Optimal sorting method and application to SSRF booster dipoles*

ZHANG Man-Zhou(张满洲)[1,2;1)] HOU Jie(后接)[1,2] LI Hao-Hu(李浩虎)[1]
LIU Gui-Min(刘桂民)[1] LI De-Ming(李德明)[1;2)]

1 (Shanghai Institute of Applied Physics, CAS, Shanghai 201800, China)
2 (Graduate University of Chinese Academy of Sciences, Beijing 100049, China)

Abstract As the dipoles of SSRF booster are powered in series, the magnet field error varies from magnet to magnet and results in bad beam quality. Sorting and installing magnets according to the measured field errors so that the errors on different magnets are partially compensated with each other, has been the easiest way in many cases to reduce the detrimental effects of the errors without introducing complications. Based on the magnet field measurement results, we investigated and implemented the sorting of dipoles using a method mixed by local cancellation and simulated annealing, and it's found to be quite effective.

Key words sorting, local cancellation, simulated annealing, mix method, SSRF booster

PACS 41.60.Ap, 41.75.Ht, 41.85.Lc

1 Introduction

The SSRF booster[1] is a two-fold symmetry structure with FODO bending arcs, including 28 cells and 48 dipoles. Windings of all dipoles are powered by the same two power supplies in series. The unavoidable field-shape imperfections due to iron saturation, persistent currents, design imperfections, coil deformations and mechanical tolerances can't be reduced easily. The Dipole errors have a detrimental effect on the distortion of the particle orbits.

Generally speaking, a sound design of the machine layout with well focused orbit functions and a suited set of correctors may be helpful in improving the beam distortion. But in our case, the correctors are powered by small DC current which can afford the effective correction only at low energy. However, the Closed Orbit Distortion (COD) may strongly depend on the specific distribution of the errors along the machine azimuth. In such case, the sorting strategies can be applied to provide the mutual compensation of the residual errors. All the SSRF booster magnets are measured carefully before sorting, with the dipoles magnetic field uniformity being within $\pm1\times10^{-3}$. Our sorting process is based on these real errors.

2 Sorting strategies

The difficulty to achieve such an effective compensation of the errors is to find an optimized magnet configuration which can significantly increase the stability domain of beams, since even for a small number of magnets, the total number of possible magnet arrangements is exceedingly large. For magnet number n, all possible permutations are growing with $N=(n-1)!/2$. In SSRF booster $n=48$, N is an astronomical number. Checking all possible cases would cost lots of time, so we try an effective method to get a better arrangement, but it should not be the best one. A sorting method, based on local cancellation[2] and simulated annealing[3], which minimizes the beam distortion is then applied. Another sorting scheme using Local-cancellation-like method is taken by Doc. Hou Jie at the same time[4].

Received 25 January 2008
* Supported by SSRF Project
1) E-mail: zhangmanzhou@sinap.ac.cn
2) E-mail: lideming@sinap.ac.cn

2.1 The cost function[5]

A cost function $W=\sqrt{A^2+B^2}$ was used to compare different permutations of the given error set, here the components (A,B) are constructed for each type of magnet differently. The kick strength k_i is defined as the difference between the measured and designed dipole bending angle: $k_i=\theta_i-\theta_0$. The closed orbit described by the vector $\boldsymbol{x}_{\rm jco}=(x_j,x'_j)$ at any position is kicked by this error and oscillates in a closed loop around the ring. And it is related by the one turn transfer matrix of the ring. The amplitude of the closed orbit is given by

$$x_j=\frac{k_i\sqrt{\beta_j\beta_i}\cos(\pi\nu-|\Delta\psi_{ij}|)}{2\sin(\pi\nu)}, \tag{1}$$

where β_j and β_i are the beta functions at the observation point and the kick position, ν is the tune of the ring and $\Delta\psi_{ij}$ is the phase advance between the kick position and the observation point. Several kicks at different locations are added by superposition to get the resulting closed orbit (x_j,x'_j) at any position. The vector $\boldsymbol{W}_j(A_j,B_j)$ is then constructed by using the local Twiss parameters

$$A_j=(\alpha_jx_j+\beta_jx'_j)/\sqrt{\beta_j}, \tag{2}$$

$$B_j=x_j/\sqrt{\beta_j}. \tag{3}$$

For a fixed error distribution, $\boldsymbol{W}_j$ changes around the ring. The individual values $\boldsymbol{W}_j$ are summed up by an rms averaging to a single number w, this is the value of the cost function of a specific error distribution. And $\boldsymbol{W}_j$ is the Courant-Snyder invariant of COD. Compared with COD, minimizing this type of cost function not only leads to small amplitudes but also to small slopes of the closed orbit dispersion.

