aperture (6D tracking) without errors (blue curve), and with errors (dots) with the orange line representing the average. Tracking point with $\beta_x = 21.7$ m, $\beta_y = 3.7$ m. Aperture requirements for 3σ and 5σ booster beam of 19 pm emittance with $\kappa = 20$ % coupling are also shown.

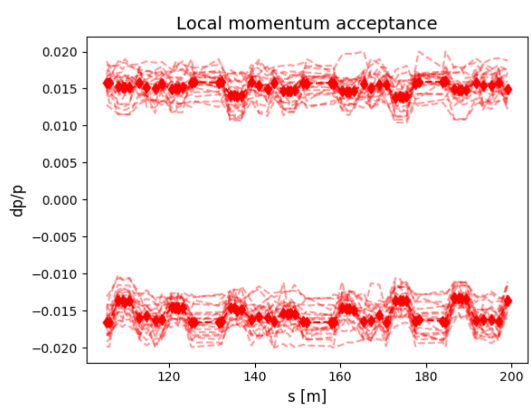

Figure 3: Local Momentum Acceptance with errors.

Table 1: Summary of Allowed Alignment and Field Integral Errors

Element	$\sigma_{\Delta x}$	$\sigma_{\Delta y}$	$\sigma_{\Delta\varphi}$	$\Delta k/k$
Dipole	50 µm	50 µm	200 µrad	1×10^{-3}
Comb.-func.	30 µm	30 µm	200 µrad	0.5×10^{-3}
Quadrupole	30 µm	30 µm	200 µrad	0.5×10^{-3}
Sextupole	30 µm	30 µm	200 µrad	1×10^{-3}
Octupole	30 µm	30 µm	200 µrad	1×10^{-3}
BPM	30 µm	30 µm		
Girder	50 µm	50 µm	200 µrad	

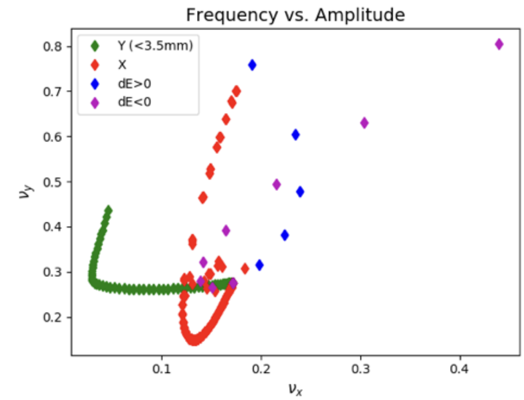

Figure 4: Detuning with amplitude and momentum.

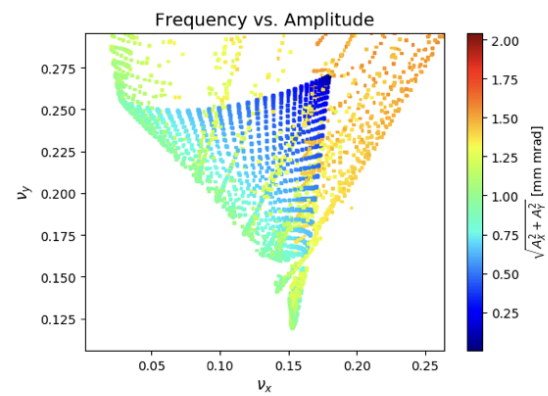

Figure 5: Betatron detuning with action.

as dynamic aperture and momentum acceptance are suffering. The effective electron beam size is a convolution of the unperturbed beam size, orbit fluctuations, beta-beating, and residual dispersion. The beam size including emittance degradation and beta beating is

$$\sigma_{u\beta} = \sqrt{(\epsilon_{0u} + \Delta\epsilon_u)(\beta_{0u} + \Delta\beta_u)}$$

where u can stand for either x or y. The beam size growth is to the first order

$$\frac{(\sigma_{u\beta} - \sigma_{u0})}{\sigma_{u0}} = \frac{\Delta\beta_u}{2\beta_{u0}} + \frac{\Delta\epsilon_u}{2\epsilon_{u0}}$$

The rms fluctuation of the beam size due to emittance growth and beta beating together with the orbit fluctuation and the residual dispersion is

$$\Sigma_u^2 = \frac{1}{4}\Sigma^2_{\Delta\beta/\beta} + \frac{1}{4}\Sigma^2_{\Delta\epsilon/\epsilon} + \Sigma^2_{r/\sigma_{u0}} + \Sigma^2_{\delta_E\eta/\sigma_{u0}} \quad (2)$$

where $\delta_E\eta/\sigma_{u0}$ is the relative beam size variation due to dispersion, r/σ_{u0} is the relative orbit jitter, and Σ's are the variations of those values. The beta beating correction level is set to 2% and below from beam dynamics considerations as described later. This contributes up to 1% increase in the

