SUPERCONDUCTING MAGNET SYSTEM FOR THE TRISTAN LOW-BETA INSERTION

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Abstract : This paper describes the design and construction of the superconducting quadrupole magnet systems for the TRISTAN low-beta insertion. Main components of the system are two superconducting quadrupoles, a power supply, two movable supporting tables, and a computer- controlled cryogenic subsystem. The magnet is an iron-free type with an inner coil diameter of 140 mm, an outer collar diameter of 280 mm, and a physical length of 1450 mm. The design field gradient is 70 T/m at 3405 A. It is cooled by single-phase liquid helium at 4.5 K. Two magnets, one on each side of the interaction point, are connected in series via superconducting bus lines which are contained in the transfer lines. The design capacity of the refrigerator prepared for the two magnets is 140 W+ 25 l/h.

Introduction

In order to increase the luminosity of a colliding beam accelerator, strong local focusing, known as a low-beta insertion, is required. In the case of the TRISTAN electron-positron collider[1], the luminosity will be doubled by means of high-field gradient superconducting quadrupoles placed on either side of each collision point. However, since the quadrupoles must be positioned quite close to the interaction points, interference with the experimental detection equipment is a large problem, imposing severe design constraints on the magnet system. Therefore, as part of a program for developing a superconducting magnet system which fulfills these severe constraints, we have developed a prototype system and have tested it successfully[2,3].

On the basis of experience with the prototype and from results obtained during its operation, together with the implications of a revised scheme for the low-beta insertion, the final design of the magnet system was completed and four systems, one for each collision point, are presently being manufactured by industry. They will be installed near the collision points of the TRISTAN main ring by the end of 1990. The layout of the superconducting magnet system is shown in Fig. 1.

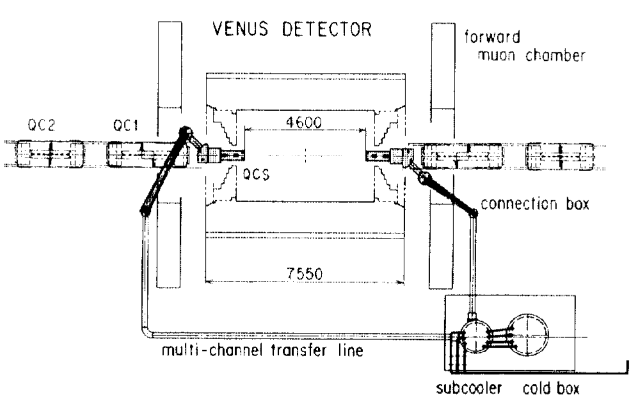

Fig 1. Layout of the superconducting quadrupole system near an experimental detector of TRISTAN. QC1 and 2 are conventional quadrupoles. They have been used to obtain higher luminosity until the installation of the superconducting quadrupole(QCS) is completed. After installation, QC1 and QCS will be used to squeeze the beam at the collision point and even higher luminosity will be obtained.

Superconducting quadrupoles

The superconducting quadrupole was designed and developed at KEK and the construction method was turned over to a private company[4]. Although an improvement of the electrical insulation structure at the ends of the magnet was required, by following this method the production of the eight quadrupoles, designated H1 through H8, was initiated and completed without serious troubles.

General design

A cross section of the magnet in the horizontal cryostat is shown in Fig. 2. The inner diameter of the warm bore is 104 mm and the outer diameter of the vacuum vessel is 400 mm. The coil cross section is a four-layer two-wedge design with an aperture of 140 mm and an outer diameter of 217.7 mm. The outer diameter of the collar is 280 mm. The magnet is designed to operate at a field gradient of 70 T/m in 4.47 K single-phase liquid helium with a current of 3405 A. The effective length of the magnet is 1.17m.

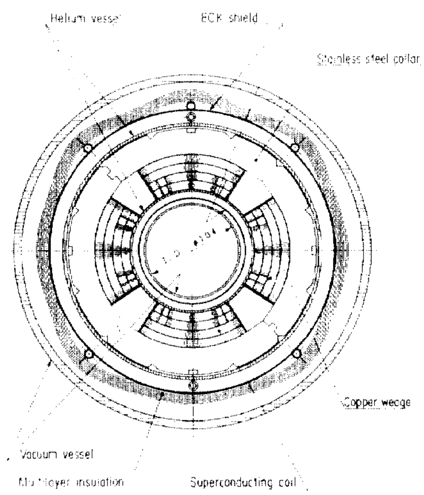

Fig 2. Cross section of the quadrupole magnet in a horizontal cryostat.

