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DESIGN OF MAGNETS FOR HEFEI ADVANCED LIGHT FACILITY*

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Abstract

The Hefei Advanced Light Facility (HALF) is a future soft X-ray diffraction-limited storage ring at National Synchrotron Radiation Laboratory (NSRL), which aims to decrease the horizontal emittance to improve the brilliance and coherence of the soft X-ray beams. The lattice of the ring depends on the use of many short and high field multipole magnets, dipole-quadrupole magnets with high gradients (DQ) and dipoles with longitudinal gradients (DL). Due to the high gradient of DQs, it is a better choice to obtain the ideal field with an offset quadrupole design. The longitudinal gradient dipoles are electromagnets with different gaps for the requirement of the field adjustment. The design of all multipole magnets relies on a new optimization method based on NSGAII and the good results have been achieved. The design has been completed and the prototype of DL2 is under construction.

INTRODUCTION

HALF is a 4th generation synchrotron radiation light source with a beam energy of 2.2GeV, undertaken by NSRL, located in Anhui China. HLS-II is an upgrade project of Hefei Light Source (HLS), greatly improving the capability and performance. Due to the gradual increase in demand, NSRL decided to carry out the design and construction of HALF, whose ultra-low emittance is better than 85pm·rad.

The present HALF lattice is a modified hybrid six-bend achromat (6BA) lattice with a long and a short straight section in each cell [1, 2]. The X-ray will be produced by the electrons of 2.2GeV running around the storage ring with 20 cells and about 680 magnets. The magnets in each cell are symmetrical about the centre line of the cell, and most multipole magnets need to change in a range of 85% to 120%.

For pervious lattice schemes, a permanent magnet design, for its small size and low operating cost, was employed for DLs for HALF [3]. At present, in order to meet the requirement of increasing the energy of the storage ring, the scheme of electromagnets with different gaps has been adopted by two coils and precisely controlled gaps.

MAGNET DESIGN

The magnets with the high quality for the storage ring bring difficulties in the design stage. The reduction of the emittance leads to the reduction of magnet aperture, and at the same time, for mutipole magnets and dipole-quadrupoles, their gaps are limited to at least 11 mm, so as to facilitate the installation of X-ray beam ports. In addition, due to the shortage of the longitudinal space of the ring, the small Aspect Ratio (AR), defined as the magnet's length over its aperture, represents HALF's multipole magnets have more serious fringe field effect, which may result in unexpected multipoles [4]. In order to solve this problem, multipoles should be suppressed as much as possible in two-dimensional design. Figure 1 gives the layout of the typical cell of the storage ring.

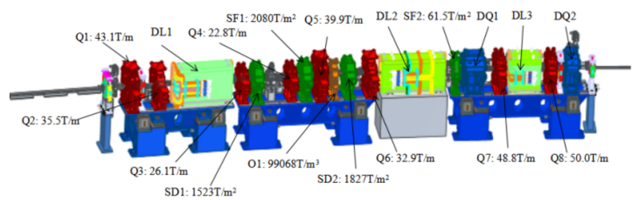

Figure 1: Layout of the half cell.

The quadrupole magnets and the sextupole magnets are obtained in a more conventional method, whose error multipole components are at the level of 10-5 in the Good Field Region (GFR). HALF's DQ magnets are designed with a symmetrical structure, and produce the required dipole field by its mechanical centre's offset to the beam. Besides, the multipole magnets and the DQ magnets are all equipped with correction coils, such as horizontal, vertical or skew-quadrupole correctors. The DL magnets are built with several poles with different gaps and contours, and the current of two coils are designed to be the same by adjusting gaps.

Quadrupole Magnets

Four types of quadrupole magnets will be used in the lattice of HALF, divided by aperture, length and gradient, and their main specifications are shown in Table 1.

Table 1: Specifications for Quadrupoles

Name	GFR [mm]	Aperture [mm]	Gradient [T/m]
Q1 Q5	13	36	43.1 39.9
Q2 Q6	13	36	35.5 32.9
Q3 Q4	13	36	26.1 22.8
Q7 Q8	8	30	48.8 50.0

The iron cores of all quadrupole magnets are made of silicon steel sheets, which improves the machining accuracy. Although their field gradient is not very high, because of the large aperture and the wide adjustment, the field strength of Q1's pole tip is indeed high. In the design, it is necessary to ensure that multipole components of the magnet can meet the requirements when the working

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current changes from the lower limit to the upper limit. In this case, more attention should be paid to the local saturation caused by sharp corners on poles, so pole shapes need to be as smooth as possible.

