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TESTING OF THE SUPERCONDUCTING SOLENOID FOR THE FERMILAB COLLIDER DETECTOR*

R. W. Fast, C. N. Holmes, R. D. Kephart, J. B. Stoffel,
M. E. Stone, R. H. Wands, and T. N. Zimmerman
Fermi National Accelerator Laboratory, Batavia, IL USA

and

K. Kondo, S. Mori, and R. Yoshizaki
University of Tsukuba, Sakura, Ibaraki, Japan

and

K. Asano
Hitachi Works, Hitachi, Ltd., Hitachi, Ibaraki, Japan

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ABSTRACT

The 3 m $\phi \times$ 5 m long $\times$ 1.5 T superconducting solenoid for the Fermilab Collider Detector has been installed at Fermilab and was tested in early 1985 with a dedicated refrigeration system. The refrigerator and 5.6-Mg magnet cold mass were cooled to 5 K in 210 hours. After testing at low currents, the magnet was charged to the design current of 5 kA in 5-MJ steps. During a 390 A/min charge a spontaneous quench occurred at 4.5 kA due to insufficient liquid helium flow. Three other quenches occurred during "slow" discharges which were nevertheless fast enough to cause high eddy current heating in the outer support cylinder. Quench behavior is well understood and the magnet is now quite reliable.

INTRODUCTION

The Fermilab Collider Detector utilizes a superconducting solenoid 3 m $\phi \times$ 5 m to produce a horizontal magnetic field of 1.5 T, to study $\bar{p}p$ collisions in the Tevatron. To minimize measurement errors for particles passing through the solenoid it is fabricated largely of aluminum and is conduction cooled.

Design details of the CDF solenoid have been presented elsewhere.[1] The single-layer coil uses an aluminum-stabilized conductor at an operating current of 5 kA. The outward radial force is reacted in an aluminum outer support cylinder. The net forces on the coil/support cylinder are carried by Inconel supports. The coil is refrigerated by a flow of two-phase helium at ~5 K through an aluminum tube welded to the outer support cylinder. The vacuum vessel, fabricated of aluminum, is attached to an iron flux return yoke.[2] A control dewar, located above the cryostat and outside the iron yoke, serves as the interface between the magnet cryostat and the refrigeration system. The fabrication of the coil, cryostat and control dewar and the initial test without iron have been described earlier.[3-5]

The refrigeration system[6] is based upon the standard Fermilab "satellite" refrigerator which has a nominal capacity of 625 W or 125 L/h. Helium of high liquid fraction is circulated through the coil cooling tube using the main compressor to provide the required pressure differential. Two transfer lines permit operation of the magnet in either the Assembly Hall for testing or in the Collision Hall for the experiments. The refrigerator is computer controlled using the same hardware and software as the Tevatron refrigerators. The refrigeration system was tested prior to magnet installation and was found to exceed its nominal capacity.

DESCRIPTION OF ELECTRICAL SYSTEM

A schematic of the dc circuit is shown in Fig. 1. The protection and interlock system can initiate a slow dump by opening SW1 or a fast dump by opening SW2/SW3. The quench detection circuit uses the voltage taps V3 to V7 to detect normal regions in the coil. A data logger built around Lecroy transient recorders and an IBM PC was used to accumulate steady state and charge/discharge data during the cooldown and test. The electrical system is described in more detail elsewhere.[7]

COMMISSIONING OF MAGNET-REFRIGERATOR SYSTEM

Assembly of Magnet at Fermilab

It was determined that the safest way to ship the magnet cryostat-control dewar from the Japanese vendor to Fermilab was by air from Tokyo to Chicago. HeavyLift Cargo Airlines, London, England, was chosen for the move since they operate the "Belfast," a large plane originally designed for military cargo use. It was necessary to separate the control dewar from the magnet cryostat by cutting the chimney vacuum shell and internal fluid lines about 300 mm from the cryostat. The cryostat and control dewar arrived at Fermilab on July 20, 1984. When the assembly of the iron yoke was completed the cryostat and control dewar were installed and rejoined.

