DESIGN AND EXPERIMENT OF THE BEPCII IR CONVENTIONAL DUAL APERTURE QUADRUPOLE

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Abstract

The quadrupole magnet Q1a is one of the final horizontal focus quadrupoles for the Beijing Electron-Positron Collider Interaction Region (BEPCII IR). The BEPCII IR lattice design specification calls for a very high field quality for the quadrupole magnet. The Q1a is a conventional dual apertures quadrupole magnet. The required integral quadrupole strengths in two apertures are the same. This magnet is a septum quadrupole with high current density and solid core. 2D pole contour optimization and pole end chamfers are used to minimize harmonic error. The design methods, experiment results and magnet performances are described in this paper.

REQUIREMENTS

The Q1a magnet is a conventional dual aperture quadrupole. This magnet is a septum quadrupole with high current density and solid core. High field quality is required for Q1a. Table 1 gives a summary of design requirements.

Table 1: Design requirements for Q1a

Field gradient for each aperture		7.0 T/m
Effective length		0.2 m
Distance between two aperture centers		196.7 mm
At the inboard end	beam stay clear	95.5×53.3 mm
	beam separation	185.30 mm
At the outboard end,	beam stay clear	99.9×51.4 mm
	beam separation	203.70 mm
Allowed multipole B_n/B_2 @53.45mm		$\leq 5\times10^{-4}$

MAGNET DESIGN

The Q1a inboard end is 3.55 m from the intersection point. The e^+-e^- beam separation is very small, about 185.3 mm apart at the inboard end of Q1a. The shape of beam stay clear in Q1a is changing and beam center is shifting over the magnet. In this case, the good field region of 106.9×53.3mm (H×V) is required for Q1a. These considerations led to the selection of “two in one” structure, the two quadrupole parts with bore radius of 58 mm were combined very tightly together and separated only by the coils with high current density. Figure 1 shows the Q1a close section. The magnet can be opened and reassembled from its mid plane to install vacuum chambers. The core consists of two half cores and It is easy for the coils to be installed into the half core. The water-cooled copper coils and solid core are selected. To achieve the required field strength in this tight package, a high current density of 52.2 Amps/mm^2 is required. The coil cooling system has the moderately more water circuits to provide ample cooling water and lower pressure drop to limit water velocity.

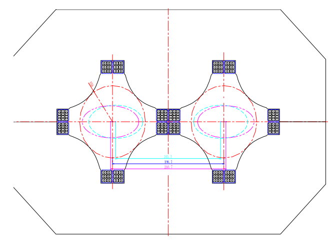
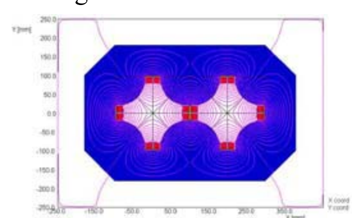


Fig. 1 the close section of Q1a

The 2D field distribution shown in Figure 2 gives the magnetic field flux map calculated with OPERA code. The field distribution is almost the same in two apertures see Figure 3.



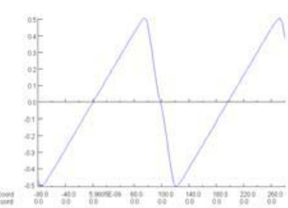


Fig.2 Magnetic field flux map Fig.3 Field distribution

There are some special considerations in the magnet design. As the magnet have large aperture and short core length, the field end effect shall be very serious for the integral field quality. Notice that, the core structure for each quadrupole part is not symmetrical. It leads that non-systematic multipole field appears. To reduce above effects, the removable pole ends with chamfer and shim are used in the magnet. Since the septum coil position is

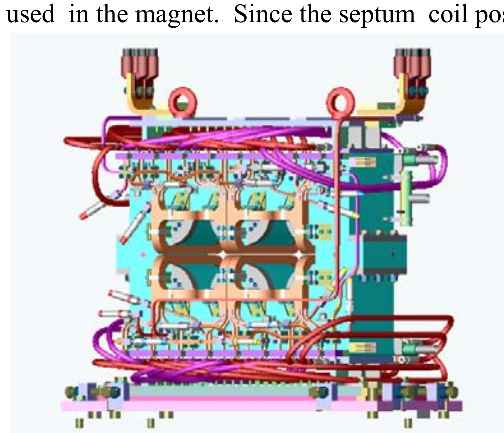


Fig. 4 Side view of Q1a

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very close to the aperture, the precision of 0.5 mm for the coil conductor position is required to decrease the influence for filed distribution. Because of the high current density used in the coils, a special coil protection device of voltage fleet patrol interlock circuit is used, besides the flow switch and thermal switch. It can find the coils over heat fleetly and turn off power supply within 0.5 second. Based on the consideration mentioned above, a much more complex magnet structure is designed. Figure 4 is the magnet side view. Table 2 summarizes the Q1a design parameters.

