

# DESIGN OF THE SUPERCONDUCTING MAGNET SYSTEM FOR THE SUPERKEKB INTERACTION REGION

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## Abstract

SuperKEKB is the upgraded accelerator of KEKB aiming at an extremely high luminosity. The machine is designed on the basis of nano-beam scheme. The beam final focusing system is the most important element for achieving the luminosity of this accelerator. The system consists of 8 quadrupoles, 4 solenoids and 43 correctors.

## INTRODUCTION

The target luminosity of SuperKEKB [1] is 40 times higher luminosity of  $8 \times 10^{35} \text{ cm}^{-2} \text{ s}^{-1}$  than that of KEKB. The 7 GeV electrons in the high-energy ring (HER) and the 4 GeV positrons in the low-energy ring (LER) collide at a single interaction point, IP, with a finite crossing angle of 83 mrad.

The accelerator is designed on the basis of the nano-beam scheme [2], and the final beam focusing system has been designed with superconducting quadrupole doublets for each beam. Since the positions of quadrupole magnets must be aligned very precisely within several nano meters, the alignment of quadrupoles is performed by the correctors [3]. In addition, from the requirement of beam optics, 43 corrector coils are installed in the system. The system has four compensation solenoids to reduce the effect of the detector solenoid field on the beams. All magnets and correctors are assembled into two cryostats.

In the paper, the design of the system is described.

## SUPERCONDUCTING MAGNET SYSTEM

### Magnet Layout in the IR

Figure 1 shows the layout of the superconducting magnets near the interaction point, IP [4]. The system consists of 8 main quadrupole magnets, 4 compensation solenoids, 35 corrector coils and 8 coils to cancel the leakage magnetic fields of QC1LP/RP. The main quadrupole magnets (QC1s and QC2s) are designed to form a quadrupole doublet for each beam. Table 1 shows the main parameters of the quadrupole magnets at the colliding energy of 11 GeV. The QC1LP/RP magnets are located at the closest position, +/- 935mm, to IP. They are quadrupole magnets without magnetic yokes in order to make the solenoid field profile for minimizing vertical beam emittance. The other quadrupole magnets have magnetic yokes.

Since the QC1LP/RP magnets are non-yoked magnets, the leakage field from the magnets to the e- beam line contains all field components as shown in Fig. 2. In order to cancel these components, the  $B_3$ ,  $B_4$ ,  $B_5$  and  $B_6$  cancel

coils [3] are wound using the helium inner vessel as the coil bobbin. A small twist of the windings which produce the normal cancel components also generates the needed skew cancel components. The  $B_7$  and  $B_2$  field components are included in the optics design.

The compensation solenoids, ESL, ESR1, ESR2 and ESR3, are designed to cancel the Belle-II solenoid field integrally along the beam lines [5]. In the ESL and ESR1 solenoids, two or three quadrupoles are assembled, respectively, as shown in Fig. 1. In the right cryostat, the additional solenoids, ERS2 and ESR3, are also installed.

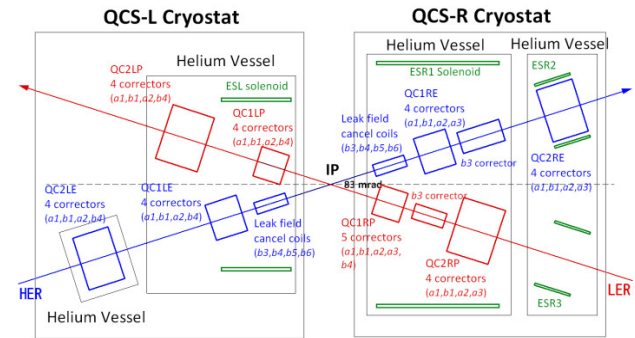


Figure 1: Layout of S.C. magnets near the IP of SuperKEKB.