The method of optimization design, combined with NSGAII, Conformal Mapping and OPERA-2d, has been used to find ideal pole shapes to deal with the situation with a large adjustment and the high field. NSGAII is a nonlinear optimization algorithm and its optimization ability ensures that it can find a better pole shape that meets the serious requirements. Based on OPERA-2d and an 8-core processor, the optimization program's convergence speed far exceeds our expectation. By the program. HALF's quadrupole magnets have reached required field qualities and all the error components are under 1×10-4 at working points. For Q1 and Q7, with high field or high gradient, Figure 2 shows their main error multipole components of different currents.

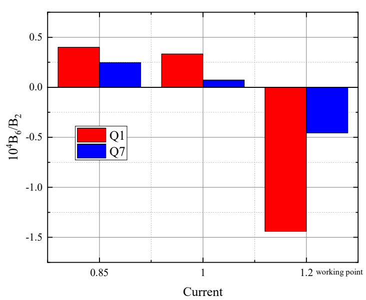

Figure 2: The 12-pole term of Q1 and Q7 varies within the range of the adjustment.

Figure 3 shows the engineering model of quadrupole magnets is shown, and the cooling water device has been placed in a way of saving longitudinal space.

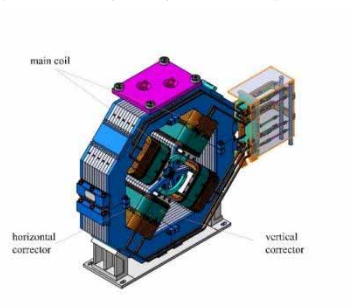

Figure 3: Engineering model of Q1 and Q5, which have been equipped with correction coils.

Sextupole Magnets

HALF's sextupoles are divided into three types by the efficient length and gradient, and their main parameters are shown in Table 2. In addition of their main function, the sextupole magnets are required to append correction field, including horizontal and vertical dipoles and quadrupoles.

Table 2: Specifications for Sextupoles (H: Horizontal Dipoles; V: Vertical Dipoles; Q: Quadrupoles.)

Name	**SD1**	**SF1 SD2**	**SF2**
Aperture[mm]	45	45	45
Gradient[T/m2]	1523	2080 1827	61.5
Length[mm]	150	150	80
GFR [mm]	13	13	8
ΔS/S	10-3	10-3	10-3
Correctors	H+V+Q	H+V+Q	H+V+Q

Figure 4 shows physical models of HALF's sextupoles, and SD1 and SF1 (SD2) share the same iron core, but they have different winding modes. Also, the pole shapes of all sextupoles are obtained by the optimization method based on NSGAII. By changing the objective function, the program can easily optimize quadrupoles, sextupoles and octupoles. The error multipole components of sextupoles are listed in Table 3.

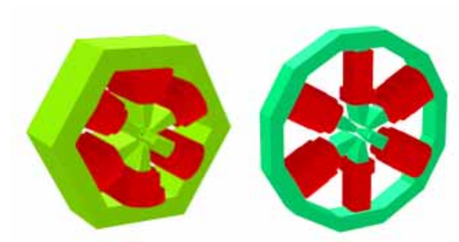

Figure 4: Physical models of sextupoles.

Table 3: Main Multipoles of Sextupoles

Harmonic	**SD1**	**SF1**	**SF2**
3	10000	10000	10000
9	0.008	-0.042	-0.324
15	-0.011	-0.015	0.019
21	-0.040	-0.034	-0.057
27	-0.030	-0.031	-0.039

Combined Dipole Quadrupoles

The HALF lattice includes two types of DQs, which have a higher gradient field than usual, as Table 4 lists.

