Correction of integrated multipoles of five IDs in SSRF

LU Jie[1, 2] ZHOU Qiaogen[1,*] WANG Hongfei[1] ZHANG Wei[1, 2]

[1]*Shanghai Institute of Applied Physics, Chinese Academy of Sciences, Shanghai 201800, China*

[2]*Graduate University of Chinese Academy of Science, Beijing 100049, China*

Abstract Five of the seven Phase I beamlines of Shanghai Synchrotron Radiation Facility (SSRF) are based on insertion devices (IDs), which include two wigglers, one elliptically polarized undulator (EPU), and two in-vacuum undulators. There were some inevitable field integral errors in manufacturing the IDs, and these would affect performance of the storage ring. The integrated multipoles were corrected by using the magic fingers technique. In this paper, we report the correction method based on the simulated-annealing algorithm. The results show that the integrated multipole components were corrected to meet the design specifications.

Key words Insertion devices, Magic Fingers, Integrated multipole components

1 Introduction

Insertion devices (IDs) are the important parts of a third-generation light source, such as the Shanghai Synchrotron Radiation Facility (SSRF). Among the seven Phase I beamlines of SSRF, five are based on IDs, which include two wigglers for X-ray absorption fine structure (XAFS) and X-ray imaging (XI), one elliptically polarized undulator (EPU) for scanning transmission X-ray microscopy (STXM), and two in-vacuums undulators for macromolecular crystal-ography (MC) and hard X-ray microfocus (HXM).

The IDs installed in the storage ring produce several effects that can degrade the overall performance, because the manufactured magnets to form the IDs fields cannot be perfect, and many other factors will cause errors of the magnetic field, too[1]. Therefore, magnetic field corrections are necessary before installation. In general, two kinds of field corrections can be used, i.e. spectral correction for restoring spectral intensity of radiation, and integrated multipole correction for reducing field error of the integrated multipole components.

At SSRF, this was done with the integrated multipole correction method using the magic fingers technique[2,3]. The magic fingers are arrangement of magnets for reducing the integrated magnetic field errors in ID. This idea is to use transverse arrays of permanent cylindrical magnets above and below the midplane, so as to correct both normal and skew longitudinal magnetic field integral errors in a device. Special holders in which cylindrical magnets can be inserted and fixed are attached to both ends of the magnet arrays on the ID. The cylindrical magnet arrangement is determined by using the simulated-annealing algorithm[4]. The measurement results show that the integrated multipoles of IDs can successfully be corrected by the magic fingers.

2 Magnetic field errors in an ID

In an ideal ID, both the first and the second field integrals are zero. In constructing the IDs, however, many factors should cause the first and the second field integrals distribution $I_{x,y}(x)$ and $II_{x,y}(x)$, such as the inhomogeneous magnetizations, position errors of installed magnets and poles, the mechanical deformations and so on [5]. The 1st and 2nd field integrals are defined as follows,.

$$I_{x,y}(x) = \int_{-\infty}^{\infty} B_{x,y}(x,y,z)\,\mathrm{d}z \qquad (1)$$

* Corresponding author. *E-mail address:* zhouqiaogen@sinap.ac.cn

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$$
\begin{aligned}
II_{x,y}(x) &= \int_{-\infty}^{\infty} I_{x,y}(x)\,\mathrm{d}z \\
&= \int_{-\infty}^{\infty}\left(\int_{-\infty}^{z} B_{x,y}(x,y,z')\,\mathrm{d}z'\right)\mathrm{d}z
\end{aligned} \tag{2}
$$

$$I_x(x) = \sum_n A_n x^{n-1} \tag{3}$$

$$I_y(x) = \sum_n B_n x^{n-1} \tag{4}$$

where $B_{x,y}(x,y,z)$ is the horizontal and vertical magnetic flux density in the IDs.

