CONSTRUCTION AND TESTING OF A 3 m DIAMETER \times 5 m SUPERCONDUCTING SOLENOID FOR THE FERMILAB COLLIDER DETECTOR FACILITY (CDF)

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A thin 3 m diameter $\times 5$ m, 1.5 T superconducting solenoid for the Fermilab collider detector facility (CDF solenoid) was constructed. Cool-down and excitation tests of the solenoid were carried out. The design current is 5000 A and the stored magnetic energy is 30×10^6 J. The solenoid utilizes the forced flow cooling method of two-phase helium and does not have a permanent inner bobbin. The material thickness of the solenoid is 0.85 radiation length in the radial direction. An aluminum-stabilized NbTi/Cu superconductor fabricated with the EFT method was used. Radially outward magnetic forces must be supported with an outer support cylinder shrink-fitted outside the coil. The helium cooling tube of 20 mm in inner diameter and about 140 m in length was welded to the outer support cylinder.

The maximum excitation current was limited to 2800 A in the present tests without an iron return yoke. Thermal response of the solenoid during the cool-down and excitation tests was very steady. A series of heater quench tests was attempted by using a heater installed at the outer support cylinder. The solenoid did not quench even for a heater input of about 10 kJ. In a warm-up test the liquid helium supply was shut off. The coil stayed superconducting for about 90 min and then the entire coil became normal very uniformly. This result is consistent with the measured heat load of the solenoid of about 35 W. The results of the present tests indicate the excellent thermal stability of the solenoid.

1. Introduction

A thin 3 m diameter \times 5 m superconducting solenoid to be used as an analyzing magnet of a p̄p colliding beam experiment in the Fermilab tevatron (CDF solenoid) was designed and constructed [1]. The design current and magnetic flux are 5000 A and 1.5 T, respectively, with an iron return yoke. The stored magnetic energy is 30×10^6 J. Cool-down and excitation tests were performed at the Hitachi Research Laboratory, Japan, in order to study various thermal, electrical, and mechanical properties of the solenoid.

Since various detector elements such as electromagnetic shower calorimeters are placed radially outside the solenoid, it is required to be thin in terms of radiation and absorption lengths in order to minimize absorption

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and scattering of particles by the solenoid [2]. Therefore the solenoid was designed and constructed to have no permanent inner bobbin and to apply the forced flow cooling method of two-phase helium. The radially outward magnetic forces must be supported with an aluminum-alloy cylinder placed outside the coil. The vacuum chamber of the cryostat was also made of aluminum alloy in order to reduce the material thickness in terms of raidation thickness. The overall material thickness of the main section of the solenoid is 0.85 radiation length in the radial direction.

Aluminum-stabilized NbTi/Cu superconductor was used to protect the coil against quenches. In order to develop a new fabrication technique and to study detailed characteristics of the conductor, a 1 m diameter \times 1 m R&D superconducting solenoid was constructed and various tests including heater quench tests were performed [3]. The present conductor was fabricated with the EFT method (extrusion with front tension) in which aluminum with high purity of approximately 99.999% was friction welded to the surface of the NbTi/Cu superconducting wire during the extrusion process [4]. High thermal conductivity and electrical conductivity of the high purity aluminum stabilizer provide thermal stability to the coil. The conductor was wound on a temporary mandrel which was removed after the coil and outer support cylinder were assembled with the shrink-fit method [5].

In the present tests the iron return yoke was not used. Thus, the maximum excitation current was limited to 2800 A because of the excessive compressive load of magnetic forces to the coil in the axial direction [6]. The coil was cooled from room temperature to liquid helium temperature in about seven days. The cooling rate was maintained at about 2 K/h until the coil was cooled to liquid nitrogen temperature and then it was raised appreciably. The thermal response of the solenoid during the cool-down and excitation tests was very steady and reasonable. A series of induced quench tests was attemped by using a heater installed at the outer support cylinder. The coil did not show any sign of development of a normal region even for a large heater input of about 10 kJ within a period of one minute at 2800 A. A warm-up test was carried out by stopping the helium flow at an excitation current of 10 A. The coil stayed superconducting for about 90 min and then the entire coil became normal very uniformly. This result is consistent with the heat load of the solenoid of about 35 W measured in a separate test. A continuous run was made successfully for about 10 h at 2800 A. Results of these tests indicate the excellent thermal stability of the solenoid.

Brief reports on the present results have been given elsewhere [7]. In the following sections we describe the general characteristics of the CDF solenoid, construction details, results of the cool-down and excitation tests, and conclusions.

2. General characteristics of the CDF solenoid [8]

The schematic side view of the solenoid system together with the other central detector components of the CDF is shown in fig. 1. The solenoid consists of a superconducting coil, an outer support cylinder, a cryostat, a chimney, and a control dewar. The main parts of the cryostat are a vacuum vessel, a support system, thermal radiation shields, and liquid helium cooling tubes. The control dewar is placed outside the iron return yoke and connected to the cryostat with the chimney in order to minimize the interference with the detector system. The total weight of the solenoid excluding the chimney and control dewar is about 11 t and the cold mass is about 5.6 t. The schematic drawing of the end section of the solenoid is shown in fig. 2.

The coil consists of a single layer helical winding of aluminum-stabilized NbTi/Cu superconductor of 1164 turns. It is mounted inside the outer support cylinder made of aluminum alloy. The length and inner diameter of the coil are 4796 and 2966 mm, respectively, at room temperature. The cross section of the conductor is $3.89 \times 20.0 \text{ mm}^2$. The conductor was wound so that the coil radial thickness corresponded to the conductor width of 20 mm. The design current and magnetic field with the iron return yoke are 5000 A and 1.5 T, respectively. The guaranteed current is 4500 A.

The wall thickness of the outer support cylinder is 16 mm in the central section and 45 mm at the axial ends of about 400 mm in length in order to minimize mechanical distortions due to forces from the support system. The coil and outer support cylinder were assembled with the shrink-fit method. Liquid helium cooling tubes of 20 mm in inner diameter, made of aluminum alloy A1100, were welded to the outer support cylinder. The cooling path of about 140 m was made in series and was mostly axially serpentine in order to avoid inhomogeneous liquid distributions due to the garden hose effect. The distance between two adjacent paths was 400 mm. The overall liquid capacity of the cooling loop is about 45 l.



Fig. 1. Schematic side view of the central section of the CDF detector system.



Fig. 2. Schematic drawing of the end section of the CDF solenoid at the chimney side. The side view of an axial support is also shown. An enlarged view shows the coil conductor and FRP layer. All dimensions are in mm.

