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Development and Test Results of the Prototype Active Shield Dipole Magnets for the KEK B-Factory

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Abstract—A novel dipole magnet with an active shield coil has been developed as a candidate of the separation dipole in the interaction region of the KEK B-Factory. This is an iron-free magnet with an inner aperture of 113.8 mm diameter and a nominal field of 0.7 T. The main coil produces a field of 1.6 Tesla, while the shield coil, which sits outside the main coil and has an opposite direction current, produces a field of -0.9 Tesla and suppresses the outside field to the level of 5 mT at a radius of 200 mm. Two prototype dipoles have been fabricated and tested. This paper summarizes the design, construction and test results of the dipoles.

I. INTRODUCTION

An asymmetric two-ring electron-positron collider for B-physics, the KEK B-Factory [1], is now under construction at KEK. In this kind of collider, to obtain the highest luminosity is an important subject, and a large number of parameters have to be carefully selected in the design of the interaction region. One scheme requires special dipole magnets of small-size and with a low-leakage field; they should be put as close to the collision point as possible to obtain the highest luminosity. One possible candidate for them might be permanent magnets. However, this has a disadvantage regarding the fine adjustment of the field strength. We have therefore pursued a novel iron-free dipole with an active shield coil [2],[3] which could be reliable and easy to handle. Two prototype dipoles have been constructed, and performance tests have been carried out in a vertical cryostat. In this paper we review the design and construction of the dipole, and report on the performance of two prototype magnets.

II. MAGNET DESIGN

The magnet design incorporates several features which are different from those of other superconducting accelerator magnets [4],[5]. We use an active shield coil to reduce the outer leakage field, no iron yoke to prevent a field distortion of the detector solenoid, a modest operating field of 0.7 T and a short magnetic length of 0.4 m. Cooling of the magnet will be performed by forced circulation of single-phase liquid helium with an operating temperature ranging between 4.35 and 4.7 K. The main parameters of the magnet are listed in Table 1.

Fig. 1 shows the cross section of the collared coil. From inside to outside, the main components are: a support cylinder which withstands the inward electromagnetic force acting on the main coil, the main coil, the FRP(G-10) spacer, the shield coil, and the collars.

The two-dimensional coil cross section was designed

TABLE I
PARAMETERS OF THE SUPERCONDUCTING ACTIVE SHIELD DIPOLE

Central field	0.70	T
Current	3871	A
Main coil inner / outer diameter	130 / 145.6	mm
Shield coil inner / outer diameter	171 / 186.6	mm
Overall length of the coils	680	mm
Collars outer diameter	240	mm
Integrated field uniformity (at $r=30$ mm)		
B_3L/B_1L	$< 5 \times 10^{-4}$	
B_5L/B_1L	$< 3 \times 10^{-5}$	
Effective magnetic length	418	mm
Max. field on the conductor	2.4	T
Outside field of the magnet (at $r=200$ mm)	< 5	mT
Stored energy	6.5	kJ
Longitudinal magnetic forces	407	kN
Resultant of magnetic forces per meter length in the coil quadrant		
F_x (horizontal)	11.9	kN/m
F_y (vertical)	53.0	kN/m

using a computer program which employs an analytical expression for computing the field harmonics. The one selected has total of 83 turns in each quadrant of two coils. The main coil has 47 turns, while the shield coil has 36 turns. In Fig. 2 we show a flux-line plot for the magnet. The maximum field occurs on the surface of the main coil at the median plane, where the flux line density is highest, and the strength is 2.4 Tesla.

At a central field of 0.7 T the resultant horizontal force of the main coil, which is directed inward, is ~ 82 kN/m; that of the shield coil, which is directed outward, is ~ 94 kN/m. 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.

Fig. 1. Cross section of the active shield dipole.

Fig. 2. Plots of the flux lines of the magnet.

By using the calculated azimuthal force and ignoring the friction between the coil and the collar, we estimated the minimum stress necessary to prevent coil motion at the pole when energized. The required calculated pre-stress of the main coil is 3.8 N/mm^2 and the maximum coil deflection in the azimuthal direction is 0.015 mm . The corresponding values for the shield coil are almost one order of magnitude smaller.

