THE SUPERCONDUCTING MAGNET SYSTEM FOR KEKB B-FACTORY

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ABSTRACT

The superconducting final focus system for the interaction region of KEKB consists of two solenoid field compensation magnets, two superconducting quadrupoles and a cooling system. This paper describes the latest design and technical solutions developed for this superconducting magnet system.

1 INTRODUCTION

KEKB is an asymmetric, two-ring electron-positron collider for B-meson physics that is currently under construction at KEK, Japan[1]. This machine has only one interaction point, where the e^- (8 GeV) and e^+ (3.5 GeV) beams collide at a finite crossing angle of ±11 mrad. A detector facility with a 1.5 T solenoid field will be built around this interaction region. Fig. 1 shows the schematics of the design of the interaction region (IR) which requires four superconducting magnets (S-R, QCS-R, S-L, QCS-L). Compensation solenoid coils, S-R and S-L, are the accelerator elements closest to the interaction point. They are followed by final focus quadrupole magnets, QCS-L and QCS-R, which include correction coils inside their bores. The QCS and S magnets on each side of the interaction point are contained in a common stainless-steel cryostat. The locations of the cryostats are completely inside the detector facility. Therefore, they must withstand large electromagnetic forces on the magnets due to the interactions with the detector solenoid field. The cryostats are connected to a refrigerator through multi-channel transfer lines which include bus lines for the quadrupole magnets.

2 COMPENSATION SOLENOIDS

The field by the detector solenoidal magnet creates optical aberration which is difficult to cancel elsewhere in the machine. To reduce its effects, two compensation solenoids S-R and S-L, having a magnetic field opposite to the detector solenoid, have been designed. The two coils have the same inner and outer diameters. However, their lengths are slightly different. Table 1 summarizes their main parameters.

Calculation of the magnetic field by the combination of these solenoid magnets and the detector solenoid, including effects of the iron yoke structure, have been done by using a computer code, OPERA-2D. A design solution has been obtained where an integral of Bz along the accelerator beam line is brought to zero. The leakage of the compensating solenoid fields distorts the field in the detector's tracking volume. However, its effect has been calculated to be small; less than 5 % of field deviation is expected, except for the region very close to the compensation solenoids.

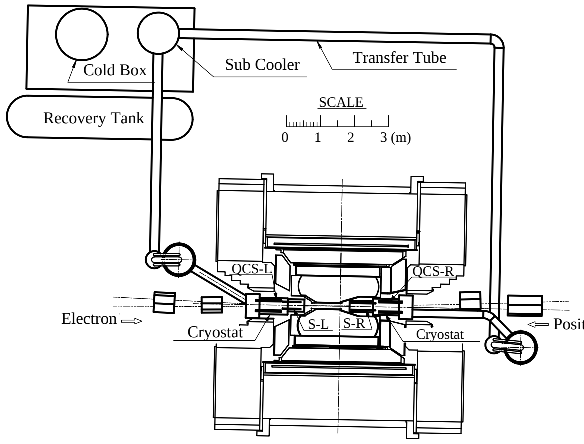

Fig. 1 Layout of the accelerator elements in the detector facility, together with the cryogenic system for the superconducting magnets, S-L, S-R, QC-L and QCS-R. Other accelerator magnets are normal-conducting.

During normal operation, because of the detector solenoidal field, the radial bursting forces of the solenoids will be different from the values in Table 1. Likewise, the peak fields on the conductors will be reduced by 1.5 T. The calculated axial magnetic forces on S-L and S-R are 22 kN and 2.8 kN, respectively. As shown in Fig. 2, for a fixed

Table 1 Main parameters of the solenoids

	S-R	S-L	
Central field	5.43	4.47	T
Current	567	486	A
Max. field on the conductor	5.45	4.54	T
Ic load line ratio	77	64	%
Stored energy	231	117	kJ
Inductance	1.44	0.99	H
Coil current density	283.5	243.0	A/mm^2
Magnetic pressure in radial direction	9.4	6.4	MN/m^2
Coil			
IR	95	95	mm
OR	111	111	mm
Length	650	470	mm
No. of turns	5200	3760	

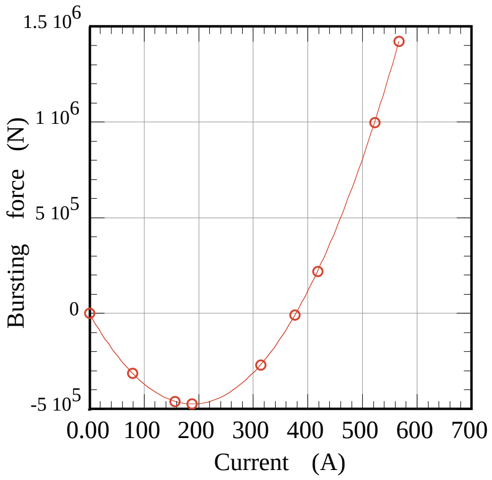

Fig.2 Excitation current dependence of the bursting force on the S-R coil in the detector solenoid field.