2.2 Sorting method

The sorting strategy is, to permute the errors and to minimize the cost function. The difficulty is how to get a new error distribution. We choose two methods which are introduced in follow sectors.

2.2.1 Local cancellation

Local cancellation proposed for the sorting is based on the local or quasi-local cancellation of the errors by pairing the magnets and placing each element of a pair along the azimuth of the accelerator separated by an opportune phase advance.

(1) Pairing at zero or 360 degree: Considering that two adjacent dipoles have close values of the optical functions and almost the same betatron phase, one can obtain a local compensation scheme by placing in adjacent positions two errors equal in strength but with opposite signs.

(2) Pairing at 180 degrees: Equal errors with the same sign cancel at 180 degrees, assuming that the motion is quasi-linear between the two locations.

In the SSRF booster cell the average phase advance between two dipoles is approximately 58 degrees, the second one is more effective.

2.2.2 Simulation annealing

The method of simulated annealing is a typically mathematic method[6]. Through it, we can obtain a new error sequence easily and astringently. The new permutation is obtained from the previous one by some few well defined steps. For a given error vector $\boldsymbol{\delta}_0$ (cost function is w_0): first, a sequence of elements are randomly chosen by the start and end elements in the given error vector. Second, this string is moved to a randomly chosen position inside the new error vector, and the other errors fill the other positions orderly. With this new error vector, a new value of the cost function w is calculated. If $\Delta w=w-w_0<0$, it is taken as a new reference $\boldsymbol{\delta}_0$. In case the new cost function is larger and satisfies the function $e^{-\Delta w/T}>\chi$ (χ is a randomly chosen threshold, here T serves as a temperature like parameter, which is lowered with increasing the number of permutations), this distribution will also be taken as the new reference.

In this way one scans the values of the cost functions in the vicinity of the present reference point but avoids being trapped in a local minimum. As a comparison, the same algorithm is used to find the worst case yielding a large cost function. The difference between the worst and best solution is a measure of the gain which is achievable with the sorting.

2.3 Sorting procedure

We mix the two sorting methods in our procedure, and there are 3 steps:

(1) Pairing out of range dipoles magnets.

(2) Placing two dipoles of equal errors 180° apart in phase for cancellation or placing two dipoles with opposite errors 360° apart in phase for cancellation.

(3) Sorting all the dipole pairs using the simulation annealing method.

The whole procedure is generated by the standard code AT[7] based on MATLAB.

3 Results

The SSRF booster dipoles are first installed on girders and prealigned. There are 4 types of girders, shown in Table 1.

The 6 dipoles (B1900-12, -34, -40, -41, -9, -19) are pre-restricted on the 1st, 20th, 23rd, 24th, 25th and 48th dipole location in the ring due to the limitations of injection and vacuum chamber. Dipoles can only be exchanged between the same types of girder.

Table 1. Booster girder type and magnets installed.

girder type	girder position	magnets installed	dipoles No.
A	1st, 3rd quadrant	QF+SF+B	14(2)*
B	1st, 3rd quadrant	QD+SD+B	10
C	2nd, 4th quadrant	B+SF+QF	14(3)
D	2nd, 4th quadrant	B+SD+QD	10(1)

∗ No. inside the bracket indicates the No. of restricted dipoles.

3.1 Dipoles measurement and data processing

All dipoles are measured from 10 A to 980 A by 10 A for a step, and B1900-24 is selected as the reference dipole during the measurement. The integral field strength (BL for sort, L is dipole length) of each dipole is given by the ratio compared with the reference dipole; both of them are measured in the same current and other condition such as temperature. For each dipole, integral field error can be written as

$$BL_{\text{error}} = (BL - BL_{24})/BL_{24}, \tag{4}$$

Then it should be changed to

$$BL_{\text{error}} = (BL - BL_{\text{av}})/BL_{\text{av}}. \tag{5}$$

Several dipole magnetic field uniformity errors are shown in Fig. 1. In the SSRF booster sorting, both of the conditions at injection (150 MeV) and extraction energy (3.5 GeV) should be considered carefully. The corresponding power supply currents are about 40 A and 1045 A. But the power supply we used in measurement can't reach so high. Fortunately, the magnetic field error is nearly constant for each dipole above 300 A, so we choose the errors at 980 A instead.

