Fermilab

TM-1272
2791.000

FABRICATION AND TESTING OF A 3-m DIAMETER SUPERCONDUCTING SOLENOID FOR THE FERMILAB COLLIDER DETECTOR*

R. W. Fast, K. Asano, R. D. Kephart, K. Kondo, I. Kurita, H. Minemura, S. Mori, R. Saito, T. Suzuki, R. H. Wands, and R. Yoshizaki

July 1984

*Presented at the 10th International Cryognaic Conference, Espoo, Finland, July 31-Aug. 3, 1984, and will be published by Butterworth Scientific, Ltd in the conference proceedings.

FABRICATION AND TESTING OF A 3-m DIAMETER SUPERCONDUCTING SOLENOID FOR THE FERMILAB COLLIDER DETECTOR

R. W. Fast, K. Asano,* R. D. Kephart, K. Kondo,† I. Kurita,* H. Minemura,† S. Mori,† R. Saito,* T. Suzuki,* R. H. Wands, and R. Yoshizaki†

Fermi National Accelerator Laboratory, Batavia, Illinois**
* Hitachi, Ltd., Hitachi, Ibaraki, Japan
† University of Tsukuba, Sakura, Ibaraki, Japan

A large, 1.5-T conduction cooled superconducting solenoid for the Collider Detector at Fermilab was designed and built as part of a US-Japan international high-energy physics collaboration. Initial tests of the coil without its iron return yoke indicated that the coil performed as designed and should operate in a very stable manner when installed in the flux return iron at Fermilab.

INTRODUCTION

The Fermilab Collider Detector is a large detector system to study $\bar{p}p$ collisions in the Fermilab Tevatron. A horizontal magnetic field of 1.5 T over a cylindrical volume 3 m ϕ × 5 m is required to provide the necessary momentum resolution. Since detectors are located outside the solenoidal field region, as well as inside, the coil and cryostat must be "thin" in terms of both radiation and absorption lengths. These requirements have resulted in a conduction cooled bobbinless superconducting solenoid with the coil and cryostat largely made of aluminum. The magnet was designed cooperatively by Fermilab, the University of Tsukuba, and Hitachi, Ltd. The coil and cryostat was fabricated by Hitachi, under contract to the University of Tsukuba.

SUMMARY OF MAGNET DESIGN

The design of the 30-MJ detector solenoid, given in the design report,[1] has been presented earlier.[2] The conductor for the single layer helical coil is a high-purity aluminum-copper-NbTi composite fabricated by Hitachi Cable, Ltd. The conductor dimensions are 3.89 mm × 20 mm and the Al:Cu:NbTi ratio is 21:1:1. The conductor current density, at the 5-kA operating current of 64.3 A/mm^2, is 60% along the load line to 4.4 K. The outward radial pressure on the coil (0.9 MPa at 1.5 T) is reacted as a hoop stress in an outer support cylinder.

The solenoid will be installed in an iron flux return yoke the basic geometry of which is two calorimeterized end walls and four flux return legs. Calorimeterized poles extend into the solenoid field volume. The pole and end wall geometry determines the axial electromagnetic force on the coil and the radial and axial decentering forces. The axial force is calculated to be ~1 MN (compressive) at 1.5 T. The radial and axial force constants are computed as approximately 12 MN/m and 18

**Operated by Universities Research Association, Inc., under contract with the U. S. Department of Energy.

MN/m respectively. The cold-to-warm support system consists of six axial members, all on one end, to provide axial stiffness and 12 tangential members on each end to carry the cold mass and provide radial stiffness. These members are thermally intercepted at 77 K and 4.4 K to reduce the heat flux to the outer support cylinder and avoid hot spots. Spherical bearings on both ends of each member eliminate bending stresses due to differential thermal contraction.

The behavior of the coil following a quench has been computer modeled including the "quench back" effect of the eddy current in the outer support cylinder and the effect of the insulating layer between the coil and the outer support cylinder. Quench back was shown to be very effective in protecting the coil since the entire coil was calculated to be normal several seconds after quench initiation. With a 74 mΩ dump resistor the maximum expected conductor temperature is less than 100 K. The coil will have five voltage taps to help locate quench origins. Heaters are installed to permit experimental quench studies.

