DESIGN OF THE MAGNETS OF THE FAR-INFRARED FEL PROJECT AT NSRL*

Tianlong He, Hongliang Xu#, Wei Xu,Shancai Zhang,
NSRL, USTC, Hefei, Anhui 230029, China

Abstract

This paper describes the magnetic design of the magnets of the far-infrared free electron laser at NSRL, including dipole magnets and quadrupole magnets with limited installing space. The dipoles are of three different effective lengths and strengths. All the magnets are designed and optimized by using POSSION and OPERA-3D. The end shimming and chamfer are modelled and fully determined by 3D simulation to meet the field uniformity requirement. The design consideration and simulation results are presented in detail.

INTRODUCTION

The far-infrared FEL project at NSRL, Hefei is under construction. The magnet system mainly consists of 11 dipoles and 20 quadrupoles. All the dipoles have C geometry and are symmetrical with respect to the mid-plane, which can be classified into two sorts depending on their own function, one is used to compress beam size and has rectangular cross section. The other is fan-shaped, including two kinds, which are used to bend 60 MeV electron beam for pi/6 rad and pi/4 rad respectively. In the following sections, the dipoles are respectively represented by its beam bending angle namely 0.3 rad, pi/6 rad and pi/4 rad. All the quadrupoles have the same geometry, the only difference between them is their working currents. All the magnets will work under DC condition, so that there is no need to consider the eddy current effect, hence, all the magnets can be casted by using material DT-4 for conveniently process.

The longitudinal length of magnets (including coil) is limited by installing space, which makes it hard to design to meet the field uniformity requirement. All the design including the pole shimming and the end chamfer, are obtained with the help of magnetic simulations in POSSION [1] and OPERA-3D [2].

DIPOLE MAGNETS

Three kinds of dipole magnets are firstly designed in POSSION to get the proper cross sections, which will then be optimized in accordance with the simulation results in OPERA-3D. The final cross sections of the three kinds of dipoles are shown in Fig. 1. The three numbers of each group from the left to right in Fig. 1 are respectively corresponding to three different dipoles 0.3 rad, pi/6 rad and pi/4 rad.

According to the physical design, the dipoles should have the same good field region (±17.5 mm) and the longitudinal integral field error requirement (<0.002), therefore, the pole geometries of the three dipoles are almost the same. The pole is trapezoidal shimmed to improve the good field region and reduce the pole width. The shimming scheme has been determined by repeatedly simulating in POSSION.

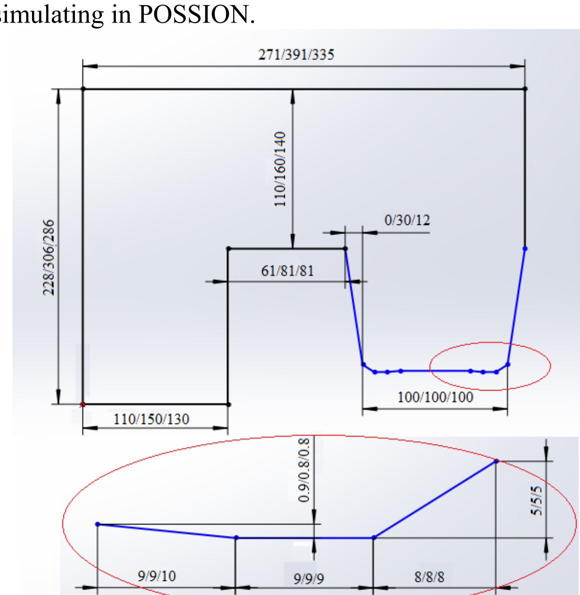

Figure 1: Cross sections (1/2) of 3 kinds of dipoles with units mm.

3D simulation needs to be carried out in OPERA to make sure the magnetic longitudinal length and the end chamfer. The methods of chamfer are usually harmonic analysis [3,4] and effective length [5,6]. This paper adopt the latter. According to the effective length method, the chamfer depth with units mm is given by.

$$y = \frac{L_{eff}(x) - L_{eff}(17.5)}{2}. \qquad (1)$$

Where, $L_{eff}(x)$ is the effective field length at x mm, which can be calculated by $\frac{\int B(x)dz}{B_0}$, B_0 is the central field strength.

The chamfer angle is chosen 45 degrees [7]. Generally, after the first chamfer the field quality still can't meet the field requirement, then the second even the third chamfer are needed. Finally, the optimum chamfer curves of y-x are obtained, as shown in Fig. 2.

The field quality is strongly influenced by the magnet length when it is short. Moreover, it is better to make the magnets longer for better field quality. So we can properly increase the magnetic effective length and reduce the length of coil package under the limitation of total

*Work supported by the National Nature Science Foundation of China under Grant Nos.11375176 and 10875118
hlxu@ustc.edu.cn

ISBN 978-3-95450-147-2

longitudinal length, which can improve the integral field distribution and reduce the current density.