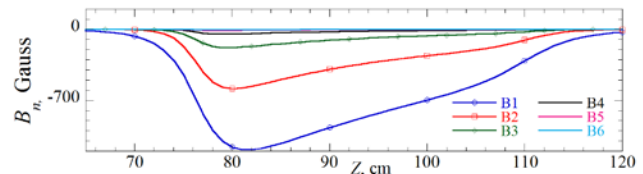


Figure 2: Leakage field profiles along the e- beam line.

Table 1: Main Quadrupole Parameters

Magnet	GL, T (T/m × m)	Type	Z, mm	θ, mrad
QC2RE	13.04 (31.12 × 0.419)	Yoke	2925	0
QC2RP	11.54 (28.15 × 0.410)	Yoke	1925	-2.114
QC1RE	25.39 (68.07 × 0.373)	Yoke	1410	0
QC1RP	22.96 (68.74 × 0.334)	no Yoke	935	7.204
QC1LP	22.96 (68.74 × 0.334)	no Yoke	-935	-13.65
QC1LE	26.94 (72.23 × 0.373)	Yoke	-1410	0
QC2LP	11.48 (28.00 × 0.410)	Yoke	-1925	-3.725
QC2LE	15.27 (28.44 × 0.537)	Yoke	-2700	0

GL is the integral field gradient (field gradient at center × effective magnetic length).

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### Alignment of Quadrupole Magnets

In Table 1, the quadrupole centers from IP and the mid-plane angles to the horizontal plane are listed. The quadrupole magnets for LER are assembled with these angles in the cryostats. Since the solenoid field and the leakage field of QC1P magnets change the e- beam orbits, the beam orbits will be controlled by dipole correctors. In order to optimize the corrector system, the magnet axes of QC1s and QC2s are shifted as shown in Table 2. In the table,  $\Delta Y$  is the shift amount in vertical direction from the horizontal plane including IP and the negative sign means downward. The plus  $\Delta X$  means the horizontal shift toward the outer direction of the accelerator ring.

Table 2: Shift Amount of Magnet Axis

Magnet	$\Delta Y$	Magnet	$\Delta X$
QC1RP	-1.0 mm	QC1RE	-0.7 mm
QC2RP	-1.0 mm	QC2RE	-0.7 mm
QC1LP	-1.5 mm	QC1LE	+0.7 mm
QC2LP	-1.5 mm	QC2LE	+0.7 mm

### QUADRUPOLE MAGNETS

The four cross sections of the quadrupole magnets are shown in Fig. 3. The magnet designs are different in order to accommodate the change of the beam pipe diameters in the cryostats. Table 3 shows the design parameters of the magnets. The numerical values are for colliding energy of 12 GeV. The magnets consist of two layer coils, and the cables are same specification except for the keystone angle. The QC1P magnets are designed without iron yokes because in the location of these magnets the solenoid fields by ESL and ESR1 integrally cancel the Belle-II solenoid field. The QC1E and QC2P magnets have Permendur yokes to avoid magnetic saturation in yokes due to local imperfection in cancelling Belle-II field by ESL and ESR1. For the QC2E magnets, the yoke material is iron because the separation between two beams is more than 200 mm.

Table 3: Design Parameters of QC1 and QC2 Magnets

	QC1 P	QC1 E	QC2 P	QC2 LE/RE
Magnetic yoke	No	Perm.	Perm.	Iron
Coil I.R., mm	25.0	33.0	53.8	59.3
Coil O.R., mm	30.49	38.49	59.29	64.79
Collar/Yoke O.R., mm	35.5	70	93	115
Turns in a pole	25	34	54	58
Field grad.at $I_d$ , G, T/m	76.4	91.6	32.0	36.4/39.3
Design curr., $I_d$ , A	1800	2000	1000	1250/1350
Magnetic length, mm	333.6	373.1	409.9	537/419
$I_d/I_c$ , %	72	73	47	50/49

