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CONSTRUCTION AND TESTING OF R&D SUPERCONDUCTING SOLENOID MAGNET FOR CDF DETECTOR*†

S. Mori and R. Yoshizaki

Institute of Applied Physics, University of Tsukuba
Ibaraki, Japan 305

H. Kawakami and K. Kondo

Institute of Physics, University of Tsukuba
Ibaraki, Japan 305

H. Hirabayashi, K. Morimoto, M. Wake and A. Yamamoto

National Laboratory for High Energy Physics
Ibaraki, Japan 305

K. Aihara, Y. Kazawa, H. Kimura, Y. Miyake*, H. Ogata
R. Saito and S. Suzuki

Hitachi Ltd., and Hitachi Cable Ltd.*, Ibaraki, Japan

R. Kephart and R. Yamada

Fermi National Accelerator Laboratory
Batavia, Illinois 60510

INTRODUCTION

Several thin walled aluminum stabilized superconducting solenoid magnets have been constructed and are being used for high energy colliding beam experiments (e.g., CELLO detector [1] and CLEO detector [2]). Construction of a similar but larger solenoid magnet, 3 meters in diameter and 5 meters long with the central field of 1.5 Tesla is being contemplated for Fermilab Collider Detector Facility [3,4,5]. To begin to study the problems associated with the design of such a magnet, a small R&D solenoid was constructed and tested. It has a diameter of one meter and is one meter long.

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The coil was tested successfully beyond the designed value and operated up to 85% of short sample data without spontaneous quenches. The maximum field at the conductor was 1.6 Tesla.

DESIGN AND PARAMETERS OF SOLENOID MAGNET

The main parameters of the solenoid are listed in Table 1 and the geometry of the solenoid is shown in Fig. 1. The conductor stabilized with high purity aluminum was used. A radiation shield cooled with liquid nitrogen surrounded the whole surface of the coil.