Special features of the design are as follows: (1) precisely machined fiber-reinforced-plastic (FRP) end spacers are used in order to make the end tight and to reduce the training; (2) a double pancake winding method is adopted to reduce the number of electrical joints between the coils; (3) two kinds of cable, each having different cable lay directions, are used for the winding in order to avoid a twist of the assembled coil; a left-handed corkscrew cable was used for odd pole windings and a right-handed corkscrew cable was used for even pole windings.

The main parameters of the quadrupole are listed in Table.1.

The conductor is a keystoned cable of the Rutherford type, composed of 27 strands of 0.68 mm diameter. Each strand contains fine superconducting filaments of high homogeneity NbTi and is coated with 1 μm silver-tin solder. The ratio of copper to superconductor is 1.8 and the residual resistivity ratio of the stabilizing copper is about 180. The insulation consists of a double layer of 25 μm Kapton foil and a layer of 50 μm Kapton with about 25 μm of B-stage epoxy on the outside surface. The 25 μm Kapton tape (14 mm width) is wrapped on the cable with a 50 % overlap and the 50 μm tape (6 mm width) is wrapped over it with 1.25 mm

Table 1. Parameters of the Superconducting Quadrupole

Field gradient	70	T/m
Current	3405	A
Overall length	1450	mm
Magnetic length	1170	mm
Inductance	58	mH
Stored energy	336	kJ
Field uniformity		
$\Delta B/B_2$	5×10^{-4}	
Max. field on the conductor	6	Tesla
Coil (4-layer)		
Inner diameter	140	mm
Outer diameter	217.7	mm
Collars		
Materials	SUS316LN	
Radial thickness, nominal	30	mm

Table 2. Conductor Parameters (specifications)

Cable dimensions	
height	9.09 ±0.05 mm
small width	1.19 ±0.02 mm
large width	1.35 ±0.02 mm
Number of strands	27
Strand diameter	0.68 ±0.005 mm
Filament diameter	less than 9 μm
Copper/super ratio	1.8 ± 0.1
RRR of stabilizing copper	180 ± 20
Critical current in cable (at 4.2K)	
	more than 6500 A at 6T
	more than 4700 A at 7T

gaps between adjacent layers. The main parameters of the cable are listed in Table 2. The critical currents of the cable were measured at both Hitachi Laboratory and Brookhaven National Laboratory and it was confirmed that the critical currents were well above the specified values.

Magnet construction

The magnet comprises eight separate coils, each consisting of a two-layer double-pancake winding. The coil production procedure was as follows. The first layer of the coil was wound on a convex mandrel by inserting an insulated copper wedge and FRP end spacers in the designed positions while the cable was held with a tension of 28-40 kgs and heat cured in a press at about 130 °C. After removal from the press, the second layer was wound onto the first layer in a similar manner, with 0.5 mm thick G-10 spacer with cooling holes between the first and second layers. The resulting two-layer coil was then cured under a pressure of 4 kg/cm^2. The third- and fourth-layer coils were made by the same process and the same pressure. In each curing process, an axial pressure was also applied to make the coil tight and to produce a uniform coil length.

In the assembling process, the eight double-pancake coils were mounted around another cylindrical mandrel. Ground insulation, made of two layers of 250 μm thick Mylar sheet, was placed on the outer surface of the coils over which 316LN stainless steel collars were stacked. The stacking was done so that two adjacent pairs of laminations were mounted perpendicular to each other so that two opposite windings were alternatively held by the central keys of the laminations. The collared magnet was then put into a collaring press which applied the correct pressure and displacement on the collars from four perpendicular radial directions. The press exerted a typical radial force of 7.0 x10^4 kg on the collars . The collars were fastened together by means of 316LN stainless steel keys while the pressure was applied, so that the applied prestress remained on the coils after the press was removed. The mandrel was then pulled out from the collared coils and the electrical connections between the coils were established by means of a special soldering jig.