On the basis of the above mentioned calculation, a mechanical analysis of the magnet structure was performed by a photo-elasticity test. As expected, the highest stress occurs in the support cylinder. However, the value is not so high ($\sim 22.5 \text{ MPa}$). The stresses in the collar are relatively small and less than 10.3 MPa . The horizontal and vertical deflection of the support cylinder were also estimated to be $\sim 40 \text{ }\mu\text{m}$, and $\sim 28 \text{ }\mu\text{m}$, respectively.

Conductor

The conductor is a NbTi superconducting cable, which has been commonly used in 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. The twist pitch of the cable is 70 mm . Each wire is 0.680 mm in diameter, containing high-homogeneity NbTi filaments $\sim 6.5 \text{ }\mu\text{m}$ in diameter, and coated with $1 \text{ }\mu\text{m}$ silver-tin solder. The copper to superconductor ratio is $2.25 : 1$ and the critical current of the cable at 4.2 K is 7291 A at 5 T . The residual resistivity ratio of the stabilizing copper is about 170 . The insulation consists of a double layer of $25 \text{ }\mu\text{m}$ Kapton tape and a layer of $50 \text{ }\mu\text{m}$ Kapton with about $25 \text{ }\mu\text{m}$ of B-stage epoxy on the outside surface.

In Fig. 3 the critical currents of the cable (at a resistivity of $1 \times 10^{-14} \text{ }\Omega\text{m}$) and the load line of the dipole are given. The currents at 4.7 K were scaled from the measured values at 4.2 K .

III. MAGNET CONSTRUCTION

The four coils of a dipole are wound separately on a solid convex mandrel by inserting copper wedges and FRP end spacers in the designed positions. The tension applied to the cable during the winding was $353\text{--}196 \text{ N}$; winding was started by applying a 353 N tension, and then gradually decrease it according to the increase in the number of turns. They are then epoxy-cured in a laminated, concave fixture at $130 \text{ }^\circ\text{C}$ under pressure in the $51.5\text{--}45.8 \text{ MPa}$ range. During each curing process, an axial pressure was also applied to make the coil tight and to produce a uniform coil length. After curing, we measured the lengths of the coil sections and confirmed that their deviations from the designed values were less than 2 mm . A photograph of the two coils (main coil and shield coil) is shown in Fig. 4.

We prepared two kinds of support cylinders for two magnets; one is made of stainless-steel and the other is made of high manganese steel with less thermal contraction relative to that of stainless-steel. The main coils were precisely assembled around the support cylinder, and FRP spacers, which separate the main and shield coils, and the shield coils were placed on the main coils. Their position were fixed with the FRP pole pieces which have special concavities for alignment. The connections between the main and the shield coil were made near to the pole turn of the

Fig. 3. Critical currents of the superconducting cable and the load line of the dipole.

Fig. 4. Cured main and shield coils.

shield coil. After assembling the coils, a ground insulation, made of two layers of 125 μm thick Kapton and 250 μm thick Mylar sheet, was placed on the outer surface of the shield coils and the collars, pre-assembled in packs, were assembled over the coil packages. They were compressed incrementally with a press, and keys were inserted to keep them closed.

IV. MAGNET PERFORMANCE

Two prototypes (called ASD1 and ASD2) were constructed. The former has a high manganese steel support cylinder, while the latter has a stainless-steel support cylinder. After assembling the ASD1 we measured the outer leakage field of the magnet with Hall probes at room temperature [3]. The field strength, which we had to measure, was so small that we had to measure it carefully, while excluding the contribution of the earth's magnetic field. The maximum leakage field at a radius of 137.5 mm was 0.06 mT at 10 A excitation. The strength and the profile of the leakage field agreed fairly well with a calculation in which the three-dimensional coil shape was taken into account. Therefore, we could deduce that the maximum leakage field at a radius of 200 mm is 4.3 mT at 3871 A.

Cryogenic tests of the magnets were carried out in a vertical cryostat filled with liquid helium at 4.2 K and 1 atm. The ASD1 was excited up to 4000 A, the maximum limit of the power leads at that time, and measured the field in the aperture. During the test of the ASD2, the power leads were replaced with larger ones, and the magnet was excited up to 6000 A. Both magnets experienced no quenches during their test. During the excitation tests, the strains of the support cylinder were also monitored. Although the strain of the ASD1 cylinder increased in proportion to the square of the currents, that of ASD2 did not show a reasonable change. This difference in behavior might occur due to a difference in the thermal contractions of the cylinder material.

