MAGNETIC FIELD DESIGN OF THE BAPS HIGH PRECISION QUADRUPOLE MAGNET

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Abstract

The Beijing Advanced Photon Source (BAPS) is a high performance light source planned to be constructed in China. High precision small aperture quadrupole magnets are required in the BAPS storage ring, which need extremely high mechanical accuracy. Instead of the conventional manufacture method, the coils are comprised of several U-shaped solid copper sheets. So two-piece structure of the iron core can be adopted to reduce assembly error and improve the poles symmetry. Design considerations, 2D and 3D magnetic field calculations are presented in detail, and the needed mechanical precision is estimated according to the error field analysis.

INTRODUCTION

The Beijing Advanced Photon Source (BAPS) is a storage ring-based light source to be built in China. It is designed to provide a 5 GeV low-emittance electron beam and high-brilliance coherent radiation. The natural emittance is recently reduced to several tens of picometers to approach the so-called ultimate storage ring [1].

The lattice design of BAPS storage ring calls for several types of small aperture multipole magnets with high field quality. High precision quadrupole magnet is one of the three R&D magnets, and its design requirements are listed in Table 1.

Table 1: Design Requirements

Parameter	Unit	Value
Magnetic length	mm	250
Bore diameter	mm	25
Field gradient	T/m	46.9
Good field radius	mm	10
Multipole field content		$<1\times10^{-4}$

The field quality requirement is stringent in such a small aperture quadrupole, which brings great challenges to the magnetic design, magnet fabrication and field measurements. The required positional accuracy of pole tip is estimated to be a few microns, which is too tight to be met by normal magnet manufacturing methods.

DESIGN CONSIDERATIONS

Usually, the yoke of the quadrupole magnet is divided into two or four pieces for installation of excitation coils and vacuum chambers. The four coils are wound separately from hollow conductor using winding mandrel, impregnated with epoxy resin, and then assembled onto each pole. Finally the two or four pieces of cores with excitation coils mounted are assembled to form the whole magnet. Using this conventional method, four-piece structure should be used for the BAPS quadrupole magnet. However, this will introduce large assembly error and non-symmetry of the four pieces. Thus, the required positional accuracy can not be achieved. Though the field quality can be improved using additional methods such as chamfers and nose pieces after the manufacture of the magnet is completed [2-3], this process needs field measurement and several iterations, and can not guarantee the final achievement of the field specification. Since there are several hundreds of quadrupole magnets in the BAPS storage ring, novel magnet design and fabrication technique should be adopted.

In theory, one-piece structure for the iron yoke which can keep a precise four-fold symmetry and avoid assembly error is a good choice. However, it is not convenient to install the vacuum chamber. So a two-piece structure for the iron core is used.

The technical difficulty of this design lies in the coil fabrication and installation, since conventional pre-wound coil can not be assembled onto the pole through the small pole gap. Similar to the integral magnetic quadrupole in the nuclear microprobe system [4], the coils are made of several U-shaped solid copper sheets. The turns of the coils are determined so that the electrical parameters for the power supply are reasonable.

DESIGN OF CROSS SECTION

The cross section of the BAPS quadrupole magnet is designed and optimized according to the 2D magnetic field calculation performed by OPERA-2D from Cobham Technical Services [5]. The main goal is to obtain desired field strength, good field quality and to avoid serious magnetic saturation in the iron yoke.

The magnet yoke consists of two pieces made of solid iron blocks, and soft iron DT4 is chosen as the yoke material for reason of cost and ease of machining. Good mechanical precision is anticipated to be achieved by wire cutting process. The magnet cross section has a four-fold symmetry, so in ideal case only systematic normal multipole field contents exist. The pole profile consists of ideal hyperbolic curve and additional pole shim, and each coil consists of 56 turns of flat copper sheets with 40×1.2 mm^2 cross section. Small current density is adopted to efficiently dissipate the heat and to control the temperature rise in a small range. So the water cooling system is not needed, which simplifies the mechanical design.

The field quality is specified by field harmonics, which are defined as coefficients in the Fourier expansion of the radial or azimuthal component of the magnetic field. The

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relative strengths of the harmonics are usually expressed in unit of 10^{-4} compared with the fundamental field.

