CONSTRUCTION OF THE FINAL FOCUS SUPERCONDUCTING MAGNET SYSTEM FOR KEKB

K. Tsuchiya, T. Ogitsu, N. Ohuchi, T. Ozaki, and N. Toge,
KEK, 1-1 Oho, Tsukuba-shi, Ibaraki-ken, 305, Japan

Abstract

A superconducting final focus magnet system for the interaction region of KEKB was constructed. It consists of two solenoid field compensation magnets, two superconducting quadrupoles and a cooling system. A system test has been successfully completed. This paper describes the construction of the magnets, cryostats, and results from the system testing.

1 INTRODUCTION

KEKB, an asymmetric two-ring electron-positron collider for B-physics, is presently under construction at KEK. In the interaction region four superconducting magnets are used: two solenoid field compensation magnets, and two final focusing quadrupole magnets with three kinds of trim coils[1]. KEK started the fabrication of the magnets, cryostats and transfer lines in 1996, the installation was completed in September of 1997 and the system was cooled down. During the test, it was found the temperature of the solenoid was not low enough for the design current operation. After repairing the cryostat, the system was cooled down again in January, 1998 and a commissioning test has been successfully completed.

2 SYSTEM LAYOUT

The basic design and the layout of the system is very similar to the TRISTAN mini-beta insertion quadrupole systems[2]. Two cryostats are installed on each side of the interaction point (IP). They are connected to a subcooler-cold-box unit near the detector facility, about 20 m below the ground level, via multi-channel transfer lines. Other components of the cryogenic system (helium compressor, gas tank etc.) are at the ground-level together with the magnet power supplies. The five coils (S, QCS, and three trim coils) on each side of the IP are contained in a common cryostat module.

Fig. 1 shows the picture of the installed cryostat, the multi-channel transfer line, and a subcooler-cold-box unit near the BELLE detector.

3 SUPERCONDUCTING MAGNETS

3.1 Compensation Solenoid

Two compensation solenoids, S-R and S-L, have been designed and constructed. They produce an axial magnetic field opposite to the detector solenoid for field compensation for the accelerator. The design field was chosen so that an integral of B_z of the detector solenoid along the accelerator beam line is brought to be zero. The two solenoids have the same inner and outer diameters, but their lengths are slightly different. Table 1 summarizes their main parameters. The coils are made of monolithic NbTi superconducting wire with a cross section of 0.9 mm $\times$ 1.2 mm (copper /superconductor ratio 1.0). The insulation is provided by polyimid group resin. After winding on the helium inner cylinder, the coils were impregnated with Epoxy resin under pressure and enclosed in helium vessels. The estimated axial compression force on the coils after the assembly were 516MN and 250MN for S-R and S-L, respectively.

Figure 1: The installed final focus magnet system. In the operating condition, the cryostat is placed completely inside the detector. From the cryostat, the transfer line is running to the subcooler-cold-box unit sitting the right side of the detector facility.

	S-R	S-L	
Central field	5.59	4.44	T
Current	602	497	A
Max. field on the conductor	5.45	4.50	T
Stored energy	247	120	kJ
Coil			
IR	95	95	mm
OR	116	116	mm
Length	624	470	mm
No. of turns	4912	3696	

Table 1: Main parameters of the solenoids

Each solenoid enclosed in the helium vessel was tested in a vertical cryostat before installation into the horizontal cryostat. An excitation test was performed without background field. The S-R magnet required a number of training quenches (40 of these) to reach the design current of 600 A. However, it showed no retraining after a thermal cycle. The performance of S-L magnet was excellent. The current reached 600 A, 120 % of the design current, without quenching. The reasons of these different training behavior between S-R and S-L are not clear yet.

3.2 Quadrupole magnet with trim coils

The quadrupole magnets was designed and constructed on the basis of experience with the TRISTAN mini-beta insertion quadrupole magnets. They are iron-free superconducting magnets. They produce a field gradient of 21.26 T/m within a coil aperture with diameter 260 mm. The coil design is based on a set of $\cos 2\theta$ windings that are clamped by stainless steel collars. Table 2 gives the main parameters of the quadrupoles and Fig. 2 shows a transverse cross section of QCS-R in its horizontal cryostat. The main components are, from the innermost part: warm bore, inner thermal shield, inner wall of the helium vessel, trim coils, main coil, 316LN stainless-steel collar, outer wall of the helium vessel, outer thermal shield and vacuum vessel. 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 $6\,\mu$m). The cable is insulated with two kinds of Upilex tape; $25\,\mu$m- and $50\,\mu$m-thick tapes.