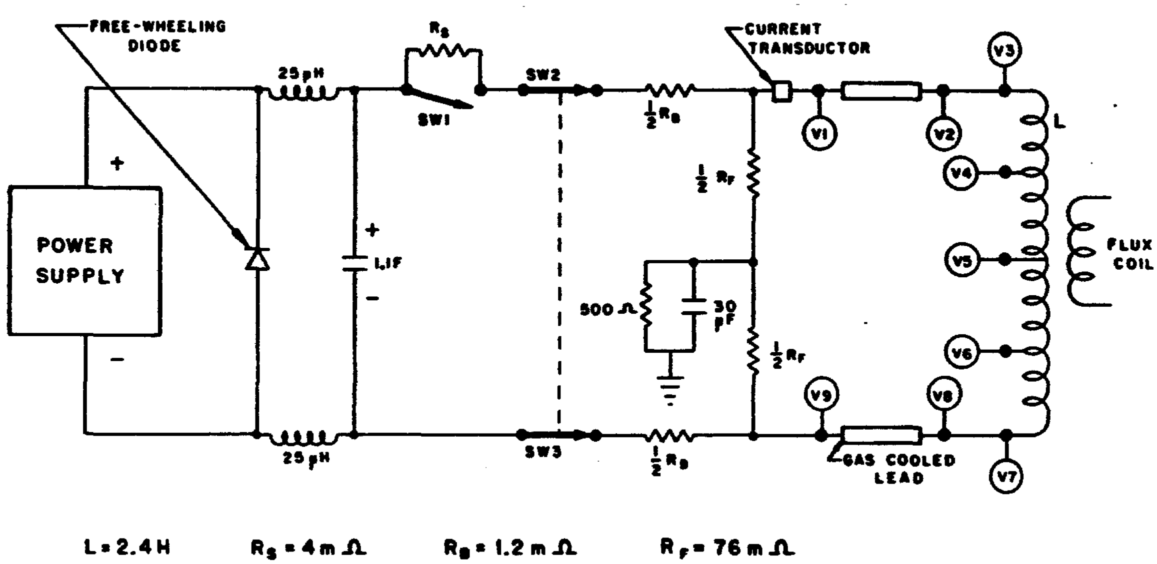

Fig. 1. dc circuit of CDF solenoid.

Cryogenic Safety Analysis and Review

In order to insure that Fermilab employees are protected against the hazards peculiar to cryosystems, Fermilab policy requires that such systems be designed in accordance with written standards and analyzed for cryogenic safety. This policy also requires that the design and safety analysis be reviewed by an independent panel of cryogenic engineers and scientists. The CDF magnet and refrigeration system was designed, safety analyzed, and reviewed in accordance with these requirements.

Hazards of liquid nitrogen and liquid helium systems. The general hazards associated with cryogenic systems have been treated elsewhere.[8] The primary hazards of the nitrogen-helium cryosystems found at Fermilab are liquid cryogen spray and oxygen deficiency both of which can result from cryogen containment failure. At many of the Fermilab installations these hazards are exacerbated by the location of major system components, e.g. superconducting magnets and liquid transfer lines, in underground tunnels or in below-grade or underground experimental halls. The standard for evaluating the oxygen deficiency hazard (ODH) associated with cryogenic installations is given in the Fermilab Safety Manual.[9]

Design of vessels and piping. The Fermilab Safety Manual requires that cryogenic vessels and piping be designed and fabricated in accordance with Section VIII of the ASME Boiler and Pressure Vessel Code and Section B31 of the ASME Code for Pressure Piping. For example, the liquid vessels of the CDF helium and nitrogen storage dewars are Code stamped. Accepted practice at Fermilab for the vacuum vessels of dewars follows common industrial practice, i.e. a collapse pressure of 0.21 MPa (30 psi). Since the pressure in a cryogenic vessel must not exceed 110% of the pressure rating during relieving, qualitative calculations of the pressure rise in the relief systems were performed. The failure modes for which the relief systems associated with the CDF magnet-refrigerator were analyzed are given in Table 1. The relief devices on the helium system are shown in Fig. 2 with details given in Table 2.

Table 1. Failure Modes Analyzed for CDF Cryogenic Vessels

Failure Mode Vessel:	LIN tank		LHe tank, LIN shielded		Cryostat & Control Dewar		
	Inner	Vacuum	Inner	Vacuum	LHe	LIN	Vacuum
Loss of vacuum							
Gas conduction	Yes	NA	Yes	NA	Yes	Yes	NA
Air condensation	NA	NA	Yes	NA	Yes	NA	NA
Fire or unexpected source of heat	Yes	NA	Yes	NA	Yes	No	NA
Operator error	Yes	NA	Yes	NA	No	No	NA
Rupture of LIN line in vacuum space	NA	No[1]	Yes	Yes	Yes	NA	Yes
Rupture of LHe line in vacuum space	NA	NA	NA	NA	Yes	NA	Yes
Rupture of inner vessel	NA	No[1]	NA	No[2]	NA	NA	Yes
Quench of coil	NA	NA	NA	NA	Yes	NA	Yes
Release of cryopumped air	NA	No[1]	NA	No[2]	NA	NA	Yes

1. Relief area = 4.5 x CGA requirement ("Insulated Tank Truck Specification CGA-341 For Cold Liquefied Gases," Compressed Gas Assoc., New York (1972).
2. Relief area = 6.5 x CGA requirement.

