DESIGN STUDY OF FINAL FOCUSING SUPERCONDUCTING MAGNETS FOR THE SUPERKEKB

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Abstract

SuperKEKB is the upgrade project of KEKB [1]. We have performed the design study of the final focus superconducting magnets for the SuperKEKB interaction region (IR). These must be located as close to the interaction point (IP) as possible so that each beams can be squeezed to the small vertical beam size of 60 nm. While the space constraints are very severe, the wider aperture with good field quality is required. In this paper, the design status of final focusing system is reported.

INTRODUCTION

The target luminosity of SuperKEKB is 40 times higher luminosity of $8\times10^{35}\,cm^{-2}s^{-1}$ 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 one IP with a finite crossing angle of 83 mrad.

For each beam, the final beam focusing system consists of the superconducting quadrupole-doublets. These quadrupole magnets have to meet specifications described below. (1) While we need to keep the same boundaries to the detector components as KEKB, these magnets must be located closer to squeeze a vertical beam size. (2) Because of the small beam separation between two beam lines, the conductor size is required to be minimized. (3) Since the beta functions for these magnets are so large, 1200 m for horizontal and 6400 m for vertical, a larger space with a good field quality is required. (4) These magnets must apply the focusing fields on electrons and positrons, independently each other. So, the reduction of the non-linear leakage fields from the adjacent beam lines is a critical issue to achieve large dynamic aperture.

IR MAGNET DESIGN

A schematic drawing of the final focus system is shown in Fig. 1. The final vertical focusing fields for HER (LER) are applied by QC1LE and QC1RE (QC1LP and QC1RP) and the final horizontal focusing fields for HER (LER) are provided by QC2LE and QC2RE (QC2LP and QC2RP). These magnets are overlapped with the compensation solenoid (ESR and ESL) which are used to compensate the 1.5 T Belle detector solenoid fields. The parameters of these magnets are listed in Table 1.

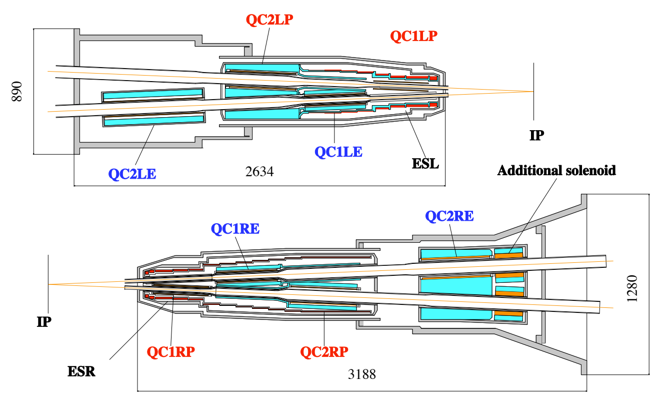

Figure 1: Schematic drawing of final beam focusing system. Orange area:the superconducting coil, aqua area: shows iron yoke.

QC1LP and QC1RP

QC1LP and QC1RP have same magnet configuration without an iron yoke. The beam pipe is designed to be room temperature and a component of the cryostat. Cross section of QC1LP is shown in Fig. 2 and the design parameters are shown in Table 2. The inner radius of 10.5 mm and the distance between the beam pipe and the magnet inner cylinder at 4 K is only 3.5 mm.

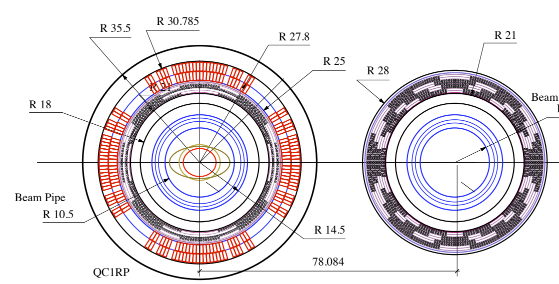

Figure 2: Cross section of QC1LP (QC1RP) and the cancel corrector coils (right) of the leakage fields at the magnet center. Main coils are shown by red lines.

Because QC1LP and QC1RP are required to be very small due to small beam separation, the cable for QC1 is required to be 2.5 mm$\times$0.93 mm in size and 2.66 degree of keystone angle. The cable consists of 10 strands in 0.5 mm in diameter. The R&D to fabricate this small cable was successfully performed. In order to reduce the peak field components of dodecapole and 20-th pole in the fringe fields, the end parts of the main coils are designed. The integral b_6 and b_{10} at the reference radius of 10 mm are designed to

Table 1: Integral field gradient (Solenoid field), locations of the magnet center from IP, magnet type, corrector magnets and leak field cancel coil.

