ANALYSIS AND COMPENSATION OF THE INSERTION DEVICE EFFECTS IN THE HALF STORAGE RING*

Gangwen Liu, Penghui Yang†, Zhouyu Zhao††, Zhenghe Bai
National Synchrotron Radiation Laboratory,
University of Science and Technology of China, Hefei, Anhui 230029, China

Abstract

The Hefei Advanced Light Facility (HALF) is a diffraction-limited storage ring light source with a beam energy of 2.2 GeV. Thirteen insertion devices (IDs) will be installed in the storage ring, which will have a substantial impact on the low-energy beam. Particularly for the long-period EPU, the nonlinear effects significantly reduce the dynamic aperture of the storage ring. In this paper, the effects of the IDs are analyzed in detail with kick-map models for the HALF storage ring. Each ID is compensated using a local quadrupole feedforward method. For some EPUs with significant impacts, additional compensation is provided through the shimming of current strips. The analysis and compensation results will be presented in this paper.

INTRODUCTION

The Hefei Advanced Light Facility (HALF) [1], a new VUV and soft X-ray diffraction-limited storage ring-based light source, is currently under construction and is expected to be in operation in 2028. The design aims to achieve a natural emittance below 100 pm·rad at an electron beam energy of 2.2 GeV with 20 long straight section and 20 short straight section available for installing insertion devices. In the first construction phase, 13 insertion devices will be installed for 10 beam lines, including 2 wigglers for beam damping. The parameters of these IDs are listed in Table 1. These IDs will introduce additional focusing effects that alter the linear optics parameters such as betatron tune and beta functions, and their field errors and misalignments can distort the closed orbit. Moreover, their nonlinear magnetic fields can reduce the dynamic aperture, impacting beam injection efficiency and lifetime [2]. These effects caused by insertion devices must be compensated to ensure the stable operation of the storage ring.

Local compensation using pairs of quadrupoles placed adjacent to an insertion device is an effective method to locally correct the induced linear optics distortions without affecting the rest of the storage ring. Nevertheless, this method still has difficulty dealing with the higher-order nonlinear effects induced by these insertion devices. As a widely and maturely applied method, current strip shimming has the ability to correct higher-order nonlinear effects by compensating the field integrals and multipole errors with current-carrying strips placed near the magnetic poles [3, 4].

Table 1: Main Parameters of the Insertion Devices in the HALF Storage Ring

ID	Period /mm	Period number	Min. Gap/mm	Max. K
IVU21	20.7	54	6	2.1
IVU21	20.7	182	6	2.1
LPU38	38.2	108	12	3.39
LPU38	38.2	108	12	3.39
Wiggler	100	41	12	16
EPU42	41.5	99	14	2.65
EPU44	43.5	33*2	14	2.94
EPU46	46	90	14	3.24
EPU63	63	65	14	5.65
HU115	115	35	14	8.89
EPU120	120	33	20	11.26

KICK-MAP THEORY

Kick-map theory is a powerful analytical framework to model the integrated effects of insertion devices on the dynamics of charged particle beams. The kick-map approach condenses the net effect into a set of transverse momentum kicks imparted to the beam as a function of its initial position and angle. The kicks are derived from the integrated magnetic field, which can be expressed using the following formula [5]:

$$\frac{dx}{ds}(\infty)=-\frac{1}{2}\left(\frac{e}{\gamma mc}\right)^2\frac{\partial\Psi}{\partial x}\quad \frac{dy}{ds}(\infty)=-\frac{1}{2}\left(\frac{e}{\gamma mc}\right)^2\frac{\partial\Psi}{\partial y}\tag{1}$$

$$\Psi(x,y,s)=\int_{-\infty}^{\infty}[(\int_{-\infty}^{s}B_x(x,y,s)ds)^2+(\int_{-\infty}^{s}B_y(x,y,s)ds)^2]ds\tag{2}$$

Where Bx, By are the magnetic field components along the insertion device. By performing Fourier transform on the magnetic field and applying a first-order approximation due to $B_{x,1}\gg B_{x,n}$ and $B_{y,1}\gg B_{y,n}$, Eq. (1) can be simplified to the following equation.