The coil is refrigerated by two-phase helium at ~4.4 K flowing from a 2000-L storage dewar through ~130 m of 20-mm ID aluminum tube welded to the outer support cylinder. After cooling the outer support cylinder, the flow is used to intercept all the support members. The storage dewar pressure, maintained by the refrigerator, provides the driving force for the helium, i.e. the system does not have a pump. A finite element thermal analysis performed on the outer support cylinder gave a maximum temperature of 5.3 K.

The coil and support cylinder are screened from 300 K radiation by inner and outer liquid nitrogen cooled shields. End shields screen the coil ends and intercept the supports.

The vacuum shells are designed in accordance with the ASME Pressure Vessel Code. The outer shell is 20-mm thick; the inner shell is 7 mm. Since the inner shell has a critical collapse pressure differential ~0.02 MPa, the vacuum space is relieved by a 200-mm ϕ gravity liftoff plate.

A control dewar, located just outside the magnet yoke, provides the interface to the magnet cryostat. It has bayonet couplings for the cryogenic lines and a 55-L LHe reservoir fed from the helium return line. The superconducting leads from the coil enter the helium vessel through insulating feed-throughs and connect with gas cooled current leads leading to 300 K. Relief valves, a vacuum pumpout, and instrumentation connectors exit the system through the control dewar. A 200-mm ϕ × 3-m chimney connects the control dewar to the magnet cryostat. The control dewar, chimney, and cryostat have common vacuum.

SUMMARY OF REFRIGERATION SYSTEM DESIGN

The refrigeration system being installed at Fermilab for the solenoid is discussed in a companion paper.[3] The total expected steady state heat load is 40 W with an additional 100 W during a 500 A/min charge due to the eddy current in the support cylinder. A modified version of the Tevatron satellite refrigerator will be used. The capacity of this refrigerator is larger than the expected heat load by a factor of approximately 2.5. It was chosen in the interest of standardization and to provide fast cooldown and quick recovery from quenches.

COIL AND CRYOSTAT FABRICATION

The coil was fabricated by wrapping the conductor with B-stage Kapton tape and winding it with a tension of 980 N on a removable mandrel (Fig. 1). An axial pressure of 10 MPa was applied and the coil heated to 135°C to cure the tape. In order to provide a uniform cylindrical outer coil surface to mate with the support cylinder, a layer of fiber reinforced plastic (FRP) was wrapped over the conductor, cured, and machined. The average thickness of the machined FRP layer was ~2.5 mm. The diameter of the conductor/FRP assembly was machined to within 0.1 mm of the design value.

Sheets of 5083 aluminum alloy were rolled and welded to form a 3-m ϕ cylinder with a wall thickness of 16 mm except for a 44-mm thick section at each end 410 mm long to provide stiffness for the support system. After the outside surface of the cylinder was machined, a supporting fixture was attached to provide mechanical rigidity. The inner surface of the cylinder was then machined to a diametral accuracy of 0.2 mm. The radial interference between the coil and outer support cylinder was 1.5 mm. The calculation of the interference, based on considerations of conductor stress, winding strain, and cooldown effects, is given in Ref. 4. The outer support cylinder was heated to 100°C and lowered over the coil. The winding mandrel was then removed, giving a final radial preload of 0.27 MPa. A final axial compressive preload of 7.6 ± 1.5 MPa was applied to the coil by means of bolts in the support cylinder.

The vacuum cylinders were also fabricated by rolling and welding 5083 aluminum plates. The two annular end flanges were machined from 5083 plate. The radiation shields, 2-mm aluminum plates with a cooling tube welded on, were supported from the vacuum vessel with preloaded stainless springs.

The axial and radial supports were fabricated of Inconel 718; the axial elements were tubes 26 mm OD × 20 mm ID, the radials were 15 mm rods. The dimensions were chosen to provide a safety factor of four on the low-temperature tensile yield stress for a worst-case magnetic unbalancing. The preload on the radial members can be adjusted from outside the cryostat.

The chimney and control dewar were fabricated of 18-8 stainless steel (Type 304), with aluminum-to-stainless transition couplings used on the fluid lines and the chimney vacuum jacket.

The superconducting leads from the coil to the gas cooled leads were fabricated of two pieces of coil conductor welded together. The positive and negative leads were clamped, through electrical insulation, to opposite sides of the helium supply line, which was immobilized by clamping to the outer support cylinder and to thermal stand-offs in the chimney. The ceramic feed-throughs at the bottom of the control dewar helium vessel were surrounded by a secondary vacuum vessel to guard the main vacuum system against helium leaks in the feed-throughs.

