The magnet design for the HLS storage ring upgrade project*

ZHANG Hao(张浩) LI Wei-Min(李为民) FENG Guang-Yao(冯光耀)[1)]
WANG Lin(王琳) ZHANG Shan-Cai(张善才) LI Wei(李为) LIANG Jun-Jun(梁军军)

National Synchrotron Radiation Lab., University of Science and Technology of China, Hefei 230029, China

Abstract: In order to improve the performance of the Hefei Light Source (HLS), in particular to get higher brilliance synchrotron radiation and increase the number of straight section insertion devices, an upgrade project called HLSII will be launched soon. The storage ring lattice, which has a double bend achromatic structure with four periods, comprises eight dipoles, 32 quadrupoles and 32 combined function sextupoles. The design and analysis of the magnets are shown in this paper, along with the optimization of the multipurpose combined function magnet, which consists of three magnets: skew quadrupole, horizontal dipole and vertical dipole, with the main sextupole magnet. This type of magnet is the first one that has been designed and used in China. The mechanical design and fabrication procedures for the magnets are also presented.

Key words: storage ring magnet, combined function, conformal mapping, water-cooling channel

PACS: 29.20.D-, 29.25.Bx **DOI:** 10.1088/1674-1137/36/1/016

1 Introduction

In order to get more straight sections for insertion devices and obtain higher brilliance synchrotron radiation, an upgrade project for the Hefei Light Source (HLS) will be launched soon. The new storage ring's circumference is the same as that of the current one, but the focusing structure is different. For the upgrade project, the new ring will be installed on the current ground settlement and all of the magnets will be reconstructed. Magnet field quality is strict for the new storage ring of the HLS. For the dipoles, quadrupoles and sextupoles, the systematic and random tolerances for the harmonic contents in the good field regions need to be of the order of 10^{-4}. The magnetic field of all the magnets have been calculated using POISSON codes [1] and Opera-3d codes [2]. The dipole and quadrupole magnets will be chamfered at the ends to meet the integrated field quality specifications, and the size of the chamfers will be determined according to the magnetic measurement results of the prototypes.

2 Storage ring magnets

The c-shaped dipoles of the new HLS storage ring are of arc structure, and the quadrupoles and sextupoles are straight magnets. The extraction of synchrotron radiation and the accommodation of the vacuum chamber have been accounted for. The yokes are made of J23-50 steel laminations compressed using end plates and longitudinal plates. In order to avoid the magnets requiring coils with a large cross section, the magnet coils are water cooled, which requires the use of conductors with cooling channels. In addition to the main coils, there are trim coils in the dipoles. The technical requirements of the magnet are given in Table 1.

2.1 Dipole magnets

For the HLSII lattice there are eight bending magnets, and each bending magnet should bend 45° compared with the previous 30°. According to the extraction of the synchrotron radiation and space for the vacuum chamber, a c-shape configuration has been

Received 13 April 2011

* Supported by National Natural Science Foundation of China (10905054, 10979045, 10875127)

1) E-mail: fenggy@ustc.edu.cn

Table 1. The technical requirements for the storage ring magnets.

type	dipole	quadrupole	sextupole
operation field	$B_y = 1.2336$ T	$G_y = 13.0$ T/m	$K_y = 330$ T/m^2
good field region	$X = \pm 38$ m	$R = 38$ mm	$R = 38$ mm
integral field errors at $\|X\| \leqslant 38$ mm	0.05%	0.05%	0.2%
higher harmonics errors B_n/B_* at $R = 38$ mm	0.03%	0.04%	0.1%
the rms dispersions	0.1%	0.3%	0.3%

chosen, which can provide good stiffness and field quality. The dipoles are made of one-piece laminations and will be installed after the vacuum chamber is in place. The main coils of all the dipoles are powered in series, and the trim coils are adjusted individually to reduce inconsistency. The major parameters for the magnet are given in Table 2.

