DESIGN AND CONSTRUCTION OF THE PROTO-TYPE QUADRUPOLE MAGNTS FOR THE SUPERKEKB INTERACTION REGION

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Abstract

Construction of the SuperKEKB accelerator started from 2010. The final focusing system in SuperKEKB was designed, and it consisted of 8 superconducting quadrupole magnets. As part of the R&D of the final focusing system, two prototype magnets were designed and constructed. The magnets were cooled to 4 K, and they were excited over the design current and the field measurements were performed.

INTRODUCTION

SuperKEKB [1] is the upgraded machine of KEKB, and the design luminosity is 8×10^{35}cm^{-2}s^{-1}, which is 40 times higher than that achieved at KEKB. SuperKEKB has a single interaction point, IP, to collide the 7 GeV e- beam and the 4 GeV e+ beam with a finite crossing angle of 83 mrad. The colliding energy is planned to be increased to 12 GeV. The design concept of SuperKEKB is based on the Nano-Beam Scheme, originally proposed by P. Raimondi for SuperB [2]. In order to focus the beam at IP with the vertical beam size of about 50 nm, a pair of the quadrupole doublet system for LER and HER [3, 4], respectively, was designed with 8 superconducting magnets. As the R&D of the final focusing system, the QC1P and QC1E prototype magnets were constructed and cold tested at 4K. In this paper, the magnet designs, constructions and test results are reported.

DESIGNS OF QC1P/QC1E MAGNETS

The QC1P and QC1E magnets were designed for the e+ and e- beams, respectively, and they are located at the closest position to IP on each beam line [3].

QC1P Magnet Design

The QC1P is the collared quadrupole magnet without iron yokes in order to make the solenoid field profile required from beam optics. The magnet cross section is shown in Fig. 1, and the parameters are summarized in Table 1. The magnet consists of two layers of the superconducting coil, and the thickness of the two-layers is 5.425 mm. Because the separation between two beams at the front end of the QC1P magnet is only 61 mm, the outer radius of the magnet was designed to be 30.425 mm while the coil inner radius was 25 mm. The field gradient of the magnet was 76.17 T/m at the design current, I_d=1800 A, and the magnetic length was 0.3372 m. I_d was for the colliding energy of 12 GeV, and the magnet current for 11 GeV was 1624 A. For this magnet, the small Rutherford cable, which consisted of 10 strands, was developed. The cable size was 0.93 mm in mid-thickness × 2.5 mm in height, and the key stone angle of the cable was 2.09 degree because the coil inner radius was 25 mm. I_d is 60 % of the critical current of the cable, I_c, at 4.7 K. The cable parameters are listed in Table 2.

The magnetic field of the QC1P magnet was calculated with the magnet cross section model and with the whole magnet model including the lead end and the non-lead end. They are summarized in Table 3. The each coil was designed with three coil blocks, and b_6 and b_{10} of two layer coils were optimized to be 0.16 units and -0.02 units in the cross section, and -0.11 units and -0.05 units in the whole magnet, respectively, at the reference radius of R_{ref}=10mm.

QC1E Magnet Design

The QC1E magnet was located behind the QC1P magnet from the IP. The prototype magnet was designed with iron yokes, and the yoke outer radius was 70 mm. The magnet consisted of two layer coils, and the inner radius was 33 mm. The superconducting cable had same parameters as those for the QC1P magnet except for the cable keystone angle of 1.59 degree. The QC1E was designed to generate the field gradient of 91.73 T/m at I_d=2000 A, and the magnetic length was 0.3774m. The magnet current for 11 GeV was 1577 A. The magnet cross section was optimized with three coil blocks of each layer as same as the QC1P magnet, for b_6 and b_{10} to be -0.04 units and -0.08 units at R_{ref}=15mm, respectively. In the whole magnet, b_6 and b_{10} were optimized to be -0.17 units and -0.20 units, respectively.

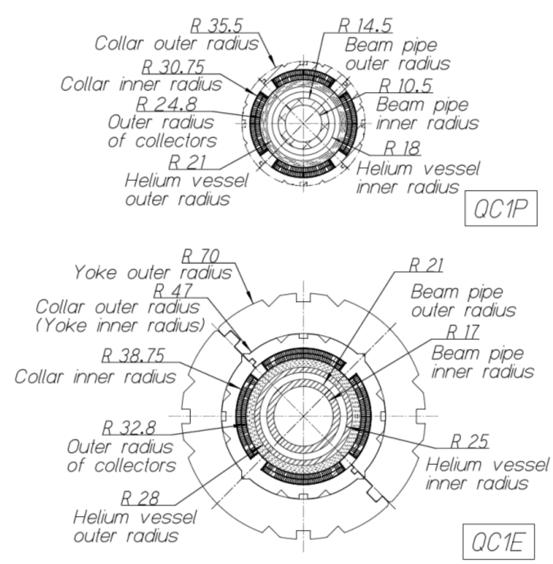

Figure 1: Cross sections of QC1P/1E prototypes.

