

# ERROR STUDY AND CORRECTION OF HEFEI ADVANCED LIGHT SOURCE\*

D. Xu, Z. Bai, W. Li<sup>†</sup>, University of Science and Technology of China, Hefei, China

## Abstract

Hefei Advanced Light Source (HALS) is a future diffraction limited storage ring. The machine performance under all kinds of magnet errors is a vital component in physical design. In this paper, we present our work on the closed orbit correction, the linear beam optics compensation and the coupling control in HALS. After correction, the dynamical aperture can suffice the injection scheme.

## INTRODUCTION

HALS is a fourth generation synchrotron radiation light source based on the Diffraction Limited Storage Ring with a beam energy of 2.4 GeV. Its designed emittance in recent lattice version is about  $25 \text{ pm} \cdot \text{rad}$  which reaches the diffraction limit of soft X-ray. In order to achieve such ultra-low emittance, HALS adopts strong quadrupoles to depress dispersion and strong sextupoles to perform chromaticities correction. As a consequence, the whole system is sensitive to the magnet errors and the lattice performance under errors has to be checked to verify the feasibility of the physical design.

The ring consists of 30 cells. Figure 1 shows the layout of one cell [1]. Each cell accommodates 12 BPMs, 12 orbit correctors, 12 sextupoles, 18 quadrupoles, 5 longitudinal gradient dipoles, 2 dipoles and 2 reverse dipoles. The positions where the orbit correctors to put are chosen to minimize the residual closed orbit in both horizontal and vertical directions [2].

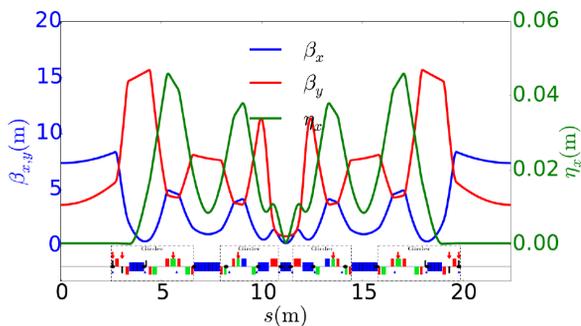


Figure 1: HALS optical functions for one cell. The blue, red and cyan squares are dipoles (with or without gradient), quadrupoles and sextupoles respectively. The black dots on the base line are BPMs. The blue triangles are orbit corrector while the red arrows are where skew quadrupoles to put.

In the following sections, we will present the orbit and linear beam optics correction results of lattice shown in

\* Work supported by the Fundamental Research Funds for the Central Universities (WK2310000077)

<sup>†</sup> liwei\_ustc@ustc.edu.cn

Fig. 1 under all kinds of magnet errors. The orbit correction is carried out with Singular Value Decomposition (SVD) method [3]. The linear beam optics is fitted by the Linear Optics from Closed Orbits (LOCO) [4].

## MAGNET ERRORS

The magnet elements of a storage ring can never be placed at their ideal positions. To simulate a real machine, we have to assume a statistical variation of their positions. Only static errors are considered in this paper, e.g. misalignments and multipole errors.

Six variables are needed to determine the position and orientation of a rigid body. Three of them are  $\Delta X/Y/Z$  to the ideal point, and the others are rotation around  $x/y/z$  axis where  $x/y/z$  refer to the horizontal, vertical and longitudinal directions respectively. We consider  $\Delta X/Y/Z$  and rotation around longitudinal axis in our simulation which is consistent with elegant [5]. In HALS, groups of magnets are mounted onto girders which introduce strong coherence between magnet elements. The girder errors also should be considered in simulation. In conclusion, Table 1 summarizes all alignment errors.

Table 1: Error Sheet for Misalignment. All values are RMS, truncated at  $3\sigma$ .

Type	$\Delta X/\Delta Y (\mu\text{m})$	$\Delta Z (\mu\text{m})$	$\Delta\theta_z (\mu\text{m})$
Element	30	100	150
Girder	50	200	150

In addition, multipole errors are also considered. The data is given in [6].

## SIMULATION RESULTS

Correction requires control of closed orbit distortion, linear beam optics compensation and coupling control in order to approximately recover the performance of the ideal lattice.

### Orbit Control

The response matrix is used for the closed orbit correction. The goal of the orbit correction is to bring the RMS orbit to the level of misalignment errors while keeping the maximum corrector strength within acceptable level. There are totally 360 BPMs and 360 orbit correctors in our scheme. Every corrector corrects the horizontal and vertical orbits at the same time. Since we have utilized NSGA-II algorithm for optimizing the global correctors layout, the correction efficiency is improved that we can use all singular values in our correction without cutoff.