Table 2. The parameters for the storage ring dipole magnet.

parameter	value
energy/MeV	800
quantity of magnet	8
bending radius/m	2.16451
gap flux density/T	1.2336
gap height/mm	55.0
magnetic length/m	1.70
good field width/mm	76
good field height/mm	40
magnetic efficiency	0.981
number of turns per pole	42
conductor size/mm	$20 \times 14\phi 7$
Ampere-Turns per pole(AT)	27975.1
current/A	666.074
current density/(A/mm^2)	2.7134
resistance per magnet/Ω	0.0283
voltage drop per magnet/V	18.85
inductance per magnet/mH	101.4
core length/m	1.670
core height/m	0.904
core width/m	0.618
magnet length/m	2.008
core weight per magnet/t	6.376
copper weight per magnet/t	0.855
water circuit	6
water pressure drop/(kg/cm^2)	5
water flow rate per magnet/(l/min)	22.55
temperature rise/℃	7.96

The effective magnetic length of the bending magnet is 1.7 m, and the core length of the dipole magnet is 1.67 m. Since the effective magnetic length is longer, the sagitta of the orbit is very large. The pole is curved following the trajectory, and the pole gap is 55 mm, which is determined by the vacuum chamber. The pole width is 210 mm, and the good field region extends horizontally from −38 to 38 mm in respect of the pole reference line, and vertically from −20 to 20 mm.

The 2D and 3D magnetic analyses have been performed using the 2D POISSON and 3D OPERA group computer codes, respectively. The magnetic field in the gap is 1.2336 T and the efficiency is above 98%. The magnetic tolerances of the good field region could be of the order of 10^{-4} through optimizing the shape of the pole tip. There are three racetracks of the main coils and one racetrack of the trim coil on each pole. Each main coil with 42 turns in three layers is made of a 20 mm×14 mm conductor with a 7 mm diameter water-cooling channel.

Each of the main coils are insulated with 0.5 mm thick, and each layer with 2 mm thick, Dacron tape.

2.2 The quadrupole magnets

There are 32 quadrupoles with two different lengths, 0.2 and 0.3 m. All the quadrupoles have the same bore diameter of 94 mm, determined by the vacuum chamber. The quadrupoles are powered independently to regulate conveniently and reduce the consistence requirement of the magnets. The cross section and the main coils of the quadrupoles are designed with the same requirements, and the maximum gradient is 13.0 T/m. The major parameters of the quadrupoles are given in Table 3.

The shape of the pole tip is optimized with conformal mapping, and the 2D magnetic analyses have been performed using the 2D POISSON group computer codes. The higher harmonics could be controlled by 0.04%.

Two quadrants are assembled as half magnets, with one on top and one on the bottom. The laminations are shuffled to ensure uniform magnetic property after precise punching and accurately stacked

Table 3. The parameters of the two kinds of storage ring quadrupole magnets.

parameter	value	
magnetic length/m	0.30	0.20
quantity of magnet	24	8
inscribed radius/mm	47	47
maximum magnetic gradient/(T/m)	13.0	13.0
good field radius/mm	38	38
number of turns per pole	62	62
Ampere-Turns per pole(AT)	12482.0	13038.0
current/A	201.32	210.30
conductor size/mm	$7\times7\phi4$	$7\times7\phi4$
current density/(A/mm^2)	5.53	5.77
conductor length per coil/m	57.42	45.02
resistance per magnet/Ω	0.122	0.096
inductance per magnet/mH	43.8	32.0
voltage drop per magnet/V	24.56	20.19
core length/m	0.275	0.175
core height/m	0.600	0.600
core width/m	0.600	0.600
magnet length/m	0.429	0.329
core weight per magnet/kg	385	233.33
copper weight per magnet/kg	108.7	85.35
water circuit	4	4
water pressure drop/(kg/cm^2)	5	5
water flow rate per magnet/(l/min)	3.84	4.176
temperature rise/°C	18.5	14.52

during magnet construction [3]. The contour dimensions of the lamination are precisely controlled within 25 μm. However, the magnet assembly accuracy is controlled within 30 μm. The top and bottom halves are aligned relative to each other with precise circular holes and pins. The two magnet halves should be keyed with respect to each other in the longitudinal direction with an accuracy of ±0.05 mm. The reproducibility of the position after reinstallation should be controlled within 30 μm. Meanwhile, the magnet can be removed without taking out the vacuum chamber. The magnets are accurately fixed on girder and without alignment. A precise reference base plate is attached to the quadrupole magnet.

On each pole, there are three racetracks of the main coils with different sizes. The main coil, with 62 turns in three layers, is made of a 7 mm×7 mm conductor with a 4 mm diameter water-cooling channel.