The integrated multipole components are measured within a range of the transverse distance on the midplane. They are derived from the polynomial least-squares fit of the first integral distribution along the transverse horizontal axis using Eqs.(3), and (4), the measured transverse distance of the five IDs in SSRF is 20 mm (x = ±10 mm). Where A_n is the skew multipole components, and B_n is the normal multipole components, which can be differentiated into various numbers and called as the dipole, quadrupole, sextupole, octupole, and so on.

The uncorrected integrated multipoles for the IDs should seriously affect the storage ring. For example, when the storage ring operates, the quadrupole induces the tune shift, and the coupling increases. The sextupole and octupole make the dynamic aperture and life time degraded [6]. The specifications of the integrated multipoles correspond to the different IDs are listed in Table 1.

Table 1 Specifications of the normal/skew multipoles for the integrated fields of the IDs.

Magnets	Beamlines	Gap / mm	Magnet structure	Quadrupole /10^{-4} T	Sextupole /10^{-2} T·m^{-1}	Octupole /T·m^{-2}
W80	XAFS	14–140	Hybrid, asymmetric	≤50	≤100	≤100
W140	XI	14–140				
EPU100	STXM	33–100	APPLE–II, symmetric	≤100	≤200	≤300
IVU25-1,2	HXM, MC	7–100	Hybrid, asymmetric	≤50	≤60	≤100

3 Magic fingers technique

3.1 Magic fingers computation model

By using the magic fingers technique, we can find a best arrangement of the small cylindrical magnets to correct the integrated multipole components at different magnetic gaps and different polarization modes. This method is to reduce the first field integral distribution for correcting the integrated multipole components.

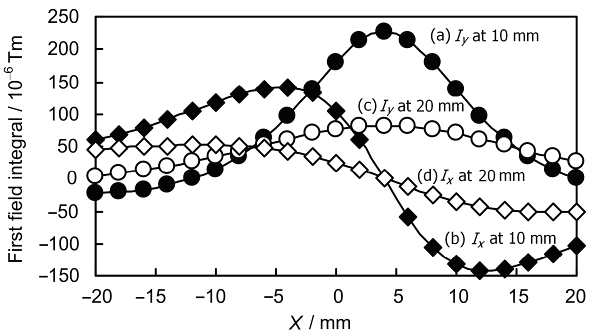


Fig.1 The 1st field integrals at 10 and 20 mm vertical positions.

Given that a cylindrical magnet model has a purely axial magnetization, and the magnet is positioned on the different heights of x-axis, its first field integrals can be analytically computed. The cylindrical magnet is of Φ5 mm×15 mm, its remnant magnetic field is 1.24 T, and the magnetization vector points locates in the direction of positive y-axis. As shown in Fig.1, the curves I_y (a) and I_x (b) are the normal and skew first field integrals distribution at 10 mm, and I_y (c) and I_x(d) are the first field integrals at 20 mm.

Considering the magnetic field shapes, it can be found that the transverse separations between the magnets should be minimized, because their combination should produce a sufficiently smooth first field integral profile. Assuming the permanent magnets are nearly unit permeability, the resultant magnetic field profiles can be generated by the linear superposition of the fields generated by the individual magnets. In fact, the situation dealing with the first field errors of real IDs is very sophisticated. Particularly, the correction made by the magnets should be effective in a range of different gaps and polarization modes.

3.2 Optimization of field integral errors

Before the correction, the 1st and 2nd field integral errors are divided into the two ends of magic fingers holders[7] as the Eqs.(5) and (6),

$$I_{\text{in-}x,y}(x_k) = \left[II_{x,y}(x_k) - I_{x,y}(x_k)L_{\text{out}} \right] / L_u \quad (5)$$

$$I_{\text{out-}x,y}(x_k) = I_{x,y}(x_k) - I_{\text{in-}x,y}(x_k) \quad (6)$$

where $I_{\text{in-}x,y}(x_k)$ and $I_{\text{out-}x,y}(x_k)$ represent the 1st field integral errors at the entrance and exit of the IDs, L_u is the ID length, and L_{out} is the distance from the exit to the flipping coil end. The cost functions for reducing the field integral distributions are described by Eqs. (7), (8), and (9).