The support system of the cold mass of the solenoid consists of six axial supports, all on the chimney end and twelve radial supports on each end. The main part of each support was made of Inconel 718. Each support member has a spherical bearing connection at each end. This arrangement allows thermal contraction of the coil, about 20 mm in length and 6 mm in radius, when it is cooled from room temperature to liquid helium temperature. Each support has a liquid nitrogen intercept relatively close to the vacuum vessel at room temperature and a liquid helium intercept in the support anchor at the outer support cylinder. The support system was designed to withstand the magnetic decentering forces of 1.8 and 1.3 t/mm in the axial and radial directions, respectively, for the maximum displacement of 20 mm in either direction from the ideal magnet center. The thermal load through the support system was estimated to be about 10 W.

The length, outer diameter, and inner diameter of the main vacuum vessel are 5067, 3353 and 2858 mm, respectively. The wall thicknesses of the outer and inner cylinders are 20 and 7 mm, respectively. They are made of aluminum alloy of A5083.

The thermal radiation shields are mostly made of aluminum sheets of 2 mm in thickness and are cooled with liquid nitrogen.

The control dewar has couplings to the supply and return lines for liquid helium and liquid nitrogen and connections to the power leads. It contains a 65 l liquid helium reservoir fed from the helium return line. The superconducting leads from the coil enter the helium reservoir through insulating feedthroughs and connect

Table 1 Main parameters of the CDF solenoid

Items	Parameters
Vacuum vessel	
Diameter; outer/inner	3353 mm/2858 mm
Length	5067 mm
Material	A5083 aluminum
Wall thickness; outer/inner	20 mm/7 mm
Central field	1.5 T
Material thickness	0.85 radiation length
Total weight	11 t
Cold mass	5.6 t
Coil	
Current	5000 A
Inductance	2.4 H
Stored energy	$30 \times 10^{6} \text{ J}$
Number of turns	1164
Winding scheme	Single layer helix
Supporting structure	Shrink-fit assembly with
	outer support cylinder;
	no inner bobbin
Conductor	
NbTi/Cu/Al ratio	1/1/21
Dimensions	$3.89 \times 20.0 \text{ mm}^2$
NbTi filaments	Nb-46.5 Ti, 50 µm
	diameter × 1700
Standard short sample current	10.4 kA at 1.5 T and 4.2 K
Purity of aluminum stabilizer	~ 99.999%
Outer support cylinder	
Material	A5083 aluminum
Thickness	16 mm
Liquid helium cryogenics	Forced flow two-phase
Liquid nitrogen cryogenics	Forced flow

with current leads cooled with cold helium gas. The outer diameter and overall height of the vacuum vessel of the control dewar, made of stainless steel SUS304, are 890 and 1580 mm, respectively.

The chimney contains a pair of superconducting current leads, four liquid nitrogen cooling lines (two for the supply lines and two for the return lines), and two liquid helium cooling lines (supply and return lines). The total length of the L-shaped chimney is about 3.5 m; 2.4 and 1.1 m in the vertical and horizontal directions, respectively. The general structure of the vacuum vessel of the chimney is a cylinder of about 200 mm in diameter, made of SUS304. The connection between the vacuum vessels of the solenoid and chimney was made with an aluminum-stainless steel transition joint.

The overall thermal load was estimated to be 40 W + 14 l/h for the steady state operation with an additional load of 100 W during the charging time.

The main parameters of the CDF solenoid are summarized in table 1.

3. Construction details

3.1. Aluminum-stabilized NbTi / Cu superconductor [3,4]

The schematic diagram of the conductor cross section is shown in fig. 3. The volume ratio of NbTi : Cu : Al is 1:1:21. The NbTi/Cu composite consists of 1700 50 μ m diameter NbTi filaments. The purity of aluminum used for the stabilizer is about 99.999%. Resistivity measured ranged from 0.58 to $0.64 \times 10^{-11} \Omega$ m at 4.2 K. Therefore, the residual resistance ratio (RRR) is approximately 4500. The magneto-resistivity shows a typical dependence common to pure aluminum as the function of magnetic field. It was $2.2 \times 10^{-11} \Omega$ m at 4.2 K and 2 T.

The conductor was fabricated with the EFT method (extrusion with front tension). Aluminum was friction welded to the copper surface of the monolithic NbTi/Cu superconductor in the extrusion process. Details have



Fig. 3. Schematic diagram of the conductor cross section. The volume ratio of NbTi:Cu:Al is 1:1:21. The NbTi composite consists of $1700 \times 50 \ \mu m$ diameter NbTi superconducting filaments. High purity aluminum of 99.999% is used. The orientation of the conductor in the coil is also shown.

been reported elsewhere [3,4]. Electrical and mechanical properties of the binding between aluminum and copper were substantially better than those made with soldering.

Fig. 4 gives measured magnetic flux versus critical current (I_c) data, together with the load line for the solenoid with the iron return yoke. Also given are the standard curves at 4.2 and 4.7 K. The standard cirtical current is 10.4 kA at 4.2 K and 1.5 T. Short sample data were measured for samples from both ends of ten conductor units used in the coil. The unit length of the conductor was about 1350 m that was determined by the unit length of the NbTi/Cu conductor. The vertical bars drawn for the measured data correspond to the ranges of the twenty data sets. Short sample data were also measured for all the NbTi/Cu conductor units before the aluminum stabilizer was co-extruded with the EFT method. Data were essentially the same as those given in fig. 4. The measured critical currents at 1.5 T were about 25% higher than the standard value.

The resistance per unit length at the boundary surface between the NbTi/Cu conductor and aluminum stabilizer was measured to be $2.0 \times 10^{-11} \Omega$ m at 2 T. The result for the conductor used in the R&D solenoid was $2.4 \times 10^{-11} \Omega$ m. The boundary diffusion thickness for aluminum-copper binary metal of the present conductor was analyzed by an X-ray microanalyzer and it was about 1–2 μ m.



Fig. 4. Measured magnetic flux versus critical current data for 20 short samples at 4.2 K. The vertical bars drawn correspond to distributions of the data. The load line for the CDF solenoid with the iron return yoke is shown. The design current is 5 kA for 1.5 T. Also shown are the standard curves at 4.2 and 4.7 K.

Dimensions of the conductor cross section were measured at numerous sections. They were well within the design values of (20.00 ± 0.25) mm (width) and (3.89 ± 0.18) mm (thickness).