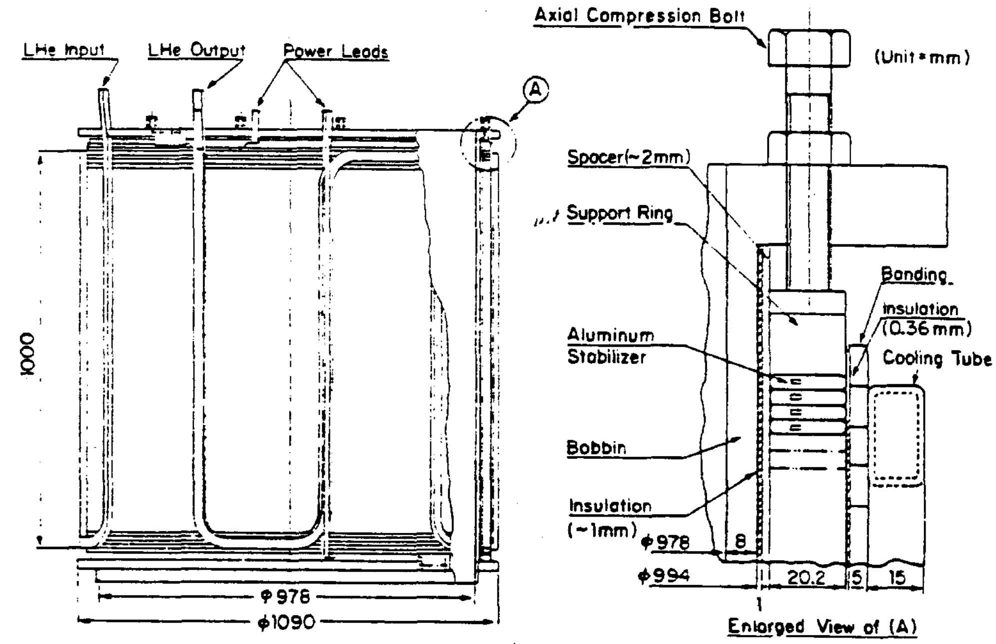

Fig. 1. Geometry of R&D solenoid magnet

Table 1. Parameters of R&D Solenoid Magnet

DIMENSIONS OF COIL	Diameter:	1 meter
	Length:	1 meter
	Turn number:	269 (excluding 2 joint layers)
	Number of joints:	2
	Joint:	1 turn overlav, 3/4 turn weld
ELECTRICAL	Inductance:	47 mH
	Stored Energy:	600 kJ at 5 kA
	Resistance:	315 mΩ at 290K (0.24 mΩ at 10K)
MAGNETIC	Central field:	1.4 T at 6000A
	Conductor field:	1.6 T at 6000A
CONDUCTOR	Filament:	50 μm φ x 1400
	Material ratio:	Al:Cu:NbTi = 24:1:1
	Purity of aluminum:	99.99% (RRR ≥ 1000)
	Short sample current:	7700A at 4.2K and 2T

MODE OF OPERATION

Refrigeration for the coil was provided by flowing LHe at 30 liters/hour through the cooling pipe wound over the coil. The coil obtains its stability as a result of the large thermal diffusivity of the high purity aluminum stabilizer. The coil is protected from damage by insuring that the magnet's stored energy is distributed over the entire coil thus limiting the maximum temperature rise in the conductor.

CONDUCTOR

The parameters of the conductor used for this magnet are given in Table 1 and its cross section in Fig. 2. A monolithic multi-filamentary NbTi superconductor with a copper to superconductor ratio of 1 to 1, was stabilized with pure aluminum. The metallurgical bonding between the superconductor and the aluminum is done by the EFT method developed at Hitachi [6]. Various mechanical and electrical tests of sample wires showed this technique to be superior to soldering. EFT stands for extrusion with front tension, and is a method in which aluminum is extruded over the superconductor wire while the wire is pulled with forward tension. During this process, the aluminum diffuses and penetrates into the copper in the binding thickness of about 2 microns. The characteristics of the EFT boundary is listed in Table 2 in comparison with those obtained by soldering. The measured resistivity of the high purity aluminum stabilizer was 1.9×10^{-9} Ωcm at 10K. The corresponding value at 290K was 2.5×10^{-6} Ωcm. The residual resistivity ratio of the aluminum was about 1250. From the heater tests, which will be described later, we estimate the resistivity was 3.5×10^{-9} and 4.0×10^{-9} Ωcm at 2 kA and 3.5 kA respectively. The increase of factor 2 is due to magneto-resistivity. The conductor joint is made by welding the adjoining turns as shown in Fig. 3. In Table 3 the measured resistances of the welded sample joints with 1 kA current at 4.2K and at 1 Tesla are also shown in comparison with the soldered sample joints. The resistance of the welded joint is inversely proportional to the total length of the joint as expected. The total resistance of two welded joints of

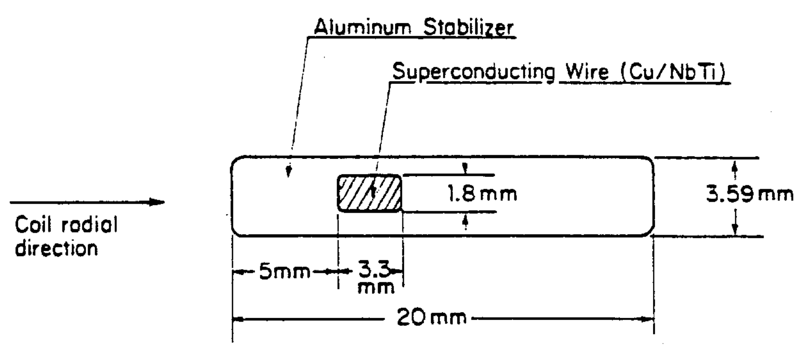

Fig. 2. Cross section of the EFT conductor

Table 2. Comparison between EFT and Soldering

	EFT	Soldering
Thickness (mm)	$< 2 \times 10^{-3}$	~ 0.1
Resistance (Ωcm)	2.4×10^{-9}	2.1×10^{-8}
Shear strength (kg/mm^2)	> 1	-

Table 3. Conductor Joint Methods and Their Resistance

	Length (mm)	Al Welding	Al Soldering
Measured resistances	50	9.3×10^{-9}	2.4×10^{-6}
(Ω)	100	5.0×10^{-9}	1.6×10^{-7}
(at 1T, 4.2K, 1kA)	200	2.5×10^{-9}	2.5×10^{-8}

400 mm each was measured to be 6.5×10^{-10} Ω. These data shows the excellence of the welded joints. The short sample data of the conductor are specified 7700A at 4.2K and 2 Tesla. These design values of the conductor at 4.2 and 4.7K and the measured short sample data at 4.2K are shown in Fig. 4.