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Table 1: Magnet Parameters of Proto-types

	QC1P	QC1E
Magnet type	Non-yoke	Yoke
Coil inner/outer radius, mm	25.0/30.425	33.0/38.425
Collar or yoke outer radius, mm	35.5	70.0
Turn number per pole	25	34
Design current (I_d), A	1800	2000
Field gradient (G), T/m	76.17	91.73
Effective magnetic length (L_{eff}), m	0.3372	0.3774
Maximum field at I_d, T	2.61	4.17
I_d/I_c at 4.7 K, %	60	73

Table 2: Cable Parameters

	QC1P	QC1E
Cable type	Rutherford cable	
Cable size (mid-width × height), mm	0.93 × 2.50	
Keystone angle, degree	2.09	1.59
Number of strand	10	
Strand diameter, mm	0.498	
Cu/NbTi ratio	1.0	
Critical current at 5T, and 4.22 K	3165	3070
Critical current at 7T, and 4.22 K	1880	1830

Table 3: Design Error Field Components

		QC1P	QC1E
Field Gradient, T/m		76.17	91.73
R_{ref}, mm		10	15
Cross section	b_6, units	0.16	-0.04
	b_{10}, units	-0.02	-0.08
Whole magnet	b_6, units	-0.11	-0.17
	b_{10}, units	-0.05	-0.20

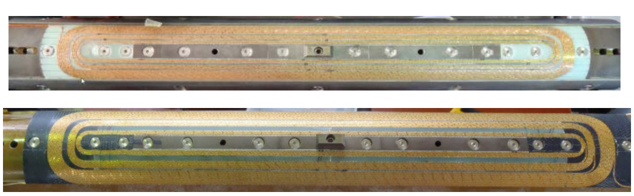

Figure 2: QC1P (upper) / QC1E (lower) coils.

CONSTRUCTION OF MAGNETS

The QC1P and QC1E prototype magnets were constructed in KEK. Since the cable was the small size of 0.93 mm × 2.5 mm, the cable tension during winding coil was carefully controlled. The tension was decreased from 130 N to 60 N as function of turn number. After winding coil, the coil was cured in the form block at the temperature of 130 degrees C. Figure 2 shows the cured coils of QC1P and QC1E. The average lengths of QC1P and QC1E coils were 384.14 mm and 430.31 mm to the design values of 384 mm and 430 mm, respectively.

The four coils were assembled together, surrounding a support bobbin in the vertical position. The coils were covered with multiple ground plane insulation layers. The 2-split High-Mn collars were assembled around the coils with 90 degree rotation every set of collars. Assembled collars were squeezed and keyed from the four directions at once with a hydraulic press. Until these assembly processes, the QC1P magnet was completed. Yoking process for the QC1E magnet was performed with the same collaring tool. The half–split iron yokes of 3 mm thickness were assembled around the collars with 90 degree rotation every set of yokes. Yokes were fitted to collars by the collaring press. Figures 3 and 4 show the completed QC1P and QC1E prototype magnets.

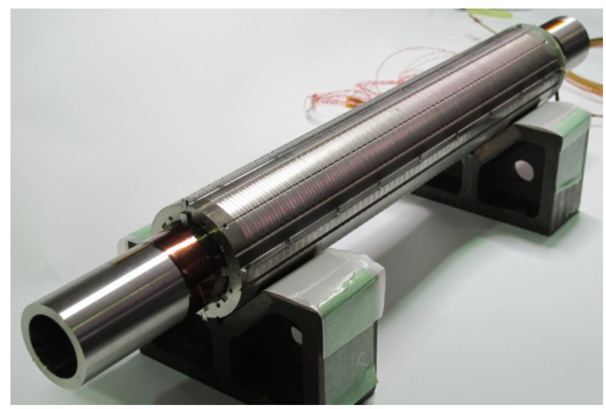

Figure 3: QC1P prototype magnet.

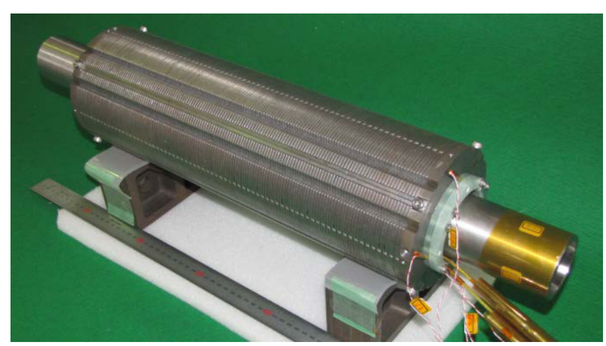

Figure 4: QC1E prototype magnet.