The stress-strain curves were measured for three samples and they were essentially linear for stresses below 2 kg/mm² at room temperature. Therefore, the maximum allowable stress of the conductor was estimated to be 2.5 kg/mm² at liquid helium temperature.

Samples of the conductor were bent or twisted in order to test the mechanical strength of the aluminum-copper binding. No damage was observed at the boundary surface.

The conductor width of 20 mm was determined primarily by the maximum voltage to ground and the maximum temperature rise during a quench. Extensive computer simulations were carried out by using quench data of the R&D solenoid in order to optimize the conductor width [9]. In the case of the CDF solenoid, when the coil starts a quench for some reason, the Joule heat in the outer support cylinder due to the eddy current causes the quench-back effect. Thus, the entire coil becomes normal within a few seconds. For the conductor of 20 mm in width the maximum temperature rise and maximum voltage were estimated to be less than 100 K and 200 V, respectively, when the external resistor of 0.07 Ω is functional at 5000 A. In case the protection circuit fails completely, the maximum temperature rise becomes about 180 K. It should be noted that, even if the main power supply with the voltage limit of 20 V is kept on, the solenoid cannot be damaged. In the worst possible case in which the quench-back does not take place for some reason and in which the protection circuit fails, the maximum temperature rise and maximum voltage of the coil were estimated to be 250 K and 300 V, respectively. This temperature rise is not necessarily safe. On the other hand it is extremely unlikely to happen. We note that wider conductors with more aluminum stabilizer are of course safer with regard to the quench protection.

3.2. Coil

The conductor was wound with a tensile force of 100 kg (equivalent to 1.29 kg/mm²) on a mandrel which could be removed after the shrink-fit assembly of the coil and outer support cylinder was completed. The orientation of the conductor is indicated in figs. 2 and 3. Fig. 5 shows a picture of the coil winding work. The conductor was inspected visually and rough surfaces were cleaned manually before wrapping insulation layers by an automated layer taping machine. Half-overlap double layers of semi-cure Kapton tape of 50 μ m in thickness were continually checked electrically by applying 500 V_{ac} on all the four side surfaces of the conductor after wrapped.



Fig. 5. Picture of the coll winding work.

The conductor was pressed in the axial direction at the contact point of the mandrel with two rollers with a total force of 20 kg. At every 30 turns an axial pressure of 1.0 kg/mm² which corresponded to the total axial load of 188 t was applied for a brief period in order to keep a newly wound coil section tight. At every 90 turns each new section was cured at 135°C for 6 h with the axial pressure of 1.0 kg/mm².

Each conductor unit of about 1350 m in length corresponded to approximately 140 turns. In total ten conductor joints, including one each at the axial ends of the coil, were made with the welding method [3]. Each joint had a full turn of double layers of the normal conductor with two welding joints of 400 mm each to make good electrical contact. The rest of the circumference of the joint was welded intermittently with rather shallow penetration of about 500 mm in length followed with no welding section of about 300 mm just to make mechanical bonding between the two layers of the conductor. The net resistance for a joint was estimated to be less than $6 \times 10^{-10} \Omega$ at 4.2 K. The total number of turns was 1164 in which each joint was counted as a single turn. After the winding work was completed, the layer insulation was checked by measuring a voltage drop for every two turns with a current of 1 A. Voltage readings ranged from 6.98 to 7.34 mV at a coil temperature of $(30 \pm 5)^{\circ}$ C. These results were quite satisfactory.

The outer diameter of the coil was measured at various points along the coil axis. It was (3008.4 ± 0.4) mm. The coil length was 4792.5 mm.

A layer of fiber-reinforced plastic (FRP) was formed on the surface of the coil and later machined in order to minimize the variation of the outer diameter of the coil and to make the coil surface smoother. The outer diameter was (3013.9 ± 0.1) mm at room temperature. The average thickness of the FRP layer was 2.8 mm. The FRP layer provides good electrical insulation between the coil and outer support cylinder.

3.3. Outer support cylinder and helium cooling tubes

The radial magnetic forces of 0.091 kg/mm² at 1.5 T must be supported with the outer support cylinder together with the coil. Since pure aluminum is very soft as described earlier, the coil has a very limited allowed stress. Therefore, the support cylinder must take a large fraction of the radial forces.

The support cylinder was fabricated by rolling and then welding sheets of A5083 aluminum alloy. The outer and inner surfaces of the cylinder were machined with supporting structures attached to provide the cylinder with mechanical rigidity. In particular, the inner surface was machined with good precision in preparation for the shrink-fit assembly. The inner diameter was 3010.82 mm. The thickness of the central section of the cylinder was made to be 16 mm so that the cylinder alone could hold the radial magnetic forces at liquid helium temperature. The length of the cylinder was 4903.6 mm.

As shown in fig. 2, the thicknesses of the axial ends of the cylinder, about 400 mm in length, were arranged to be 45 mm in order to minimize mechanical distortions due to forces from the radial and axial support systems. Detailed finite element analyses were carried out to determine this thickness [1]. It should be noted that the material thickness of the solenoid near the axial ends does not cause any problems for physics experiments because these areas are shadowed with shower detectors installed inside the solenoid.

Liquid helium cooling tubes were welded to the outside surface of the support cylinder. Fig. 6 shows a picture of the welding work. The tubes of aluminum A1100 were extruded in the form shown in fig. 7. The inner diameter of the tubes is 20 mm and the minimum wall thickness is 3 mm. The flat section of 36 mm in width and 4 mm in thickness was made for ease of fillet welds. The welds were intermittent and staggered.

The liquid helium cooling path was arranged to be a single loop which consists of the cooling path of the support cylinder and the intercept path connecting the



Fig. 6. Picture of the welding work of liquid helium cooling tubes to the outer support cylinder.



Fig. 7. Schematic diagram of the cross section of the liquid helium cooling tube of 20 mm in diameter, made of aluminum alloy A1100. All dimensions are in mm. Fillet welds are intermittent and staggered.

support systems. The inlet was connected to the support cylinder path and then to the intercept path.

The support cylinder loop is mostly axially serpentine to avoid inhomogeneous liquid distributions. The distance between two adjacent paths is 400 mm. A hydraulic pressure test was made successfully for the loop with a pressure of 1.2 kg/mm². The hydraulic rupture pressure was measured to be 2.13 kg/mm² for a sample of the tube. The result was consistent with the estimated value.