Test results

After assembly in a factory, the magnets were transported to KEK and tested in a vertical cryostat. During the test, each magnet was excited with a ramp rate of about 10 A/sec. The magnets were

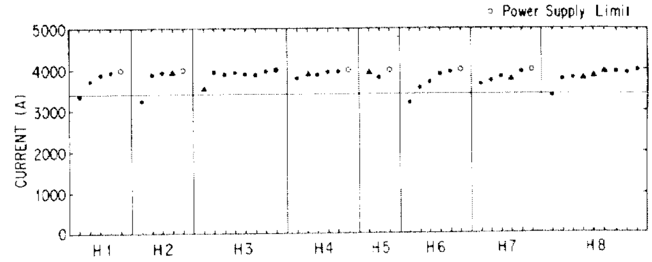

Fig 3. Training history of eight quadrupoles. The black circles and the black triangle indicate inner coil quenches and outer coil quenches, respectively. The white circles indicate no quenches.

trained until the current reached 4000A, the maximum current of the power supply, and the field measurement was performed with a 1.5 m long room temperature rotating coil of 39.4 mm radius inserted in the bore of the magnet.

The training performance of the eight quadrupoles in liquid helium at 4.2 K is shown in Fig. 3. Although the same construction method was applied, the magnets demonstrated slightly different training behavior. However, the quench currents were all well above the design current after one training quench and reached 3970 A, corresponding to 94% of the short sample critical current, within several quenches.

Figure 4 shows the integrated harmonic content expressed as the ratio of the harmonic field strength to the quadrupole field at the radius of the measuring coil.

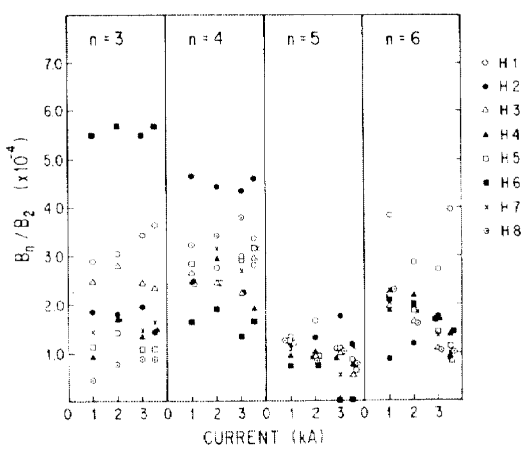

Fig 4. Harmonic content of the integrated magnetic field.

Electrical system

A schematic of the electrical circuit for a superconducting magnet system corresponding to one collision point is shown in Fig. 5. The power supply system is composed of a 4kA, 15V main power supply, a 40A, 15V auxiliary power supply, and a quench protection circuit.

The main power supply excites two quadrupoles in series, and the auxiliary power supply adds a small current to one quadrupole to compensate the field strength difference between the two quadrupoles. The principal circuit of the main power supply is a twelve-pulse bridge converter connected to the isolated wye and delta secondary windings of a transformer. SCRs are used to rectify and stabilize the output current by controlling their switching phase. Ripple and thyristor switching noise are reduced by a combination of an active and two passive filters.

The quench protection circuit is composed of a high speed SCR switch, two energy dump resistors, and three quench detectors corresponding to two quadrupoles and a superconducting bus line. Therefore, in case of a quench, the magnet current will decay

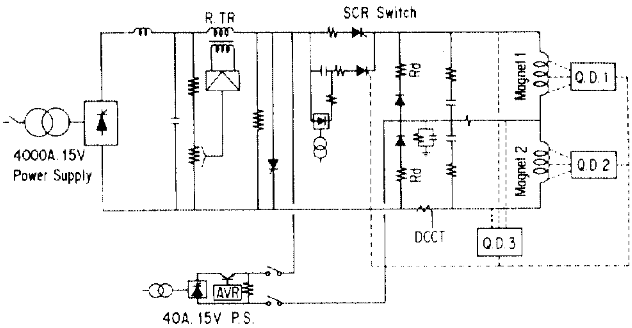

Fig 5. Electric circuit of the superconducting magnet system. Rd is 125 mΩ.

through the protection resistors with a time constant of 0.48 sec. Quench detection is done by the conventional center-tap balance method. The typical quench threshold is set at 1V for 10 ms or more. Furthermore, the pressures of the magnet cryostats are always monitored, and if they rise above 2.5 kg/cm^2, the protection circuit will be triggered.

