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Y. DOI and A. KIMURA

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Superconducting Magnets in the Interaction Region of the KEK B-Factory

K. TSUCHIYA, T. M. KOBAYASHI, T. HARUYAMA, Y. AJIMA, Y. DOI

KEK, National Laboratory for High Energy Physics,
Tsukuba, Ibaraki, Japan

A. KIMURA

The Graduate University for Advanced Studies
Tsukuba, Ibaraki, Japan

Abstract---The interaction region of the KEK B-Factory requires four superconducting magnets, two dipoles and two quadrupoles. Due to their detrimental effect on the experimental detector, the leakage field of the magnets needs to be as small as possible. For achieving this smaller leakage field, we have designed special iron-free dipoles with an active shield coil. Due to the active shield method, the stray field of the magnets is suppressed to a level of 10 mT outside the radius of 0.25m. The quadrupoles are also iron-free magnets, but have no shield coil. This paper presents the results of the two- and three-dimensional electromagnetic studies along with the structure of these magnets.

I. INTRODUCTION

An asymmetric two-ring electron-positron collider for B-physics, the KEK B-Factory [1], is now being planned as one of the future projects at KEK. In this kind of collider, to obtain the highest luminosity is an important subject, and a large number of parameters have been carefully selected in the design of the interaction region (IR). The present IR design [2] of the B-factory is shown in Fig. 1. The nearest accelerator elements to the interaction point are separation bending magnets (BR and BL) which are followed by final focus quadrupole magnets (QR and QL). Since these magnets must be positioned perfectly inside the experimental detector, interference with the detector elements is a large problem, imposing severe design constraints on the magnets: small leakage field, small size, etc. For the separation bending magnets, we cannot adopt conventional iron magnets, since the iron yoke would disturb the solenoid field in the tracking detector region. Permanent magnets may be one possible candidate. However, they have a disadvantage regarding fine adjustment of the field strength. We are therefore designing iron-free superconducting dipoles with active shield coils [3], although they would require a slightly large amount of magnetomotive forces. At present, the final focus quadrupoles are being designed as iron-free superconducting magnets having no active shield coil, because the outer field of the quadrupoles decrease more rapidly and their positions are more distant from the tracking detector than in the case of dipole magnet.

In the following sections we mainly describe the right-side magnets (BR and QR); the values regarding the left side magnets (BL and QL) are given in parentheses, since the basic structure of the left-side magnets is the same as that of the right-side magnets.

Fig. 1. Layout of the accelerator elements in the experimental detector. BR and BL are superconducting dipoles and QR and QL are superconducting quadrupoles.

II. DIPOLE MAGNET WITH ACTIVE SHIELD COIL

A. General design

In designing the dipole, we took into account the following requirements and constraints:

1. The warm bore diameter of the dipole should be 80 mm (110 mm).
2. The operating field is 0.78 T (0.85 T) and the effective length is 0.4 m (0.46 m).
4. The outer leakage field of the dipole should be less than 20 mT at a radius of 250 mm.
5. The outer diameter of the magnet should be less than 310 mm (420 mm).
6. The cables for the main and shield coil should be the same.
7. The main and the shield coil should be excited in series.

The magnet design incorporates several features which are different from that of other accelerator superconducting magnets [4]-[6]. We use an active shield coil to reduce the outer leakage field, no iron yoke to prevent field distortion of the detector solenoid, a modest operating field (0.78T (0.85T)), and a relatively large warm bore (80 mm(110mm))

TABLE 1
PARAMETERS OF THE ACTIVE SHIELD DIPOLE MAGNETS

	BR	BL	
Central field	0.78	0.85	T
Current	4398	4013	A
Main coil			
Inner diameter	130	170	mm
Outer diameter	145.6	185.6	mm
Shield coil			
Inner diameter	171	237	mm
Outer diameter	186.6	252.6	mm
Overall length of the coils	521	617	mm
Collars outer diameter	240	312	mm
Integrated field uniformity (at $r = 30$ mm)			
B_3L/B_1L	$< 5 \times 10^{-4}$	$< 5 \times 10^{-4}$	
B_5L/B_1L	$< 3 \times 10^{-5}$	$< 3 \times 10^{-5}$	
Effective magnetic length	400	460	mm
Max. field on the conductor	2.9	2.4	T
Outside field of the magnet (at $r=250$ mm)			
Stored energy	8.3	16.3	kJ
Longitudinal magnetic forces	28.6	49.4	kN
Resultant of magnetic forces per meter length in the coil quadrant			
F_x (horizontal)	16.3	26.0	kN/m
F_y (vertical)	-72.5	-90.2	kN/m

to reduce any unwanted beam background near to the interaction region. The other parameters of the BR and BL magnets are listed in Table 1.