The load line of the conductor at the maximum field, which is at the center turn of this coil, is also shown in Fig. 4. The magnet is designed to operate at 4.5 kA with the maximum field of 1.21 Tesla. In the second test run, the magnet was excited up to 6 kA without any quench, to the maximum field of 1.6 Teslas, corresponding to 85% of short sample data at 4.7K. The superconductor of the coil is actually in a magnetic field, where its magnitude varies from the central field at one edge of the conductor to almost zero field at the other edge. Therefore the average field is about the half of the specified field. This fact should give an additional safety factor for the stability of the conductor.

CONSTRUCTION METHOD

The flow chart of the R&D coil construction is shown in Fig. 5. The coil bobbin was made of 5083 aluminum. Its surface was first covered one millimeter thick insulation layer, which consists of mica sheets and glass tape impregnated with polyester resin. We made a rather heavy insulation layer to prevent ground faults from the coil winding to the bobbin. The conductor itself was wrapped with 0.1 mm thick polyamied-imide tape impregnated with B-staged epoxy.

Instead of winding the conductor directly on the insulated bobbin, the conductor was wound and cured with polyester resin on a separate metal winding form. With this procedure we could easily apply the axial compression of 82 kg/cm^2 on the conductor during the winding to prevent conductor movement in the axial direction when excited [7]. After curing the resin, the winding form was disassembled and removed. The cured conductor winding was then placed over the insulated bobbin, and the ∿ 2 mm gap between was filled with glass tape. Next an insulation layer of mica tape and polyimide tape impregnated with polyester resin was wound on the conductor winding. Then a 5083 aluminum band, 10 mm wide and 5 mm high was wound over this insulation with a tension of 100 kg. After curing of the polyester resin at room temperature, the cooling pipe was installed. The pipe was glued to the surface of the band with Stycast resin and banded again with aluminum wire. The coil was then placed in a LN_2 shielded can and instrumentation and power leads were installed. The conductors between the power leads and the ends of winding were carefully cooled with separate liquid helium pipes.

The hoop stresses in these components layers were calculated for two cases, with bonded a insulation layer and unbonded insulation layer. The stress after banding, cooldown and excitation up to 1.5 Tesla are calculated and shown in Fig. 6. In both cases of bonded and unbonded insulation layers, the stress in the pure aluminum conductor is below the elastic limit of 2 kg/mm^2. The stress in the band is below 4 kg/mm^2, which is lower than the design stress of 9.4 kg/mm^2 for 5083 aluminum. The quality of the insulation layer is not clear but the whole system seems sound.

TEST RESULTS

Two test runs were done on this R&D solenoid magnet. The first in April 1981 and the second in July 1981. The magnet was cooled

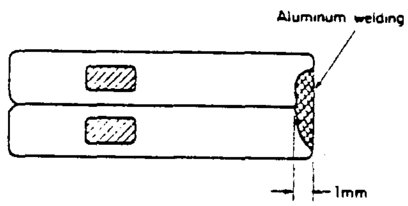

Fig. 3. Joint for EFT conductor The welding is made keeping superconductor part cool by water-cooling devices.