Magnet	**GL** (T)	**z** (mm)	**Type**	**Corrector**	**Cancel coil**
QC2RE	12.91 (34.9 T/m × 0.370 m)	2925	S.C. + Iron yoke	a_1, b_1, a_2, b_4	
QC2RP	10.92 (27.17 × 0.4135)	1956	S.C. + Iron yoke	a_1, b_1, a_2, b_4	
QC1RE	24.99 (66.22 × 0.3774)	1410	S.C. + Iron yoke	a_1, b_1, a_2, b_4	
QC1RP	22.43 (66.52 × 0.3372)	932	S.C.	a_1, b_1, a_2, b_4	b_3, b_4, b_5, b_6
QC1LP	22.91 (67.94 × 0.3372)	-932	S.C.	a_1, b_1, a_2, b_4	b_3, b_4, b_5, b_6
QC1LE	26.67 (70.68 × 0.3774)	-1410	S.C. + Iron yoke	a_1, b_1, a_2, b_4	
QC2LP	10.96 (27.15 × 0.4135)	-1930	S.C. + Iron yoke	a_1, b_1, a_2, b_4	
QC2LE	14.13 (20.2 × 0.70)	-2700	S.C. + Iron yoke	a_1, b_1, a_2, b_4	
ESR	4.3 T (max.)		S.C. Solenoid		
ESL	4.7 T (max.)		S.C. Solenoid (Iron bobbin)		

Table 2: Design parameters of QC1LP and QC1RP

	QC1LP	**QC1RP**
Coil inner radius (mm)	25	
Coil outer radius (mm)	30.5	
Turns/pole	25	
B'L (T)	22.9	22.4
Field gradient (T/m)	67.9	66.5
Effective length (m)	0.34	
Magnet current (A)	1609	1576
Max. field in coil with solenoid (T)	3.9	3.8
Operation point to B_c at 4.7 K	79 %	76 %

be less than 4×10^{-6}. Figs. 3 and 4 show the main coil design and the field profiles along longitudinal position from magnet center, respectively.

Corrector coils of a_1, b_1, a_2 and b_4 are embedded in a main coil. The correction coil of b_4 is used to increase a dynamic aperture on momemtum. The leakage fields on the HER beam line from QC1LP and QC1RP are not negligible. Fig. 5 shows the leakage field profile along HER beam line is shown. In order to reduce that, the cancel coils of b_3, b_4,f b_5 and b_6 for the HER beam line are designed. The b_1 and b_2 components are not canceled and included in the optics calculation. Fig. 3 (lower) shows the canceling coils of b_3 and b_4.

QC1LE and QC1RE magnets

QC1LE and QC1RE magnets have iron return yokes and the magnetic shield on adjacent beam pipes. By introducing the iron yokes to quadrupole magnets, the cancel coils for leakage fields can be omitted. The cross section of QC1LE (QC1RE) is shown in Fig. 6 and the design parameters are shown in Table 3. Fig. 6 shows two dimensional calculation by Opera-2d [2] and Fig. 8 shows b_3 changes of main coils as a function of the distance between two beams. The field quality for main coil is affected by the magnetic shield but the b_3 component is enough small.

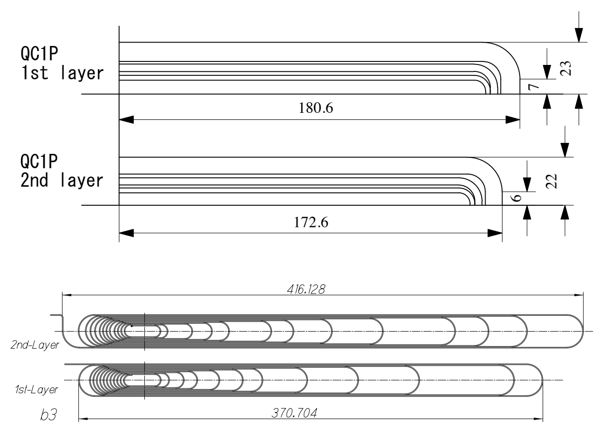

Figure 3: Upper:1st layer and 2nd layer design of QC1LP main coil, Lower: the special shaped canceling coil of b_3.

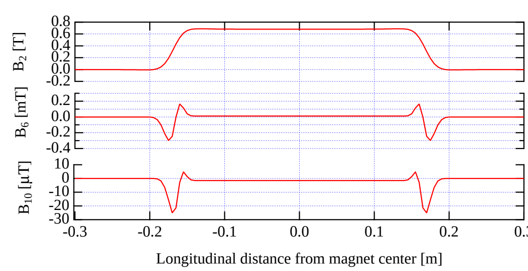

Figure 4: B_2, B_6 and B_{10} field profiles of QC1LP along longitudinal direction.

Compensation solenoid

The fringe field of the compensation solenoids degrade the vertical emittance. To make the vertical emittance small enough, ESL and ESR are divided into small coils and produce a slow change of solenoid field profile along the Belle axis. The Solenoid field profile along the Belle axis is shown in Fig. 9. In order to make the integrated solenoid field zero, the additional small solenoids with iron yoke are placed at the back of QC2RE in both beam lines.