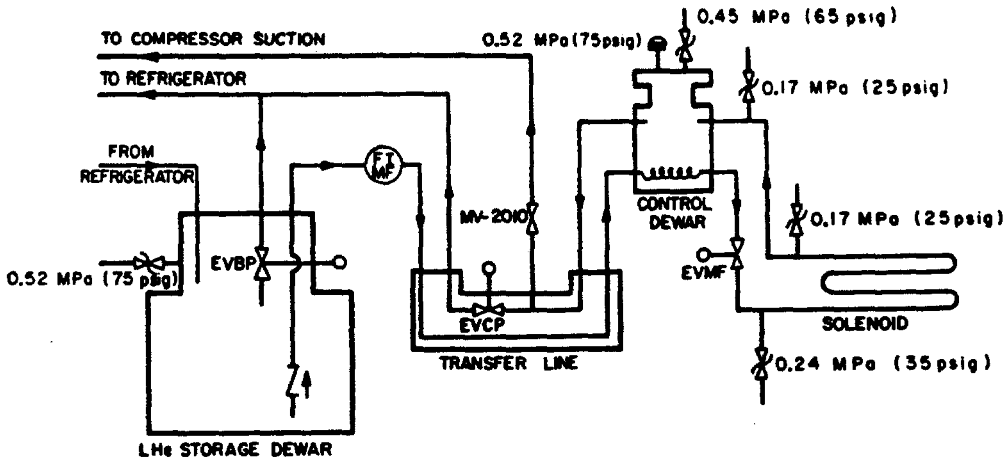

Fig. 2. Helium system flow schematic.

Assembly Hall ventilation and ODH analysis. The ventilation system required to prevent an ODH in an enclosed area may be sized by equating the mass flow rate of inerting fluid into the building to the capacity of the ventilation system to remove it. In the CDF Assembly Hall an ODH associated with liquid nitrogen is prevented through use of a fan with a capacity of 3.8 m^3/s which has an inlet at the lowest level of the hall and an outdoor discharge. The fan is controlled by an oxygen monitor at the low level. The helium ODH is alleviated with roof louvers actuated by an oxygen monitor near the ceiling.

Table 2. Relief Systems for CDF Cryogenic Vessels.

Vessel/Piping	Manufacturer	Type	Setting MPa (psig)	Air Capacity L/s (SCFM)
LIN Tank				
Inner vessel	AGCO[1]	relief valve	0.34 (50)	54 (114.5)
Inner vessel	Fike[2]	burst disk	0.40 (58)	675 (1431)
Vacuum vessel	—	parallel plate	0.002 (0.25)	653 (1384)
LHe Tank				
Inner vessel	AGCO	relief valve	0.52 (75)	345 (731)
Inner vessel	Fike	burst disk	0.66 (95)	464 (984)
Vacuum vessel	—	parallel plate	0.002 (0.25)	156 (330)
Cryostat and Control Dewar				
He vessel & piping	AGCO	relief valve	0.17 (25)	152 (321)
He vessel & piping	AGCO	relief valve	0.17 (25)	152 (321)
He vessel & piping	AGCO	relief valve	0.24 (35)	189 (401)
He vessel & piping	Circle Seal[3]	relief valve	0.45 (65)	56 (119)
He vessel & piping	Fike	burst disk	0.52 (75)	378 (800)
Vacuum vessel	—	parallel plate	0.007 (1)	1109 (2350)

1. Anderson, Greenwood & Co., Bellaire, TX.
2. Fike Metal Products Corp., Blue Springs, MO.
3. Circle Seal Corp., Anaheim, CA.

System Cooldown

Cooldown procedure. The helium circuit for the magnet-refrigerator is shown in Fig. 2. During cooldown, flow from the refrigerator passed through the storage dewar, transfer line and magnet cooling circuit and back through the return side of the transfer line. The electrically operated valve EVCP and the manual valve MV-2010 were used to create an imbalance by returning a portion of the flow directly to compressor suction. The pressure in the storage dewar was maintained at 0.17-0.21 MPa (25-30 psig) by the computer control system, which sensed dewar pressure and regulated EVBP. The control dewar pressure varied with the positions of EVCP and MV-2010, but ranged between 0.04 and 0.08 MPa (6-12 psig).