The correction result is listed in Table 2. After correction,

Table 2: Orbit Correction Results. 1000 random seeds are computed. Values are the mean value over 1000 error sets. Orbits at BPMs and all elements are counted separately.

Lattice	Elements	$x_{rms}$	$y_{rms}$	$x_{max}$	$y_{max}$
Before	BPM(mm)	1.7	5.1	6.7	14.8
	ALL(mm)	1.8	5.1	6.7	14.9
After	BPM( $\mu\text{m}$ )	5.9	15.3	22.5	43.9
	ALL( $\mu\text{m}$ )	14.7	18.9	120	82.0
	COR( $\mu\text{rad}$ )	115	83.0	581	336

statistic of the maximum closed orbit all over the ring is shown in Fig. 2, while result of the maximum corrector strength is shown in Fig. 3. It shows that the closed orbit distortion in two directions are both well controlled and the corrector strength are appropriate. The orbit correction scheme meets the requirements of orbit correction.

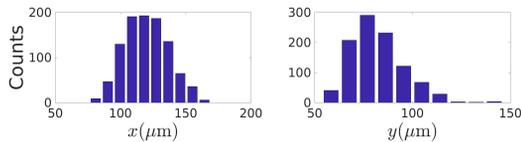


Figure 2: Statistic of maximum closed orbit.

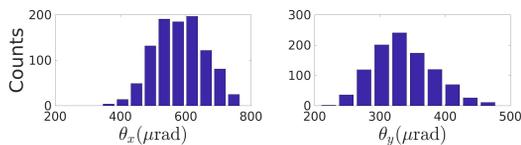


Figure 3: Statistic of maximum corrector strength.

### Optics Correction and Coupling Control

There are two ways to correct the linear beam optics and coupling. The first one is to deal with optics correction coupling correction together with vertical dispersion separately. The other way is to fit dispersion and off-diagonal response matrix terms as well. We adopt the latter one in our simulation. As a result, there are  $720 \times 721$  matrix elements in the fitting. A weighting factor of 5 to the vertical dispersion is applied in LOCO setup.

The correction is performed by fitting the response matrix with 540 normal quadrupoles and 240 skew quadrupoles. As seen in Fig. 1, the neighbouring quadrupoles are so close to each other that the coupling between the 780 fitting parameters is strong. Therefore, LOCO with constraints version is used in the correction and the minimization method used

to fit the data is the scaled Levenberg-Marquard [7]. The changes to the quadrupole settings applied to symmetrize the optics are calculated fitting the dispersions and the response matrix with a scaling constant lambda of 0.001 and the rejection threshold of singular values is  $10^{-4}$ , as used in [8].

The correction is repeated 3 times or more. Five iterations are performed every time. The final results are shown in Table 3. The fitting matrix elements and the parameters are very large in our case. It takes about one hour to perform a complete correction. Therefore, only 5 correction results are listed here.

Table 3: Linear Beam Optics Correction Result. The top rows are results of  $x$  direction and the bottom ones are results of  $y$  direction. Five seeds are listed here and they are labeled as “Error 1” to “Error 5” in the order from top to bottom in the following sections.

$\beta$ -beat(%)		$\eta$ -error(mm)		$\Delta\nu$	Coupling
MAX	RMS	MAX	RMS	( $\times 10^{-4}$ )	( $\times 10^{-2}$ )
4.0	0.62	1.6	0.42	1.7	0.70
4.0	0.53	1.0	0.24	0.20	
2.6	0.77	1.5	0.39	0.40	0.55
3.0	0.57	0.99	0.26	-1.9	
3.1	0.66	1.1	0.29	1.4	0.37
2.0	0.38	0.84	0.26	0.14	
3.2	0.70	1.4	0.31	-0.70	1.2
2.3	0.50	1.0	0.24	0.80	
3.8	0.68	1.2	0.25	-0.19	0.40
3.4	0.56	0.85	0.20	0.27	

A typical simultaneous  $\beta$ -beat and dispersion result is shown in Fig. 4. The corresponding relative change of quadrupole is shown in Fig. 5.

In summary, the  $\beta$ -beat and the dispersion error are typically corrected to less 1.0% rms and  $\sim 0.3$  mm rms. The tune change has a magnitude of  $10^{-4}$ . The variation of quadrupoles is within 2.0%. Therefore, we conclude that LOCO is applicable to HALS.

### Dynamical Aperture

Successful correction of closed orbit, optics and coupling should largely restore the dynamics of the ideal lattice. We then perform 6D dynamic tracking for the corrected lattice. The tracking point is at the midpoint of the long straight section which is the injection point. The aperture is shown in Fig. 6. The remain aperture is about 2 mm which is acceptable for HALS injection scheme.