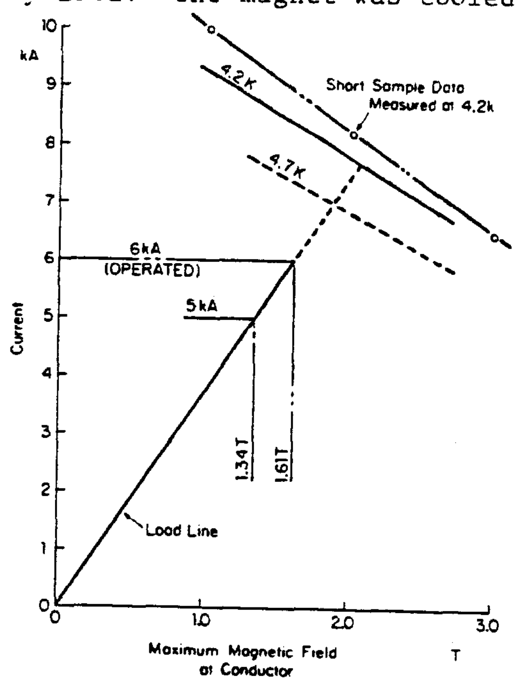

Fig. 4. Load line of R&D solenoid and short-sample data.

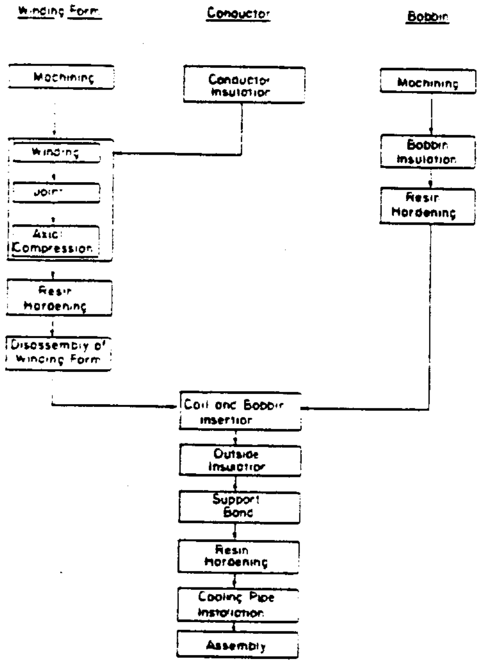

Fig. 5. Flow chart for construction of R&D coil.

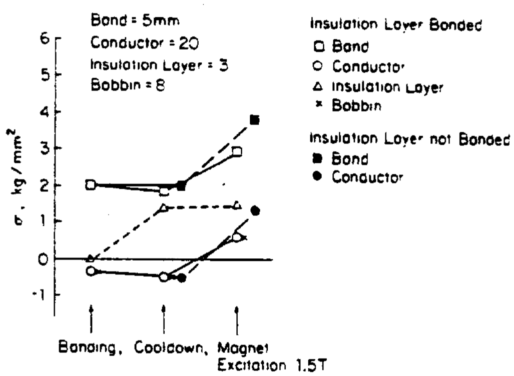

Fig. 6. Stress in coil components

down from room temperature to 4.5K in 36 hours, using liquid nitrogen and liquid helium from a storage dewar. During the test liquid helium flow from a dewar was used. In the first test run, the magnet reached the design excitation current of 4.5 kA. That would give the magnetic field of 1.5T, if there had been an iron yoke. At that time an attempt was made to raise the excitation current up to and above 5 kA, but it was unsuccessful due to unexpectedly higher local temperature in the coil. It was estimated that the temperature of the conductor was about 6.5K at some point. After the test a bundle of instrumentation wires was found thermally shorting between the nitrogen shield and the coil structure. Also there was some indication that the power leads were not cooled efficiently. These thermal defects were corrected and several other modifications made to cool the conductor more efficiently for the second test run. During the first test run the propagation velocity of the normal zone was measured at 2, 3 and 3.5 kA during heater tests. In addition from the data of spontaneous quenches, the propagation velocity was also measured at 2.7, 4.1 and 4.55 kA. In the second test run the magnet was cooled down to 4.5 ± 0.1K and ran successfully at a current of 5, 5.5 and 6 kA without causing any quench. The heater quench tests were performed at 3.5, 4, 4.5, and 5 kA to measure the propagation velocity of the normal zone. In this 6 kA excitation run the current was raised at the rate of 400 A/min from 0 to 4 kA and at 100 A/min from 4 to 6 kA. No unusual behaviors such as temperature rise was observed.

