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Superconducting Magnets for the Interaction Region of KEKB

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Abstract—A superconducting final focus magnet system for the interaction region of KEKB was constructed. It consists of two solenoid field compensation magnets and two superconducting quadrupoles with three kinds of correction coils. The system test has been successfully completed. This paper describes the design, construction and the test results of these magnets.

I. INTRODUCTION

KEKB is an asymmetric-energy, two-ring electron-positron collider for B-meson physics that is currently under construction at KEK [1]. KEBK circulates electron (8 GeV) and positron (3.5 GeV) beams in opposite directions and collides them at one interaction point (IP) with a finite crossing angle of ± 11 mrad. The beam line design near the IP requires a pair of compensation solenoids and a pair of final focus quadrupoles which are sufficiently small to fit inside the detector facility for physics experiments. For this goal, the decision was made in 1994 to build these magnets using the superconducting technology.

The fabrication of the magnets was started in 1996 and the installation completed in September of 1997. During the initial cool-down test in October, the temperature near the front end of the solenoids was found to be higher than our expectation and their operational currents were limited by quenching at about 200 A. However, expeditious remedial measures were taken, and the second cool-down in January of 1998 saw a fully successful commissioning test [2], which allowed the field measurement of the magnets [3] in combination with the BELLE detector solenoid [4].

Compensation solenoids, S-R and S-L, are the accelerator elements closest to the IP. They are followed by final focus quadrupole magnets, QCS-R and QCS-L, which include correction coils inside their bores. The five coils (S, QCS and three correction coils) on each side of the IP are contained in a common stainless-steel cryostat. In the cryostats, the magnetic axes of S-R and QCS-R are on the same line, however, the QCS-L axis is shifted horizontally by 35 mm with respect to the axis of the S-L. Since the cryostats are situated completely inside the detector facility, they must withstand big electromagnetic forces on the coils created through the interactions with the detector solenoid field of 1.5 T. The cryostats are held by cantilever supports made of an open stainless steel bracket which is held via a box structure. The transfer line which comes out

Fig. 1 The installed final focus superconducting magnet system. The cryostat is placed completely inside the detector. The transfer line from the cryostat runs down and extends horizontally towards the sub-cooler-cold-box unit sitting the right side of the BELLE detector facility.

from the magnet cryostat is connected to a service cryostat, placed side way from the support. From the service cryostat, another transfer line runs down and extends horizontally towards the sub-cooler-cold-box unit which sits next to the BELLE detector. Fig. 1 shows the picture of the installed superconducting magnet system.

II. COMPENSATION SOLENOIDS

In order to minimize the effect of the detector solenoid field on the accelerator beams, two compensation solenoids, S-R and S-L, having a magnetic field opposite to the detector solenoid, were designed and built. Table I summarizes the main parameters of their coils. While the two solenoids have the same inner and outer diameters, their lengths are slightly different. Calculation of the magnetic field by the combination of these solenoids and the detector solenoid, including the effects of the iron yoke structure, had been done by using a computer code, OPERA-2D. The design solution was selected where an integral of B_z along the beam line was brought to zero. In normal operation, because of the detector solenoidal field, the peak fields on the conductors and the central fields are reduced by 1.5 T from the values listed in Table I, and the axial repulsive forces work on the solenoids. The calculated forces on S-L and S-R are 22 kN and 2.8 kN, respectively. As shown in Fig. 2, for the given detector solenoidal field of 1.5T, the current dependence of the radial bursting forces on the S-L and S-R is quite difference from ordinary solenoids. To manage such forces, a rather thick bobbin (helium inner cylinder) of 7 mm thickness was selected. Then the windings were impregnated

TABLE I
MAIN PARAMETERS OF THE SOLENOIDS

	S-L	S-R	
Central field	4.53	5.80	T
Current	487	603	A
Ic load line ratio @4.5K	59	75	%
Max. field on the conductor	4.59	5.83	T
Stored energy	121	258	kJ
Coil			
ID	190	190	mm
OD	230	230	mm
Length	461	616	mm
No. of turns	3749	4981

Fig. 2 Excitation dependence of the bursting force on the S-R coil in the detector solenoid.

with epoxy resin.

The coils were made of monolithic NbTi superconducting wire with a cross section of 1.1 mm × 1.9 mm (Cu/SC ratio 1.0). The insulation is provided by polyimide group resin. After wound on the helium inner cylinder, the coils were impregnated with Epoxy resin under pressure, and enclosed in helium vessels while axial compression force are applied. The estimated force on the coils after the assembly were 516 MN and 250MN for S-R and S-L, respectively.

Each solenoid inside the helium vessel was tested in a test vertical cryostat before installation into the horizontal cryostat. The excitation test was performed without background magnetic field. The S-R magnet required a number of training quenches (40 of these) to reach the design current. However, it showed no retraining after a thermal cycle. The training behavior is shown in Fig. 3. The performance of S-L magnet was much superior. The current reached 600 A, 123% of the design current, without quenching. The reasons for these different training behavior between S-R and S-L are not clear yet in spite of the careful inspection during the fabrication process.