Supporting table

As the positioning accuracy of the magnetic axis in the TRISTAN ring is required to be less than 0.1 mm, which is the limit of the alignment by a telescope, the magnets are placed on movable supporting tables. Via a CAMAC highway bus, the tables can be moved from the remote accelerator control room in order to improve the beam collision by finely adjusting the location of the magnets. The tables can be moved vertically and horizontally along the axes perpendicular to the beam axis, and can be rotated around these two axes. The smallest step of the movement is 1 μm for the displacement, and 3 μrad for the rotation. The coordinate of the tables is monitored with linear optical gauges, whose smallest count is 1μm.

Cryogenic system

The system consists of a helium compressor, a cold box, a subcooler, multi-channel transfer lines, two magnet-cryostats, two gas tanks and a liquid nitrogen storage tank. The compressor and tanks are placed on the surface but the others are located near the collision point down to 16 m below the surface.

A flow diagram of the cryogenic system, which cools two quadrupoles, is shown in Fig. 6. Helium gas, compressed to 1.6MPa, flows into the cold box and comes out at a temperature of 6K. The helium then flows into a subcooler box where the pressure

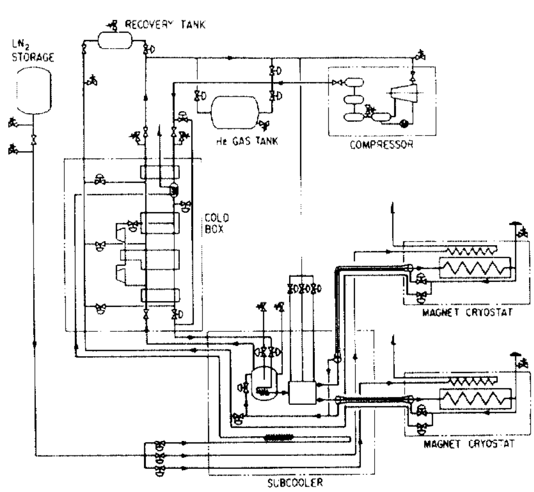

Fig 6. Flow diagram of the cryogenic system.

Table 3. Estimated LHe heat load of the largest cryogenic system among the four magnet systems.

Cryostat (inc. 2 valves and a connection box)	x 2	36 W
Transfer line (inc. 2 connection boxes)	30 m	47 W
Subcooler (inc. valves and transfer tube between cold box and subcooler)		27 W
Current leads		20 W
Ohmic heat at SC cable joints		2 W
Total		112 W + 20 L/h

is reduced to 0.162MPa by a control valve. At this point the helium is in a two-phase state at 4.8K and 0.162MPa. The helium next goes into a subcooler where it is further cooled to a single-phase state of 4.47K and 0.162MPa. After passing through the current lead dewar, the helium is divided between two magnet cryostats. The mass flow rate in each cryostat is 10 g/s. At the outlet points of the cryostats, the single-phase liquid helium is expanded by a J-T valve and turns into a two-phase state. Both the single-phase and the two-phase LHe flow coaxially in the transfer tube between the subcooler and the magnet cryostat. The single-phase LHe flows to the magnet through the inner tube while the two-phase LHe returns to the subcooler in the outer tube. The two-phase LHe in the return line helps cool the input single-phase liquid. The boil-off helium in the subcooler returns to the cold box from where it goes back to the compressor.

A special feature of this cryogenic system is the multi-channel transfer line which contains superconducting bus lines for the serial connection of the two quadrupole magnets. This feature permits fewer leads which direct the magnet current from room temperature regions to liquid helium temperature regions, thereby reducing the required refrigerator capacity at the cost of a somewhat more complicated transfer line.

The estimated heat load of each component is listed in Table 3. Allowing for a safety margin of 1.25, we chose a refrigeration capacity of 140 W + 25 L/h.

A process-control computer system is installed to automate the operation of four magnet system and to assist the operators. The system comprises eight process operator's consoles, four multi-task controllers, a color hard-copy unit and six printers. Each cryogenic system can be controlled from each local control room and also from the central control room.

Acknowledgement

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