$$\frac{dx}{ds}(\infty)=-\left(\frac{e}{\gamma mc}\right)^2\frac{N\lambda_0^3}{16\pi^2}\frac{\partial(B_{x,1}^2+B_{y,1}^2)}{\partial x}\tag{3}$$

$$\frac{dy}{ds}(\infty)=-\left(\frac{e}{\gamma mc}\right)^2\frac{N\lambda_0^3}{16\pi^2}\frac{\partial(B_{x,1}^2+B_{y,1}^2)}{\partial y}\tag{4}$$

Where λ_0 is the period length of the insertion device, N is the period number, $B_{x,1}$and $B_{y,1}$.are the first-order terms

* This work was supported by the Fundamental Research Funds for the Central Universities (No. WK2310000107) and the National Natural Science Foundation of China (No.12205299).

† penghui1@ustc.edu.cn
†† yuzz@ustc.edu.cn

in the Fourier expansion of the longitudinal periodic magnetic field of an ID. From the Eq. (3) and Eq. (4), it can be seen that the dynamic integrated field effect of the insertion device is inversely proportional to the square of the electron energy, and proportional to the cube of the insertion device period length. With a beam energy of only 2.2 GeV and the use of several long-period EPUs, the influence of insertion devices on the HALF storage ring is particularly significant.

COMPENSATION METHOD

EPU120 is the insertion device that exerts the strongest influence on the storage ring, having the longest period length of 120 mm. In particular, its vertical polarization mode (EPU120V) exhibits a very strong nonlinear integrated field effect, which significantly affects both the linear and nonlinear characteristics of the storage ring. Incorporating the kick-map model of EPU120V into the HALF storage ring for simulation reveals that the horizontal and vertical beta-beatings reach 81.8% and 13.3%, respectively, while the dynamic aperture in both planes are reduced to only 2.4 mm and 2.5 mm.

To achieve local compensation for EPU120V, 14 current strips are installed on both the upper and lower sides of its vacuum chamber. The magnetic fields generated by these current strips can cancel the higher-order nonlinear magnetic fields produced by EPU120V, effectively reducing the kicks in the both planes. In this paper, the horizontal kick-map (y=0) is taken as the optimization objective, the kicks can be reduced to a low level by adjusting the intensities of the 14 current strips independently. The optimization results are shown in Fig. 1 and Fig. 2. The red line represents the kick angles before shimming with current strips and the blue line shows the kick angles after shimming.

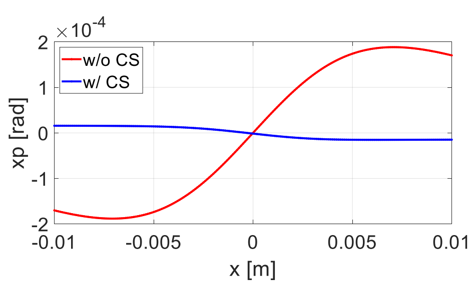

Figure 1: Horizontal kick angles (y = 0).

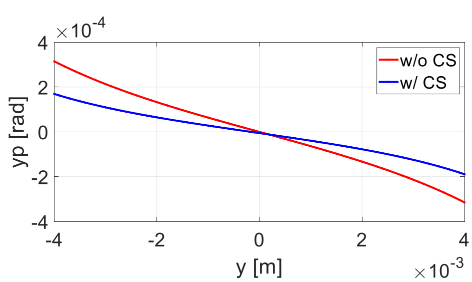

Figure 2: Vertical kick angles (x=0).

After shimming with the current strips, the beta-beatings are reduced to 3.9% and 7.8% in the horizontal and vertical directions respectively. However, these values remain too high for stable storage ring operation. By further compensating with the six quadrupoles on both sides of EPU120V, the beta-beating can be reduced to less than 1%. Since four of the six quadrupole pairs are located in the arcs, changes in their strengths will cause variations in the dispersion function. Therefore, the dispersion function must be compensated simultaneously. After compensation, the maximum dispersion deviation is less than 0.25 mm. The compensation outcomes are depicted in Fig. 3, Fig. 4 and Fig.5. The red line shows the beta-beating without compensation. The blue line shows the beta-beating after compensation with current strips and the green line shows the beta-beating after compensation with current strips and quadrupoles.