During the charging time of the solenoid the eddy current is induced circumferentially on the support cylinder. The Joule heating power due to this induction current, P, can be given by

$$P = \frac{1}{R} \left(M \frac{\mathrm{d}I}{\mathrm{d}t} \right)^2,\tag{1}$$

where R is the resistance of the support cylinder in the circumferential direction, M the mutual inductance between the coil and support cylinder, and dI/dt the charging rate. R and M were estimated to be 2.8 $\mu\Omega$ and 2.0 mH, respectively. Therefore, for example, with a charging time of 10 min for the full excitation of 5000 A, P = 100 W.

3.4. Shrink-fit assembly

Details of the shrink-fit assembly of a dummy solenoid coil of 3 m in diameter and 0.65 m in length have been reported elsewhere [5]. In this section we describe mainly results for the present solenoid. The outer diameter of the coil and the inner diameter of the support cylinder were 3013.9 and 3010.8 mm, respectively, at room temperature. Thus the interference in radius was 1.5 mm. The coil was placed on a stand in the vertical position and the entire surface of the coil was wetted with epoxy before the shrink-fit assembly. After being heated up to about 130°C, the support cylinder was moved above the coil and lowered slowly by a crane. After the two members were matched at the right position, the temperature of the support cylinder was gradually lowered from the bottom section while supporting forces provided with bolts attached outside the support cylinder were loosened.

After the shrink-fit assembly was completed with the mandrel still in position, the inner radius of the support cylinder was expanded by 0.89 mm (0.65 mm) at the central section (end sections). This corresponds to the calculated contact pressure of 0.051 kg/mm² (0.103 kg/mm²). When the mandrel was removed, the amount of radius expansion of the support cylinder was reduced to 0.50 mm (0.28 mm) which corresponds to the calculated contact pressure of 0.028 kg/mm² (0.043 kg/mm²).

Fig. 8 shows radial deformations of the inner diameters of the coil and support cylinder measured at one axial end after the mandrel was removed. The reference radius shown corresponds to the normalized inner radius for the coil and support cylinder before the shrink-fit assembly was made. Radial deviations from ideal circles were less than 2 mm when the expansion and shrinkage of the radius due to the shrink-fit assembly for the support cylinder and coil, respectively, were taken into



Fig. 8. Measured radial deformations of the inner diameters of the coil and outer support cylinder at one axial end, after the mandrel was removed. The reference radius corresponds to the normalized inner radius for the coil and support cylinder before the shrink-fit assembly was made. Radial deviations from ideal circles are less than 2 mm when the expansion and shrinkage of the radius due to the shrink-fit assembly for the coil and support cylinder, respectively, are taken into account.

account. Deformations measured at the other axial end were very similar to those shown in fig. 8. The azimuthal dependence of deviations was consistent at the two axial ends. Namely, there was essentially no twist of the cylindrical shape of the coil.

The radially outward magnetic pressure of 0.091 kg/mm² must be shared approximately proportionally to the thicknesses of the coil and support cylinder. Therefore, in the central section where the thickness of the support cylinder is 16 mm, the corresponding shared pressures are 0.051 and 0.040 kg/mm². Then, for the contact pressure of 0.028 kg/mm², the net outward pressures are 0.023 and 0.068 kg/mm² for the coil and support cylinder, respectively. They correspond to hoop stresses of 1.7 and 6.4 kg/mm², which are smaller than the allowed stresses of 2.5 and 9.4 kg/mm² for the coil and support cylinder, respectively, at liquid helium temperature.

3.5. Support system

The support system must support both the weight of the cold mass of the solenoid and axial and radial decentering forces due to magnetic forces. In addition, thermal leaks from room temperature to liquid helium temperature through the support system must be reasonably small. The decentering forces were estimated to be 1.8 and 1.3 t/mm in the axial and radial directions, respectively. Assuming the maximum displacement of 20 mm for the solenoid from the ideal magnetic center, the design maximum loads due to magnetic forces were determined to be 36 and 26 t in the axial and radial directions, respectively.

The support system consists of 6 axial and 24 radial supports. The schematic drawing of the support

arrangement is shown in fig. 9. All the axial supports were placed at the chimney end of the coil. On the other hand, six pairs of 12 radial supports were placed at each end of the coil, connected approximately tangentially to the outer support cylinder. This arrangement allows nearly freely thermal contraction of the coil, about 20 and 6 mm in the axial and radial directions, respectively, when the coil is cooled from room temperature to liquid helium temperature. A spherical bearing at each end of a support reduces the stress due to the thermal contraction.

The side view of an axial support is shown in fig. 2. The distance between the centers of two spherical bearings is 340 mm. The main part of the axial support consists of a cylinder made of Inconel 718, 20 and 26 mm in inner and outer diameters. It was designed to work either in tension or compression. Each axial support member must support a decentering force of 6 t. The maximum stress of the cylinder is 28 kg/mm² which is a comfortable value compared with the yielding and ultimate stresses of 106 and 130 kg/mm², respectively, for Inconel 718.

Stress-strain curves of all axial supports fabricated were measured with both compression and tensile loads. Maximum strains at 6 t were 1.0 and 1.2 mm for the compression and tensile loads, respectively. The stress-strain relations were essentially linear up to a load of 6 t. A breaking test of an axial support sample was carried out with tensile load. The housing of the spherical bearing broke at 18.6 t (= 90.6 kg/mm²). No damages to other parts were observed.

A liquid nitrogen intercept is located 115 mm from the vacuum vessel of room temperature and a liquid He intercept is located at the support anchor on the outer support cylinder. A variation of the distance between



Fig. 9. Schematic diagram of the arrangement of the radial and axial support system.

the end wall of the vacuum vessel and the support anchor can be measured by the position monitoring device installed at each support anchor. It provides information about compression or tensile stresses in the axial supports.

The section view of a radial support is shown in fig. 10. The distance between the centers of two spherical bearings is 320 mm. The support consists of an Inconel 718 rod of 15 mm in diameter. Liquid nitrogen and liquid helium intercepts are arranged in the same way as in the axial support. The radial supports must be adjusted so that they are mostly in tension and that thermal load is not excessive when the coil is cold. When all the 24 radial support members are in tension, the maximum stresses are estimated to be 2.3 and 12.0 kg/mm^2 for the weight of the cold mass of 5.6 t and decentering force of 26 t, respectively. The decentering force is assumed to be applied in an arbitrary direction. They correspond to the maximum loads of 0.40 and 2.13 t for each radial support. Therefore, the total primary stress is 14.3 kg/mm², which is appreciably smaller than the allowable stress of 32.5 kg/mm^2 for Inconel 718. The differential thermal stress of the radial supports is estimated to be 60 kg/mm² when the coil is cooled from room temperature to liquid helium temperature.