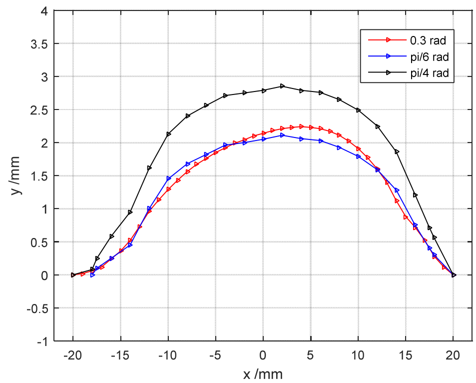

Figure 2: The last chamfer curve.

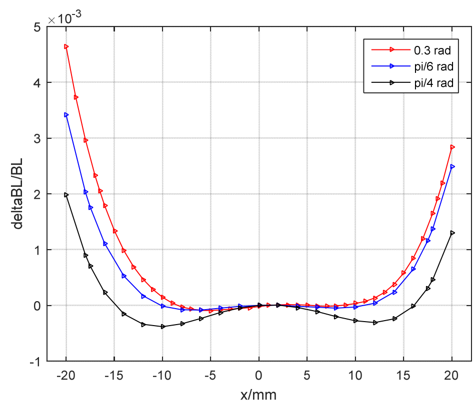

Figure 3: The distribution of integral field error.

The distributions of the longitudinal integral field error of three dipoles are given in Fig. 3. Obviously, the design can meet the field uniformity requirement. The main parameters of the dipoles are summarized in Table 1.

Table 1: Main Parameters of the Dipoles including 3kinds

Magnetic material	DT-4		
Pole gap[mm]	46		
Function	Compressing	Bending	
Bending angle[rad]	0.3	pi/6	pi/4
Bending radius[mm]	419.33	295.32	283.93
Effective field length [mm]	126	154	223
Central field[T]	0.2426	0.6835	0.7110
Magnet core length[mm]	78	100	170
Magnet and coil length [mm]	118	180	250
Current[A]	126.0	214.1	222.2
Conductor size[mm]	6.0×6.0 ,Φ4.0	7.5×7.5 ,Φ5.0	
Cross section of coil[mm]	20.0×76.0	40.0×94.0	
Current density[A/mm^2]	5.376	5.846	6.067
Coil resistance(20℃)[Ω]	0.023	0.039	0.043
Coil voltage(20℃)[V]	2.953	8.349	9.531
Number of turns (per pole)	3×12	5×12	
Number of water circuits	2		
Pressure drop [kg/cm^2]	3		
Power[kW]	0.37	1.07	1.27
Flow rate/water[l/min]	1.58	1.68	1.59
Water temperature rise[℃]	1.7	4.6	5.7

QUADRUPOLE MAGNETS

According to the requirements of physical design, the aperture radius should be at least 23 mm, the good field region 35 mm, the longitudinal length of the quadrupole including coil should be less than 65 mm, the requirement of the integral gradient field error is the same as the dipoles less than 0.002, and for the 60 MeV electron beam, the maximum magnetic gradient should reach 1450 Gs/cm. Each quadrupole magnet will be powered by an individual power converter.

The cross section of the quadrupole is designed and optimized in POSSION, especially the pole tip should be carefully optimized for good field quality, which is shown in Fig. 4. The pole tip geometry is made of a part of hyperbola and of straight lines. The high order harmonics with respect to the main field in units of 10^{-4} are b_6=3.34, b_{10}=1.36, b_{14}=2.64, which are calculated at a radius of 17.5 mm.

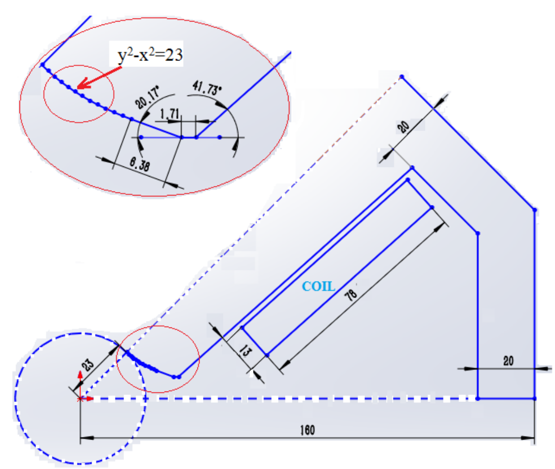

Figure 4: Cross section (1/8) of quadrupole magnets with units mm.

