DESIGN AND CONSTRUCTION OF THE QC2 SUPERCONDUCTING MAGNETS IN THE SUPERKEKB IR

N. Ohuchi[#], Y. Arimoto, N. Higashi, M. Iwasaki, M. Kawai, Y. Kondo, K. Tsuchiya, H. Yamaoka, X. Wang, Z. Zong, KEK, Tsukuba, Japan, H. Kono, T. Murai, S. Takagi, MELCO, Kobe, Japan

Abstract

The first stage commissioning of SuperKEKB is going on without the final focus system from Feb. 2016. The final focus system, which consists of 55 superconducting magnets, is still in the construction stage. The 8 main superconducting quadrupole magnets are designed to consist of quadrupole doublets as QC1 and QC2 for each beam line. All of the quadrupole magnets were constructed. In this paper, the design and the construction of the quadrupole magnets, QC2, are presented.

INTRODUCTION

SuperKEKB with a target luminosity of 8×10^{35}, which is 40 times higher than KEKB [1], is now being operated without the final focus system from February 2016 as the Phase-1 commissioning [2]. The accelerator design is based on the Nano Beam Scheme [3] with a large horizontal crossing angle of 83 mrad between the electron (e-) and positron (e+) beams and the beam sizes of about 50 nm at the interaction point (IP), where the beam energies of e- and e+ are 7 GeV and 4 GeV, respectively. The final focus system [4] was designed with 55 superconducting magnets of 8 main quadrupoles, 4 compensation solenoids and 43 correctors [5]. Final beam focusing is obtained with quadrupole doublets of the main quadrupoles, QC1 and QC2, for each beam. For the e+ beam line, QC2LP and QC2RP were constructed for the left and right hand side to IP, respectively, and for the e- beam line, QC2LE and QC2RE were constructed.

These superconducting magnets are assembled into two cryostats, and they are installed inside of the particle detector, Belle II [6]. Therefore, the final focusing system is operated under the magnetic field of 1.5 T by the Belle solenoid. For reducing the influence of this solenoid field on the beam collision, the compensation solenoids, which generate the solenoid fields of the opposite field direction, are installed into the cryostats. QC2LP and QC2RP are assembled inside of the compensation solenoid bores. QC2LE and QC2RE are assembled out of the solenoids.

The QC1 magnets were already reported in the reference [7]. In this paper, the design and the construction of the QC2 magnets are reported.

MAGNET DESIGN

Magnet Cross-section Design

The cross sections of QC2P, QC2LE and QC2RE are shown in Fig. 1. The magnet parameters are listed in Table 1. QC2LP and QC2RP have the same configuration. These magnets consist of two-layer coils, which have two coil blocks. The inner and outer coil radii are 53.8 mm and 59.2 mm. The four coils are cramped with the YUS130S collars, and Permendur yokes are assembled on the collars. Permendur was selected due to the higher saturated magnetic flux density of 2.3 T than iron. With this material, the leak field of QC2P to the e- beam line can be reduced from 50 Gauss to 2 Gauss with the magnetic field increment of 1 T in the yokes by 1 % imperfection in cancellation of the detector solenoid field.