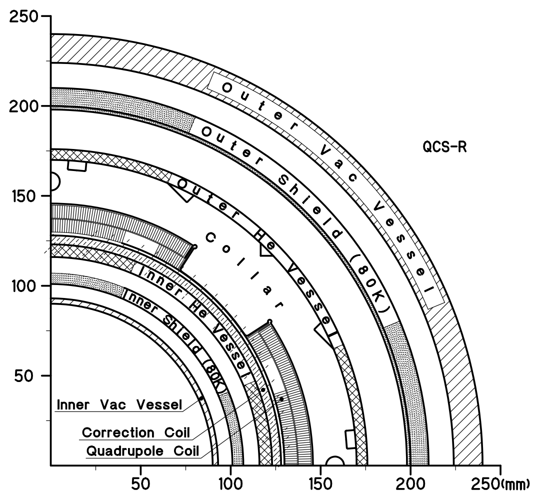

Fig. 3 Cross section of QCS-R.

detector solenoidal field, the current dependence of radial bursting forces on the S-L and S-R is quite different from ordinary solenoids. To manage these forces, a bobbin of ~7-mm thickness will be placed inside the coil.

3 QUADRUPOLE MAGNETS

The quadrupole magnets are built as iron-free superconducting magnets. They produce a maximum gradient of 20.5 T/m within a coil aperture diameter of 260 mm. The design is based on a set of cos2θ windings that are clamped by stainless steel collars. We take the same 2-dimensional structure for both QCS-L and QCS-R. However, the dimensions of the cryostats will be different because of the spatial constraints from detector facility. Table 2 shows the main parameters of the quadrupoles.

Fig. 3 shows a cross section of QCS-R in a horizontal cryostat. The inner diameter of the warm bore is 178 mm and the outer diameter of the vacuum vessel is 480 mm. Starting with the innermost part, the main components of the magnet are: a warm bore, inner radiation shield, inner wall of the helium vessel, correction coils, main coil, 316LN stainless-steel collar, outer wall of the helium vessel, outer radiation shield and vacuum vessel. The main coil is made of two layers of windings. An approximately cos2θ current distribution is created by using a copper wedge in the first layer. To keep higher multipole fields within the tolerance, the two-dimensional cross section of the coil has been determined by using a code based on an analytical formula of field harmonics. Fig. 3 shows the resultant shape. The total number of turns is 105, including the first and second layer in each of four quadrants.

The superconducting cable is NbTi/Cu Rutherford type cable, consisting of 24 multifilamentary strands of 0.59 mm diameter (copper/superconductor ratio 1.8) twisted with a pitch of about 60 mm (filament size 6 µm). The cable is insulated with two kinds of Upilex tape; 25 µm- and 50 µm-thick tapes.

Effects of various fabrication errors of windings have been investigated with 2-D calculations, assuming a basic eight-fold symmetry in the coil geometry. Table 3 summarizes the results. The quoted numbers are for a 0.5 mm variation of parameters listed in the left column. Since QCS-L and QCS-R are shorter than typical accelerator

Table 2 Main parameters of the quadrupole magnets.

	QCS-R	QCS-L	
field gradient	20.542	20.542	T/m
Current	2913	2913	A
Effective magnetic length	385	483	mm
Max. field on the conductor	4.2	4.2	T
Ic load line ratio	70	70	%
Main coil			
Inner radius	130	130	mm
Outer radius	144.9	144.9	mm
Overall length of the coils	521	617	mm
Collars outer diameter	340	340	mm
Integrated field uniformity (at r= 40 mm)			
B_6L/B_2L	< 1 x 10-5	< 1 x 10-5	
$B_{10}L/B_2L$	< 1 x 10-5	< 1 x 10-5	
Stored energy	69.7	87.5	kJ
Longitudinal magnetic forces	180	175	kN
Resultant of magnetic forces per meter length in the coil quadrant			
Fx (horizontal)	149.7	149.7	kN/m
Fy (vertical)	-363.7	-363.7	kN/m

Table 3. Effect of fabrication errors

Parameters changed	ΔG 10^{-4}	Δb_6 10^{-4}	Δb_{10} 10^{-4}
Radius of inner coil	-33.0	-0.09	-0.00
Radius of outer coil	-39.0	0.09	0.00
Radius of inner No.1 coil	-27.0	-0.35	0.00
Radius of inner No.2 coil	- 6.0	0.27	-0.00
Pole angle of inner coil	5.0	-0.01	-0.00
Pole angle of outer coil	17.0	0.25	-0.00
Wedge of inner coil	-11.0	-0.33	-0.00

The values show the effect of 0.5 mm change in the given parameter on the quadrupole field strength, the higher harmonics at r=40 mm.