Extensive instrumentation was provided to monitor coil and refrigerator system behavior. Carbon and platinum resistance sensors were used; 9 in fluid lines and 26 on the coil, shields, and supports. There were 12 voltage taps on the leads and coil. Each of the 24 radial supports had a strain-gauge type force transducer, while the force in the axial supports was determined from axial position sensors. Thermocouple and cold cathode ion gauges monitored the main and secondary vacuum systems.

The coil was installed into the vacuum vessel (with its attached shields) in a vertical orientation. The final assembly is essentially all welded; the only o-rings are on the vacuum liftoff plate and the radial supports, where two rings are used with a provision for pumping the annular space between rings.

INITIAL TEST AND RESULTS

The first test of the solenoid was performed at the Hitachi Research Laboratory in the spring of 1984, with data recorded by representatives from the University of Tsukuba and Fermilab. Since this test was done without an iron flux return the current was limited to 2.8 kA. The cryogenic system for the test and the test results are described elsewhere.[3] The resistance of the coil at ~10 K was measured to be 2 mΩ, which corresponds to an average RRR (residual resistivity ratio) = 1885. During the excitation tests the helium mass flow rate was 17 g/s, with a coil inlet temperature ~4.7 K and absolute pressure ~0.16 MPa.

A 100 mΩ dump resistor was used for the electrical tests. Temperature, current, and voltage data were recorded by a data logger-personal computer system and

by several multichannel strip chart recorders. The excitation and dump schedule is given in Fig. 2. The maximum test current of 2.8 kA was chosen because at this current the axial magnetic force without iron is equal to the final compressive preload applied to the coil. The inductance without the yoke was measured during a charge as 1.92 H, so the stored energy at 2.8 kA was ~7.5 MJ. The coil reached the maximum test current at 100 A/min without a spontaneous quench.

The coil was ramped to 2 kA and back down at rates of 250, 333, and 400 A/min. Neither a quench nor a normal region was observed at these rates. The temperature increase of the outer support cylinder during the ramp was constant with time and is shown in Fig. 3. A series of induced quench tests using the heaters was attempted (Fig. 4). Adding ~10 kJ with three, 3.4-kJ pulses (340 W × 10 s) 14 s and 27 s apart did not cause an observable normal region at 2.8 kA. Further high power tests were not attempted because of the possibility of damaging the heaters and FRP insulation. Following the heater tests, the coil was operated at 2.8 kA for 10 h without incident. The stability of the coil was further demonstrated by stopping the helium flow with the coil at 10 A. After about 60 min the control dewar helium vessel boiled dry; about 10 min later the superconducting lead went normal. The entire coil went normal in about another 10 min, an indication that there were no hot spots in the winding.

CONCLUSIONS

The obvious conclusion from the initial test is that at about 50% of the design field the coil is remarkably stable. Figure 3 indicates that charging the magnet to 1.5 T in 10 min is unlikely to cause a quench with a helium flow rate of 17 g/s. The charging and quench behavior of the coil, with the complete iron circuit, to the guaranteed field of 1.35 T, and hopefully, to the design field of 1.5 T, as a function of helium flow rate, will be investigated in a comprehensive test program at Fermilab, beginning in the fall of 1984.

REFERENCES

(1) Fast, R. et al. 'Design report for an indirectly cooled 3-m diameter superconducting solenoid for the Fermilab Collider Detector Facility, TM-1135', 1982, Fermi National Accelerator Laboratory, Batavia, Illinois.

(2) Wands, R. et al. IEEE Trans in Magnetics 1983, MAG-19, 1368-1371

(3) Fast, R. et al. 'Refrigeration tests of the cryogenic system and solenoid for the Fermilab Collider Detector', Proc. 10th Intl Cryo. Engr. Conf. Butterworth, London