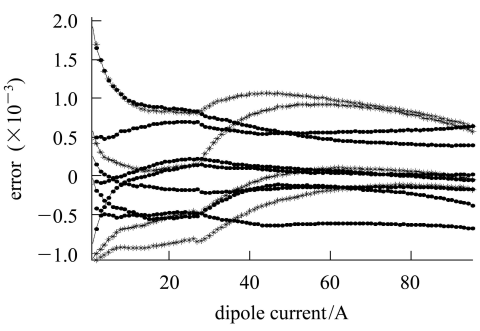

Fig. 1. Errors at different currents.

The measured magnetic field uniformity errors of all dipoles at 40 A and 980 A are shown in Fig. 2, the rms value is 1.2×10^{-3} and 6×10^{-4} at each current, while the average value of them is 1.8×10^{-7} and -3.6×10^{-7} at 40 A and 980 A.

3.2 Measurement error

Repetitive measurements are made twice for each dipole. We adopt the difference of the two repeated measurements as the approximate measurement resolution of magnetic field uniformity. The error between these two measurements is about 5×10^{-5} at 980 A, but at 40 A it is much larger due to remanence. The measurement errors of each dipole at injection and extraction energy are shown in Fig. 2.

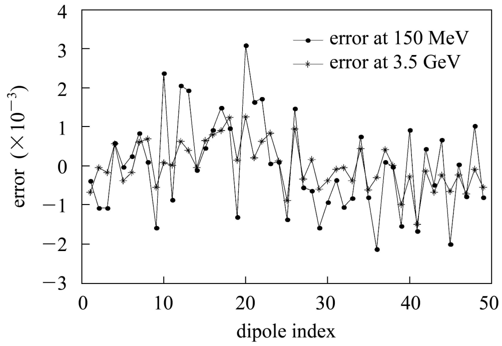

Fig. 2. Field uniformity error and measurement error of each dipole.

3.3 Sorting result

In order to calculate the sorting effect, 1000 random queue of dipoles at each energy was given. Fig. 3 show the horizontal COD distributions without sorting procedure. The rms COD is from 0.5 mm to 3.5 mm, the absolute peak value of COD is from 1 mm to 8 mm at 3.5 GeV. It's about twice value at 150 MeV.

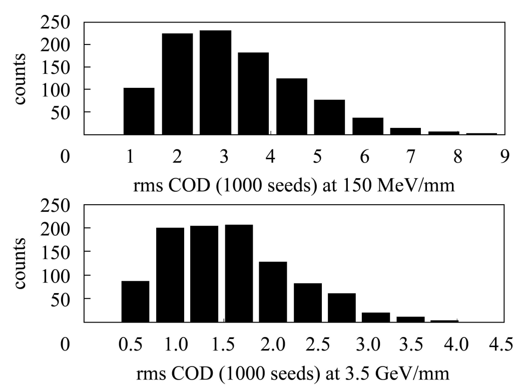

Fig. 3. CODs without sort.

In order to minimize the COD at 3.5 GeV, and at the same time the COD at 150 MeV is as small as possible, we made a new cost function by combining $W_{\text{extaction}}$ and $W_{\text{injection}}$,

$$W = \alpha W_{\text{extaction}} + \beta W_{\text{injection}}, \tag{6}$$

Here

$$\alpha^2 + \beta^2 = 1\ . \tag{7}$$

It's important to choose a proper weight α and β in the object function. We choose β=0.15 after several tests, the final horizontal COD after sorting and distribution of horizontal COD is introduced in follow sector.

As shown in Fig. 4, The maximum COD at 3.5 GeV is 0.58 mm, the rms COD is 0.25 mm, they are 2.83 mm and 1.12 mm at 150 MeV. With the correctors working at low energy we can get a better performance. In the sorting process, we find that the biggest error source is the 41st magnet (25th in the ring). If its position can be changed, we can get a better sorting result. The CODs in the whole ramping process are also considered and shown in Fig. 5. As energy rises, the max COD and rms COD almost come down, but there is a bulge on the curve. The reason is that in the measurement of several magnets, the reference magnet isn't measured at the same time. We can see the same bulge at some dipoles in Fig. 1.