Load tests were successfully made for all radial supports fabricated at a tensile load of 4 t. The average stiffness of the radial supports is 4.1 t/mm. The breaking load was measured to be about 19 t. Loads on the radial supports can be monitored by signals from stress



Fig. 10. Schematic section view of the radial support. All dimensions are in mm. Although not shown explicitly, a liquid helium intercept is located at the support anchor.

transducer washers installed at the main support nuts which are located outside the vacuum vessel for easy access or replacement.

The overall heat load through the support system was estimated to be about 10 W.

3.6. Vacuum vessel

The vacuum vessel was constructed in accordance with the American Society of Mechanical Engineerings (ASME) code and the Japanese Industrial Standards (JIS). The thicknesses of the outer and inner cylinders are 20 and 7 mm, respectively. The inner cylinder was made thicker than the code requirement in order to give some flexibility for future installation of inner detectors. The cylinders were fabricated by rolling and then welding sheets of A5083 aluminum alloy. The end sections were fabricated by machining plates of A5083 aluminum alloy. The length, outer diameter, and inner diameter of the vacuum vessel are 5067, 3353 and 2858 mm, respectively.

All the main assembly joints were welded directly or with covers of aluminum sheets after the assembly was completed. No elastic seals such as O-rings were used for the main joints except for the relief valve at the chimney in order to eliminate any vacuum problems. As seen in fig. 10, double O-rings were used for the radial supports. After the solenoid is installed in the CDF detector, an aluminum cover will be welded to seal the O-rings for each radial support.

3.7. Control dewar and chimney

As shown in fig. 1, the control dewar, located outside the magnet return yoke, is the interface between the cryogenic transfer lines and the solenoid. It has couplings for the helium supply and return lines and the liquid nitrogen supply and return lines. The simplified section view of the control dewar is shown in fig. 11. A liquid helium reservoir of 65 l is fed from the helium return line and serves as the heat exchanger for the helium supply line which is connected to a J-T valve before entering the chimney. The helium supply line after the heat exchanger and the helium return line from the helium reservoir are not shown in the figure. The superconducting current leads from the chimney enter the helium reservoir through insulating feedthroughs and connect with helium gas cooled current leads of normal conductor [10].

The chimney is the vacuum vessel that contains all cryogenic and electrical lines to the coil from the control dewar. The schematic diagram of the cross section at a typical point of the chimney is shown in fig. 12. The vacuum vessel was mostly made of a SUS 304 cylinder of 216 mm in outer diameter and was welded to the main vacuum chamber of the solenoid with an



Fig. 11. Simplified schematic diagram of the cross section of the control dewar. The liquid helium supply line after the heat exchanger and the liquid helium return line from the 65 1 helium reservoir are not shown.

aluminum-stainless steel transition joint. This transition joint is called a "Criocoup joint" [11] which was manufactured with the explosive cladding method. The joint was welded to the vacuum vessel of the solenoid permanently. Assembly or disassembly of the chimney was designed to be made at the stainless steel joint by welding. The total length of the L-shaped chimney is about 3.5 m; 2.4 and 1.1 m in the vertical and horizontal directions, respectively. It contains four liquid nitrogen cooling tubes (two for the supply lines and two for the return lines) and two liquid helium cooling tubes (supply and return lines).

A pair of superconducting current leads, each made of two layers of the regular superconductor welded together, were bound around the helium supply cooling tube with insulation. The last turn of the coil at each end and also the current leads inside the main vacuum vessel were made of the twin conductor in order to increase the thermal stability of the conductor.

During the assembly work of the solenoid and chimney, connections of the current leads of twin conductor were made by soft soldering at the chimney end for ease of disassembly. Therefore, each current lead consists of



Fig. 12. Schematic diagram of the cross section at a typical section of the chimney. The superconducting current leads were made of two layers of the regular superconductor welded in the same way as for conductor joints in the coil. Braces which hold the current leads and liquid helium cooling tubes were made of aluminum and placed with intervals of about 600 mm. Sliding supports allow thermal contraction for the cold section of the chimney.

4 layers of the regular superconductor at the soldered connections of about 400 mm in length.

Mechanical supports for the cooling lines, current leads, and thermal insulation inside the chimney were arranged to allow sliding along the chimney axis in order to avoid damages due to thermal contraction of the lines, about 9 and 4 mm in the vertical and horizontal directions, respectively.

The control dewar and chimney have common vacuum with the solenoid cryostat.

3.8. Instrumentation

A variety of devices are used to measure temperature, voltage, strain, and pressure at various points of the solenoid. In total 21 carbon resistors (4-30 K) and 23 platinum resistors (30 K to room temperature) were installed for temperature monitoring. They are located at critical sections such as the outer support cylinder, radial and axial support areas, liquid helium cooling lines, radiation shields, and liquid nitrogen cooling lines. For example, TR32 is the temperature monitoring device of a carbon resistor installed at the middle of the outer support cylinder.

In total fourteen voltage taps were installed at the coil and current leads; four at the coil, two on the current leads at the bottom of the chimney, and eight along the current leads. Voltage taps VT1 and VT9, respectively, are located at the input end and the chimney end of the current lead which is connected to the coil at the chimney side. VT14 is located at the same place as VT9, but it is on the other current lead. VT10 is located at the coil, one quarter coil length away from the coil end of the chimney side. Two voltage taps were installed at the center of the coil.

Washer-type strain gauges were installed at all the 24 radial supports (fig. 10). For example, strain gauges SS18, SS19, and SS20 are located at three radial supports at the far end from the chimney. In addition, position monitoring devices, DS1 to DS6, were installed for all the six axial supports. They can provide information about compression or tensile loads on the axial supports.

Two heaters were installed at the middle and near the axial end of the outer support cylinder in order to make heater quench tests. Each heater consists of a coil of 20 mm in outer diameter, made of manganese wire, and has about 60 Ω . It was installed in a hole of 24 mm in diameter drilled through the wall of the support cylinder and is in contact with the FRP layer between the coil and support cylinder. This arrangement was made in order to maximize heat transfer from the heater to the coil and also to avoid any potential hazard to cause ground fault of the coil through the heaters. In the case of the R&D solenoid a heater was installed directly inside the aluminum stabilizer of the conductor.

Other instrumentation includes six pick-up coils,

three pressure gauges, and a vapor pressure thermometer.