$$F_{\text{normal}} = \sum_j w_j \sum_k \left[\sum_i f_{ij}(x_k) + F_j(x_k) \right]^2 \quad (7)$$

$$F_{\text{skew}} = \sum_j w_j \sum_k \left[\sum_i g_{ij}(x_k) + G_j(x_k) \right]^2 \quad (8)$$

$$F = F_{\text{normal}} + F_{\text{skew}} \quad (9)$$

where i is a cylindrical magnet in the magic fingers holder, j is a gap or polarization mode, k is the number of points measured by the flipping coil system along the x-axis[2], $F_j(x_k)$ and $G_j(x_k)$ are the normal and skew first filed integrals distribution, $f_{ij}(x_k)$, $g_{ij}(x_k)$ are the normal and skew first field integrals distribution generated by the magnets, and w_j is the optimized weight coefficient. In the simulation, the dipole components can be neglected because the trim coils located upstream and downstream can easily correct them.

To correct a given random first field integral errors, a procedure must be established to predict the effect of any specified arrangements of the magnets. An arrangement contains the magnet positions in the holders and the magnetization vectors. It is an inverse problem of finding the best arrangement that corrects the errors, and a solution space, over which the cost function must be minimized, is a discrete and very lager configuration space. In this case, the simulated-annealing algorithm is applicably.

Fig.2 is the logic diagram of the simulated-annealing optimization process used in the simulation. By the procedure, the optimal solution can be obtained in a relatively short period of time. Here, ΔF is a variation of the cost function caused by this cycle procedure, T is temperature, and α is cooling factor. Eq.(10) is the probability function, which means the probability of accepting the ΔF for a new solution in the optimization. In order to specify the optimizations of different IDs, we adjusted the w_j and simulated annealing control parameters T and α to get the optimal solution.

$$p = \begin{cases} 1, & \Delta F < 0 \\ \exp(-\Delta F / T), & \Delta F \geq 0 \end{cases} \quad (10)$$

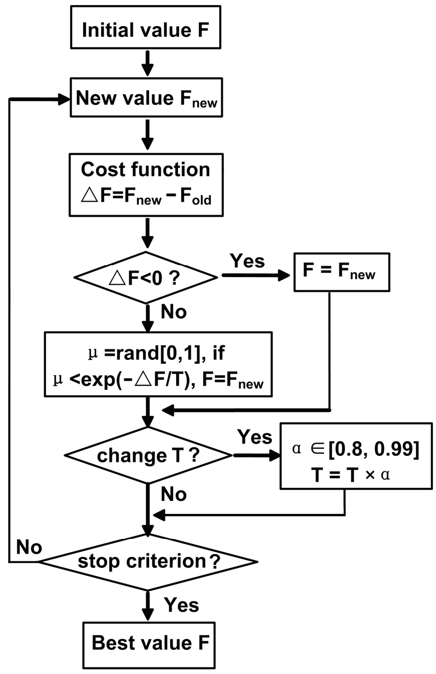
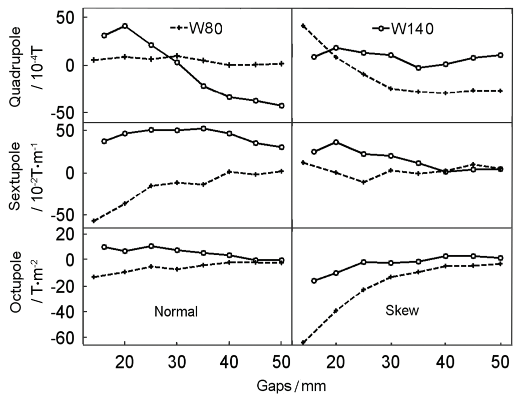


Fig.2 The logic diagram of simulated-annealing optimization procedure.