(4) Minemura, H. et al. Nucl. Instr Meth 1984, 219, 472-478

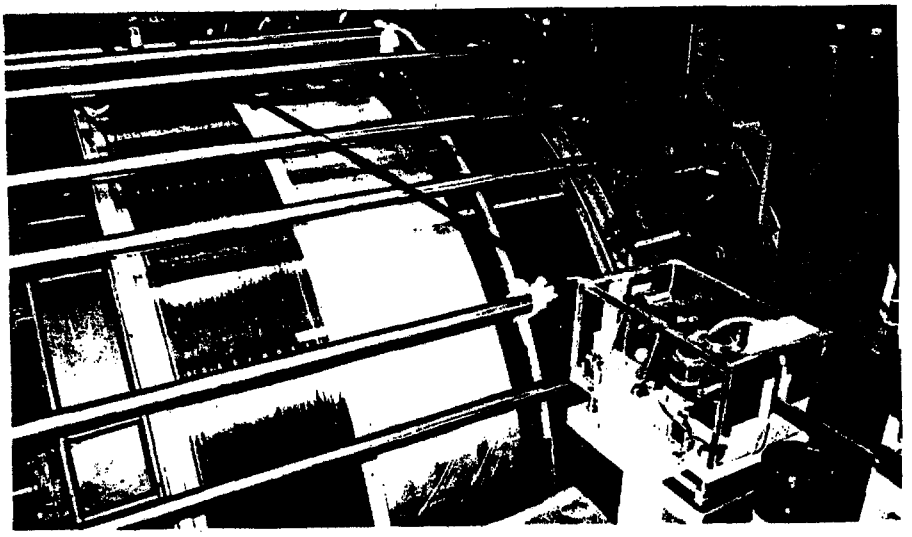

Fig. 1 Coil winding - CDF solenoid

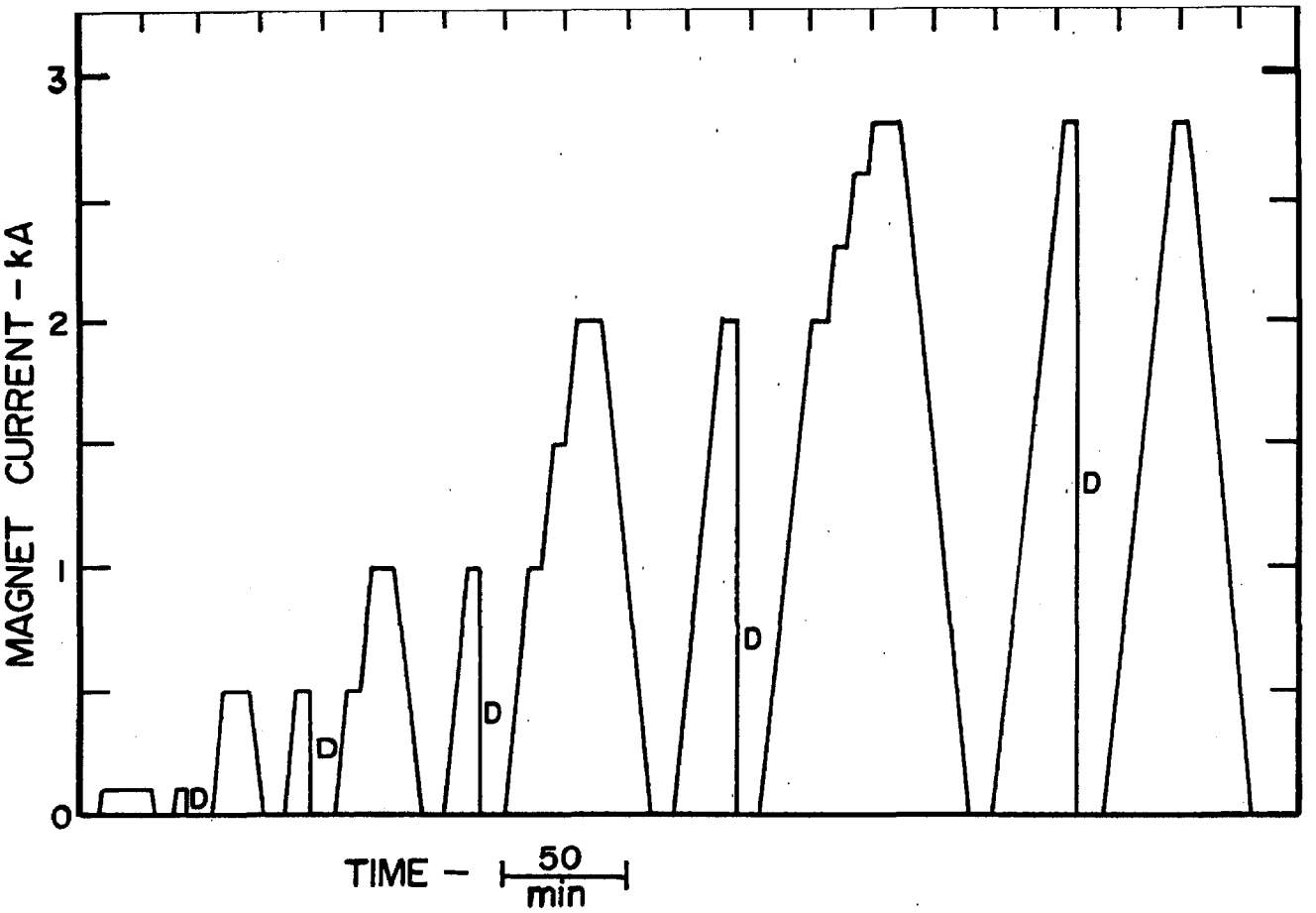

Fig. 2 Magnet excitation schedule. A dump discharge is indicated by D. Do not scale the time between successive charges