Table 4 Major electromagnetic force and torque works on each coil.

	Fx	Fy	Mx	My	Mz
QCS-L	-1000 N (yoke)	800 N (det. sol) 1000 N (S-L)	200 Nm (det. sol) -500 Nm (S-L)		
Normal D-L	51800 N (QCS-L)	-1800 N (det. sol) 200 N (S-L)	1100 Nm (det. sol) -100 Nm (S-L)		
Skew D-L	-1900 N (det. sol) 200 N (S-L)	55200 N (QCS-L)		-1200 Nm (det. sol) 100 Nm (S-L)	
Skew Q-L					4800 Nm (QCS-L)
Normal D-R	42400 N (QCS-R)	400 N (det. sol) -200 N (S-R)	2300 Nm (det. sol) -100 Nm (S-R)		
Skew D-R	400 N (det. sol) -200 N (S-R)	45300 N (QCS-R)		-2400 Nm (det. sol) 100 Nm (S-R)	
Skew Q-R					3800 Nm (QCS-R)

In parenthesis is the coil or the yoke which produces the force and/or torque.
The coils listed in the left column, except for the QCS-L, are correction coils in the QCS-L or QCS-R.

superconducting magnets, effects of the end parts are not negligible. Three-dimensional field calculations were done to optimize the shape of the coil end for minimizing the integral values of undesirable higher multipoles. Also, peak values of the multipoles along the beam axis have been reduced by adjusting the directions of each pole winding. The peak value of the skew quadrupole fields at the lead end was decreased from 0.18 mT to 2.4 μT at R=4 cm. Effects on the integral higher multipoles due to the fabrication errors at the ends have been found to be small; the changes of 12-th and 20-th pole to occur for coil misalignments of 1 mm are less than 1×10^{-5}.

The quadrupole axis of QCS-L has to be shifted horizontally by 35.1 mm from the detector axis. Higher order multipoles and the asymmetric magnetic forces can arise, because of the image current in the end yoke of the detector. This effect has been evaluated by a 2-dimensional treatment. Analyses on the beam dynamics have found that the higher multipoles are well within an acceptable level in terms of dynamic apertures. The strength of the attractive force between the end yoke and QCS-L is about 2.3 kN, and it is in the manageable range.

Three kinds of correction coils (horizontal and vertical steering, and skew quadrupole) will be embedded inside the main quadrupole winding. The field strength of the dipoles is <0.05 T and the gradient of the skew quadrupole is <0.4 T/m. A multi-wiring technique developed for RHIC and SSC correctors [2] will be used.

Various forces exerted on each coil within the QCS stystem have been studied by using Biot-Savart's law. Table 4 tabulates major forces that act on each coil.

Table 5 Estimated LHe heat load

Cryostat (including connection box)	x 2	35	W
Current leads			
for QCS-R and QCS-L		15	L/h
for S-R and S-L		7	L/h
for six correction coils		7	L/h
Transfer line (including 2 connection boxes)	~35 m	46	W
Total		81 W + 29 L/h	

4 COOLING SYSTEM

Two cryostats will be built and installed on each side of the interaction point. Design of these cryostats takes into account many practical constraints near the interaction point, including: desire for a small outer diameter, narrow thermal insulation space, sufficient mechanical strength to sustain the forces acting on the magnets, small heat load, and others. The heat load of a pair of cryostats is estimated to be less than 35 W.

The estimated heat load of each cryogenic component is listed in Table 5. The cooling system that has been used for the TRISTAN mini-beta insertion quadrupoles since 1991 has a capacity of 190 W + 30 L/h, therefore, it will be reused with an enough margin. The magnets will be cooled by single phase liquid helium of 4.5 K and 0.16 MPa.

REFERENCES

[1] S. Kurokawa, KEKB status and plans, Proc. of the 1995 Particle Accelerator Conf. and Int. Conf. on High Energy Accelerators, p.491.

[2] A. Morgillo et. al., Superconducting 8 cm corrector magnets for the Relativistic Heavy Iron Collider (RHIC), Proc. of the 1995 Particle Accelerator Conf. and Int. Conf. on High Enertgy Accelerators, p.491.