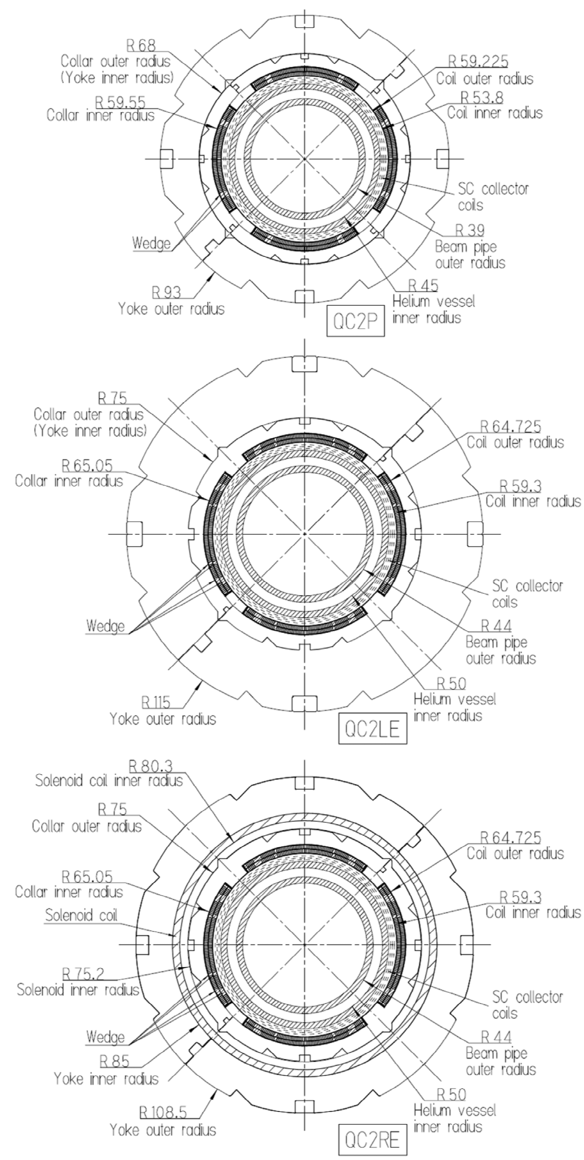

Figure 1: Magnet cross sections of the QC2P, QC2LE and QC2RE magnets.

Norihito.ohuchi@kek.jp

Table 1: Design Parameters for QC2P and QC2LE

Parameters	QC2P	QC2LE
Design field gradient, T/m	31.97	36.39
Design current, A	1000	1250
Peak field in coil winding, T	2.43	2.63
Load line ratio at 4.7 K, %	44	39
Coil		
layer number	2	2
inner/outer radius, mm	53.8/59.2	59.3/64.7
coil length, mm	443.6	573.9
1st layer turns	27	29
2nd layer turns	28	32
Collar inner/outer radius, mm	59.6/68.0	64.7/75.0
Yoke inner/outer radius, mm	68.0/93.0	75.0/115.0
Physical magnet length, mm	495.5	618.9
Magnetic length, mm	409.9	537.0
Inductance, mH	7.32	13.28

The design field gradient of QC2P at 1000 A is 31.97 T/m, and the currents of QC2LP and QC2RP at the nominal operation are 877.4 A and 882.1 A, respectively.

The cross section designs of QC2LE and QC2RE are different. While the collared magnet of QC2LE and QC2RE are designed in the same dimension, QC2RE has the compensation solenoid between the collars and the yokes, as shown in Fig. 1. This compensation solenoid is different from the compensation solenoids which are assembled with QC1s and QC2P. The solenoid length is 720 mm and it is designed to generate 0.3 T by the current of 210 A. QC2LE and QC2RE consist of two-layer coils and three coil blocks per each layer. The inner and radii of QC2LE are 59.3 mm and 64.7 mm, respectively. Yoke materials for QC2LE and QC2RE are iron because the amount of iron in the beam separation is sufficient to reduce the leakage field to the e+ beam line to almost zero. The design field gradients of QC2LE and QC2RE are 36.39 T/m and 40.95 T/m with the currents of 1250 A and 1350 A, and the currents of QC2LE and QC2RE at the nominal operation are 977.0 A and 1068.5 A, respectively. QC2LE has the longer magnetic length than that of QC2RE of 419.0 mm.

Field Quality and Magnet End Design

The calculated error field components with the 2D cross sections and with the 3D models are listed in Table 2. The field qualities of QC2P and QC2E are designed at the reference radius of 30 mm and 35 mm, respectively. For QC2P and QC2E, the amplitudes of the error field components are designed to be smaller than 0.5 units.