Table 2: Design parameters for Q1a

Field gradient for each aperture	7.0 T/m
Core length	0.2 m
Bore radius	58 mm
Distance between two aperture centers	196.7 mm
Required good field region	106.9×53.3 mm
Design excitation per pole	9463.15Amp-turns
Turns per pole	6
Design current	1577.2 A
Conductor size	7.5×5, ∅3, mm
Current density	52.2 A/mm^2
Magnet resistance	0.031 Ω
Magnet inductance	0.0003 H
Magnet power	77.1 kW
Cooling circuits per pole	3
Design water pressure drop	2 kg/cm^2
Flow velocity	4.54 m/s
Magnet flow	0.77 l/s
Temperature rise	23.4 °C

MAGNET MEASUREMENT AND EXPERIMENT RESEARCH

Excitation Test

The excitation test of Q1a up to full current of 1577 A corresponding to the field gradient 7 T/m succeeded. The temperature rise of the magnet coils was less than 25°C. An experiment of cut off the water supply was performed when the magnet operating at full excitation. The experiment results show that, after the water supply cut off, the coil protection system shut down the power and let the current reduced rapidly to 30% of full value within 0.05 second and delete them to zero within 0.07 second.

Optimum Shape of Q1a Pole End Chamfer

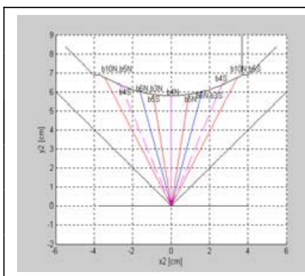
Before the end chamfering, there are some much higher harmonic contents. Te field harmonic contents were measured with rotating coils (see Figure 5). Table 3 gives the measured harmonic contents at R53.45 mm before the Q1a pole end chamfering. The dodecapole (b_6) and 20-pole (b_{10}) are caused by the end effect. The sextupole (b_3) and octopole (b_4) are from the magnet not symmetrical structure and manufacturing error.

Fig. 5 Harmonic measurement of Q1a

Table 3: Harmonic contents@53.45 before end chamfer

n	Left aperture	Right aperture
3	7.78×10^{-4}	8.16×10^{-4}
4	2.56×10^{-4}	6.52×10^{-4}
5	3.00×10^{-4}	6.09×10^{-5}
6	6.09×10^{-3}	6.60×10^{-3}
10	9.71×10^{-4}	9.51×10^{-4}
14	1.6×10^{-5}	4.8×10^{-5}
18	8.51×10^{-5}	1.11×10^{-4}

The end effect will be counteracted by the pole end chamfer. The width of effectual end chamfer should be larger than the multipole zero shim positions. According to the harmonic end shim analysis results, the zero shim positions for each multipoles are different which shown in Figure 6. For Q1a, to reduce both normal dodecapole (b6) and 20-pole (b10), the pole end chamfer width should be large than $2\times0.6R_{bore}$.



	x2	Angle
B3n	-0.2781R	15°
B3s	0.2781R	-15°
B4n	0	0°
B4s	±0.4551R	±22.5°
B6n	±0.2781R	±15°
B10n	±0.1604R, ±0.5921R	±9°, ±27R

Fig. 6 Zero shim points in coordinates (x2,y2)

The chamfer depth should satisfy the requirements for reducing b_6 and b_{10} close to zero. Figure 7 is the experiential curves of Q1a end chamfer, which shows the normalized B_6/B_2 and B_{10}/B_2 @53.45mm vs the end chamfer depth. From Figure 7, the optimum end chamfer shape of 7 mm depth with 57° angle was found for Q1a. After using this end chamfer, the normalized dodecapole B_6/B_2 and 20-pole B_{10}/B_2 are reduced to 4.5×10^{-4} and 2.5×10^{-4}, respectively. Figure 8 shows the optimum shape of the Q1a pole tip end chamfer.