The temperature of the coil/outer support cylinder was monitored with platinum and carbon resistors mounted on the support cylinder at several locations. The temperatures of the supply and return helium flows were measured with similar resistors in the piping.

Cooldown. Cooldown began on the morning of February 28, 1985, when liquid nitrogen flow was started to the precooling heat exchanger of the refrigerator. A total compressor flow of ~40 g/s was established. The helium flow through the magnet cooling loop was measured by the venturi flowmeter FIMF as ~5 g/s. Control valves on the liquid nitrogen shield and intercept circuits were placed under computer control to regulate at 180 K as measured by platinum resistors. The maximum valve positions were limited to keep the cooling rates low. As cooldown progressed these set temperatures were lowered and the valves allowed to operate over a wider range until full computer control was achieved at the operational set points of 90 K and 80 K for the shield and intercepts, respectively.

The coil reached a temperature of 97 K in 144 hours, at which time the gas expansion engine was started. FIMF indicated a flow of approximately 8 g/s through the magnet at this point. Twenty-four hours later, at a coil temperature of 72 K, the liquid expansion engine was started. The coil resistance, which was continuously monitored during the cooldown, indicated that the coil became superconducting approximately 205 hours into cooldown. The operating temperature was reached 5 hours later. The average cooldown rate was 1.5 K/h. Figure 3 shows the measured coil temperature as a function of time.

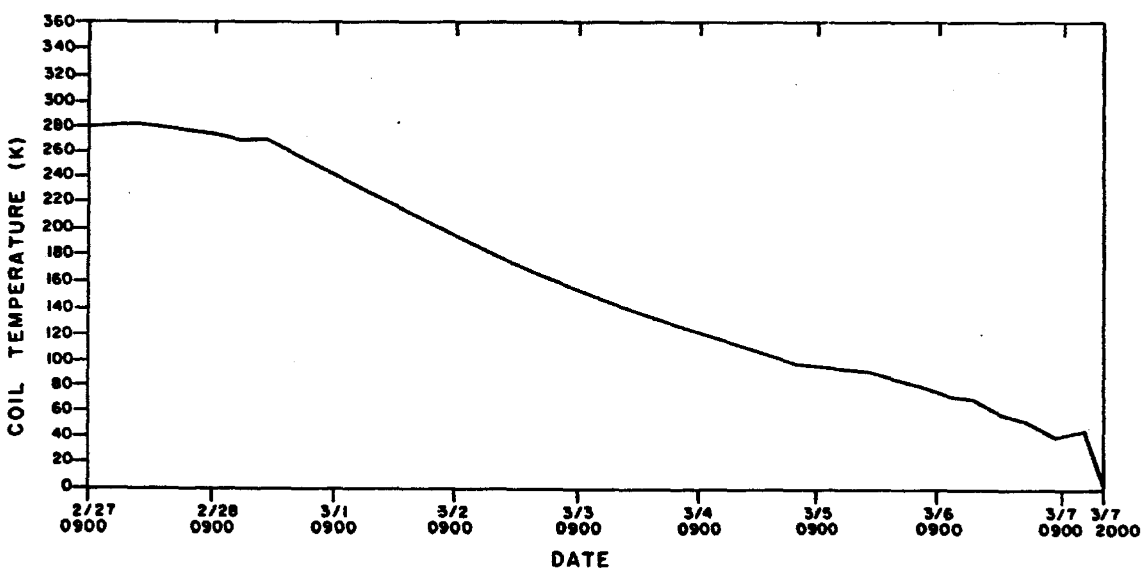

Fig. 3. Cooldown of magnet-refrigerator system.

With the coil cold, MV-2010 was completely closed to send all flow back through the refrigerator. Liquid began to accumulate in the storage dewar, and a liquid flow was established through the coil, filling the control dewar. The storage dewar was then filled to about one-half of its 2000-L capacity, and the computer control loop enabled to maintain this liquid level by regulating liquid expansion engine speed. The set point of the storage dewar pressure control loop was set to 0.04 MPa (6 psig). The operation of EVCP, which regulated the control dewar pressure, was placed under computer control at a set point of 0.028 MPa (4 psig). These pressures provided the differential for driving the magnet flow. The flow was also regulated by a control loop which monitored FIMF and adjusted EVMF accordingly. This flow was set at approximately 10 g/s initially. The system was then stabilized under full computer control to await electrical testing.