In the system test of January 1998, the solenoids were excited, with and without detector solenoid field of 1.5 T. Pseudo-quench tests were also performed to see the interference effects between the solenoids and the detector solenoid. No quenching occurred for currents up to the power supply limit of 650A (110% of the design values) with excellent performance.

Fig. 3 Training history of S-R in a vertical cryostat.

III. QUADRUPOLE MAGNETS WITH CORRECTION COILS

A. Description of the quadrupole magnets

The quadrupole magnets are iron-free superconducting magnets. They were designed and built on the basis of experience with the TRISTAN mini-beta insertion quadrupole magnets [5]. They produce a field gradient of 21.7 T/m within a coil aperture diameter of 260 mm. The coil design is based on a set of cos2θ windings that are clamped by stainless steel collars. We took the same 2-dimensional structure for both QCS-L and QCS-R. However, the lengths are slightly different.

Since the quadrupoles considered here are rather short and have large aperture, the effect of the end parts seemed to be important. Therefore, we performed 3-dimensional field calculations and optimized the shape of the coil end. Table II shows the main parameters of the quadrupoles and Fig. 4 shows a transverse cross section of the quadrupole with its helium vessel. The main components are from the innermost part: inner wall of the helium vessel, correction coils, quadrupole coil, 316LN stainless-steel collar, outer wall of the helium vessel.

The superconducting cable is NbTi/Cu Rutherford type cable, consisting of 24 multifilamentary strands of 0.59 mm diameter (Cu/SC ratio 1.8) which are twisted at a pitch of about 60 mm (filament size 6 μm). The residual resistivity ratio of the stabilizing copper is about 160. The width and the mid-thickness of the bare cable are 7.000 ± 0.025 mm and 1.090 ± 0.006 mm, respectively. The cable is insulated with two kinds of Upilex tape; 25 μm- and 50 μm-thick tapes.

The coil production procedure was similar to that of the TRISTAN mini-beta quadrupole magnets; the first layer of the coil was wound on a convex mandrel by inserting FRP end-spacers and a copper wedge in the appropriate positions. The coil was wound under 294-196 N tension. Initial winding was done under 294 N tension to harden the winding; the tension was gradually decreased for increasing coil turns. Then the coil was heat-cured in a concave curing press at about 130 °C. The azimuthal oversize of the cured first-layer coil was 0.2 mm. After heat curing, a special FRP end piece was attached to the end of the winding post in order to accommodate the ramping of the cable from the coil first layer to the second layer.

TABLE II
MAIN PARAMETERS OF THE QUADRUPOLE MAGNETS

	QCS-L	QCS-R	
Field gradient	21.66 (21.78)	21.73 (21.78)	T/m
Current	2963	2963	A
Effective length	483 (486.1)	385 (387.7)	mm
Max. field on the conductor	4.3	4.3	T
Ic load line ratio	70	70	%
Main coil			
Inner radius	130	130	mm
Outer radius	144.9	144.9	mm
Overall length	617	521	mm
Collars outer dia.	340	340	mm
Stored energy	87.5	69.7	kJ
	() ; measured values

Fig. 4 Cross section of the QCS-R magnet.

The second layer was wound onto the first layer in a similar manner. A 0.5 mm thickness fishbone-type G-10 spacer is inserted between the first and second layers. The resulting two-layer coil was then cured together in the press without an oversize. In each curing process, an axial pressure was also applied to tighten the coil and to produce a uniform coil length. After the completion of the double pancake, 2-layer coil, they were cured again in the press without an oversize. This final curing process was very useful to compensate the small size-difference between the layers and to get a good field quality.

In Fig. 5, the Young's modulus and the azimuthal stress required to compress the coil to the design size are shown for both quadrupoles. Each data point represents the overall average of six measurements taken along the coils. The standard deviation of the data are shown as error bars.

The four double pancake coils were mounted around another cylindrical mandrel. Ground insulation, made of two layers of 100 μ m thick polyimide sheet, and brass shoes were placed on the outer surface of the coils, over which 316LN stainless steel collars were stacked. The collared magnet was then put into a collaring press, which applied the correct pressure and displacement on the collars from four perpendicular radial directions. The first squeezing process brought the collars into a shape oversized by 1 mm, compared to the design diameter. Next, the inner mandrel was replaced with the helium inner cylinder where three correction coils were mounted before-

Fig. 5 Young's modulus and the azimuthal stress of the cured coils

hand. The collars were, then, squeezed to the design size and fastened together by means of 316LN stainless steel keys so that the applied prestress remained on the coils after the press was removed. The radial forces required to close the collars were 2.9×10^5 N and 4.9×10^5 N for QCS-R and QCS-L, respectively. The electrical connections between the coils were established by means of a special soldering jig. The length of the splice at each connection was about 50 mm.