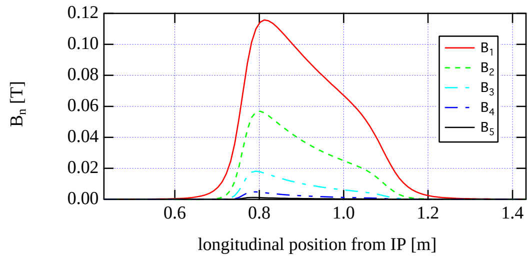

Figure 5: Leakage field profile along HER beam line from QC1LP mail coil.

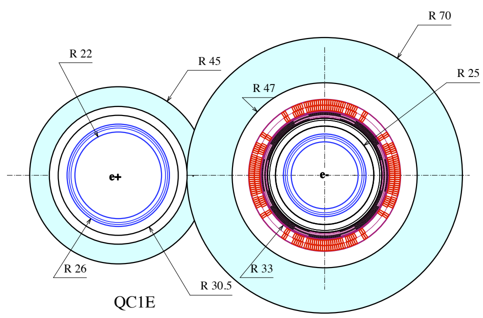

Figure 6: Cross section of QC1LE (QC1RE) (right) and the cancel coils (left) of the leakage fields at the magnet center. Red lines: main coils, black points: correctors, aqua area: iron yokes and magnetic shield.

On the other hand, the magnetic flux density for QC1LE, QC1RE, QC2LP and QC2RP magnets, which have iron return yoke must be minimized because these magnets are placed inside of the compensation solenoid. Since the material of ESL support bobbin is an iron, the flux densities in the iron yokes for QC1LE and QC2LP can be reduced to less than 0.5 T.

ESL and ESR are subject to repulsive the electro-magnet forces against the Belle detector and iron yoke for the QC magnets is subject to Maxwell stress. The Lorentz force for ESL is about 5.2 ton and total Maxwell stress for QC1LE, QC2LP and ESR iron yokes is about about 1.2 ton. ESR has no iron bobbin and the Lorentz force is about 7.7 ton and the Maxwell stress for QC2RE iron yoke is 1.5 ton. These forces are manageable level but support structure design must be taken care.

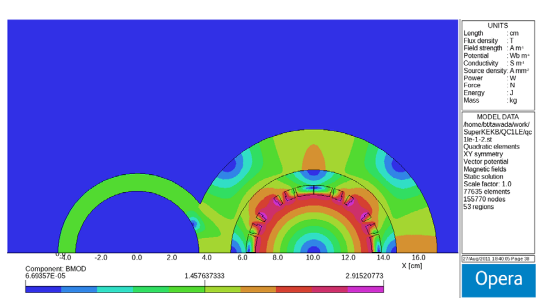

Figure 7: Two dimensional calculation for QC1LE at the most closet location at IP.

Table 3: Design parameters of QC1LE and QC1RE

	QC1LE	QC1RE
Coil inner radius (mm)	33.0	
Coil outer radius (mm)	38.4	
Turns/pole	34	
B'L (T)	26.7	25.0
Field gradient (T/m)	70.7	66.2
Effective length (m)	0.34	
Magnet current (A)	1560	1460
iron return yoke (mm)	94×140 (I.D×O.D)	
shield yoke (mm)	70×90 (I.D×O.D)	

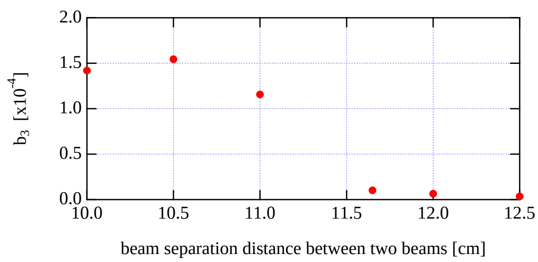

Figure 8: The b_3 changes of QC1LE with the separation distance between two beams at the reference radius of 15 mm.

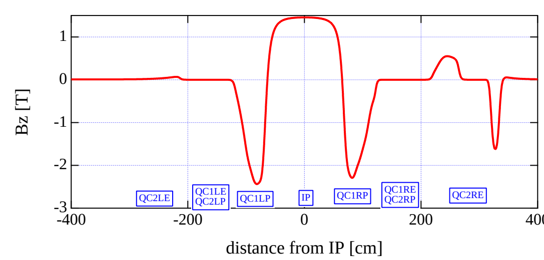

Figure 9: Solenoid field along the Belle axis from IP.

SUMMARY

Final focusing system for SuperKEKB interaction region is designed. Three dimensional calculations the compensation solenoid and the QC magnets with Belle detector solenoid are necessarily and on-going now. Practical design of magnets, cryostat and cryogenic system are also in progress. However, there are still issues to be studied, e.g. cryostat vibration in the Belle solenoid field.

REFERENCES

[1] H. Koiso, WEZA02, in these proceedings.

[2] OPERA®, Cobham Technical Services; http://www.vectorfields.com.