DESIGN STUDY OF SUPERCONDUCTING MAGNETS FOR THE SUPER-KEKB INTERACTION REGION

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Abstract

The Super-KEKB is the next generation collider for B factories, and its target luminosity is 4×10^{35} $cm^{-2}s^{-1}$. From the various points of view, the reality of this machine was discussed, and the magnet system in the interaction region has been also studied intensively. Especially, the study of the superconducting magnet system, which consists of the final focus quadrupoles and the compensation solenoids, has progressed. In this paper, the layout and the parameters of these superconducting magnets are reported.

INTRODUCTION

The KEKB accelerator [1,2] has been operated for almost six years and the present integrated luminosity is already beyond the amount of 425 fb^{-1}. This collider achieved the design luminosity of 1.0×10^{34} $cm^{-2}s^{-1}$ in May 2003, and it reached to 1.5×10^{34} $cm^{-2}s^{-1}$ in March 2005. In order to go much higher luminosity of 4×10^{35} $cm^{-2}s^{-1}$, the KEKB accelerator group started the design work of the extremely sophisticated collider, as Super-KEKB [3,4]. The design of Super-KEKB is based on the present machine for re-using the present hardware effectively. On the other hand, modifications and developments of many components are required with increasing the beam currents of low and high energy rings, LER and HER, to 9.4 A and 4.1 A, respectively.

In the interaction region, IR, the accelerator components need to be redesigned for the new beam optics. Especially, since the full crossing angle of two beams at the interaction point, IP, is increased from 22 mrad to 30 mrad, the magnets and the beam chamber will be re-constructed. Figure 1 shows the layout of the magnets in the IR. The eight quadrupole magnets are required from the beam optics as same as KEKB [5,6]. In Table 1, the integral field gradients and its locations from the IP are listed. The final focus quadrupole magnets, QCSR and QCSL, are designed to focus both beams in the vertical direction, and these magnets are superconducting magnets. The QC1 magnets extra-focus the HER beam of 8 GeV, while the LER beam energy is 3.5 GeV. The QC2 magnets focus the beams in the horizontal direction. Presently, the normal conducting QC1 and QC2 magnets are considered to be applied.

From the analysis of beam optics, the superconducting solenoids, ESR and ESL, are required near the IP in order to eliminate the influence of the detector solenoid field. In Fig. 1, ESR and ESL are overlapping with the QCS magnets on the beam line.

In this paper, the results of the design study on the superconducting magnets, QCS and ES are reported.

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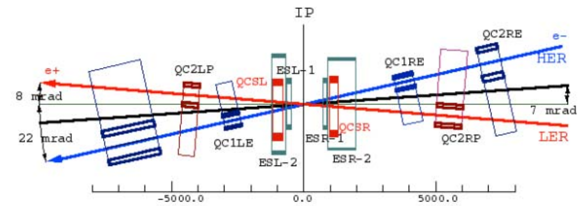

Figure 1: Magnet layout in the Super-KEKB IR.

Table 1: Magnet integral field gradient and location

	In. *G* (T/m)m	*Z* mm		In. *G* (T/m)m	*Z* mm
QCS-L	14.33	-969.4	QCS-R	11.99	1163.3
QC1-LE	9.92	-2799.6	QC1-RE	9.00	3800.0
QC2-LP	4.02	-4306.4	QC2-RP	3.40	5507.0
QC2-LE	6.80	-6712.7	QC2-RE	7.02	7214.0

CONSTRAINTS FOR MAGNET DESIGN

In Fig. 2, the beam physical apertures and the cryostat bores are described on the horizontal plane, schematically.

The QCS and ES magnets for each side of the IP are installed in a single cryostat. Inside the bore, the beam chamber for two beams is connected with the IP chamber. In this beam chamber, the incoming beams go through the quadrupole center of the QCS magnets. Each beam has the physical aperture, which is determined by the beta function and the beam acceptance. From the QCSR and QCSL magnets, the synchrotron radiations are emitted, of which intensities are calculated to be 179 kW and 64.6 kW, respectively. The radiations including the effect of the dynamic beta function are not serious for the design of QCS and ES magnets, while they turn to stringent constraints for the QC1 magnets.