In 3D design, for the end of quadrupoles, the chamfer angle is usually 45 degrees [8], and the best chamfer depth is obtained by repeatedly simulating in OPERA-3D. The model of the quadrupole is shown in Fig. 5. As it's known that, the high order harmonics would affect seriously the distribution of the integral gradient field as the length of the magnet is very short, and make it hard to meet the field requirement by chamfer. For example, two magnets with only different lengths of 27 mm and 37 mm are simulated in OPERA-3D. The results are shown in Fig. 6. Only when the length reach 37 mm, the field quality can reluctantly satisfy the field uniformity requirement. So the length of the magnet is better to designed to be 37 mm, while the length of coil package should be 13 mm. The total length of magnet and coil is 62 mm.

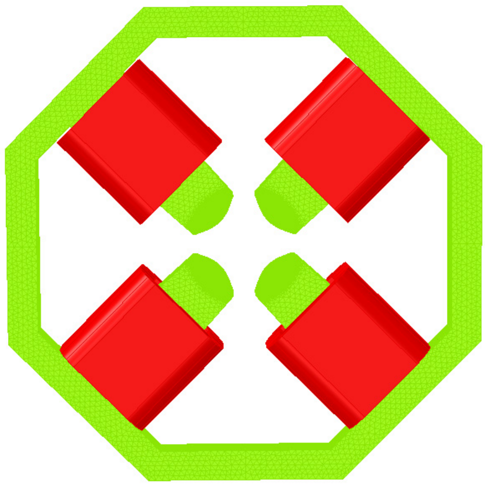

Figure 5: The model of the quadrupole simulated in OPERA-3D.

The field quality shown in Fig. 6 is not as good as expected, so the extra space should be reserved for auxiliary coils, as shown in Fig. 4. The main parameters of the quadrupoles are summarized in Table 2.

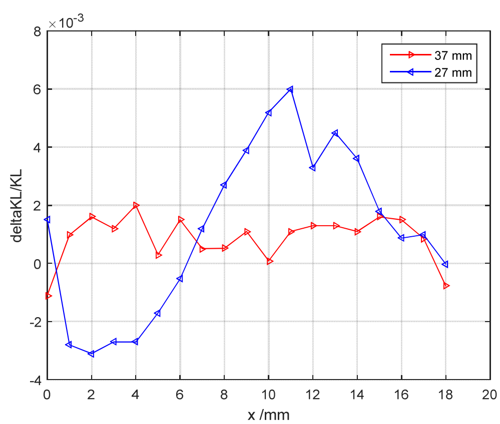

Figure 6: The distribution of the integral gradient field error in quadrupoles with longitudinal lengths of 27 mm and 37 mm.

Table 2: Main Parameters of the Quadrupoles, Maximum Operation Energy 60 MeV

Magnetic material	DT-4
Aperture radius[mm]	23
Magnetic effective length[mm]	62
Field gradient[Gs/cm]	1450
Field at a pole tip[T]	0.34
Magnet core length[mm]	37
Magnet core height[mm]	320
Magnet core width[mm]	320
Magnet and coil length [mm]	63
Conductor size[mm]	4.0×4.0,Φ2
Cross section of coil[mm]	13.0×78.0
Current density[A/mm^2]	4.49
Current[A]	57.73
Coil resistance（20℃）[Ω]	0.070
Coil voltage（20℃）[V]	4.061
Number of turns per pole	3×18
Number of water circuits	4
Pressure drop [kg/cm^2]	3
Power[kW]	0.234
Flow rate/water[l/min]	0.277
Water temperature rise[℃]	3.2

CONCLUSION

The design of the main magnets of the far-infrared FEL at NSRL was introduced, and the results of the field quality simulated in POSSION and OPERA-3D were showed and discussed, which indicated that the design parameters listed in Table 1 and 2 can meet the field requirement.

REFERENCES

[1] "SFCODES.DOC", Los Alamos National Labs, 1987.

[2] "Opera-3d User Guides and Reference Guides", Vector Fields, Nov. 2011.

[3] Z.S. Yin, Y.Z. Wu et al., Nucl. Instrum. Methods Phys. Res.A, vol. 573, no. 3, pp 323, 2007.

[4] Zhu Yingshun et al., "Design and end chamfer simulation of PEFP beam line curved dipole magnets", Chinese Physics C, vol. 35, no. 7, pp 684-688, 2011.

[5] W. Chen, C.T. Shi et al., "End Chamfer Study and Field Measurements of the BEPC II Dipoles". Proceedings of PAC 2005, Knoxville, USA. pp 919.

[6] Pont M, Boter E, Lopes M et al. ,"Magnets for the Storage Ring ALBA". Proceedings of EPAC 2006, Ediburgh, Scotland. pp 2562.

[7] Yin Zhaosheng et al., "Principle of Harmonic Shim and Application for conventional Accelerator Magnets", Atomic Energy Science and Technology, vol. 47, no. 2, pp 277-286, 2013.

[8] A. Milanese et al, "Design of the Main Magnets of the SEAME Storage Ring", Proceedings of IPAC 2014, Dresden, Germany.

ISBN 978-3-95450-147-2