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STUDY OF THE DYNAMIC APERTURE REDUCTION DUE TO ERROR EFFECTS FOR THE HIGH ENERGY PHOTON SOURCE*

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Abstract

The 6 GeV High Energy Photon Source (HEPS) employs a lattice of 48 hybrid 7BA cells, aims to achieve a natural emittance between 30 to 60 pm, within a circumference of about 1.3 km. In the performance evaluation of optimized lattices, we found that the dynamic aperture of the bare lattice were sufficient for on-axis swap-out injection, but a large reduction in the dynamic aperture was observed in the simulation when including lattice imperfections and even after dedicated lattice corrections. In this paper, we identified the feed-down effects of sextupoles as the major source of DA reduction, and proposed to use dedicated sextupole movers to efficiently reduce the orbit offsets in sextupoles, to partially recover the dynamic aperture, sextupole mover-based optics correction schemes were also discussed.

INTRODUCTION

The High Energy Photon Source is a 6 GeV, 1.3 km, diffraction-limited storage ring light source to be built in the Huairou District, northeast suburb of Beijing, China. The lattice design is based on 48 hybrid 7BA cells, to reach a sub-60 pm natural emittance. PSO and MOGA algorithms are used as the engine of lattice optimization [1], to obtain optimal solutions with a large photon brightness, as well as a large "effective" dynamic aperture (DA) and momentum acceptance (MA), in the middle of straight sections. Recent optimization has obtained two reference lattices for accelerator physics studies and hardware R&D, including a 48-period 58 pm lattice and a 24-period 34 pm lattice with interleaved high-β and low-β straight sections [2]. For both designs, the DA of the bare lattice looks promising, much beyond the requirement of on-axis swap-out injection. However, further evaluation of the lattice performance includes introduction of typical alignment and magnetic field errors, as well as comprehensive orbit and optics corrections, a significant shrink in the DA area is observed, which brings concerns that the requirement of swap-out injection cannot be easily met, and a modification of the lattice optimization method might be necessary to introduce "typical errors" in the evaluation of the DA and MA.

In this study, we first analyzed the potential contributors to DA reduction, via step-by-step removing different contributors from an imperfect lattice, then we manually removed the offset of sextupole centers compared to the local closed orbit from an imperfect lattice step-by-step and identified the sextupole feed-down effects as the major contributor to the DA reduction, schemes to recover the DA was finally discussed.

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THE CONTRIBUTORS OF DA REDUCTION

The effects of alignment and magnetic field errors can be categorized into the following groups:

- closed orbit distortion: for example dipole field and roll error, feed-down effects due to offsets in quadrupoles, sextupoles, octupoles and multipolar errors, orbit correctors, etc.
- β-beating and phase advance error: for example the field error of quadrupoles and combined-function dipoles, the feed-down effects due to offsets in sextupoles, octupoles and multipolar errors, the gradient errors of dipoles, a subset of quadrupoles used in optics corrections to compensate for the gradient errors, etc.
- transverse linear coupling error: roll error of quadrupoles and combined-function dipoles, feed-down effects due to offsets in sextupoles, octupoles and multipolar errors, skew quadrupole correctors, etc.
- errors that only affect nonlinear dynamics: multipolar errors (higher than the order of gradient error) of all magnets, field strength errors of sextupoles and octupoles, etc.

Note that the above category assumes only a weak transverse coupling, which is the default operation condition for HEPS. While a round beam operation is another viable option in particular for filling patterns with a high single bunch charge, to this end, the second and the third categories shall be redefined based on Mais-Ripken parameterization [3] in the presence of strong coupling, which is beyond the scope of this paper.

To understand the major contributors that lead to the DA reduction, one particular imperfect lattice seed after correction of the 58 pm lattice is analyzed, via step-by-step removal of one particular contributor and evaluate the DA result, as shown in Fig. 1. Removing the closed orbit errors while keeping all the feed-down effects does not lead to an obvious different DA, while the normal and skew gradient errors have a large effect on the DA, in contrast, multipole errors of higher order only have a very small effect on the

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DA. Different lattice seeds have different DA-limiting resonances but the normal and skew gradient errors are the major contributors to the DA reduction.

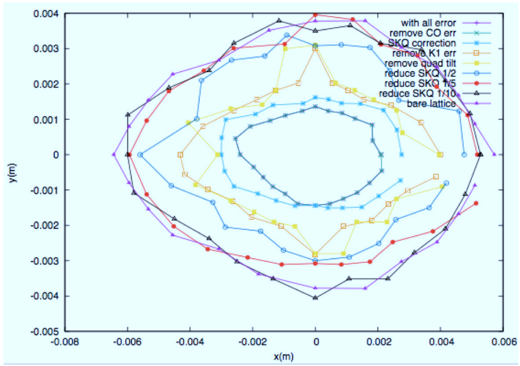

Figure 1: Step-by-step removal of potential contributors of DA reduction and the consequent DA. SKQ correction means using skew quadrupole correctors to correct coupling in order to recover the vertical emittance after removing vertical bends contributions; reducing SKQ 1/2 means reducing the skew quadrupole corrector strength to 1/2 the original value.