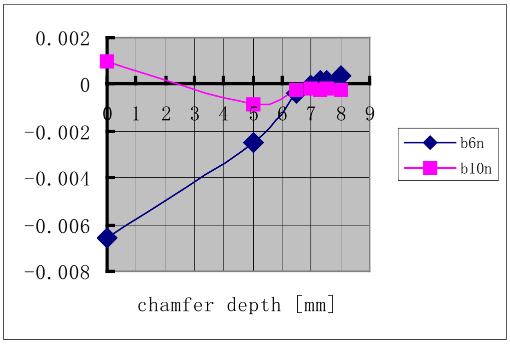


Fig. 7 Result of chamfer depth experiment

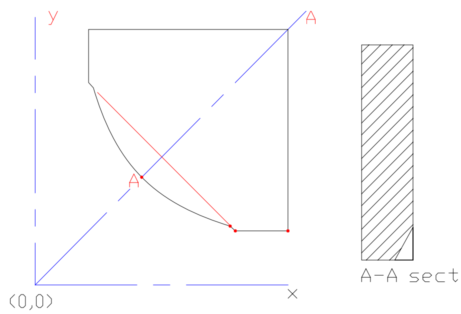


Fig 8. The optimum shape of Q1a end cham

Discovery of Skew Dodecapole (b_6s) in Q1a

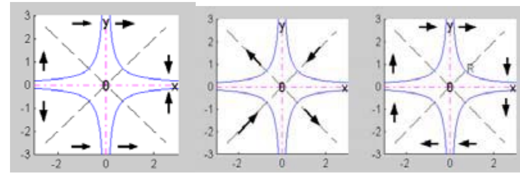
In the preceding pole end chamfer experiment, the detail data are shown in Table 4. We notice that the dodecapole (b_6) have a different magnitude and phase when the depth changed. Specially, there is a minimum value of about 5×10^{-4} with 90° phase which surpasses the main quadrupole phase when the chamfer depth is 7 mm. The results mean that there is an obvious skew dodecapole (b_6s) in this septum quadrupole.

Table 4: Discovery of skew dodecapole in Q1a

Chamfer depth [mm]	5	6.5	7	7.3	7.5
B_6/B_2@53.45 [10^{-4}]	25	6.6	4.54	5.7	5.79
Angle of b_6 [°]	169	125	92.1	74.4	69.4
Normal b_6(b_6n) [10^{-4}]	-25	-4.0	-0.44	1.35	1.78
Skew b_6 (b_6s) [10^{-4}]	3.63	5.25	4.52	5.54	5.51

End Shim for Non-systematic Multipoles

After end chamfering, there are some non-systematic multipoles, such as sextupole b_3n, skew octopole b_4s (only in right aperture) and skew dodecapole b_6s, should be reduced. According to the end shim harmonic analysis results for the quadrupole end shim, the methods for reducing b_3n, b_4s and b_6s are shown in figure 9 (a), (b) and (c), respectively. The removable pole ends should be shifted their positions a little along the arrow showed in Figure 9. In the real case, the better way is integrating the three different shift requirements together.



(a) For b_3n shim (b) for b_4s shim (c) for b_6s shim
Fig. 9 Q1a End shim for Non-systematic multipoles

Magnetic Influence Between Two Apertures

Considering that the field nearby septum coils is excited by the common septum coils, the test for the magnetic influence between two apertures was performed by the method of measuring the field in one aperture while disassembling some removable pole end in another aperture. The test results show that the field change on the harmonic contents is very slight even the field in another aperture was changed. Distinctly, such results are only happened in unsaturated core.

Final Field Quality of Q1a

After above pole end chamfering and shiming, the final harmonics of Q1a at R53.45 mm are shown in Table 5.

Table 5: Harmonic contents@53.45 after end shim

n	Left aperture	Right aperture
3	3.40×10^{-4}	3.46×10^{-4}
4	2.92×10^{-4}	2.77×10^{-4}
5	1.83×10^{-4}	1.05×10^{-4}
6	2.92×10^{-4}	3.63×10^{-4}
10	2.41×10^{-4}	2.29×10^{-4}
14	7.62×10^{-5}	7.01×10^{-5}
18	1.38×10^{-4}	1.26×10^{-4}

SUMMARY

The dual aperture quadrupole Q1a for BEPCII Interaction Region was designed, made and tested elaborately. The field qualities of Q1a satisfy the severe requirements. The magnet operation is in security. We will continue to improve the performance of the magnet

ACKNOWLEDGMENTS

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