4. Cool-down and excitation tests

The present cool-down and excitation tests were performed at the Hitachi Research Laboratory in order to study the thermal, electrical, and mechanical properties of the CDF solenoid. In addition to cool-down and excitation of the solenoid, the tests included heater tests, continuous operation run, warm-up test, and thermal load measurement. Figs. 13 and 14 show schematic drawings of the refrigeration system and electrical circuit used in the tests. The iron return yoke was not used. The overall picture of the test arrangement is shown in fig. 15. Due to the height limitation of the test area the solenoid was rotated around the axis by 90° from the normal orientation and the chimney was connected horizontally to the solenoid with a transition joint as shown in the picture.

4.1. Cool-down test

A 300 W Hitachi refrigerator with the helium liquefaction capacity of 100 l/h was used in tests. It contained two-stage turbine expansion engines. A 2000 l dewar was by-passed in most of the tests except for the thermal load measurement in which it was used as a



Fig. 13. Schematic diagram of the refrigeration system used in the cool-down and excitation tests. The 300 W refrigerator contains two-stage expansion engines and has a liquefaction capacity of 100 l/h. The 2000 l liquid helium dewar was bypassed in most of the tests except for the thermal load measurement.





Fig. 14. Schematic diagram of the electric circuit used in the excitation test. The outer support cylinder forms the secondary circuit of a single turn. The mutual inductance between the coil and support cylinder is 2.0 mH. The resistance of the support cylinder in the circumferential direction in which induced eddy currents flow is $2.8 \ \mu\Omega$.

reservoir of liquid helium. Since the thermal load of the solenoid was estimated to be less than 50 W for the steady state operation with additional loads less than 100 W during charging or discharging times due to eddy currents in the outer support cylinder, as discussed in section 3.3, the refrigeration system had an adequate cooling capacity.

It is one of the greatest advantages of the forced flow cooling method that the coil with a large cold mass of 5.6 t could be cooled steadily with the desired temperature gradient over the entire cold mass volume. Large temperature differences could cause undesirable mechanical stresses to the solenoid due to differential thermal contraction. Temperatures of the sections cooled with liquid nitrogen must also be maintained within reasonable temperature limits accordingly.

Temperatures at various sections of the solenoid and the coil resistance measured during the cool-down period are shown in fig. 16 as the function of the time of the cool-down. The coil was cooled by using cold helium gas or two-phase helium from room temperature to liquid helium temperature in about seven days with the cooling rate of about 2 K/h. During the cool-down period temperatures near the inlet of the helium supply line were colder and those near the outlet became warmer. The maximum temperature difference was about 20 K when the coil was still warm near room temperature and it decreased as the coil became colder. It was less than 0.5 K near liquid helium temperature.



Fig. 15. Picture of the test arrangement at the Hitachi Research Laboratory. The solenoid was rotated by 90° from the normal orientation and the chimney was connected horizontally to the solenoid.



Fig. 16. Temperatures at the coil, radiation shield, and liquid nitrogen intercept during the cool-down period. After about 30 h of cool-down, the liquid nitrogen flow was slightly reduced in order to adjust temperatures at the sections cooled by liquid nitrogen. Also shown is the resistance curve of the coil. It became superconducting in about seven days.

While the coil temperature was above 200 K, only the liquid nitrogen heat exchanger was used in the refrigerator. Below 200 K the turbine expander engines were turned on, one unit at the beginning and then both units. Temperature, pressure, and mass flow rate of the supply helium were adjusted according to the coil temperature. The pressure and flow rate, respectively, were 0.015 kg/mm^2 and 5 g/s at the helium temperature of 200 K, and 0.003 kg/mm^2 and 17 g/s for the steady state operation at 4.5 K.

As can be seen in fig. 16, the flow rate of liquid nitrogen was adjusted so that the temperature difference between the liquid nitrogen cooling sections and the liquid helium sections was adequate. In about 30 h after the start of the cool-down the liquid nitrogen sections



Fig. 17. Tensile load curves of radial supports during the cool-down test. SS18, SS19 and SS20 correspond to three radial suports located at the axial end far from the chimney. Small dips appeared after about 30 h of the cool-down were caused by reduction of the flow rate of liquid nitrogen.

became colder than desired and the flow rate of liquid nitrogen was reduced.

As mentioned earlier, the cool-down of the coil from room temperature to liquid helium temperature caused thermal contraction of about 20 mm in length and 6 mm in radius. No mechanical contact between the warm sections and cold sections was induced during the cool-down. The vacuum of the cryostat was about 10^{-3} Pa at room temperature and about 10^{-4} Pa at 4.5 K. Thus no apparent vacuum leak was developed.

Figs. 17 and 18 show typical examples of loads on radial support members and displacements of axial support members during the cool-down. Those loads were measured for the radial support members at the far end from the chimney. They increased essentially monotonically as the coil temperature decreased. Small dips which appeared after about 30 h of the cool-down corresponded to temperature rises at the liquid nitrogen intercepts of the support members when the liquid nitrogen flow rate was reduced (see fig. 16). The net load for each radial support member was about 6 t and essentially independent of the azimuthal location. Although it seems to be rather small compared with the estimated load of 11.6 t, this discrepancy was probably partly due to some mechanical loosening of the support system and partly due to uncertainties in the calculations.

The displacements of the axial support members shown in fig. 18 do not display any apparent correlation among the members. The final values at liquid helium temperature, however, turned out to be almost identical and reasonably small. Therefore, there seem to be no appreciable thermal stresses created after the cool-down.

The coil resistance was measured by applying a current of 1 A. It was 3.7 Ω at room temperature and 1.8 m Ω immediately before the coil became superconducting. Thus, the RRR value of the aluminum stabilizer is about 2000. Since this value is substantially



Fig. 18. Displacements of three axial support members during the cool-down period.

larger compared with that for the conductor used in the R&D solenoid (RRR ≈ 1000) [3], the present conductor should provide better thermal and electrical stability. It should be noted that the RRR value of the conductor is appreciably smaller than that measured before the extrusion process.

Drops of dew or frost were not observed near the support areas on the outer surface of the cryostat even though the tests were carried out in the very high humid climate. Furthermore, no cold spot was found by the touch. This indicates that heat leaks through both the radial and axial support systems were negligible.

Some frosting was observed on the top of the control dewar while the current leads inside the control dewar and chimney were tested prior to the present tests. This frosting could be prevented with installation of a small heater pad of a few watts.