This is a preprint — the final version is published with IOP

Content from this work may be used under the terms of the CC BY 3.0 licence (© 2019). Any distribution of this work must maintain attribution to the author(s), title of the work, publisher, and DOI

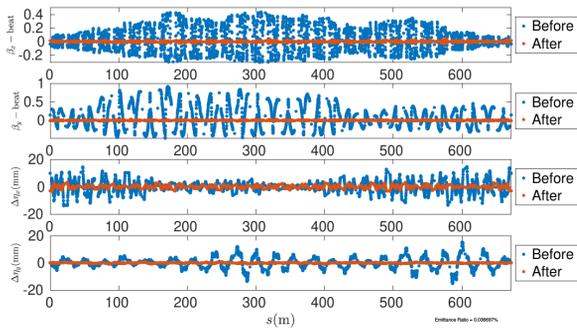


Figure 4: A typical correction result.

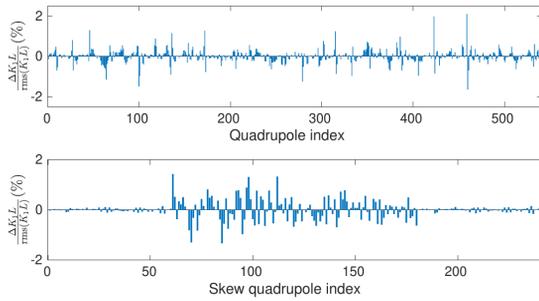


Figure 5: The change of quadrupole strength.

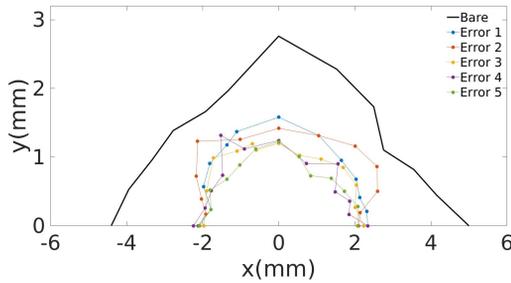


Figure 6: Dynamic aperture of the corrected lattice listed in Tab. 3.

## CONCLUSION

Up to now, we have assessed the effect of alignment errors and multipole errors for HALS. We have simulated the

orbit correction, the linear beam optics correction and the coupling control for the disturbed lattice. It is found that the closed orbit can be well controlled and the linear beam optics can restore to the ideal lattice under current error level. The dynamic aperture of the corrected lattice is sufficient for HALS injection scheme.

The next step is to take the calibration errors into consideration, e.g. BPM reading errors, BPM coupling errors, corrector strength fluctuation and corrector coupling. In addition, the nonlinear magnets can also be optimized to maximize the dynamic aperture for the corrected lattice.

## REFERENCES

- [1] Z. Bai *et al.*, “Study of Seven-Bend Achromat Lattices with Interleaved Dispersion Bumps for HALS”, presented at the 10th International Particle Accelerator Conf. (IPAC’19), Melbourne, Australia, May 2019, paper TUPGW040, this conference.
- [2] D. Xu *et al.*, “Corrector Layout Optimization Using NSGA-II for HALS”, in *Proc. 9th Int. Particle Accelerator Conf. (IPAC’18)*, Vancouver, Canada, Apr.-May 2018, pp. 4629–4631. doi:10.18429/JACoW-IPAC2018-THPMK135
- [3] Y. Chung, G. Decker, and K. Evans, “Closed Orbit Correction Using Singular Value Decomposition of the Response Matrix”, in *Proceedings of 5th Particle Accelerator Conf. (PAC’93)*, Washington, DC, USA, May 1993, pp. 2263-2265. doi:10.1109/PAC.1993.309289
- [4] J. Safranek, “Experimental Determination of Storage Ring Optics Using Orbit Response Measurements”, in *Nuclear Instruments and Methods in Physics Research Section A*, 388(1997), pp. 27-36.
- [5] M. Borland, “elegant: A Flexible SDDS-Compliant Code for Accelerator Simulation”, Advanced Photon Source LS-287, September 2000.
- [6] J. Bengtsson, and A. Streun, “Robust Design Strategy for SLS-2”, SLS2-BJ84-001, PSI, June 2017.
- [7] X. Huang, J. Safranek, and G. Portmann, “LOCO with Constraints and Improved Fitting Technique”, *ICFA Beam Dyn. Newsletter*, 44: 60-69, 2007 44. SLAC-PUB-13686, 2009.
- [8] G. Benedetti *et al.*, “LOCO in the ALBA Storage Ring”, in *Proceedings of IPAC2011*, San Sebastián, Spain, 2011, pp. 2055-2057.