Table 4: Specifications for DQs

Name	**DQ1**	**DQ2**
Aperture[mm]	39	36
Gradient[T/m]	41.700	46.769
Field[T]	0.2609	0.1448
Length[mm]	360	220
GFR[mm]	8	8

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Because of the high gradient field, it is convenient to design quadrupole magnets and place them eccentrically to produce the required dipole field. Compared with the previous design, a single sided quadrupole [5], the current scheme increases power consumption, but the field quality is better and processing is much easier. Figure 5 shows the multipole components of DQs.

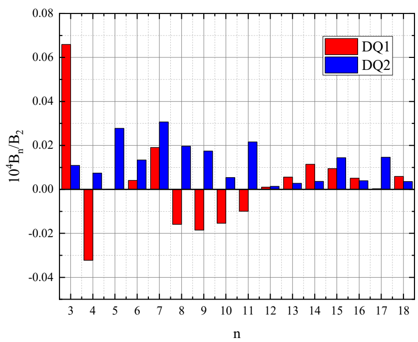

Figure 5: Multipole components of DQs, and 2-pole term and 4-pole term are not included.

Longitudinal Gradient Dipoles

For HALF's dipoles with longitudinal gradients, we choose an electromagnet design to meet the requirement of adjusting the dipole field. There are three types of DLs in HALF's lattice, each of which has completed the physical design, as Fig. 6 shows. The DLs ensure the magnetic field of each step by adjusting the gap size precisely, and the small secondary coil is used to ensure the gaps will not be too large. In addition, insert plates are added on both sides of the magnet to reduce the fringe field.

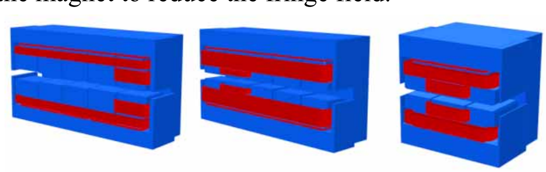

Figure 6: Physical models of DLs.

Because the gap of each step is different, each pair of pole shapes needs to be optimized separately to improve the integrated field uniformity. Due to the difficulty in both installing the secondary coil of DL2 and the high dipole field, we intend to build its prototype to verify the scheme. Because of the secondary coil, the gaps of DL2 vary from 30 mm to 54mm, and the smaller gap ensures the lower fringe field. HALF puts forward the requirement of trajectory deviation of less than 0.1 mm. In order to minimize the influence of first-order integral field to the trajectory as much as possible, the field longitudinal distribution By(z) should be strictly consistent with the ideal distribution in the design. Figure 7 shows the model of DL2's prototype and its By(z).

Considering that the centre of the GFR is the actual trajectory of electrons, the transverse range of DL2's longitudinal integrated field is larger (≥ ±28mm).

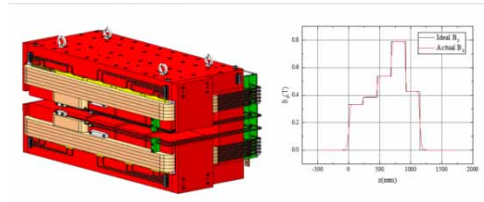

Figure 7: a) Engineering model of DL2; b) DL2's longitudinal field distribution By(z).

Through pole surface optimization and longitudinal chamfers, the longitudinal integrated field uniformity of DL2 is less than 1×10-4 in GFR. Compared with the requirement of 5×10-4, during error analysis, we found that this design left room for introducing machining errors. Figure 8 shows the longitudinal integrated field uniformity and the trajectory deviation of DL2.

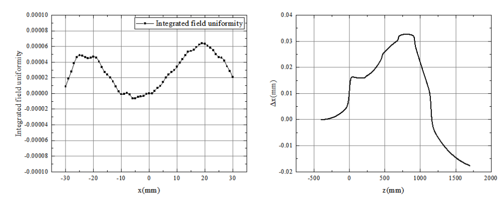

Figure 8: a) Longitudinal integrated field uniformity; b) Trajectory deviation of DL2.

CONCLUSION

The physical design and mechanical design of all magnets has been finished for HALF, and the prototype of DL2 is under construction. The optimization program based on NSGAII has achieved ideal results in design stage, and the error components of all multipole magnets are less than 1×10-4. For DLs, the electromagnet design is used to achieve a wide range of field adjustment, and the equal gap scheme is not adopted because its coil winding is complicated. All magnet designs will be verified by the manufacture and measurement of prototypes.

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