Adjustment of supports. Special consideration was given during cooldown to the 24 radial support rods which suspend the coil within the vacuum shell. This is a tension-only support system which relies on the thermal contraction of the coil and support rods during cooldown to provide a preload force. A titanium alloy (6Al-4V) was used for the spherical bearing housings on the rod ends and, as this alloy exhibits very low ductility and fracture toughness at cryogenic temperatures, it was necessary to monitor the rod stress closely and adjust the tension individually if needed. To make this possible, the radial support system had been designed so that the room temperature end of each rod was attached to a tensioning device which penetrated the vacuum shell end rings through a double o-ring seal. This device contained a threaded shaft and nut. Adjusting this nut against the vacuum shell end ring applied tension to the support rod. Calibrated strain gauge washers installed under the nuts provided an accurate, computer monitored indication of rod tension.

The rods were designed for a maximum force of 7.9 Mg, corresponding to a total radial decentering force of 25.5 Mg. Because certain of the rods bear the cold mass of ~5.6 Mg, the preload force varied from 4.8 Mg to 5.8 Mg. The tensions were adjusted during cooldown to maintain these desired values ±1 Mg.

Magnet Test Procedures and Basic Results

A series of tests at low current (100 to 1000 A) were performed to verify proper operation of the interlock and quench protection systems and to calibrate and debug the instrumentation. When this was complete the coil was energized to succeedingly higher currents in 5-MJ steps as shown in Table 3.

Table 3. Summary of Magnet Tests

Current (kA)	Stored Energy (MJ)	Tests Performed
1.0	1.2	FD, SD*
1.5	2.7	FD, SD
2.0	4.8	FD
2.9	10.1	FD, SD
3.5	14.7	H†, FD
4.1	20.2	FD, H
4.6	25.4	FD
5.0	30.0	FD, SD

* FD = Fast discharge (dump),
SD = Slow discharge (dump)
† H = Heater tests

The coil was typically charged with the power supply voltage regulating to give a linear ramp ~250 A/min over most of the charge. When the current in the coil was close to the desired value the power supply is switched to a current regulating mode which monitored a current transductor located on the coil bus. After the coil reached the current for each step, the magnetic field in the bore, measured with a Hall probe, the electromagnetic forces on the coil supports and the deflections of the yoke and end plug structures were recorded. Then a fast dump was manually initiated. The coil voltages, temperatures and helium circuit pressures resulting from the discharge were studied before proceeding to the next higher step in current. For some current values a slow dump was also manually initiated. For currents less than 2 kA it was deduced that the coil remain superconducting throughout the fast discharge since the observed time constant (30.9 s) was in good agreement with that expected for a superconducting discharge, $\tau = L/R_F = 2.4$ H/0.076 $\Omega = 32$ s.

Above ~3 kA, eddy currents flowing in the outer support cylinder caused the coil to quench during a fast discharge. In this case the coil resistance, in series with R_F, shortens the effective time constant of the discharge as shown in Table 4, which also gives the maximum temperature reached in the center of the outer support cylinder after each fast discharge. The forces on the supports and deflections of the end wall and plug at 5 kA are given in Table 5.

Measured Stability - Heater Tests

To study coil stability and quench propagation two heaters are imbedded in holds in the outer support cylinder. One is located at the center of the coil while the other is near one end. Each heater consists of a small spool of resistance ribbon mounted so that it is in good thermal contact with the FRP layer on the outer diameter of the coil yet thermally isolated from the support cylinder. The heater simulates a release of mechanical energy at the support cylinder/FRP boundary. We were unable to quench the coil with a 24-s, 2.7-kJ heater pulse at currents of 3.5 and 4.1 kA. The peak temperature of the outer support cylinder approximately 100 mm from the heater was 8.5 K. The thermal time constant for the system to recover from such a temperature excursion was about one minute. An estimate of the energy balance between the ohmic heating of a section of normal conductor and the conduction cooling by the outer support cylinder gives an equilibrium temperature of ~10 K for this magnet current. It is possible that a small section of conductor beneath the heater does quench, but it recovers by conduction cooling if the magnet current

Table 4. Fast Discharge Characteristics

Current (kA)	Effective time constant (s)	Maximum temperature (K)
1.0	30.9	7
1.5	30.9	8
2.0	30.9	10
2.9	29.4	21
3.5	28.3	28
4.1	27.0	34
4.5	26.0	37
5.0	19.5	45

Table 5. 5 kA Deflections and Forces

End Wall Deflection	2.5 mm
End Plug Deflection	5.0 mm
Axial Decentering Force	27 Mg
Radial Decentering Force	-1 Mg

is sufficiently low. Heater pulses of greater energy were not applied due to concern about damaging the FRP insulation. Heater tests were not attempted at higher excitations.