B. Description of correction coils

Inside the quadrupole winding, three kinds of correction coils (horizontal and vertical steering, and skew quadrupole) were embedded. The field strength of the steering coil is about 0.05 T and the gradient of the skew quadrupole is about 0.4 T/m. The physical length of all kinds correction coils is about 600 mm. The effective lengths are about 500 mm and 440 mm for skew quadrupole and steerings, respectively. These are con-

TABLE III
MAIN PARAMETERS OF THE CORRECTION COILS

	Design	Measured Values		
		Left side	Right side	
Skew quad coil				
GL	0.2174	0.212	0.2122	(T/m)m
Coil IR	123.5			mm
Number of turns	106	106	106	turns/pole
Stored energy	28.7			J
Alignment error	0	0.22	-27.43	mrad
Horizontal steering coil				
BL	0.0244	0.0255	0.0250	Tm
Coil IR	126.9			mm
Number of turns	213	213	213	turns/pole
Stored energy	63			J
Alignment error	0	4.59	3.85	mrad
Vertical steering coil				
BL	0.0242	0.0253	0.0247	Tm
Coil IR	125.2			mm
Number of turns	211	211	211	turns/pole
Stored energy	54.7			J
Alignment error	0	1.57	-13.04	mrad

Design current of these coils are 50 A.

Alignment error is the angular difference between the mid-planes of QCS coil and corrector.

sidered enough to rotate the quadrupole field about 10 mrad, and to steer the beam about 3 mm. The main parameters of the coils are shown in Table III.

Since these coils are placed in the fields of the quadrupole and the solenoids, various forces and torques exert on each coil. These strengths were studied by using Biot-Savart's law. The major forces that act on each coil have been published in [6]. To control the deflections and deformations produced by the forces, we used thick-walled stainless steel support tube which became an inner cylinder of the helium vessel (8 mm thickness).

The basic fabrication process of these coils is similar to that adopted for the corrector magnets for RHIC [7]: First, the one-layer coils were wound by a computer-controlled winding machine using ultrasonic power to bond the wire into an epoxy-coated flat substrate. These flat coils were made at BNL by using a 0.33 mm diameter superconducting wire covered with 25 μ m thick Kapton insulating film and coated with special adhesive. Then they were transported to the company via KEK and the inner coil (Skew Q) was wrapped onto a stainless steel support tube (helium inner cylinder). In the process, G-10 coil supports were installed into a wound flat coil. They are to act as a filler for locations where the wires were not located, and make the thickness constant throughout the assembly. The coil was then bonded to the support tube with epoxy, supported with fiberglass cloth. With the same method, V-steering coil and H-steering coil were assembled and bonded, concentrically one by one. The completed correctors on the helium inner cylinder were inserted inside the quadrupole magnet.

C. Performance of quadrupole magnets with correction coils

After finishing the assembly of the quadrupole, the magnets were tested in a vertical cryostat to see the quench behavior at 4.2 K. Preliminary field measurements were performed with a rotating coil system. The performance of the main coil and correction coils were very good. All coils reached 110% of their design currents without quenching. The combined excitations of these coils were also performed well. No natural quenching occurred during the test.

In the system test of January 1998, the magnets were ex-

cited up to 110% of their design currents without quenching, now, under the field of 1.5 T of the detector solenoid. The final field measurement of these magnets were also done under various combinations of the coil excitations. Figure 6 shows the measured integrated harmonics of the quadrupoles at various excitations. In case of QCS-L, we note that the measurement axis is shifted 35 mm from the magnet axis by design. From these measurements, alignment errors of each coils were also studied. Some of the data are shown in Table III.

IV. CONCLUSIONS

A superconducting magnet system for the interaction region of KEKB was built and a commissioning test has been successfully completed. All magnets have been confirmed to have good margins for operating at their design currents. They are sufficiently robust to withstand various electromagnetic forces expected during operation and current ramping. The field quality of all these magnets have been found to satisfy design specifications and the alignment accuracy of these coils are also acceptable.

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REFERENCES

- [1] S. Kurokawa, "Present Status of KEKB Project," presented at the 6th European particle Accelerator Conf. (EPAC 98).
- [2] T. Ogitsu et al., "Final Focus Superconducting Magnet System for the Interaction Region of KEKB," presented at the 6th European particle Accelerator Conf. (EPAC 98).
- [3] T. Ogitsu et al., "Field Quality of the Final-Focus Superconducting Magnets for KEKB Interaction Region," presented at the 6th European particle Accelerator Conf. (EPAC 98).
- [4] Y. Makida et al., "Development of a Superconducting Solenoid Magnet System for the B-Factory Detector (BELLE)," to be published in Adv. in Cryogenic Engineering, Vol. 43 (1998).
- [5] K. Tsuchiya et al., "Performance of the Eight Superconducting Quadrupole Magnets for the TRISTAN Low-Beta Insertions," IEEE Trans. Magn. MAG-27 (1991) p 1940.
- [6] K. Tsuchiya et al., "The Superconducting Magnet System for KEKB B-Factory," Proc. the 5th European particle Accelerator Conf. (EPAC 96), p 2287.
- [7] A. Morgillo et al., "Superconducting 8 cm Corrector Magnets for the Relativistic Heavy Ion Collider (RHIC)," Proc. of the 1995 PAC and Inter. Conf. on High-Energy Accelerators, p 1393.

Fig. 6 Harmonics of the QCS-R and QCS-L at 40 mm radius.