The cryostat bore, the beam chamber, the beam physical apertures, and the synchrotron radiations must be designed not to have any interference.

There exist the spatial boundaries against the Belle detector components. The boundaries are shown in Fig. 2, with broken lines.

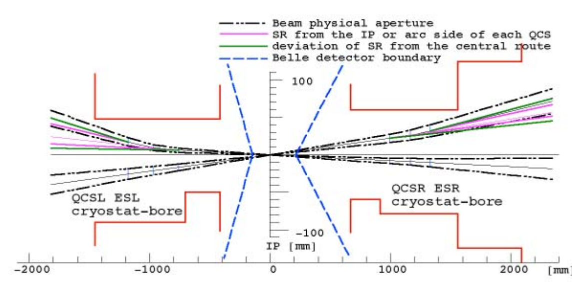

Figure 2: Spatial constraints for the QCS-ES cryostats on the horizontal plane.

MAGNET CONFIGURATION IN CRYOSTAT

Figures 3 and 4 show the cross sections of the magnet-cryostats in the horizontal plane. The QCS magnets are designed to locate the closest position to the IP under the spatial constraints as mentioned above. In order to get this QCS position, the ES magnet is divided into two parts. One is placed in front of the QCS magnet, and the other is overlaid on the QCS magnet. The QCS centers are not on the Belle axis, and the positions for QCSR and QCSL are (x,y,z)=(9.3, -0.2, 1163.3) and (21.2, -0.1, -969.4), respectively. The ES axes are coincident with the Belle detector axis.

The cross section of QCSR-ESR cryostat at the QCSR magnet center is shown in Fig. 5. Inside of the ESR magnet, the QCSR magnet is installed. The QCSR center is shifted from the ESR center by 9.3 mm horizontally and –0.2 mm vertically. In the QCSR bore, the beam envelops are depicted. The LER beam is designed to pass through the QCSR center.

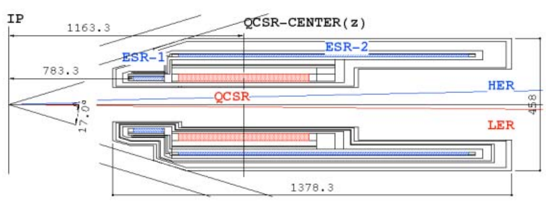

Figure 3: QCSR-ESR cryostat in the horizontal plane.

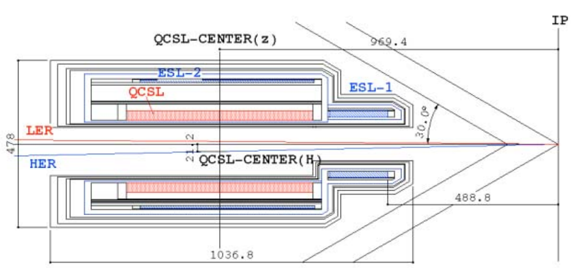

Figure 4: QCSL-ESL cryostat in the horizontal plane.

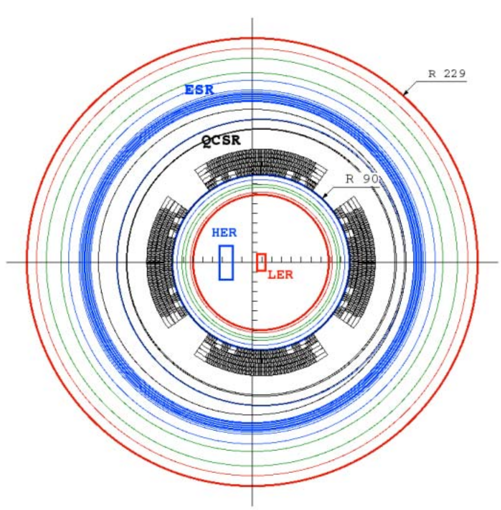

Figure 5: Cross section of QCSR cryostat.