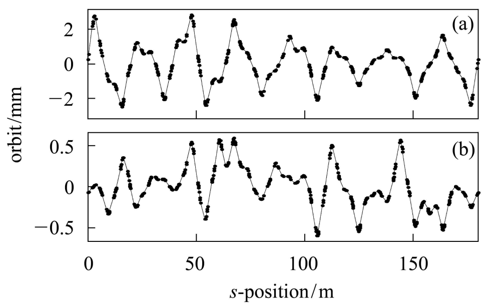

Fig. 4. The sorting result at 150 MeV and 3.5 GeV. (a) sorted rms cod 1.12 mm and sorted max cod 2.83 at 150 MeV; (b) sorted rms cod 0.25 mm and sorted max cod 0.58 at 3.5 GeV.

In order to conclude the measurement errors, we add 100 random errors (σ=5×10^{-5}, 3σ cut off) at 3.5 GeV. Fig. 6 shows the results. The rms COD varies from 0.224 mm to 0.462 mm while the absolute peak value of COD goes from 0.584 mm to 1.282 mm, the typical rms COD value is around 0.25 mm, the typical peak value of COD value is around 0.6 mm to 1 mm. Both of the horizontal and vertical COD distribution after sorting and error distribution meet the requirements of optimization.

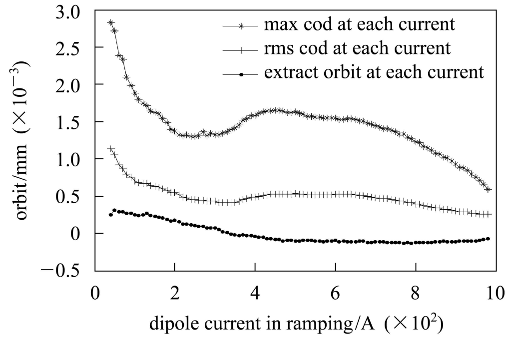

Fig. 5. The sorted result in ramping.

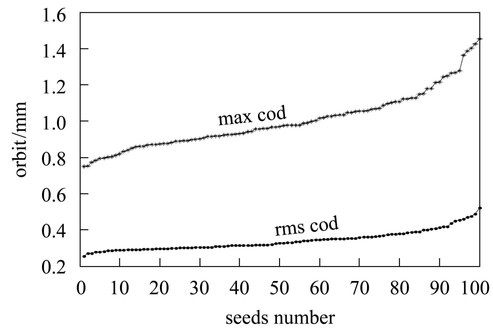

Fig. 6. CODs with measurement errors.

4 Conclusions

Based on the magnet filed measurement of SSRF booster dipoles, we did some sorting simulations by a method mixing by local cancellation and simulation annealing to minimize the COD at 3.5 GeV and 150 MeV at the same time. And the effect of measurement errors and the whole ramping process also are considered.

The rms magnetic filed uniformity error of SSRF booster dipoles is 6×10^{-4} at 980 A. After sorting, the peak values of closed orbit deviation are 0.58 mm and 2.83 mm at 3.5 GeV and 150 MeV, and the rms CODs are 0.25 mm and 1.12 mm. Even with the measurement error as 5×10^{-5}, it is well within the suitable size.

References

1 LI D M, GU Q, ZHAO Z T. New Scheme of the SSRF Injector. In: Asian Particle Accelerator Conference, Proceedings of the 2004. 2004, 394—396

2 Bartolini R, Scandale W, Giovannozzi W et al. Sorting Strategies for the LHC Dipoles. In: Particle Accelerator Conference, Proceedings of the 1997. 1997, **2**: 1469

3 Ziemann V. Sorting the LHC Dipoles using Simulated Annealing. In: European Particle Accelerator Conference, Proceedings of the 1994. 1994, 1054—1056

4 HOU Jie, LIU Gui-Min, LI Hao-Hu et al. Chinese Physics C (HEP&NP), 2008, **32**(4): 285

5 Abo-Bakr M. Sorting of Magnets for the BESSY II Booster and Storage Ring. In: European Particle Accelerator Conference, Proceedings of the 1996. 1996, 1314—1316

6 Press W H et al. Numerical Recipes — The Art of Scientific Computing. London: Cambridge University Press, 1992, 549

7 Terebilo A. Accelerator Toolbox for MATLAB, SLAC-PUB-8732. 2001, 10—35