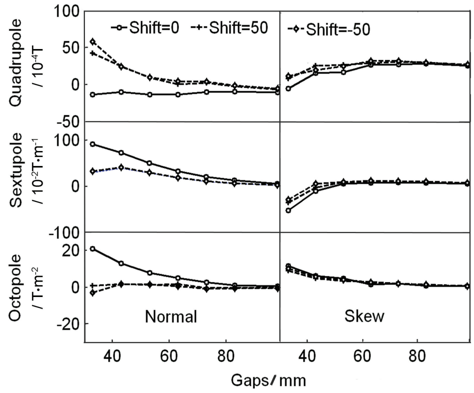
4 Optimized results of the five IDs

In the design of the magic fingers holders, a double row of holes are used to increase the effective density of magnets in the available space. Each ID has four magic fingers holders at ends, Especially, In view of the structure of APPLE-II type EPU100[8], eight magic fingers holders of the same type are mounted on the four longitudinal magnet arrays ends, respectively.

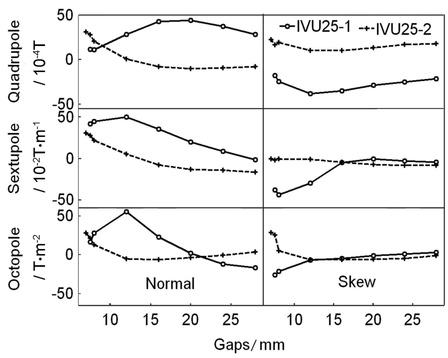
The corrected field integrated multipole components' performances of the IDs at various gaps are shown in Fig.3. The final achieved components are summarized in Table 2. Comparing the data with the integrated multipole tolerance specifications in Table 1, one finds that the integrated multipole components of the IDs are corrected to meet the design requirements.



(a)



(b)



(c)

Fig. 3 Gap *vs* integrated multipole components of (a) W80 and W140, (b) EPU100, and (c) IVU25-1, 2.

Table 2 Field integrated multipole components achieved on the normal/skew magnets of the IDs.

Magnets	Quadrupole /10^{-4} T	Sextupole /10^{-2} T·m^{-1}	Octupole /T·m^{-2}
W80	<42	<60	<65
W140	<45	<55	<16
EPU100	<80	<120	<30
IVU25-1	<44	<50	<55
IVU25-2	<25	<50	<8

5 Conclusion

In this paper, we discussed the correction of field integrated multipoles using the magic fingers technique, which was a convenient and effective method suitable for different types of IDs. The results showed that the normal and skew integrated multipole errors can be effectively corrected by this technique over all operating gaps and polarization modes. The parameters of the five IDs were in agreement with the design specifications. Now the five IDs have been successfully used in the storage ring of SSRF, and operated smoothly.

References

1 Tanaka T, Kitamura H. Rev Sci Instrum, 2000, **71**: 3010–3014.

2 Hoyer E, Marks S, Pipersky P, *et al.* Rev Sci Instrum**,** 1995, **66**:1901–1903.

3 Diviacco B, Bracco R, Knapic C, *et al.* Trim Magnets for Field Integral Correction of APPLE Type Undulators, Sincrotrone Trieste Technical Note ST/SL–04/01, April 2004

4 Kang L S, Xie Y, You S Y, *et al*. Simulated annealing algorithm. Beijing: Science Press, 1998.

5 Wang H F, Lu J, Zhou Q G, *et al.* HPLPB, 2008, **20**: 871–875.

6 Tanaka T, Seike T, Kitamura H. Nucl Instrum Meth Phys Res, 2001, **A465**: 600–605.

7 Lu J, Zhou Q G, Wang H F. HPLPB, 2009, **21**: 1597–1600.

8 Zhou Q G, Zhang M, Li Y, *et al*. An Apple–II Type Helical Undulator for SSRF. APAC2007, 714–716.