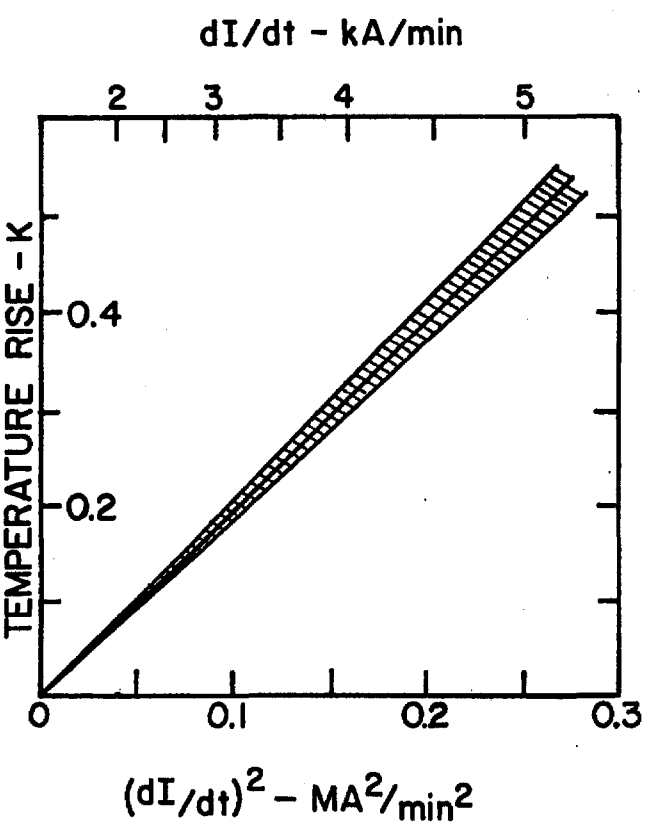

Fig. 3 The increase in the temperature of the outer support cylinder during charges

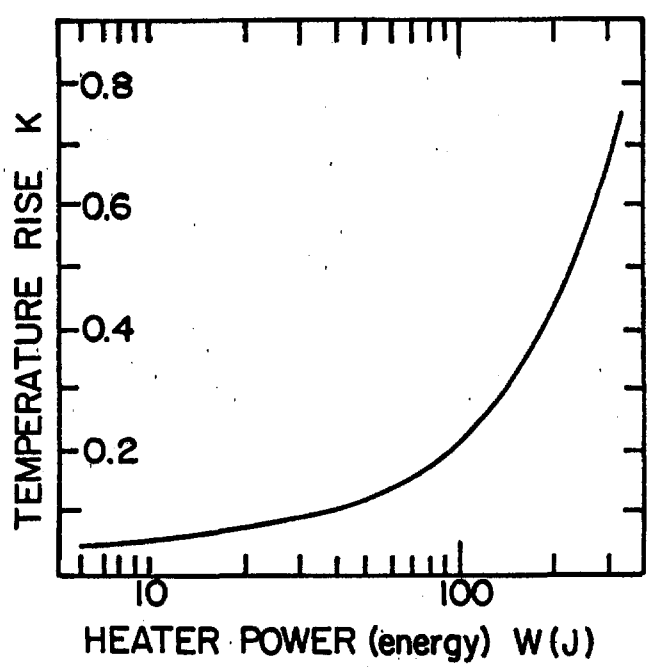

Fig. 4 The increase in the temperature of the outer support cylinder during heater tests