As a case study, a model lattice of 59.2 pm similar to the 58 pm lattice was studied, for 50 seeds of imperfect lattices, the root mean square errors of integral normal (K1) and skew (KS1) gradient errors for different magnets are plotted in histograms, as shown in Fig. 2. In the case of the normal gradient error, the sextupole feed-down effect is the dominating contribution, the contribution from quadrupole field errors is one order weaker, while in the optics correction quadrupoles are used as the knobs to compensate for the normal gradient errors, in particular for the sextupole feed-down effect, therefore, the normal gradient error due to the "fudge" factors of quadrupoles used in the correction is the same order as that of the sextupole feed-down effect. On the other hand, in the case of the skew gradient error, the sextupole feed-down effect is also the dominating contribution, much stronger than the contributions from tilt error of quadrupoles and combined-function dipoles (denoted as BQ in the figure), while the skew quadrupole correctors used in the coupling and vertical dispersion corrections contribute the same order as that of the sextupole feed-down. From this analysis, it is clear the sextupole feed-down effects are the major contributors for the normal and skew gradient errors. Moreover, after optics correction using the quadrupoles and skew quadrupoles as knobs, the sextupole feed-down effects are not compensated locally, but additional normal and skew gradient errors are introduced in the quadrupoles and skew quadrupoles. Then it becomes natural to ask if the reduction is mainly due to the sextupole feed-down effects, and if the DA can be recovered provided the sextupole feed-down effects can be alleviated.

Based on 20 seeds of imperfect lattices after trajectory and orbit correction but before optics correction using quadrupoles and skew quadrupoles, the sextupole offsets

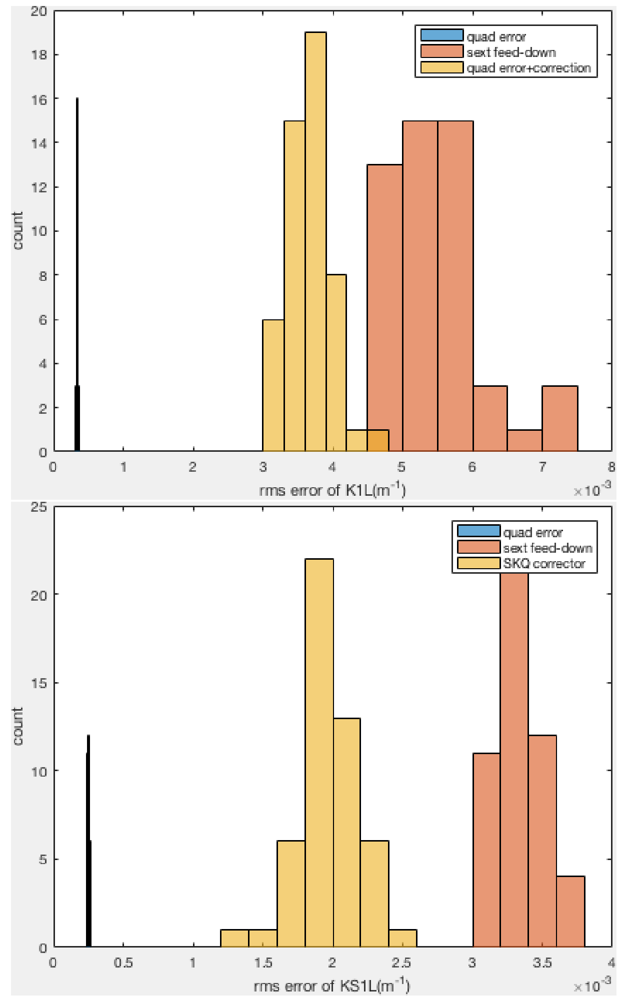

Figure 2: Histograms of the rms errors of integral normal (upper plot) and skew (lower plot) gradient errors for different types of magnets.

are reduced proportionally step-by-step, a gradual recovery of DA is observed, as shown in Fig. 3, so are the β-beating and transverse beam emittances. Note that the best recovery of DA area is about 80%, the residual DA reduction compared to the bare lattice, might be due to alternative sources of normal and skew quadrupole errors, as well as higher order multipole errors. This also inspires the idea to realize local compensation of sextupole feed-down effects.