The magnetic measurements were performed with a rotating coil system, which had a 1.5 m long coil for measuring the integral field in the axial direction and a 0.02 m long short coil for measuring the central part of the straight section of the magnet. The radii of the long and short coils were 39.4 mm and 34.4 mm, respectively. By changing the axial position of the rotating coil system, the field profile along the magnet axis was also measured.

The integrated harmonic contents, expressed as the ratio of the harmonic field strength to the dipole field at a radius of 30 mm, are given in Table 2. The values of ASD1 and ASD2 are for measurements at 3871 A and 4000A, respectively. For the unallowed terms we applied centering corrections.

As can be seen from the table, the major harmonics are normal sextupole(b_3) and normal decapole(b_5), which are allowed harmonics for the dipole. These must mainly come from conductor placement errors at the ends. In this kind of short magnet, the effect of the end region becomes great and the dimensional tolerance of the coil ends becomes very severe. In addition, the central dipole field strength, which is a reference of this multipole expression, is relatively small due to the active shield structure; therefore, the effect of any

TABLE II
HARMONIC CONTENT OF THE INTEGRATED MAGNETIC FIELD IN UNIT OF 10^{-3} AT R=30 MM.

n	ASD1		ASD2	
	bn	an	bn	an
2	-0.53	-0.60	-0.61	-0.66
3	1.18	-0.0	3.5	-0.18
4	-0.13	-0.53	-0.17	-1.10
5	0.90	0.16	1.1	-0.10

coil placement error is expected to be enhanced compared to other superconducting dipoles.

Figs. 5-7 show the major multipole distribution along the magnet axis measured with the short coil. The measurement was performed at a current of 1500 A. In the figures, the lead end and the connection between the main and shield coils

Fig. 5. Variation of the skew dipole (a_1) component along the magnet axis.

Fig. 6. Variation of the sextupole (b_3 , a_3) components along the magnet axis.

Fig. 7. Variation of the decapole (b5, a5) components along the magnet axis.

exist in the positive coordinate region. The bump in the skew dipole is due to splices between the main and shield coils and the asymmetric coil configuration in the lead end. This effect can also be seen in other harmonics as a left-right asymmetry in the plots. The distributions of these multipoles were compared with the calculated ones, which were obtained from a three-dimensional field calculation of the magnet. It has been confirmed that the measured distribution agrees well with the calculations. Furthermore, the effect of the splice and the asymmetric conductor positioning in the lead end were studied, and the followings were found: (1) About one third of the skew components of the allowed multipoles are due to the splice, and the remains are to the asymmetric coil configuration in the lead end. Therefore, they appear only in the lead end region. (2) The skew components can be reduced by choosing a small operating current; i.e. when we take a half-size conductor and reduce the current to half, the components would become half. (3) Since the peaks in the normal multipoles are mainly dependent on the distributions of the coil turns in the ends, they cannot be reduced by changing the size of the conductor.

The current dependence of the multipole components of the magnets were also studied during tests. In Fig. 8 we show the results for the ASD2 magnet. As can be seen in the figure, the normal sextupole (b_3) displays the well-known hysteresis effect caused by persistent currents at low magnet excitation. The hysteresis curves of two magnets (ASD1 and ASD2) were very similar, and agreed well with the model calculation. However, the shape of decapole harmonics in both magnets were different from the calculation. The reason for this is not clear at present. Other features of these plots are a gradual increase of the normal sextupole and decapole harmonics in the high-current region. This behavior was observed only in the ASD2 magnet. This change is well

Fig. 8 Variation of the sextupole harmonics with currents.

explained by an oval coil deformation ($\Delta x = \sim 100 \mu\text{m}$) of the main coil due to the electromagnetic force.

IV. CONCLUSION

Two dipole magnets with active shield coils have been constructed and tested. The first magnet (ASD1) reached the design current (3871 A) and the second one (ASD2) achieved 6000 A without any quench, although the magnetic forces acting on the coils were very different from that of the usual superconducting dipole. There appears to be no serious problems with the basic design of the coil support system. The outer leakage field of the magnet was also within an acceptable level, and agreed fairly well with the calculation. However, the multipole components in the aperture were slightly larger than our expectations. In this kind of short active shield magnet, the effect of the coil end region becomes predominant, and, hence, accurate positioning of the conductor becomes very important.

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