2.3 The combined function sextupole magnets

The HLSII storage ring has 32 sextupoles of the same length, the same bore diameter of 100 mm, and the same cross section. The multifunctional sextupole magnet is the first one designed and used in China. The sextupole magnetic field is designed for natural chromaticity correction and to produce a horizontal and vertical magnetic field for the beam orbit distortion correction and a skew quadrupole magnetic field for adjusting the transversal coupling of the storage ring. A conventional sextupole magnet type is chosen. The magnet is divided into three parts, and the cross section is shown in Fig. 1.

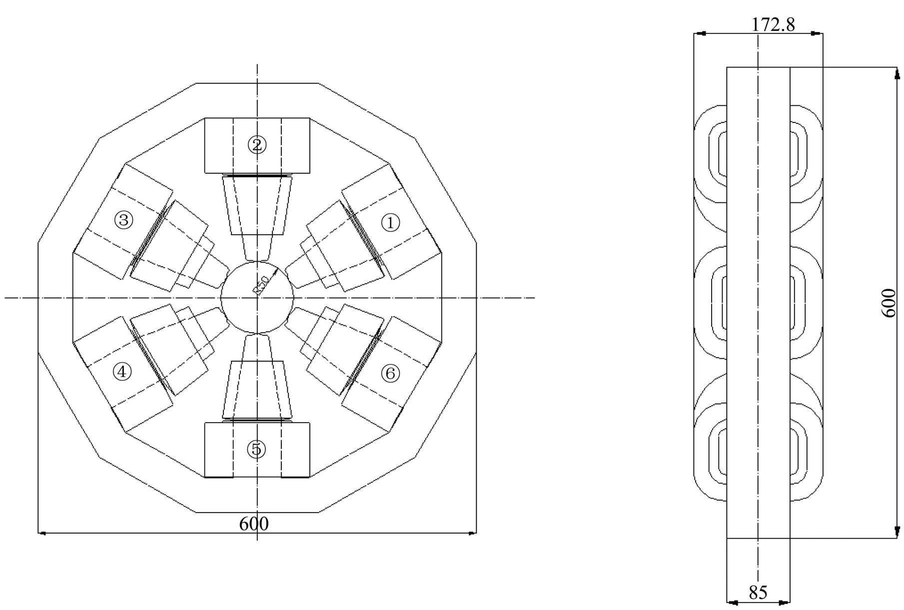

Fig. 1. The end and overhead view of the sextupole magnet.

According to Halbach's perturbation theory [4], the first order perturbation effects in iron-dominated 2D symmetrical magnets are expressed in terms of generation or changes in multipole coefficients. For a symmetric $2N$-pole magnet, the potential is:

$$F(z)=\sum C_n z^n, \tag{1}$$

where C_n are the multipole coefficients, and $n = N(2m+1)$, m =0, 1, 2, 3,$\cdots$. The comparison between the field components H_n and H_N is written as a function of these coefficients:

$$\left|\frac{H_n}{H_N}\right|=\frac{n}{N}\frac{C_n}{C_N}Z^{n-N}. \tag{2}$$

For a particular perturbation, the theory provides the sensitivity of the coefficients $\Delta C_n(\alpha)$ for a reference pole centered in the horizontal axis. Numerical values are given in Halbach's paper as normalized coefficients

$$\frac{n}{N}\frac{C_n(0)}{i\varepsilon},$$

where ε is the strength of the perturbation. The effect of this same perturbation applied to a pole whose symmetry axis is rotated by α is described by $\Delta C_n(\alpha)$, and obtained as follows:

$$C_n(\alpha)=C(0)\sum_j \mathrm{e}^{-ina_j}. \tag{3}$$

Eq. (2) can then be re-written as:

$$\left|\frac{H_n}{H_N}\right|=i\varepsilon\left(\frac{n}{N}\frac{C_n(0)}{i\varepsilon}\right)\sum_j \mathrm{e}^{-ina_j}. \tag{4}$$

So, if a vertical dipolar field is required, which can be obtained by using the six dipolar coils shown in Fig. 1, the coils corresponding to poles 1, 2 and 3 are of opposite polarity to those of 4, 5 and 6. From symmetry, we will give the same current I_1 to coils 1, 3, 4 and 6, and the same current I_2 to coils 2 and 5, and the $I_2=2I_1$.