FINAL FOCUS QUADRUPOLE

Design Parameters of QCS Magnets

The QCS magnet consists of 6 layer coils with an innermost radius of 90 mm. The design field gradient is 40.124 T/m. The QCSR and QCSL magnets have the same cross section, but the effective lengths are 0.299 m and 0.357 m, respectively. The magnet parameters are listed in Table 2.

The QCS magnets are operated, being combined with the ES solenoids under the magnetic field of the Belle solenoid. The maximum field on the QCS coil is calculated with the 3-D model. Without the Belle detector solenoid field of 1.5 T, the maximum fields of QCSR and QCSL are 5.97 T and 5.26 T with the ES fields, respectively. With the Belle field, which has the opposite direction to the ES field on the Belle axis, the maximum fields are decreased to 4.99 T and 4.77 T. The operating points defined by the ratio of the operating current to the critical current, I_{op}/I_c, are 75.1 % and 74.2 % for the QCSR and QCSL, respectively. For these operating conditions, the maximum temperatures at quench for the QCS magnets were calculated, and they were comfirmed to be less than 60 K.

The superconducting cable for the QCS magnet is the NbTi keystoned cable. The nominal size and keystone angle of the bare cable are 1.0 mm×3.9 mm and 0.72 degree. The parameters of this cable are listed in Table 3.

Table 2: Design parameters of the QCS magnet

	QCSR	QCSL
Field Gradient, G, T/m	40.124	40.124
Effective Length, L, m	0.299	0.357
Operating Current, I_{op}, A	1186.7	1186.7
Max. field with Belle & ES, T	4.99	4.77
Max. field with ES, T	5.97	5.26
I_{op}/I_c with Belle & ES @4.7 K, %	75.1	74.2
I_{op}/I_c with ES @4.7K, %	83.6	77.1
Inductance, mH	69.98	83.55
Stored Energy, kJ	49.3	58.8

Table 3: Parameters of the NbTi cable for QCS magnet

Cable thickness in the mid-part , mm	1.00
Cable width, mm	3.90
Keystoned angle, degree	0.72
Critical current @4.2 K and 5 T, A	2850.0
Cu/NbTi	1.8
Strand diameter, mm	0.55
Number of strands in the cable	14
Filament diameter, mm	0.01

Field Quality of QCS Magnets

The QCSR and QCSL magnets have the short magnet straight section of 170.0 mm and 228.3 mm, respectively, in addition to the large inner diameter of 180 mm. Due to these magnet geometries, there is no region of the flat field profile along the magnet axis. In Fig. 6, the b_2, b_6 and b_{10} profiles along the magnet axis are shown. The multipole components on the reference radius of 50 mm are normalized by the quadrupole field at the magnet

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center. In the coil ends, large allowed multipoles of b_6 and b_{10} are calculated at local position. However, these integral components along the magnet axis are reduced to be less than one of 10^4 compared to the quadrupole component by tuning the configuration of the coil ends. The calculation results are summarized in Table 4 with the multipole fields calculated by the 2-D cross section shown in Fig. 5. These profiles are used in the analysis of beam optics for studying the dynamic aperture.

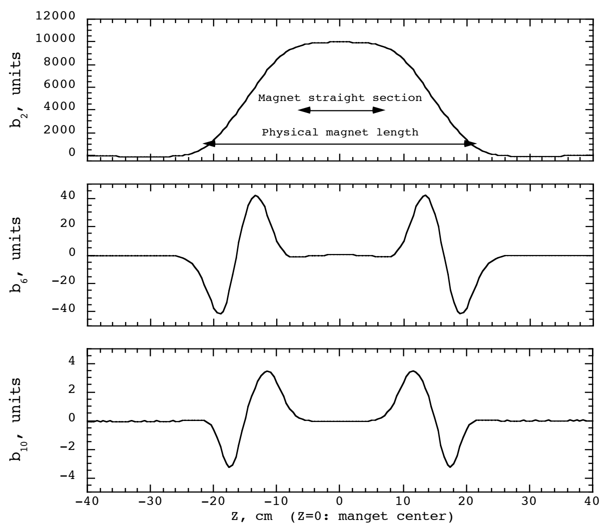

Figure 6: b_2, b_6 and b_{10} profile of QCSR.