Under the space constraint in the cryostat, the coil ends are designed to be as short as possible, as shown in Fig. 2. The coil ends of QC2P and QC2E are designed within the

Table 2: Design Error Field Components

	QC2P	QC2LE
2D cross section	@R30 mm	@R35mm
b_6 units	0.05	-0.24
b_{10} units	-0.15	-0.14
3D model(integral field)	@R30 mm	@R35mm
b_4 units	-0.06	0.07
b_6 units	0.28	-0.13
b_8 units	0.11	0.06
b_{10} units	-1.43	-1.92

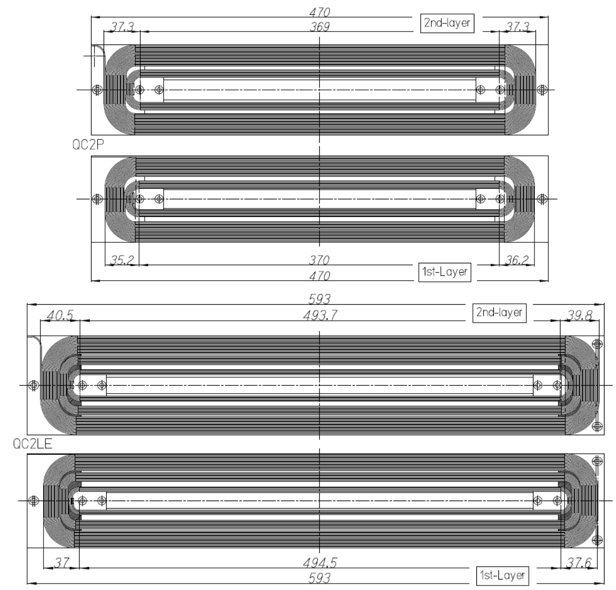

Figure 2: Coil designs of QC2P and QC2LE.

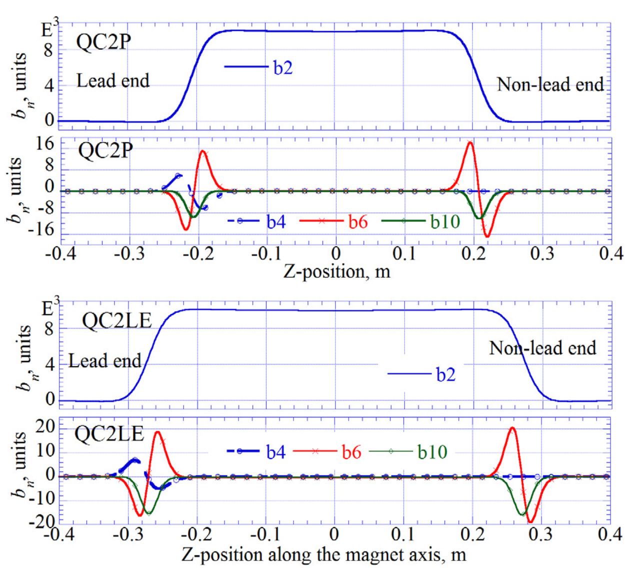

Figure 3: Field profiles along the magnet axis of QC2P and QC2LE. From the top plot, QC2P-(b_2), QC2P-(b_4, b_6, b_{10}), QC2LE-(b_2) and QC2LE-(b_4, b_6, b_{10}).

ISBN 978-3-95450-147-2

space of 51.6 mm and 57.5 mm including the G-10 spacers, respectively. In order to exclude the skew components in the coil lead end, the quadrant coils have mirror symmetry to the neighbor coils, while b_{4n} components are induced. Fig. 3 shows the field profiles along the magnet lengths of QC2P and QC2LE. In the plots, the position of Z=0 corresponds to the longitudinal magnet center. The field components are normalized by the quadrupole field at the magnet center as 10000. In the lead ends, the b_4 components show the peaks of +7.0/-5.0 units for QC2P and +6.0/-6.6 units for QC2LE. The integral b_4 components of QC2P and QC2LE were controlled at -0.06 units and 0.07 units, respectively, as shown in Table 2. The maximum error field components are b_{10}, and they are -1.43 units and -1.92 units for QC2P and QC2LE, respectively.