	QCS-R	QCS-L	
Field gradient	21.26 (21.80)	21.26 (21.68)	T/m
Current	2963	2963	A
Effective length	385 (387.8)	483 (487.6)	mm
Max. field on the conductor	4.3	4.3	T
Ic load line ratio	70	70	%
Main coil			
Inner radius	130	130	mm
Outer radius	144.9	144.9	mm
Overall length	521	617	mm
Collars outer dia.	340	340	mm
Stored energy	69.7	87.5	kJ

Table 2: Main parameters of the quadrupole magnets. Numbers within parentheses are measured values.

In side the quadrupole winding, three kinds of trim coils (horizontal and vertical steering, and skew quadrupole) are embedded. The field strength of the steering coil is about 0.05 T and the gradient of the skew quadrupole is about 0.4 T/m. These are considered enough to steer the beam about 3 mm, and to rotate the quadrupole field by about 12 mrad. The flat coils were made at BNL by the multi-wiring technique, and they were assembled on the helium inner cylinder in the company.

After finishing the assembly of the quadrupole, the magnets were tested in a vertical cryostat to see the quench behavior at 4.2 K. During this test, the main coil and trim coils were first excited independently up to 110 % of their design currents. Then the various combination tests were performed. The performance was very good. No quench had occurred during the tests. Field measurements were also performed with a rotating coil system[3]. The measured values of the field gradient and the effective magnetic length of each magnet were shown in Table 2. The allowed and unallowed harmonics at the current of 2966 A are listed in Table 3.

Multipole	QCS-R		QCS-L	
	b_n	a_n	b_n	a_n
3	-1.15	0.38	0.99	0.72
4	0.64	0.33	1.79	0.45
5	0.06	0.06	-0.52	1.55
6	-0.19	-0.06	-1.08	-0.54
7	0.01	0.02	0.50	-0.89
8	-0.01	0.01	0.79	0.44
9	0.0	0.0	-0.43	0.67
10	-0.02	0.0	-0.55	-0.36

Table 3: Multipole components of QCS magnets at the radius of 48 mm.

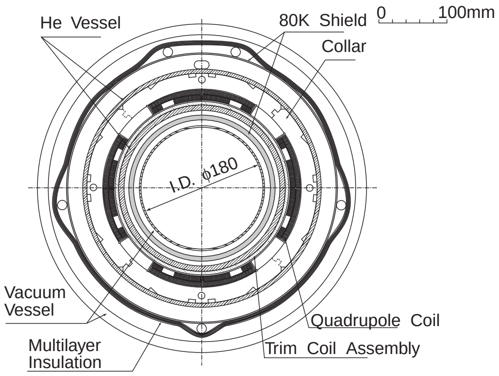

Figure 2: Cross section of the QCS-R magnet.

4 CRYOSTAT

Two compact cryostats in which the magnets are cooled by single phase LHe of 4.5 K were constructed for each side of the interaction point taking into account the following constraints and requirements: small outer diameter and a large warm bore, sufficient mechanical strength to sustain the forces acting on the magnets, a small heat load, etc.

Fig. 3 shows the right side cryostat just arrived at the interaction region. The cryostat consists of three parts: horizontal annular vessel containing the magnets, vertical vessel called connection box, and a bent pipe connecting both vessels. The major components of the annular part are a helium vessel, a thermal shield, suspension system, and a vacuum vessel. The helium vessel is made of 316L stainless steel and the sizes of the cylinders enclosing solenoid and quadrupole are different. In case of the left side cryostat, the quadrupole axis was shifted horizontally by 35 mm from the axis of the solenoid. The design pressure of the vessel is 0.4 MPa to accommodate the pressure rise following magnet quench, and to simplify the cool down and warm up procedures. Welded seams are used throughout to ensure leak tightness of the helium vessel. On the surface of the helium vessel, Aluminum tape was attached to improve the emissivity coefficient, and no super insulation was used between the helium vessel and the thermal shield. However, between the thermal shield and the vacuum vessel, Aluminized Kapton was arranged to screen the radiation heat from the vacuum vessel. The thermal shield is made of 316L stainless steel to reduce the induced current during magnet quenching. The helium vessel was suspended by eight tension rods made of titanium alloy (Ti-6Al-4V ELI). The tilt angle and length of the rod were determined to compensate the thermal contraction of the helium vessel and to accommodate the conflicting requirements, small size and small heat leakage through the rods.