4.2. Excitation tests

When the coil is excited at 5000 A with the iron return yoke, a magnetic compressive force of about 100 t acts on the conductor in the coil axial direction. In addition, a radially outward pressure of 0.091 kg/mm² is exerted on the coil. In the present tests without the return yoke the axial compressive force becomes about six times larger than that with the return yoke. Since a large compressive force could damage the coil, the maximum excitation current was limited to 2800 A. The axial compressive force at 2800 A corresponds to a compressive force of 190 t which was applied during the curing periods of the coil winding process.

Excitation tests were carried out by raising the flat top current gradually with the charging rate of 250 A/min. The flat top currents tested were 100, 500, 1000, 2000 and 2800 A. For each current two tests were made. In the first test the solenoid was charged up, kept excited at the flat top current for 10 min, and then discharged with a rate of 250 A/min. In the second dump test the power supply was disconnected by opening the switches after the solenoid was excited for 5 min at the flat top current.

Neither quench nor abnormal response was detected through the excitation tests. During charging and discharging times the coil temperature rose by about 0.1 K within the first five minutes and reached equilibrium. When the excitation current was held constant or zero, the coil temperature dropped slowly to the original value. This thermal response of the coil was essentially independent of the flat top current. The temperature rise of the coil was caused mostly by the eddy current in the outer support cylinder. The heat load due to the eddy current depends only upon the current changing rate and is estimated to be about 27 W at 250 A/min (see eq. (1) in section 3.3).

When the power supply is disconnected at t = 0, the

coil current I can be approximately expressed as

$$I = I_0 \exp\left(-\frac{t}{\tau_1 + \tau_2}\right),\tag{2}$$

where I_0 is the flat top current, and τ_1 and τ_2 are the circuit time constants for the coil and support cylinder, respectively. As indicated in fig. 14 and as discussed in section 3.3, we have $\tau_1 = 1.9 \text{ H}/0.1 \Omega = 19 \text{ s}$ and $\tau_2 = 2.3 \mu \text{H}/2.8 \mu \Omega = 0.83 \text{ s}$. Therefore, the coil current should decrease with a time constant of $\tau_1 + \tau_2 = 20$ s, when the coil does not have any normal region. In the dump test the coil current was measured to decrease consistently with a time constant of 20 s. In addition, no imbalance of voltages among the voltage taps was observed. This implies that a series of dump tests did not cause any detectable normal section in the coil.

The temperature rises of 0.5, 2.7, 8.0 and 14 K were measured in the dump tests for the flat top currents of 500, 1000, 2000 and 2800 A, respectively, and they were approximately proportional to the square of the flat top currents. There are two plausible explanations for the reason why the coil did not show any sign of a quench in the dump test at 2800 A. Firstly, since the coil temperature was measured at the outer support cylinder, the actual tempeartures at the superconducting filaments were lower than the critical temperature of 9.3 K. Secondly, even though the coil developed normal sections due to high temperatures, observation of quenches was very difficult because the excitation current was reduced appreciably by that time.

In the dump tests the relief valve of the helium cooling system was manually opened in order to protect the refrigeration system from over-pressurizing. No measurement of the pressure rise of the helium cooling system of the solenoid alone was made.

The charging rate was raised from 250 A/min to 333 and 400 A/min for the flat top currents of 2000 and 2800 A. No quench was detected. Estimated eddy current heat loads were about 49 and 70 W at the charging rates of 333 and 400 A/min, respectively. Temperature rises of the coil were 0.13, 0.20 and 0.28 K for three charging rates.

4.3. Heater tests

From the standpoints of safety and steady operation of the solenoid it is crucial to understand the quench properties of the coil. To this end two heater sets of about 60 Ω each were installed at the middle and near the axial end of the outer support cylinder, as described in section 3.8. A series of heater pulses of 6 to 340 J was applied for the heater installed at the middle of the support cylinder at the excitation currents of 1500, 2000 and 2800 A in order to induce quenches in the coil. The pulse width was 1 s. The coil temperature near the heater rose by up to 0.8 K, but no quench was observed. In the final heater test three heater pulses of 3.3 kJ each were applied at 2800 A. These pulses of 10 s in width were 14 and 27 s apart. The coil temperature rose to about 12 K, but again no quench was observed. It was not clear whether the superconductor temperature exceeded the critical temperature. It seems to be conceivable that, after a normal region appeared locally, it was annihilated with good thermal conduction of the aluminum stabilizer.

In the case of the R&D solenoid a heater was embedded inside the aluminum stabilizer and quenches were induced by heater pulses less than 20 J [3]. In the present case a large fraction of the heater power could have dissipated inside the support cylinder and only a small fraction could have reached the coil since the FRP layer between the support cylinder and coil was good thermal insulator. Nevertheless, it is a striking result that the solenoid with the forced flow cooling system did not quench for a heater input of about 10 kJ. This thermal stability of the CDF solenoid is probably thanks to the mechanical structure, i.e., the coil and outer support cylinder were assembled with the shrink-fit method and the solenoid does not possess a permanent inner bobbin.

4.4. Continuous operation test

In order to test the long term stability of the solenoid it was run continuously for 10 h at 2800 A. The run was very steady and no unusual behaviour of the coil temperature was observed. The loads and displacements of the support systems were also stable and unchanged.

4.5. Warm-up test

In order to study the thermal stability of the solenoid the warm-up test was made by shutting off the liquid helium flow from the refrigerator at the coil current of 10 A. At the start of the test the helium reservoir of the control dewar was filled with 53 l of liquid helium and all the temperature readings were normal. Fig. 19 shows the coil temperature of TR32 and voltages between various voltage terminals. The curves for VT1-VT9, VT9-VT10, and VT9-VT14 correspond to one side of the whole current leads, one quarter of the coil length of the chimney side, and the entire coil, respectively. In the case of VT1-VT9 the steady state voltage due to the non-superconducting section at the normal operation was subtracted. The coil temperature started rising slowly almost immediately after the test began. The helium reservoir of the control dewar became empty after 60 min. The superconducting current leads started gradually becoming normal after 80 min as can be seen from the voltage reading of VT1-VT9. In about another 15 min all the voltage readings between the voltage terminals of the coil showed that the entire coil became



Fig. 19. Coil temperature curve for TR32 and voltage curves for VT1-VT9, VT9-VT10, and VT9-VT14 during the warm-up test. The coil current was 10 A. For example, the voltage curve for VT1-VT9 corresponds to the voltage between the two voltage taps VT1 and VT9. VT1 and VT9, respectively, are located at the input end and the chimney end of the current lead which is connected to the coil at the chimney side. VT14 is located at the same place as VT9, but on the other current lead. VT10 is located at the coil, one quarter coil length away from the coil end of the chimney side. Therefore, the curves for VT9-VT10 and VT9-VT14 correspond to resistances for the one forth of the coil at the chimney side and the entire coil, respectively. The latter is essentially four times larger than the former. The nearly flat distributions of the two curves after 100 min indicate that the entire coil became normal by that time. The curve for VT1-VT9 corresponds to the whole length of one of the current leads and shows that the current leads gradually became normal some time before the coil became normal. In the case of VT1-VT9 the steady-state voltage due to the non-superconducting section at the normal operation was subtracted.

normal within a few minutes. Nearly flat voltage distributions after about 100 min show that no superconducting section was left in the coil. The voltage reading of VT9–VT14 was approximately four times larger than that of VT9–VT10. Namely, the voltage rise was approximately proportional to the conductor length in the coil.