In 2D simulation, only a quarter of the magnet is modeled. The magnetic flux lines distribution and magnetic flux density distribution are shown in Fig. 1 and Fig. 2, respectively.

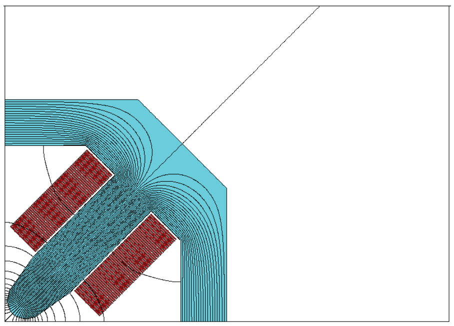


Figure 1: 2D Magnetic flux lines.

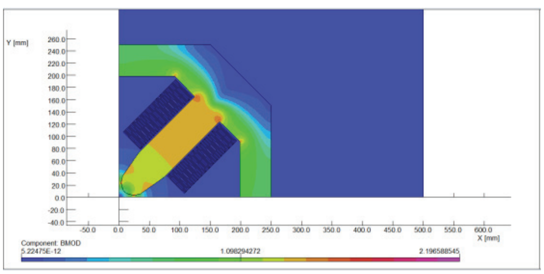


Figure 2: Magnetic flux density distribution.

Table 2 lists the harmonic field content normalized to the quadrupole field.

Table 2: 2D Field Harmonics @ r=10mm (unit)

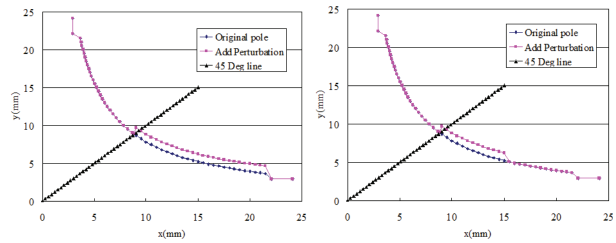
n	bn
2	10000
6	1.39
10	0.19
14	0.003

The 2D field quality is quite good. The calculated multipole field contents normalized to the quadrupole field are well below one unit except b6 with a value of 1.39 unit, which can compensate part of the 3-D fringe field effect.

2D ERROR FIELD ANALYSIS

To study the sensitivity of the position error on the field quality and determine machining tolerances needed to meet the specifications, various kinds of perturbations are added to the pole profile and magnetic calculations are performed. To simplify the calculation and for ease of comparison, top-bottom symmetry of the magnet is assumed, and the left part of the magnet remains unchanged. Therefore, the impact of mechanical error on lower order field harmonics can be investigated. In calculation, the maximum position error is 0.01mm.

Two extreme cases in which the position errors exist in different parts of the pole hyperbolic curve are shown in Fig. 3.



Case 1 Case 2

Figure 3: Two extreme cases of position errors.
(For clarity, the actual error is enlarged by 100 times)

The calculated multipole field contents at a reference radius of 10 mm are listed in Table 3.

Table 3: Field Harmonics b_n @ r=10mm (unit)

n	Case 1	Case 2	Case 3 Randon error (typical value)	Case 4 Pole shim error
2	10000	10000	10000	10000
3	4.29	4.03	-1.10	0.2
4	-3.81	-3.49	1.20	-0.01
5	2.33	1.99	-1.01	-0.14
6	0.80	1.12	1.71	1.38

Comparing the results of Case 1 and Case 2, it can be seen that about one half of the pole near the 45 deg line contributes most of the field errors. The result of Case 3 indicates that, to achieve the required field quality, the mechanical precision of pole central part should be strictly controlled to be within 5 microns. The mechanical precision of other part of the pole tip and the shim can be relaxed.

3D MODEL AND MAGNETIC PERFORMANCE

3D magnetic performance is investigated using OPERA-3D/TOSCA. Because of the symmetry, it is sufficient to solve the magnetic field using only one eighth of the model. The post processor of OPERA-3D can replicate the model to obtain the complete magnet. The end chamfer size is optimized by 3D simulation to fulfill the field harmonics requirement.