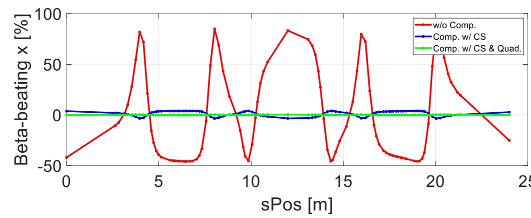

Figure 3: Horizontal beta-beatings before and after compensation.

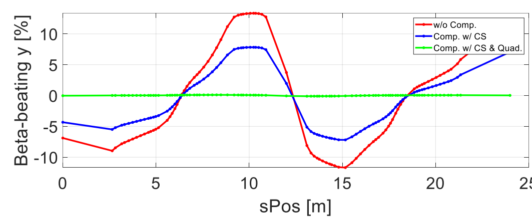

Figure 4: Vertical beta-beatings before and after compensation.

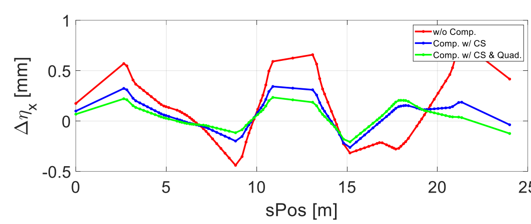

Figure 5: Dispersion deviations before and after compensation.

The horizontal dynamic aperture increases to about 7.1 mm after shimming with current strips, which is shown in Fig. 6. When using quadrupoles to further compensate the linear optics parameters, there is a relatively small impact on the dynamic aperture.

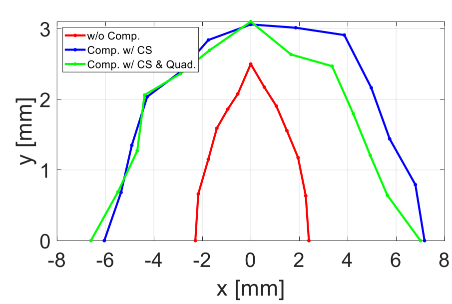

Figure 6: Dynamic apertures before and after compensation.

COMPENSATION RESULTS FOR ALL INSERTION DEVICES

All of the IDs are well compensated locally with the methods mentioned above. These IDs with significant nonlinear effect, including EPU120, HU115, EPU63 and EPU46, require additional compensation via current strip shimming. The other IDs only need compensation using quadrupoles. After compensating each insertion device and incorporating all of them into the HALF storage ring, some of the parameters of the storage ring have changed significantly, which are listed in Table 2. All IDs are in the minimum gap condition, and all EPUs are operated in the vertical polarization mode. Natural emittance decreases by 29.6%, energy loss per turn increases by 88.7%. The transverse tunes are well corrected. The final linear optics after compensation are shown in the Fig. 7 and Fig. 8. Except for some beta-beating remaining at the straight sections with insertion devices installed, the beta-beating in the arcs is less than 1%. Similarly, the dispersion deviation is mainly located in the straight sections and is less than 1 mm, which does not significantly affect the light source performance.

Table 2: Parameters of the HALF Storage Ring Before and After Compensation for All IDs

Parameter	Bare Lattice	Lattice w/ IDs
Emittance [pm rad]	85.9381	60.4765
Tune (x/y)	48.1511 /17.1511	48.1517 /17.1516
Energy lose in one turn [keV]	181.4153	342.3238
Energy spread	6.0734e-4	6.7500e-4
Momentum compaction factor	9.4101e-5	9.4348e-5
Damping time (x/y/z) (ms)	28.50/38.82 /23.70	17.34/20.43 /11.25

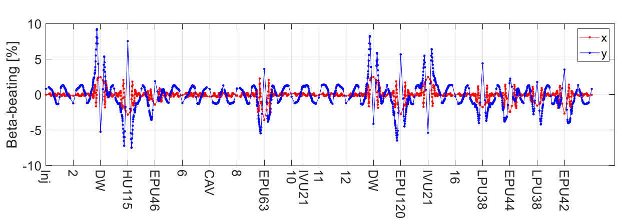

Figure 7: The horizontal and vertical beta-beatings after compensation for all IDs.