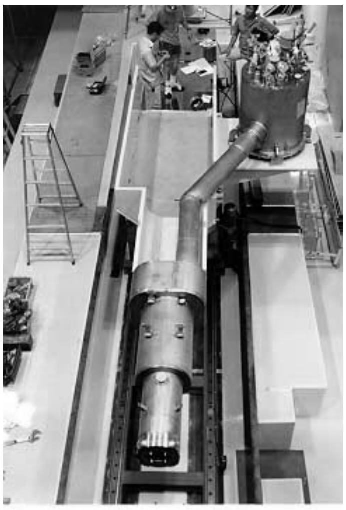

Figure 3: The right side cryostat before installation.

The connection box functions as an interface between the cryostat and the multi-channel transfer line coming from the subcooler box. On the top flange of the connection box there are bayonet joints for liquid helium and liquid nitrogen, current leads for solenoid and trim coils, two control valves, and some service ports. One of the helium bayonet joints is a coaxial two-channel type (LHe flow and LHe return) and contains superconducting bus lines for QCS magnet in the central channel. The current leads for QCS magnets are on the subcooler box and they are excited in series.

5 SYSTEM TEST

After finishing the installation of the magnet system, the first cooldown test was performed by forced circulation of cold gaseous helium. The temperature of the gas was reduced gradually in order to follow the magnet cooldown.

All these controls were done remotely by a process control computer. Fig. 4 shows a typical cooldown curve of the magnet system. When the solenoid S-L was charged with the aim of achieving its design current, it was found that the solenoid quenched at a current of about 200 A and didnt go higher current. When the temperature distribution in the helium vessel was analyzed, it became clear that the temperature of the front end of the solenoid was higher than we expected, about 8 K. In order to solve this problem, we decided to make helium flow channels in the front end of the helium vessel and completed the improvement by the end of 1997.

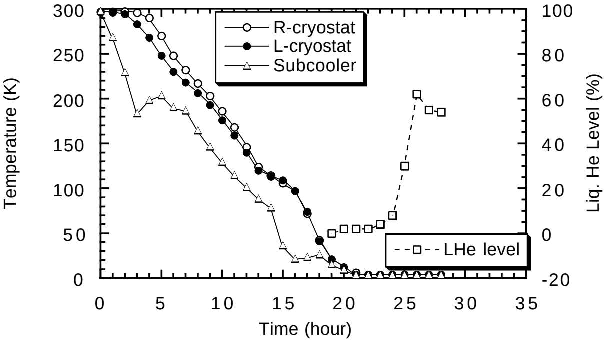

Figure 4: Cooldown curve of the magnet system.

In January 1998, the second cooldown test was performed and the solenoid was successfully excited up to its 110 % design current without quenching. During the test, all magnets were excited to their power supplies limit or 110 % of their design currents. And also various combination of the excitations were done in order to confirm the soundness of the magnet designs and the reliable operation.

The magnet cryogenic system performed well even during and after a quench at full currents. The heat loads of the system estimated from the redundant cooling power of the refrigerator is about 75 W+ 30 L/h.

6 ACKNOWLEDGMENTS

We are very grateful to our colleagues of the KEKB magnet group for their contribution to this work. We are also grateful to Dr. Ozaki and his group at BNL for making the trim coils.

7 REFERENCES

[1] K. Tsuchiya et al.: ‘The Superconducting Magnet System for KEKB B-Factory’, Proc. of the 5th European Accelerator Conf. (EPAC 96), p2287.

[2] K. Tsuchiya et al.: ‘Helium Cryogenic Systems for the Superconducting Insertion Quadrupole Magnets of the TRISTAN Storage Ring’, Advances in Cryogenic Engineering, Vol.37, Part A, P667, 1992.

[3] N. Ohuchi et al.: ‘Magnetic Field Measurements of the Superconducting Magnets for KEKB Interaction Region’, to be published in the Proc. of MT-15, Beijing, Chine, 1997.