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beam size. Residual dispersion in undulators can lead to emittance growth when IDs are closed. The average residual dispersion at ID BPM locations of approx. 1 mm will result in approx. 4% emittance growth. This requirement sets the limit on the dispersion correction. The influence of insertion devices on beam emittance in PETRA IV is strong, with one ID contributing on average 7% emittance damping. Thus, while small gap changes in several IDs or opening and closing up to two IDs would not lead to more than ten percent change in the beam size, need to stabilize more severe gap changes might require installation of additional emittance feedback insertion devices. The requirements on beta beating, dispersion correction, orbit and emittance stability to reach 10% beam size stability are summarized in Table 2.

In the uncorrected lattice harmful resonances are excited, the most prominent being the half-integer resonance crossed by particles with large momentum deviation. This resonance is not excited when the optics is corrected sufficiently well, which in the case of PETRA IV corresponds to 2-3% beta beating, precision achievable e.g. with the LOCO algorithm.

The orbit stability requirements for the beam size fluctuation to not exceed 10% is 800 nm in the horizontal and 160 nm in the vertical direction. Magnet support-to-orbit amplification factors at the BPM locations next to the insertion device are 90 in horizontal and 125 in vertical direction when defined as rms. orbit deviation value and 300 and 380 respectively when defined as the maximum deviation value. The amplification factors scale with the square root of the beta function and could vary by approx. factor of two in other location of the lattice.

For the PETRA site the ground vibration integrated down to 1 Hz lies in the 0.1 µm range. Due to the approximately fourth inverse power dependency of the ground motion spectrum on frequency ground vibrations above 100 Hz can be neglected. For the PETRA site the ground vibrations integrated above 100 Hz lie below 0.1 nm. On the other hand, vibrations at low frequencies have long coherence length: all accelerator components and the photon beam transport line will move as a whole and no impact on the experiment will be seen. So, for the APS-U site the coherence length was estimated as $L_x \approx \frac{100}{f^{1.1}}$ and $L_y \approx \frac{125}{f^{1.4}}$. Assuming similar situation at the PETRA site, below 1 Hz the coherence length is larger than 100 m in both planes. Coherence length measurements will be performed at the DESY site during further design work, but the estimates indicate that the lower frequency cut-off of the orbit feedback system should lie in the range of 1-3 Hz. If all orbit correctors are used simultaneously for slow and fast feedback the AC part of the correction required to stabilise 0.1 µm vibrations will be below 1 µrad. Some headroom is left to optimize the corrector configuration by having only a subset of correctors run in AC and DC mode simultaneously, an approach taken in the ESRF EBS design. Similar concept can be used at PETRA IV (see Figure 6). With three correctors per cell rms magnet vibrations up to 1 µm can be compensated with maximum corrector strength below 10 µrad.

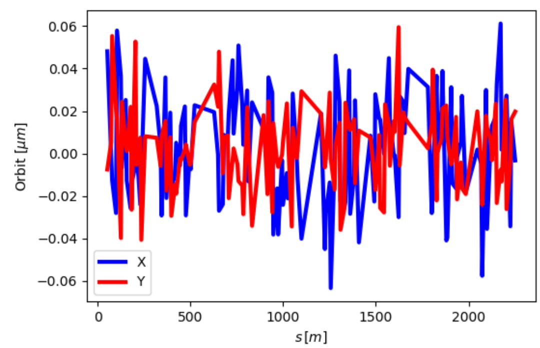

Figure 6: Residual closed orbit at ID BPMs after correction with 192 fast correctors (3 per cell). The distortion is 1 µm rms.

Table 2: Summary of Requirements on Beam Stabilisation

Parameter	Specification
Beam size variation. at ID, x,y	less than 10 %
Spurious dispersion at ID BPMs, x	less than 700 µm
Spurious dispersion at ID BPMs, y	less than 180 µm
Orbit stability at ID BPMs, x	less than 800 nm
Orbit stability at ID BPMs, y	less than 160 nm
$\Delta\beta/\beta$ correction, rms , x, and y	2 %
$\Delta\epsilon/\epsilon$ max., x, and y	10 %
BPM resolution	140 nm at 600 Hz
BPM vibration amplitude	50 nm above 10 Hz
Compensation bandwidth	at least 600 Hz
Corrector strength DC	at least 1 mrad
Corrector strength AC	at least 100 µrad

ACKNOWLEDGEMENTS

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REFERENCES

[1] I. V. Agapov *et al.*, “Status of the PETRA IV project”, presented at the 10th Int. Particle Accelerator Conf. (IPAC’19), Melbourne, Australia, May 2019, paper TUPGW011, this conference.