The present warm-up test indicates clearly that the

coil does not have any local hot spots and also that the coil can be operated safely against disruptions of the refrigerator system.

4.6. Thermal load measurement

The 2000 1 liquid helium dewar was used in the present thermal load measurement. The helium refrigerator was not connected to the system. No coil current was applied. During the steady state operation of about 90 min the flow rate of the liquid helium supply was measured to be 3.6 g/s at a gauge pressure of 0.3 atm and the flow rate of the outlet helium gas to be 2.9 g/s at the gauge pressure of 0.04 atm. In addition, liquid helium was accumulated in the helium reservoir of the control dewar at the rate of approximately 26 1/h during the measurement. Therefore, the total input power to the helium system was estimated to be 51 W. The thermal load between the supply helium dewar and the helium supply line at the control dewar was measured to be about 16 W. Therefore, the thermal load of the solenoid in the present measurement was approximately 35 W. This result is in reasonable agreement with the thermal load value calculated by using data obtained in the warm-up test.

4.7. Cool-down and excitation tests of the control dewar and chimney

Prior to the present tests of the solenoid cool-down and excitation tests of the control dewar and chimney were carried out at the excitation current of 6000 A. The current leads were connected together at the far end of the chimney to make a circuit loop. The system was cooled down from room temperature to about 100 K with liquid nitrogen and then to about 5 K with liquid helium after purging liquid nitrogen with helium gas. It took about 3 h from room temperature to 100 K and about 1.5 h from 100 K to 5 K without including the purging time of liquid nitrogen. In the initial test the circuit was excited up to 500 A to check the arrangement of the system. Then, the current was turned up at the rate of 250 A/min to 6000 A with three pauses of 30-90 min at 2800, 4500 and 5000 A. It was held for about 90 min at 6000 A and then turned down. No normal region was observed in the superconducting leads during the excitation test. Operation of the system was very stable.

The helium flow rate of about 0.35 g/s for each lead was required for stable operation of the leads at 6000 A. The overall heat load of the system was about 10 W. The voltage drop at the power leads was measured to be 60 mV at 6000 A which is consistent with the design value. As mentioned earlier, the head of the control dewar was covered with frost during the cool-down test. It seemed that the convection of cold helium gas in the

upper section of the partition wall of the control dewar caused this effect (fig. 11). A heater was installed to prevent frosting.

5. Conclusion

Construction of the CDF solenoid was completed without encountering any noticeable difficulty. The shrink-fit assembly of the coil and outer support cylinder was made very successfully and the temporary mandrel was removed without causing any damages to the coil. The inner surface of the coil looked very clean and uniform. The contact pressure between the two members was measured to be 0.028 kg/mm² which is consistent with the design value. Measured radial deformations of the coil and support cylinder assembly were less than 2 mm from the ideal circle.

The quality of the turn-to-turn insulation was tested by measuring voltage drops for every two turns with a current of 1 A at room temperature. They were very uniform for the entire coil. Therefore, there existed no bad spot in the turn-to-turn insulation. The coil to ground insulation was checked with 1500 V_{ac} .

All the major joints of the vacuum system of the solenoid, chimney, and control dewar were welded after the assembly was completed. The only exception was the safety relief valve at the chimney. The vacuum system was checked good.

Cool-down and excitation tests of the solenoid were carried out. During the cool-down period, the thermal response at various sections of the solenoid and stresses at the support members were very steady and reasonable. It took about seven days from room temperature to liquid helium temperature at a cooling rate of approximately 2 K/h. The cooling rate was raised after the coil was cooled to liquid nitrogen temperature. The coil became superconducting at about 9 K. Drops of dew or frost were not observed near the support areas on the outer surface of the cryostat. Furthermore, no cold spot was found either by touch. This indicates that heat loads through the support members were negligibly small.

Since the iron return yoke was not used in the present tests, the maximum excitation current was limited to 2800 A because of excessive loads to the coil due to magnetic forces in the coil axial direction. The solenoid was charged at a rate of 250 A/min to various flat-top currents and then the currents were discharged at the same rate as in charging or dumped by opening the switches at the power supply manually. Thermal response of the solenoid was again reasonable during these tests. Reasonable temperature rises less than 0.3 K due to eddy currents in the outer support cylinder were observed. The charging rate was raised to 333 and 400 A/min. No unusual temperature behavoir was ob-

served. No quench was detected during the excitation and dump tests.

A continuous opearion at 2800 A was performed successfully for about 10 h. A series of heater quench tests was carried out by using a heater installed at the middle of the outer support cylinder in order to induce quenches in the coil. No sign of development of a normal zone was detected even for a heater input of 10 kJ within a period of one minute at 2800 A. The coil temperature near the heater rose up to 12 K in this test.

The thermal load of the coil was measured to be about 35 W for the steady state operation. The warm-up test was carried out by shutting off the flow of the liquid helium supply at an excitation current of 10 A. The coil stayed superconducting for about 90 min and then the entire coil became normal very uniformly. This implies that no hot spot existed in the coil. The thermal load estimated from the warm-up test is consistent with the measured thermal load of 35 W.

The results of the present tests reveal the excellent thermal stability of the solenoid. It is a remarkable result that the CDF solenoid with the forced flow cooling system did not quench for a heater input of 10 kJ. This thermal stability may be in part due to good quality of the aluminum-stabilized NbTi/Cu superconductor with the EFT method, in part due to the shrink-fit assembly of the coil and outer support cylinder, in part due to the mechanical structure of the coil without having a permanent inner bobbin, in part due to the arrangement of the cooling tubes which welded to the outer support cylinders and in part due to the good design of the cryostat.

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