ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-MOPM044

STUDY OF MAGNETS SORTING FOR THE HEPS BOOSTER *

Y.M. Peng†, J.X. Zhou, J.T. Pan, Key Laboratory of Particle Acceleration Physics and Technology, Institute of High Energy Physics, CAS, Beijing, 10049, China

Abstract

The High Energy Photon Source (HEPS) is a 1360.4 m, 6 GeV, ultralow-emittance light source, being built in the suburb of Beijing, China. The HEPS booster contains 128 dipoles,148 quadrupoles and 68 sextupoles, which are divided into several groups. The magnets in one group are connected in series, and powered by a single power supply. To minimize the impact on beam dynamics, magnets sorting needs to be done. The RMS values of closed-orbit distortion and beta-beating were used as the merit functions of dipole sorting and quadrupole sorting, respectively, and the sextupoles were grouped with the integral field differences between magnets. This paper will present the sorting process and the results of beam dynamics after sorting.

INTRODUCTION

The High Energy Photon Source (HEPS) is a 6 GeV diffraction-limited storage ring light source, being built in the suburb of Beijing, China. A full energy booster is designed to accelerate the electron beam energy from 500 MeV to 6 GeV [1]. The HEPS booster adopted a traditional FODO lattice with four-fold symmetry. The main parameters of the HEPS booster were listed in Table 1.

Table 1: Main Parameters of the HEPS Booster

Parameter	Unit	Value
Injection energy	GeV	0.5
Extraction energy	GeV	6
Length of the straight sections	m	8.8
Circumference	m	454
Repetition rate	Hz	1
Emittance @ 6 GeV	nm.rad	16.3
Tune(H/V)		21.15/11.21
Energy spread @ 6 GeV		9.6×10^{-4}
Natural chromaticity(H/V)		-27.4/-18.7
Momentum compaction factor		2.3×10^{-3}
Energy loss per turn @ 6 GeV	MeV	3.88
Damping time @ 6 GeV	ms	4.68/4.68/2.34

The HEPS booster consists of 128 dipoles,148 quadrupoles, 68 sextupoles. They are divided into several groups and the same types of magnets in one group are connected in series and powered by a single power supply. In the ideal lattice, the magnets of the same type were designed with same integral field. However, due to the factors of material differences, machining deviations and so on, there are some integral field deviations (IFD) between the magnets of the same type. These differences of integral fields can be compensated by adjusting the current of power supply (PS) if each magnet is powered individually. When several magnets are connected and powered by a single PS, the IFD couldn't be compensated by adjusting the PS current only. This is an important error source which will impact the beam performance. The IFD of bending magnet will cause closed orbit distortion (COD), and the IFD of quadrupoles will cause beta-beating. So, magnetic sorting is very important and necessary for efficient operation of light sources.

In the HEPS booster, there are 128 dipoles,148 quadrupoles and 68 sextupoles and 92 correctors. The magnetic field measurements of all the HEPS booster magnets were finished at the end of 2021. After the measurement was completed, the sorting for magnets which are connected in series, was carried out immediately and completed in the Jan. 2022.

Usually, the IFD has larger affect at the low energy than the high energy in booster, the sorting in low energy should be pay more attentions. However, the HEPS booster was designed as an accumulation ring at 6 GeV for the "booster high energy accumulation" injection scheme to provide the bunch charge more than 14.4nC, the COD and beta beating also need be considered at this energy. So, the integral field used at 500 MeV beam energy was added to the integral field used at 6 GeV to find the FID which was used for bending magnets sorting. The FID which was used for sorting given by the formula (1).

The dipole and quadrupole magnets were divided to several groups according to the IFD, and rearranged for reducing the RMS values of closed-orbit distortion (COD) and beta-beating, respectively. After dividing the sextupoles into 6groups according to the IFD, the DA nearly no reduction. So, the sextupoles were only grouped according to the IFD from the mean value.

This paper will present the sorting process and the results of beam dynamics after sorting for the HEPS booster.

SORTING OF BENDING MAGNETS

There are128 dipoles in the HEPS booster, which form 4 arcs. Each arc contains 32 dipoles which are connected in series and powered by a single PS. The effective length of dipole is 1.45 m, the working interval of dipole field from 560-Gs to 0.68-T, corresponding the excitation currents are about 64-770A. In order to measure and correct the beam orbit, 72 BPMs and 92 correctors were installed in the HEPS booster.