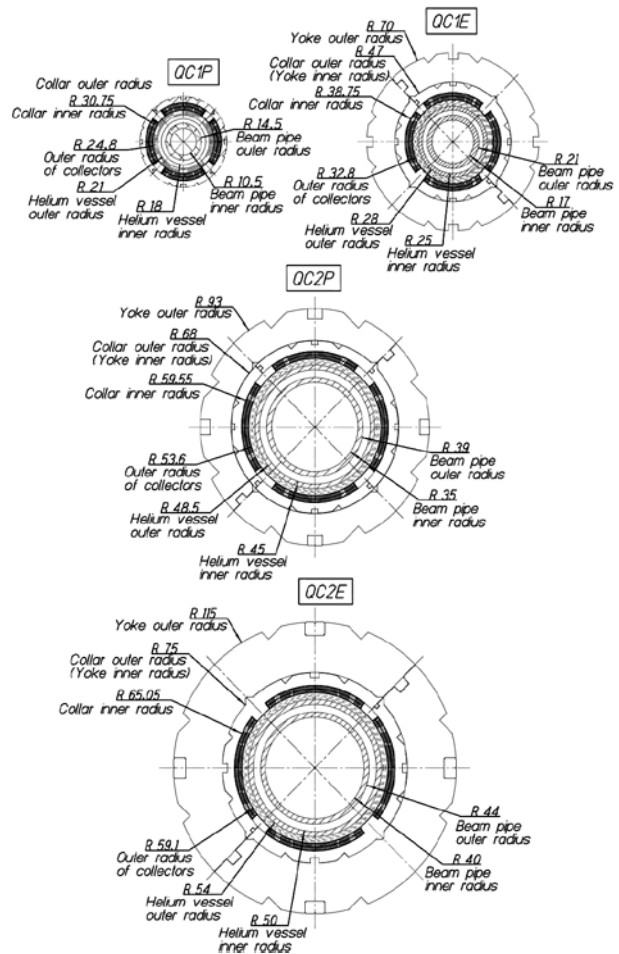


Figure 3: Quadrupole magnet cross sections.

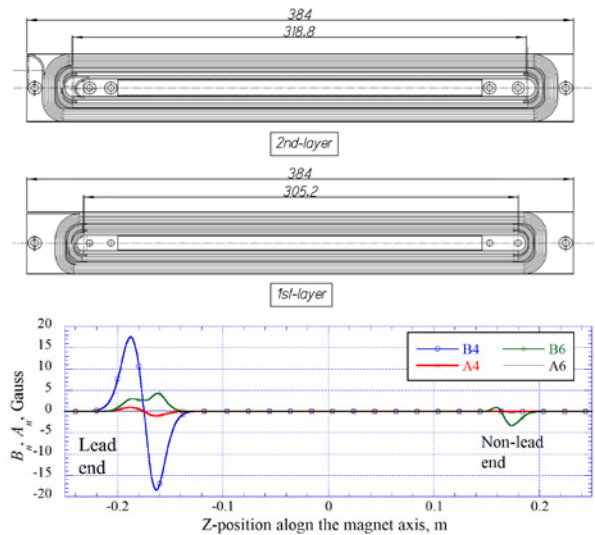


Figure 4: Coils of QC1P magnet and error field profiles.

In Fig. 4, the coils of QC1LP and the profiles of  $A_4$ ,  $B_4$ ,  $A_6$  and  $B_6$  components are shown. The coil ends are designed to reduce the absolute peaks of the error fields to less than 20 Gauss and the integral error fields to less than

1 unit. From the asymmetry configuration of the lead end, the  $B_4$  component has the peaks of +/- 18 Gauss. The Touschek life time are calculated with these field profiles. As the result, the lead ends of the magnets are positioned at the IP side in the cryostat because the smaller size beam at the IP side is less sensitive to the higher order error fields. The other quadrupole magnets are placed in the same way.