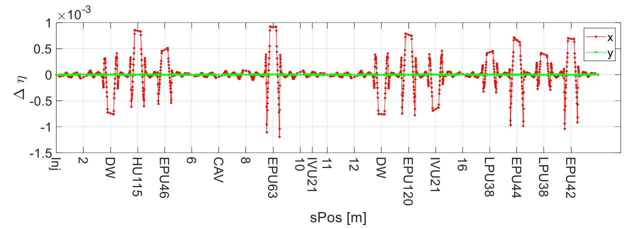

Figure 8: The horizontal and vertical dispersion function deviation after compensation for all IDs.

The dynamic aperture was investigated through detailed tracking simulations, as illustrated in Fig. 9. The black line represents the 6D dynamic aperture without considering IDs or errors, while the red line corresponds to the dynamic aperture considering IDs but no errors. The blue × markers indicate the dynamic aperture under different error seeds, and the green line shows the dynamic aperture with both IDs and errors included. All ID effects are well compensated, and each set of storage ring errors is corrected. The simulation results demonstrate that under the combined influence of insertion devices and errors, the dynamic aperture of the HALF storage ring exceeds 6 mm, providing sufficient acceptance for off-axis beam injection.

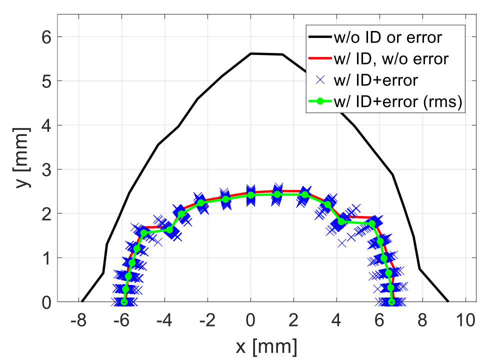

Figure 9: Dynamic apertures with different conditions.

SUMMARY AND OUTLOOK

As a low-energy storage ring light source, HALF is equipped with a large number of insertion devices, including several long-period EPUs. These IDs significantly impact both the linear and nonlinear optics of the storage ring. To mitigate these effects, two local compensation strategies are adopted. Quadrupole feed-forward compensation is primarily employed to correct linear optics distortions introduced by all IDs, while current strip shimming is used to compensate for IDs with pronounced higher-order nonlinear fields. A kick-map model serves as the theoretical framework for the IDs. Using EPU120V as an example, the compensation process for IDs is briefly described. After compensating all IDs, the resulting changes in the main linear and nonlinear optics parameters of the HALF storage ring are presented. The beta-beating is controlled to within 1%, and the horizontal dynamic aperture is more then 6 mm. These IDs are currently under manufacture and are being delivered successively. Magnetic field measurement and correction, along with compensation based on measured field data, will be carried out in the next stage.

REFERENCES

[1] Z. H. Bai *et al.*, "Progress on the Storage Ring Physics Design of Hefei Advanced Light Facility (HALF)", in *Proc. 14th Int. Particle Accelerator Conf. (IPAC'23)*, Venice, Italy, May 2023, pp. 1075-1078.
doi:10.18429/JACoW-IPAC2023-MOPM038

[2] B. Singh *et al.*, "Impact of insertion devices on Diamond-II lattice," in *Proc. 13th Int. Particle Accelerator Conf. (IPAC'22)*, Bangkok, Thailand, Jun. 2022, pp. 539–541.
doi:10.18429/JACoW-IPAC2022-MOPOTK037

[3] J. Bahrdt *et al.*, "Active Shimming of the Dynamic Multipoles of the BESSY UE112 Apple Undulator", in *Proc. 11th European Particle Accelerator Conf. (EPAC'08)*, Genoa, Italy, June 2008, pp. 2222-2224.

[4] B. Singh *et al.*, "Active Shimming of Dynamic Multipoles of an APPLE II Undulator in the Diamond Storage Ring," in *Proc. 4th Int. Particle Accelerator Conf. (IPAC'13)*, Shanghai, China, May 2013, pp. 1997–1999.

[5] P. Elleaume, "A New Approach to the Electron Beam Dynamics in Undulators and Wigglers," in *Proc. 3rd European Particle Accelerator Conf. (EPAC'92)*, Berlin, Germany, Mar. 2008, pp. 661-663.