Table 4: Integral multipole fields of the QCS at R=50 mm

	QCSR units	QCSL units	2-D cross section, units
b_6	-0.04	-0.02	0.12
b_{10}	0.46	0.38	-0.04
b_{14}	0.02	0.04	0.12

COMPENSATION SOLENOID

The compensation solenoid, ES, has the function of cancelling out the influence of the Belle solenoid field on both beams. The cancellation is required on each side of the IP because the x-y coupling of the beam at the IP induced by the solenoid field may lead to unwanted beam-beam blow-up. Therefore, on each side of the IP, the integral solenoid field of the ES magnets along the Belle axis is designed to be the same absolute value as that of the Belle solenoid, but with the opposite sign.

The design parameters of the ES magnets are listed in Table 5. The ESR-1 and ESL-1 generate the higher field than the ESR-2 and ESL-2, respectively. The ESR-2 and ESL-2 magnets have strong interference with the Belle magnetic field near the end cap iron yoke. The electro-magnetic forces of 2.2×10^4 N and 3.8×10^4 N act on the ESR-2 and ESL-2 magnets, respectively. For the reduction of the EMF, the ratio of the solenoid fields between the ES-1 and the ES-2 is tuned. The maximum field of ESL-1 with QCS-L is 5.83 T without the Belle solenoid field, and the ratio of I_{op}/I_c at 4.7 K is estimated to be 92.4 %. Since the ESL magnets are operated with the Belle field, the maximum field and the I_{op}/I_c are decreased to 4.33 T and 80.0 %, respectively.

Figure 7 shows the B_z profiles of the Belle solenoid plus the ES magnets with open circles. The profile shown by the blue line corresponds to the Belle solenoid field.

Table 5: Design parameters of the ES magnets

	ESR1	ESR2	ESL1	ESL2
Inner Dia., mm	164.6	330.0	154.0	354.0
Outer Dia., mm	191.0	347.6	189.2	367.2
Coil Length, mm	100	1000	166	500
I_{op}, A	647.2	647.2	656.2	656.2
Max. field with QCS, T	4.26	3.64	5.83	2.65
Max. field with Belle & QCS, T	2.76	2.61	4.33	2.39
I_{op}/I_c with QCS @4.7 K, %	75.3	70.0	92.4	61.0
I_{op}/I_c with Belle & QCS @4.7K, %	62.8	59.9	80.0	55.6

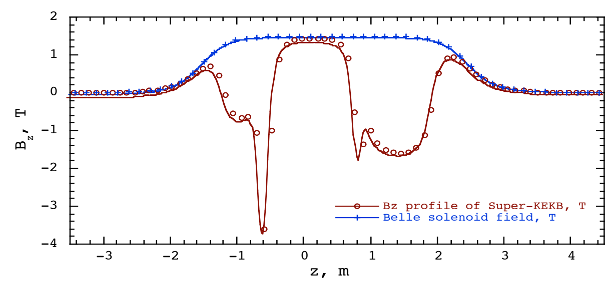

Figure 7: B_z profiles on the Belle axis.

CONCLUSION

The superconducting final focus quadrupoles, QCS, and the compensation solenoids, ES, are required for the IR of Super-KEKB, and these magnets were studied intensely.

(1) From the beam analysis and the magnet design work, the ES is devided into two parts in the single cryo-stat for placing the QCS at the closest position to the IP .

(2) The QCS consists of six layer coils with the inner most radius of 90 mm. The design field gradient is 40.124 T/m, and the ratios of I_{op}/I_c are 75.1 % and 74.2 % for the QCSR and QCSL, respectively. There exist sufficient operating margins.

(3) The ES has strong interference with the Belle field. The electro-magnetic forces of 2.2×10^4 N and 3.8×10^4 N act on the ESR and ESL, respectively. The design of the mechanical support becomes important.

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