In the case of the horizontal dipolar field, this can be obtained by using four dipolar coils driven by the same current, I_3. The coils of poles 1 and 6 are of opposite polarity to those of 3 and 4. Coils 2 and 5 are not used in this case. As for the skew quadrupole, we can use two coils on poles 2 and 5 with the same polarity, driven by the same current, I_4, and poles 1, 3, 4 and 6 with the opposite polarity to those of 2 and 5, drive by the same current, I_5. The 2D and 3D magnetic analyses have been performed for different excitation currents using the POISSON and OPERA-3d codes, respectively. The shape of the pole tip is optimized with conformal mapping, and the major parameters of the sextupoles are given in Table 4.

Table 4. The parameters of the storage ring sextupole magnet.

parameter of the main coils	value
quantity of magnet	32
inscribed radius/mm	50
max.sextupole $K=\mathrm{d}^2B/\mathrm{d}x^2/(\mathrm{T/m^2})$	330
magnetic length/m	0.125
good field radius/mm	38
number of turns per pole	30
Ampere-Turns per pole(AT)	6376.0
current/A	212.6
conductor size/mm	$6.5\times6.5\phi3.3$
current density/$(\mathrm{A/mm^2})$	6.31
conductor length per coil/m	15.9
resistance per magnet/Ω	0.0536
inductance per magnet/mH	7.5
voltage drop per magnet/V	11.40
core length/m	0.1
core height/m	0.6
core width/m	0.6
magnet length/m	0.188
core weight per magnet/kg	120.0
copper weight per magnet/kg	92.5
water circuit	3
water pressure drop/$(\mathrm{kg/cm^2})$	5
water flow rate per magnet/(l/min)	2.214
temperature rise/℃	15.2
parameters of the trim coils	**value**
vertical dipole	value
integrated field/Gaussm	34
Ampere-Turns per pole(AT)	1218
current/A	7.81
current density/$(\mathrm{A/mm^2})$	1.61
voltage drop per magnet/V	9.34
horizontal dipole	value
integrated field/Gaussm	34
Ampere-Turns per pole(AT)	1348/629
current/A	6.42
current density/$(\mathrm{A/mm^2})$	1.33
voltage drop per magnet/V	9.45
skew quadrupole	value
integrated field gradient/T	0.2
Ampere-Turns per pole(AT)	1850/1500
current/A	8.57
current density/$(\mathrm{A/mm^2})$	1.77
voltage drop per magnet/V	16.90

The yoke of the sextupoles consist of three sections with the same size. On each pole there are three racetracks of the main coils. The main coil with 30 turns in three layers is made of a 6.5 mm×6.5 mm conductor with a 3.3 mm diameter water-cooling channel.

3 The end chamfer

Magnet uniformity specifications typically require the integrated field to be uniform, have a uniform integrated gradient, or to have a uniformly parabolic field integral for the dipole, quadrupole or sextupole, respectively [5]. In order to achieve a uniform field integral, it is necessary that the magnet effective length, which is given by,

$$L_{\mathrm{eff}} = \frac{\displaystyle\int B\mathrm{d}z}{B_{\mathrm{center}}},$$

does not change with the transverse position. As for the dipole, the distribution of the effective length of the magnet is maximum at the center and reduces in a nonlinear fashion transversely near the edge of the pole. So the size of the chamfering is different along the transverse direction. The length of the quadrupole fringe field varies along the vector equipotential lines, which describe the directions of the flux lines. So the center of the pole should be shortened more than the edge. We use a straight angle machine cut at the end of the pole tip; the simple cut removes the most material from the center of the pole. The depth of the cut decreases as one nears the edge of the pole. The real size of the chamfer of the dipole and quadrupole would be determined by the measurement results.

4 Summary

In this paper, the magnet system for the HLSII storage ring upgrade project is described. The field designs of all the magnets give a few 10^{-4} of the multipoles, and the integrated field qualities will be of the order of 10^{-3}. The chamfer of the magnet ends will be determined by the magnetic measurements of the prototypes. The mechanical design of the magnets has been finished, and all of the prototypes will be finished in May 2011.

References

1 Poisson Superfish Code, Los Alamos National Laboratory, Los Alamos, U.S.A

2 OPERA-3D/TOSCA, Vector Fields Limited, Oxford, England

3 Hwang C S, Chang C H et al. Status of Magnet Design For The Accelerator Lattice of The TPS Project, Proceeding of PAC09, Vancouver, BC, Canada: 2009

4 Halbach K. Nucl. Instrum. Methods, 1969, **74**(Issue 1): 147–164

5 Jack T. Tanabe Iron Dominated Electromagnets Design, Fabrication, Assembly and Measurements. Singapore: World Scientific Publishing Company, 2005. 231–239