*Work supported by NSFC (12005239)
† pengym@ihep.ac.cn

ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-MOPM044

The integral field was obtained by a long coils magnetic measurement system with the ramped magnetic field measurement method. The results of IFD with four different excitation currents (64A, 128A, 385A, 770A) were presented in Fig. 1. As shown in the Fig. 1, IFDs are changing under different excitation currents. If magnet sorting is based on the FID at 500 MeV, the COD becomes even lager at 6 GeV than the values without sorting, the results in the horizontal direction was shown in Fig. 2. Therefore, the sorting of magnets with the IFD were carried out by the formula (1) is necessary.

$$IFD(i) = (BL_{500\,\mathrm{MeV}}(i) + BL_{6\,\mathrm{GeV}}(i)) / \frac{\sum_{i=1}^{128}(BL_{500\,\mathrm{MeV}}(i) + BL_{6\,\mathrm{GeV}}(i))}{128} - 1 \qquad (1)$$

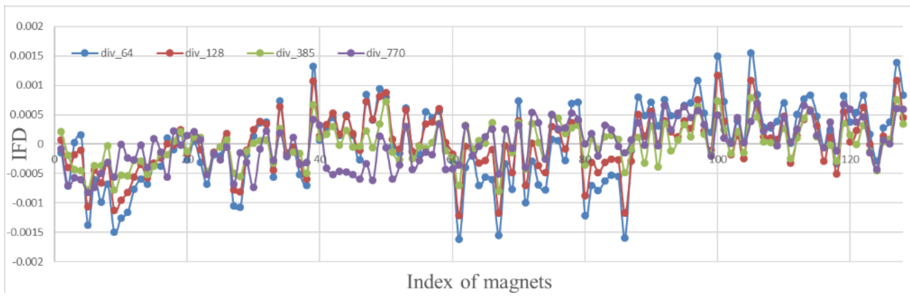

Figure 1: IFD of dipoles with four different excitation currents.

Theoretically, we can select the solution with the smallest COD by placing each bending magnet at different positions, However, it's difficult for HEPS booster, because of the large number of bending magnets. Therefore, we do not consider finding the optimal solution, but sorting according to the beam dynamic characteristics replaces finding the optimal solution.

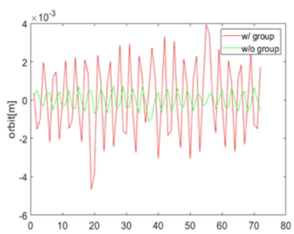

Figure 2: The COD at 6 GeV before and after magnets grouped with IFD at 500 MeV.

First, the magnets were grouped to minimize the IFD of the bending magnets powered by the same PS, which cannot be compensated by adjusting the current of the power source. And the group which has the larger integral field was placed closer downstream to the RF cavities. With this step, the RMS of COD in horizontal become 0.62 mm and 0.58 mm at 500 MeV and 6 GeV, respectively.

Because of the 4-fold symmetry structure of the HEPS booster, the optics are the same for each super-period. So, we choose one group magnets for sorting to confirm the magnet placement position. The bending magnets of other group were arranged in this order according to the IFD. The sorting based on 'randperm' command in AT code [2], 500000 seeds of magnet sequence data were randomly generated. The seed with the smallest COD in horizontal at 500MeV as the order of magnet placement.

After sorting, the RMS of COD in horizontal become 0.11 mm and 0.23 mm at 500 MeV and 6 GeV, respectively, which were shown in Fig. 3 and Fig. 4. The green line presents the COD in horizontal direction after the magnet grouped, but without using 'randperm' command optimization. The red line presents the COD in horizontal after sorting.

With the IFD and the placement of bending magnets given by sorting, the orbit variation in the ramping process was simulated, and the results were shown in Fig. 5.

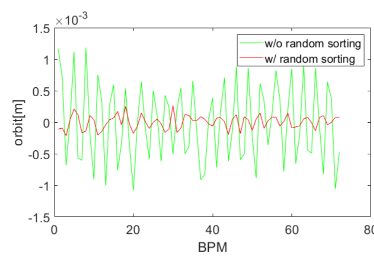

Figure 3: The COD at 500 MeV.

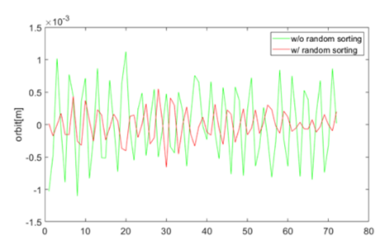

Figure 4: The COD at 6 GeV.

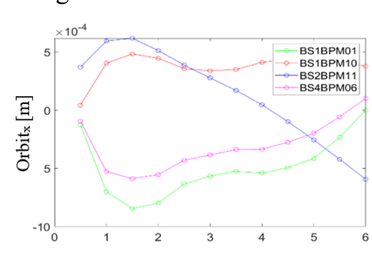

Figure 5: The COD in the ramping process at 4 BPMs.

ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-MOPM044

SORTING OF QUADRUPOLES

The quadrupole magnets in the HEPS booster had three types, and the effective length is 0.3 m, 0.4 m and 0.5 m, respectively. There are 68 quadrupoles with a 0.3 m effective length, all of these quadrupoles are defocusing in horizontal direction, and they are powered by 3 PSs. There are 64 quadrupoles with a 0.4 m effective length, all of these quadrupoles are focusing in horizontal direction, and they are also powered by 3 PSs. The 16 quadruples with a 0.5 m effective length were divided into two groups in series, each group contained 8 quadrupoles. One group are focusing in horizontal direction, and the other group are defocusing in horizontal direction.

Similar to the bending magnets, the IFD of quadrupoles at different exciting currents was different. Meanwhile, each group of quadrupoles had different gradient values. The sorting of quadrupoles with the IFD need at a certain current.

First, the magnets with the effective length of 0.3 m and 0.4 m were grouped according to the IFD of 10A exciting current, and the magnets with the effective length of 0.5 m were grouped according to the IFD of 30A (among them, 2 quadrupoles do not participate in sorting because the yoke shapes of them were special).

After grouping, the placement positions of each group quadrupoles were determined according to the size of beta function. Then, the 'randperm' command in AT was used to randomly generate 500,000 permutations for the two groups of quadrupoles with the largest number of magnets, and then compare the RMS value of beta-beating, focusing quadrupole magnet were compared in horizontal direction, and defocusing quadrupole magnet were compared in vertical direction.

After sorting these two groups with the largest number of quadrupoles, other groups with fewer quadrupoles were added and carried out sorting one by one.

The beta-beating results in horizontal and vertical direction were shown in Fig. 6 and Fig. 7, respectively. Before sorting, the RMS values for horizontal and vertical beta-beating were 1.75% and 1.55%, respectively. After sorting, the RMS values for horizontal and vertical beta-beating reduced to 0.69% and 0.50%, respectively. maximum beta-beating was less than 2% both in horizontal and vertical direction.

With the placement of quadrupoles given by sorting and the IFD, we simulation the tune shift in the ramping, the range of tune shift was approximate ± 0.0004 in both horizontal and vertical direction.

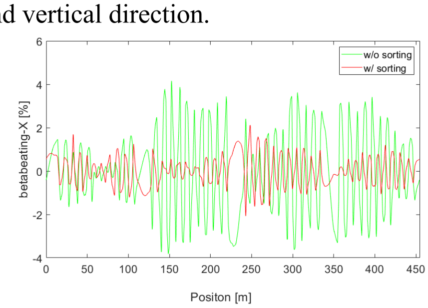

Figure 6: The beta-beating in horizontal.

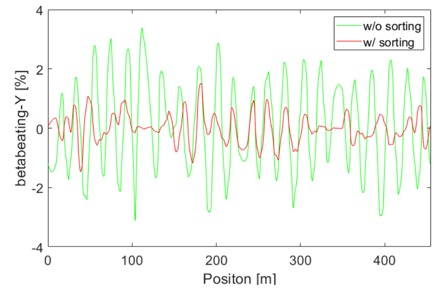

Figure 7: The beta-beating in vertical.

SORTING OF SEXTUPOLES

The HEPS booster has 68 sextupoles, and which are powered by 6 PSs. Since the time cost of dynamic aperture (DA) tracking was very high, these sextupoles were only divided into 6 groups according to the IFD from the mean value. Then, DA was tested to see if it was acceptable.

The sextupoles were sequencing with IFD at 70 A exciting current. First, the sextupoles were arranged in order according to the FID value from largest to smallest, and divide the sextupoles into 6 groups, with different numbers of sextupoles in each group. Then, the DA and chromaticity were compared to the bare lattice, and the results are shown in Fig. 8. There is nearly no reduction in DA, and the difference of chromaticity between the lattice with sextupoles' IFD after sorting and the bare lattice was on the order of 1E-4.

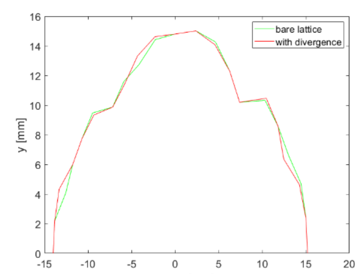

Figure 8: The DA (the green is the DA of bare lattice; the red line is the DA of lattice with sextupoles' IFD after sorting).

SUMMARY

The magnetic field measurement and sorting of magnets which connected in series in HEPS booster had been finished in HEPS booster. After sorting, the RMS of COD in horizontal became 0.11 mm and 0.23 mm at 500 MeV and 6 GeV, respectively, and the maximum beta-beating was less than 2%. After dividing the sextupoles into 6groups according to the IFD, the DA nearly no reduction. All magnets were installed into the tunnel according to the placement given by sorting.

REFERENCES

[1] Yuemei Peng, et al. "Design of the HEPS booster lattice", Radiation Detection Technology and Methods (2020) 4:425–432, doi.org/10.1007/s41605-020-00202-z

[2] A.Terebilo, Accelerator Toolbox for MATLAB, SLAC-PUB-8732, 2001