DA RECOVERY METHODS

To realize local compensation of sextupole feed-down effects, there are two possible schemes. First, one can implement auxiliary windings on sextupoles supplying normal and skew gradient fields, if the normal and skew gradient error of each sextupole due to the feed-down effects can be deduced from some beam-based measurements, then local compensation can in principle be achieved. However, this scheme is not favored because this functionality would make the magnetic field control more challenging for these sextupoles with already very strong field. On the other hand,

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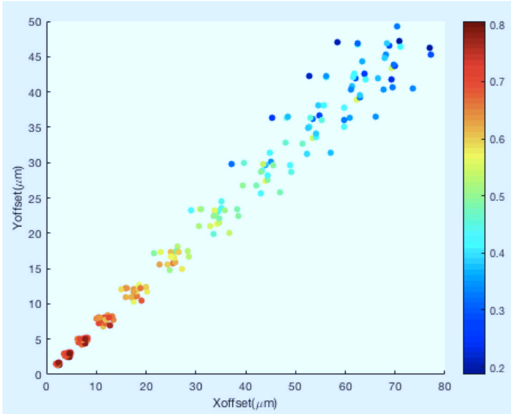

Figure 3: Dependence of the normalized DA area (the color bar) on the rms horizontal and vertical sextupole offsets.

sextupole movers implemented in the final focus system in linear colliders [4] to correct nonlinear aberration, can be implemented here to reduce the transverse offset in sextupoles, and reduce the sextupole feed-down effects. To this end, we propose to employ sextupole movers with online tuning capability for each of the 288 sextupoles in the HEPS lattice, and two different DA recovery approaches based on this idea has been studied.

First, since the normal and skew gradient errors are primarily contributed by sextupole feed-down effects, in the LOCO-based optics correction scheme, the normal and skew gradient errors in the sextupoles, can be used as knobs to reduce the difference in the measured response matrix and the modelled response matrix [5]. Then, the fitted normal and skew gradient errors can be used to deduce the transverse offset of sextupole center compared to the closed orbit, and sextupole movers can be activated to compensate this error. This scheme is described in detail in Ref. [6], and has been implemented in the lattice error correction procedure for HEPS.

Alternatively, dedicated beam-based sextupole alignments (BBSA) can be applied to directly measure the sextupole offsets. Different from previous studies of BBSA in electron storage rings [7], with the capability of remote controllable sextupole movers, the adjustment of sextupole offsets are not dependent on the local orbit bump and can be realized with a rather high precision, for example the sextupole mover design for HEPS promises a resolution of better than 5 μm rms. In addition, if either horizontal or vertical offset is small, the measurement of offset in the other plane can suffer from a bad signal to noise ratio, accordingly, the sextupole can be displaced further in this plane and improve the quality of measurement in the other plane. Therefore, though the closed orbit difference due to the sextupole feed-down effect is rather small, the sextupole offsets can be measured with a good resolution, as shown in Fig. 4. However, it is also clear that there is a systematic error in the horizontal plane, which is due to some nonlinear contributions in the fitting, correction of this systematic error is now under study.

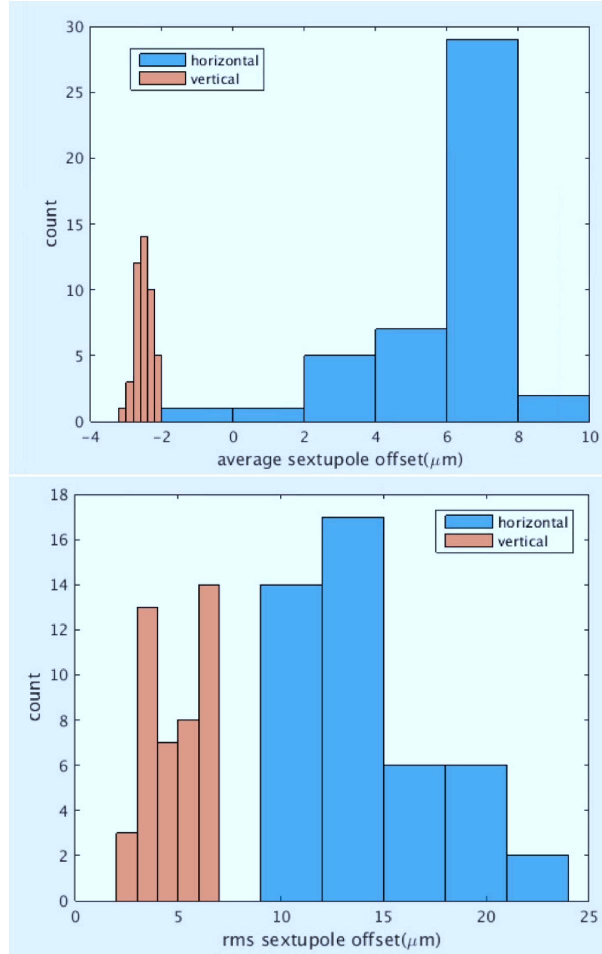

Figure 4: Histograms of the average (top figure) and rms (bottom figure) relative sextupole offset error using beam-based sextupole alignment methods among the 288 sextupoles in HEPS.

CONCLUSION

This work systematically studies the cause of DA reduction for HEPS, DA recovery approaches based on sextupole movers have been developed. Further understanding of the systematic error in the beam-based sextupole alignment is underway, and we'll have a comparison and evaluation between the two approaches, alternative usage of the sextupole movers will also be studied.

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