The propagation speed of the normal zone was tested as a function of excitation current using a heater embedded into the coil conductor at the central turn. The heater was powered with a pulse current of 0.12 sec duration,and the energy needed to start the normal region was 22.5 and 13 joules at the operation currents of 3.5 and 5 kA. There are about a dozen voltage terminals used along the whole conductor length. Signals from these terminals were used to obtain time when the normal zone arrived at those points. The voltage increases yielded information about the change of resistance of the conductor in that region. The measured propagation speed is shown in Fig. 7. The data from the heater test are shown with solid lines for the first and second test runs. The estimated velocity of the normal zone along the conductor length (if we assume the normal zone is spread only in that way) is shown on the left ordinate axis. The effective velocity along the axis of the solenoid is shown on the right axis. The propagation speeds of the normal zone during the spontaneous quenches of the first test run are shown with dashed lines. One velocity was measured near the quench origin and the other near the center of the coil. The velocity near the quench origin was about twice as much as near the center of the coil. These quench origins were at 20 to 30 turns from the top of the coil. Other data indicated local abnormally high operating temperature in this region. On the other hand, the

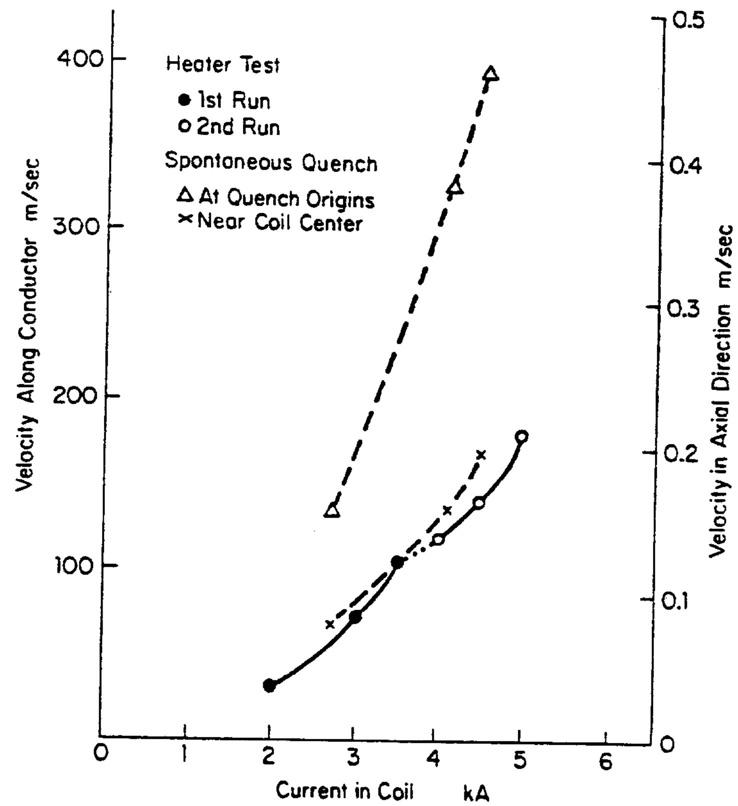

Fig. 7. Propagation speed of normal zones

velocity data near the center of the coil in the first test run indicated the temperature around there were not abnormally high.

During the first test run, an estimated energy of about 1.3 MJ was unintentionally dumped into the magnet, while the stored energy was about 400 KJ. The current remained on at $\sim$ 4000A for 30 sec after the quench. The temperature of the coil went up to 65K. The interesting fact is that the coil was very stable and can absorb quite a lot of energy without causing any serious damage. In the second test run, the power supply was kept on intentionally for 3.6 sec at 5000A, without causing any damage, after inducing a quench with the heater. The quench properties was investigated by using computer programs [8]. The agreement between the data and calculated numbers on the temperature rise is fairly good.

CONCLUSION

This R&D coil was excited beyond the designed values without any quench. The effective value of I x H was tested 40% more than the designed value. The coil was subjected to quite strong axial stress, because the test was done without iron yokes. With this successful test,it seems the whole construction scheme and especially the EFT aluminum stabilized conductor together with its weld joints, are satisfactory for the construction of a large solenoid.

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