EXCITATION TESTS

Two magnets were installed into the vertical cryostat, individually, and they were cooled by liquid helium. The QC1P and QC1E prototype magnets were excited to 2100 A and 2157 A without quench, respectively. The maximum currents were limited by the power supply. The current of 2100 A of the QC1P magnet corresponded to 70 % of I_c on the load line at 4.7 K. The current of 2157 A of the QC1E magnet was 87 % of I_c.

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MAGNETIC FIELD MEASUREMENTS

Magnetic field measurements were performed with the harmonic coils. Two coils of 600 mm and 40 mm long were used for measuring the integral field and the field profile, respectively.

Integral Field Measurements

The integral field was measured with the 600 mm long harmonic coil. The coil radius was 9.55 mm. At the magnet currents of 1701.7 A for QC1P and 1561.7 A for QC1E, the measured integral field gradients were 24.32 T and 26.22 T, respectively. For comparison, the calculated integral field gradients of the QC1P and QC1E magnets at these currents are 24.28 T and 27.03 T, respectively.

The measured error field components at R=9.55 mm are shown in Table 4. From the result, the both magnets had large sextupole field components. The components can be converted at the reference radius of each magnet. a_3 and b_3 for QC1P are 2.95 units and 3.83 units at R_{ref}=10mm, and a_3 and b_3 for QC1E are 1.79 units and 8.64 units at R_{ref} =15mm, respectively. The beam optics simulation showed these sextupole components remarkably degraded the Touschek beam life time.

Table 4: Measured Error Field of Prototypes in Units

	QC1P		QC1E	
n	a_n	b_n	a_n	b_n
2	0	10000	0	10000
3	2.82	3.66	1.14	5.50
4	2.08	0.24	0.18	-0.28
5	0.35	0.23	0.06	-0.48
6	0.03	-0.56	-0.06	-0.31
7	0.07	0.13	-0.01	0.01
8	0.03	0.01	0.05	-0.00
9	-0.08	0.05	0.02	-0.00
10	0.02	0.01	-0.00	-0.02

Field Profile Measurements

The field profiles of the prototype magnets were measured with the 40 mm long harmonic coil. The coil radius was 9.74 mm. Figures 5 and 6 show the profiles of the field gradient, a_3 and b_3 along the axes of the QC1P and QC1E magnets, respectively.

From Fig. 5, a_3 and b_3 in the QC1P magnet straight section (-100mm<position<100mm) are in the range from -2 units to 2 units. On the other hand, in the QC1E magnet, b_3 is from 5 units to 8 units while a_3 is within plus or minus 1 unit.

For the QC1E magnet, the error field due to the coil deformation was calculated. The b_3 and a_3 components were produced by the dipole deformation of 4 quadrant coils. The coil movements in the radial direction by the measured b_3 component were calculated to be plus and minus 30 μm for the two coils in the left and right sides of the magnet cross section, respectively. For the QC1P magnet, the b_3 and a_3 of 3 units was produced by the dipole deformation of 10 μm.

As the results of the field measurements, the b_3 and a_3 correctors has been decided to be installed in the final focusing system in order to attain the acceptable Touschek beam life time of 600 seconds.

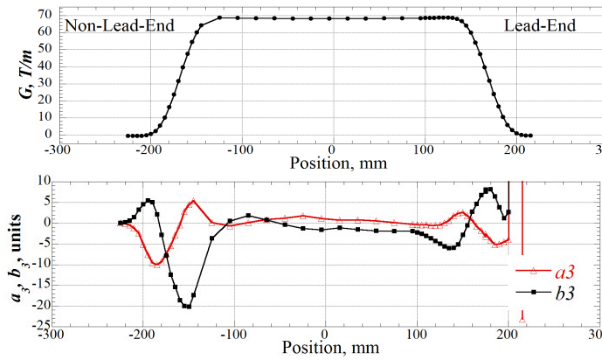

Figure 5: QC1P field profile measurement. I=1627 A.

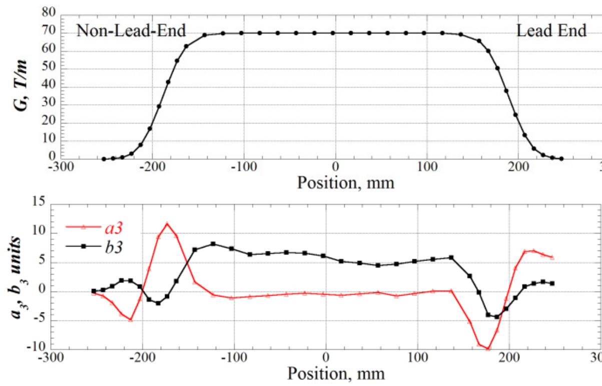

Figure 6: QC1E field profile measurement. I=1561 A.

SUMMARY

As the R&D of the SuperKEKB final focusing system, the prototype magnets of QC1P and QC1E were constructed and tested at 4K. The magnets were excited over the design current without any quenches. From the field measurements, the b_3 and a_3 correctors were decided to be installed in the final focusing superconducting magnet system.

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