MAGNET CONSTRUCTION

Coil Winding and Curing Process

The coils for the quadrupole magnets were manufactured with a double pancake winding technique. The 1st layer coil was wound on the mandrel with keeping the cable for the 2nd layer coil. The cable tension was controlled during winding coils with the initial tension at 130 N and reducing the tension of 10 N every three or four turns. The cable parameters are listed in Table 3. After the winding process, the coils were cured in the design shape at 130 degree C and 20 MPa with the forming block. In Table 4, the measured coil sizes of the 16 coils are shown. In the table, the average coil length and thickness of the 4 coils in the magnet are shown with the standard deviation, 1σ. The design coil lengths of QC2P, QC2LE and QC2RE are 470 mm, 593 mm and 535 mm respectively. The design coil thickness is 5.425 mm.

Collaring and Yoking

Four coils were assembled together surrounding a collaring mandrel of which outer diameter was same as the design inner diameter of the magnet. The collars were split at the mid-plane and rotated 90 degree every each set of collars. The coils were squeezed to the design outer perimeter of the magnet with four hydraulic-press jacks. The coils were designed to have pre-stress of 30 MPa at room temperature in order to have pre-stress in the coils when being excited at 4 K. During the collaring process, the coils were aligned to the magnet end plates with mechanical keys. The quadrupole fields of QC2Ps, QC2LE and QC2RE were mechanically aligned to the other magnets within an angle error of 1 mrad.

The yokes were split at the mid-plane and rotated 90 degree every each set of yokes, in the same way as the collars. After yoking the magnets, the field qualities of the magnets were measured at room temperature, and the sextupole field components of the magnets were confirmed to be smaller than 10 units. The field measurement results at 4 K will be reported at this conference [8].

Table 3: Parameters of Superconducting Cables

	QC2P	QC2L/RE
Strand (NbTi)		
Diameter, mm	0.498	0.498
Cu/S ratio	1.0	1.0
Filament diameter, μm	7.7	7.7
No. of filaments	2113	2113
RRR of Cu	178	183
Ic @ 5T, 4.22 K, A	307	313
Cable		
Width/mid-thickness, mm	2.50/0.93	2.50/0.93
Keystone angle, degree	1.00	0.94
No. of strands	10	10

Table 4: Measured Coil Length and Thickness

	QC2LP	QC2RP	QC2LE	QC2RE
Ave. length	470.0	470.0	593.1	535.1
1 σ	0.02	0.01	0.01	0.07
Ave. thickness	5.419	5.420	5.415	5.413
1 σ	0.003	0.007	0.005	0.005

CONCLUSION

The superconducting quadrupole magnets QC2P and QC2E for the SuperKEKB beam final focusing system were designed and constructed with good fabrication accuracy. The field qualities were confirmed to be sufficient good for the beam operation.

ACKNOWLEDGMENT

The authors would like to thank K. Aoki for the excellent technical support in designing the magnets with CAD.

REFERENCES

[1] K. Akai et al., in *Proc. IPAC'12*, New Orleans, June 2012, paper TUPPR006, pp. 1822-1824.

[2] Y.Funakoshi, presented at IPAC'16, Busan, Korea, May 2016, paper TUOBA01, this conference.

[3] P. Raimondi, 2nd SuperB Meeting, Frascati, 2006.

[4] N. Ohuchi et al., in *Proc. NA-PAC'13*, Pasadena, September 2013, WEODA1, pp. 759-961.

[5] B. Parker et al., presented at IPAC'16, Busan, Korea, May 2016, TUPMB041, this conference.

[6] Z. Dolezal and S. Uno, "Belle II Technical Design Report," KEK Report 2010-1, July, 2010.

[7] N. Ohuchi et al., *IEEE Transactions on Applied Superconductivity*, Vol. 25, No. 3, June 2015, 4001202.

[8] Y. Arimoto et al., presented at IPAC'16, Busan, Korea, May 2016, paper THPOR004, this conference.