The OPERA-3D model is shown in Fig. 4.

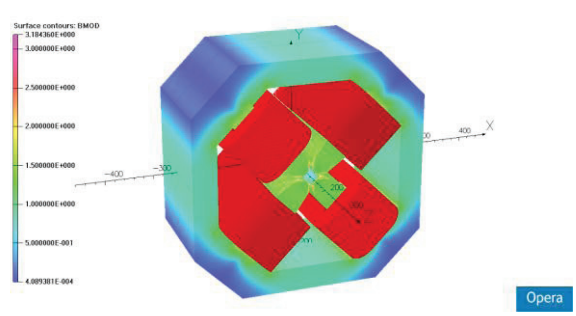


Figure 4: OPERA-3D model.

To meet the central field gradient and magnetic length requirement, the needed Ampere-turns per pole is 3000 and the required yoke length is 240 mm. The multipole field contents for un-chamfered magnet are obviously larger than that in 2D case because of the fringe field effect. A chamfer of 1.5mm×60° at the pole end is sufficient to minimize all the systematic harmonics (see Fig. 5). The calculated integral field harmonics without and with end chamfer are shown in Table 4.

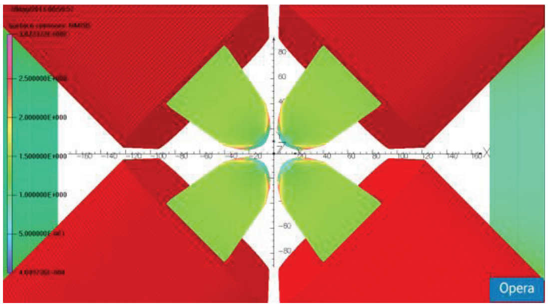


Figure 5: Chamfered pole end.

Table 4: Integral Field Harmonics bn (unit)

n	Un-chamfered	Chamfered: 1.5mm×60°
2	10000	10000
6	-8.02	-0.12
10	0.79	0.05
14	-0.26	-0.24

The field quality of the chamfered magnet meets the requirement. The magnetic flux density is mainly smaller than 1.5T in the iron, and the magnet works in the linear region of the excitation curve. Main parameters of the quadrupole magnet are summarized in Table 5.

Table 5: Design Parameters

Parameter	Unit	Value
Ampere-turns per pole	AT	3000
Coil turns per pole		56
Excitation current	A	53.6
Conductor size	mm	40×1.2
Current density	A/mm^2	1.1
Resistance of whole magnet	Ω	0.07
Inductance of whole magnet	H	0.086
Voltage drop	V	3.7
Joule loss	W	199.3
Core width and height	mm	500×500
Core length	mm	240

CONCLUSION

The magnetic field design of the BAPS quadrupole magnet has been finished. To meet the stringent field harmonics requirement, unconventional design of the coil is adopted. The magnetic performance of the chamfered magnet meets the requirement. However, the actual field quality depends on the material property, fabrication tolerance and assembly error. The position error of the central part of the pole has a great influence on the field quality, and its manufacture precision should be better than 5 microns.

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REFERENCES

[1] XU Gang, JIAO Yi, "Towards the ultimate storage ring: The lattice design for Beijing Advanced Photon Source," *Chinese Physics C*, 2013, 37 (5): 057003 (1-8)
[2] M. Rehak *et al.*, "Design and Measurement of the NSLSII Quadrupole Prototypes", *Proceedings of PAC09*, Vancouver, BC, Canada, pp: 142-144
[3] T.V. Rybitskaya *et al.*, "Quadrupole Harmonics Tuning by Nose Pieces," *Proceedings of RUPAC2012*, Saint-Petersburg, Russia, pp: 489-491
[4] V.A. Rebrov *et al.*, "The new design of magnetic quadrupole lens doublet manufactured from a single piece," *Nucl. Instrum. Methods in Phys. Res. B*, 2007, 260: 34–38
[5] OPERA, Vector Fields Software, Cobham Technical Services, http://www.vectorfields.com

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