### SUPERCONDUCTING CORRECTORS

The corrector specifications are summarized in Table 4. In Table 4,  $R_r$  is the reference radius, and  $A_n$  and  $B_n$  are the skew and normal correctors, respectively. The  $A_1$  and  $B_1$  correctors are designed to be able to shift the magnet axis in the range of 0.5 mm to 1.0 mm. The  $A_2$  corrector can rotate the mid-plane angle of the quadrupoles from 12 mrad to 15 mrad. The sextupole  $A_3$  and  $B_3$  correctors cancel the error fields of the quadrupole magnets induced by magnet assembly errors. The required integral sextupole field strengths are equivalent to  $1 \times 10^{-3}$  of the quadrupole fields.  $R_r$  values of  $B_3$  coils for LER and HER are 15 mm and 30 mm, respectively. Installation of sextupole correctors was decided from the results of QC1P/1E proto-type magnets [6]. The  $B_4$  correctors increase the dynamic transverse aperture.

Table 4: Integral Field Strengths of Correctors

Magnet	$R_r$ mm	$A_1$ T•m	$B_1$ T•m	$A_2$ T	$A_3$ T/m	$B_3$ T/m	$B_4$ T/m <sup>2</sup>
QC1RP	10	0.016	0.016	0.64	7.6	17.2	60
QC2RP	30	0.03	0.03	0.31	1.36		-
QC1RE	15	0.027	0.046	0.75	7	27	-
QC2RE	35	0.015	0.015	0.37	1.5		-
QC1LP	10	0.016	0.016	0.64	-	-	60
QC2LP	30	0.03	0.03	0.31	-	-	60
QC1LE	15	0.027	0.046	0.75	-	-	60
QC2LE	35	0.015	0.015	0.37	-	-	60

### COMPENSATION SOLENOIDS

Figure 5 shows the field profile of Belle-II solenoid and the combined field profile with ESL and ESRs. As shown in Fig. 5, Belle-II solenoid generates the solenoid field of 1.5 T, and the field is cancelled by the reverse solenoid fields in the areas of QC1LP and QC1RP. In order to produce the combined field profiles required by beam optics, ESL and ESR1 are divided into 12 and 15 small solenoids, and they produce the integral fields of 2.31 T•m and 3.69 T•m, respectively. These integral fields correspond to the integrated Belle-II solenoid fields from the IP. The maximum fields in ESL and ESR1 coils with the Belle-II fields are 3.4 T and 3.3 T, respectively.

Since QC1Es and QC2Ps have the Permendur yokes and the combined fields are designed to be less than 0.01 T, the residual solenoid fields are negligible on the beam

lines. Between QC2RP and QC2RE, the Belle-II fringe field is in the range of 0.6 T because of no magnetic shields. The fringe field is cancelled by ESR2 or ESR3. The solenoid parameters are summarized in Table 5.

The design of the cryostat is difficult because the compensation solenoids have large repulsive electromagnetic forces from the Belle-II field. The forces on ESL and ESR1 amount to 38 kN and 48 kN, respectively. The forces affect the magnet-cryostat alignment, and this is the next important problem to be solved.

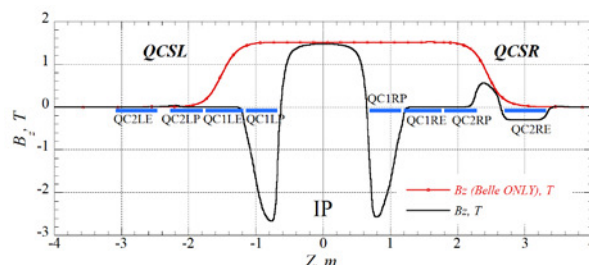


Figure 5: Solenoid field profiles along the beam lines.

Table 5: Design Parameters of Compensation Solenoids

	ESL	ESR1	ESR2/3
Integral field, T•m	2.31	3.69	0.17
Design current, A	348	462	210
Inductance, H	2.14	2.64	0.02
Maximum field, T	3.6	3.3	0.3
Magnet length, mm	905	1575	720
$I_d/I_c$ , %	68	72	<20

### SUMMARY

The final focusing superconducting magnet system of SuperKEKB has been designed after many steps of iteration. The designed system consists of 8 quadrupole magnets, 4 compensation solenoids and 43 corrector coils.

They are now in the construction stage, and the completion of the system is scheduled in 2015.

### REFERENCES

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