Fig. 2 shows a cross section of the BR magnet in a horizontal cryostat. The inner diameter of the warm bore is 80 mm (110 mm) and the outer diameter of the vacuum vessel is 310 mm (420 mm). From the inside to the outside, the main components of the magnet are: a tube which bears correction coils or steering coils and is at the same time the inner wall of the helium vessel, a stainless-steel support cylinder which withstands the inward electromagnetic force acting on the main coil, the main coil, the FRP(G-10) spacer, the shield coil, the stainless-steel collars, and the outer helium vessel.

The main coil is made of one layer of the winding, and the $\cos\theta$ configuration is approximated by using two copper wedges. The shield coil is also a one-layer winding and has approximately a $\cos\theta$ configuration. However, the current

direction is opposite to that of the main coil. The size and position of the wedges in the coils are determined so as to minimize the allowed 6-pole, 10-pole and 14-pole components in the field by a two-dimensional field calculation. In this design, the stray field of the magnet could be suppressed to a level of 5 mT (12 mT) outside a radius of 250 mm.

The support cylinder is made of high manganese steel with a high tensile strength and a smaller thermal contraction coefficient than regular stainless steel to support the inward electromagnetic force on the main coil. The thickness of the cylinder is 5 mm. The correction (steering) coil is made by a multiwire technique with superconducting wire of ~ 0.4 mm.

B. Conductor

The coils are wound from a NbTi superconducting cable, which is commonly used in many accelerator magnets. This is a flat, keystoneed 23-strand cable of the Rutherford type. The bare cable width is 7.80 mm and its average thickness is 1.26 mm, with a keystone angle of 1.2 degrees. Each wire is 0.680 mm in diameter, containing high-homogeneity NbTi filaments ~ 6.5 μ m in diameter, and coated with 1 μ m silver-tin solder. The copper-to-superconductor ratio is 2.25: 1 and the critical current of the cable at 4.2 K is more than 6,000 A at 5 T. The residual resistivity ratio of the stabilizing copper is higher than 90. The insulation consists of a double layer of 25 μ m Kapton tape and a layer of 50 μ m Kapton with about 25 μ m of B-stage epoxy on the outside surface.

C. Coil design

The two-dimensional coil cross section was designed using a computer program which uses an analytical expression for computing the field harmonics [7]. The selected one has a total of 83 turns (104 turns) in each quadrant in two coils. The main coil has 47 turns (61 turns) and the shield coil has 36 turns (43 turns). In this design, the main coil produces a field of 1.92 T (1.76 T) in the aperture and the shield coil cancels the field down to 0.78 T (0.85 T), while the outer leakage field is suppressed to the level of 5 mT (12 mT) outside a radius of 250 mm.

Fig. 2. Cross section of the BR magnet in the horizontal cryostat.

Fig. 3. Flux-line plots of the BR magnet.

TABLE 2
EFFECT OF RANDOM ERRORS

Parameters changed	B mT	b_3 10^{-4}	b_5 10^{-4}	B_{out} mT
Radius of main coil	+2.4	0.00	0.00	-0.28
Radius of shield coil	-1.1	-0.00	0.01	0.21
Pole angle of main coil	0.2	-0.75	-0.38	0.03
Pole angle of shield coil	-0.2	0.11	0.12	-0.03
Wedge No. 1	0.5	8.53	1.67	0.06
Wedge No. 2	0.6	3.08	-1.22	0.07
Wedge No. 3	-0.2	-1.89	-0.28	-0.03
Wedge No. 4	-0.3	-1.58	0.08	-0.06
Coil block No. 1	-1.3	-8.47	-1.21	0.16
Coil block No. 2	-0.8	3.76	2.38	0.09
Coil block No. 3	-0.3	4.69	-1.17	0.03
Coil block No. 4	1.3	-16.49	4.74	-0.19
Coil block No. 5	1.5	-18.43	3.91	-0.23
Coil block No. 6	1.1	-20.02	4.61	-0.15

The values show the effect of 0.1 mm change in the given parameter on the dipole field strength, the field harmonics and the outside field strength at $r=200$ mm.

The field distribution was also studied using the computer code OPERA-2D. In Fig. 3 we show a flux-line plot for the BR magnet.

In the actual magnet, the design parameter of the coil may turn out to be somewhat different from the desired value. This would cause a change in the field harmonics and the leakage field. Therefore, the effects of these errors in various cases were also estimated assuming the basic four fold symmetry in the coil geometry. In Table 2 the results for the BR magnet are listed for a nominal 0.1 mm variation in the given parameter. The counting of the wedges and coil blocks in the table is done by starting from the inner coil and from the midplane of each coil. The reference radius of the harmonics is 30 mm.

This magnet is so short compared to other accelerator superconducting magnets that the effect of the end parts seems to be very important. We therefore performed three-dimensional calculations to investigate the field distribution and to optimize the coil end shape. Fig. 4 shows the leakage field distribution of the BR magnet in the y-z plane. At the end part of the coil, the leakage field grows slightly larger due to the separation of the coils. However, the contour line of 5 mT is still within a radius of 250 mm.

Fig. 4. Contour map of the leakage field in the Y-Z plane.

Fig. 5. Electromagnetic forces in the coils of the BR magnet at 0.78 T.

Since the maximum field reached in the windings is an important parameter for the superconducting magnet, we studied it in two- and three-dimensional calculations. The computation shows that the maximum field occurs on the outer surface of the main coil at the median plane, where the flux line density is highest, and the strength is 2.9 T (2.4 T).

D. Electromagnetic force

The magnetic force study was performed using the program OPERA-2D. In Fig. 5 we show the direction and magnitude of the total force in each coil block. The arrows represent the size and the magnitude of the force. At a central field of 0.78 T (0.85 T), the resultant horizontal force of the main coil, which is directed inward, is ~ 108 kN/m (~ 83 kN/m), and that of the shield coil, which is directed to the outward, is ~ 124 kN/m (~ 112 kN/m).

Fig. 6. Magnitude of the electromagnetic force on each turn of the BR magnet. F_r^{in} and F_r^{out} correspond to the forces of the main and the shield coil, respectively.

The radial and azimuthal components of the magnetic force on each turn were also calculated using OPERA-2D. The results are shown in Fig. 6. The turn numbers are counted from the mid plane. Though the radial forces on the turns in the main coil and the shield coil have almost the same strength, the directions are opposite: the radial component of the main coil squeezes it inward and that of the shield coil expands it outward. This behavior of the azimuthal components of both coils is extremely different from that of the usual superconducting dipoles. In this kind of active shield dipole, the azimuthal component does not increase with the number of turns. Therefore, the accumulation of the azimuthal compression force is very small.

By using the calculated azimuthal force and ignoring the friction between the coil and the collar, we can estimate the minimum stress necessary to prevent coil motion at the pole and the maximum coil deflection when energized. The calculated required pre-stress of the main coil is 4.7 N/mm^2 and the maximum coil deflection in the azimuthal direction is 0.019 mm . Here, we assumed a conductor modulus of $3.9 \times 10^3 \text{ N/mm}^2$. The corresponding values for the shield coil are almost one order of magnitude smaller.

III. QUADRUPOLE MAGNET

The design of the final focus quadrupole is conditioned by the following points:

1. The warm bore diameter should be 120 mm (160 mm).
2. The operating field gradient is 16 T/m and the effective length is 0.5 m .
3. The maximum allowable outer size of the magnet, including the cryostat, is 400 mm (520 mm).

The magnet was designed as an iron-free quadrupole having no shield coil. Fig. 7 shows the cross section of the QR magnet in the horizontal cryostat. The coil is wound using cable with the same specifications as that for the

Fig. 7. Cross section of the QR magnet.

dipoles and is made of one layer of the winding. The winding is divided into blocks of 23 and 8 turns with a copper wedge. The size of the wedge was chosen so as to minimize the allowed 20-pole and 28-pole components in the field. The QL magnet consists of two layers of winding due to its larger coil diameter. The inner layer has two blocks of 31 and 11 turns and the outer layer has also two blocks of 33 and 12 turns. The main parameters of the quadrupoles are listed in Table 3.

IV. CONCLUSION

Four superconducting magnets, two dipoles and two quadrupoles, for the interaction region of the KEK B-Facility were designed. The dipoles are iron-free and have an active shield coil. This novel structure is a unique solution to the requirement for a small leakage field. Due to the structure, the magnetic forces acting on the coils are very different from that of the usual superconducting dipoles and the required magnetomotive force of the coils is slightly larger. However, these difficulties can be overcome. Although the quadrupoles have also been designed as iron-free magnets, they don't have an active shield coil, since the small size requirement was given priority.

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TABLE 3
PARAMETERS OF THE QUADRUPOLE MAGNETS

	QR	QL	
Field gradient	16	16	T/m
Current	3174	2330	A
Coil			
Inner diameter	170	239	mm
Outer diameter	185.6	271.6	mm
Overall length of the coils	571	609	mm
Collars outer diameter	236	320	mm
Integrated field uniformity (at $r=30 \text{ mm}$)			
B_6L/B_2L	$< 5 \times 10^{-4}$	$< 5 \times 10^{-4}$	
$B_{10}L/B_2L$	$< 3 \times 10^{-5}$	$< 3 \times 10^{-5}$	
Effective magnetic length	500	500	mm
Max. field on the conductor	1.8	2.4	T
Outside field of the magnet (at $r=400 \text{ mm}$)			
	< 15	< 65	mT
Stored energy	7.2	34.4	kJ
Longitudinal magnetic forces	73.6	307.6	kN
Resultant of magnetic forces per meter length in the coil octant			
F_x (horizontal)	25.2	73.2	kN/m
F_y (vertical)	-59.2	-167.3	kN/m