Quench Behavior

On four occassions during magnet testing and the two months of coil operation for magnetic field mapping and drift chamber testing, the coil quenched due to a rapid change of field and/or by inadequate flow of helium. We believe that we understand the observed quench behavior.

Quench #1 - 4.5 kA quench while charging. This quench occurred when rapidly charging the magnet (390 A/min) with a helium flow rate of 13 g/s. The quench began in the end of the coil that has both axial and radial supports. Since this end has the higher conduction heat load and since the helium-temperature support intercepts lie at the end of the cooling circuit it is believed that the liquid fraction was sufficiently low that the intercepts were ineffective, causing local hot spots at the support attachments. A plot of the observed voltages across each of the coil quadrants is shown in Fig. 4 for the few seconds before the time (t = 0) that the quench detection circuit activated the dump switches. From t = -0.75 s to t = 0, the voltage VC1 = V3 - V4 increased by 0.34 V indicating a normal region growing in this quadrant. Similarly since the power supply voltage was maintained at a constant value, VC2 = V4 - V5, VC3 = V5 - V6

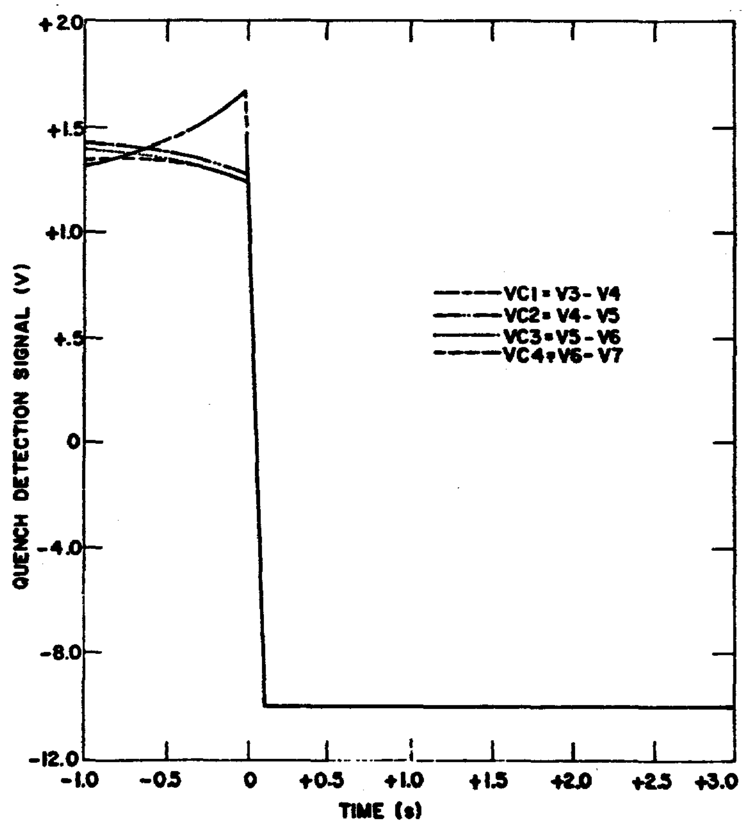

Fig. 4. Voltages observed across coil quadrants showing quench initiation.

and VC4 = V6 - V7 all show a corresponding drop of 0.11 V. Our instrumentation does not allow us to determine whether the dominant mode of quench propagation was axial from turn to turn or circumferentially along the conductor. (In the testing of a 1 m ϕ R&D coil[10] both modes were present.) However, if we assume that the propagation is purely circumferential we can estimate an effective circumferential quench velocity. In the 0.75 s before t = 0 the coil absorbs 15.2×10^6 A^2-s (15.2 MIITS). From the plot of maximum conductor temperature as a function of absorbed energy[11] we concluded that the hot spot temperature at t = 0 must have been ~25 K. The measured resistance of the coil per unit length of conductor is 0.17 μΩ/m at 10 K and ~0.3 μΩ/m at 25 K. If we use a value of 0.23 μΩ/m as the average conductor resistance in the 10-25 K region then a length of normal conductor of 324 m is consistent with ΔVC1, giving an average circumferential quench velocity of 430 m/s.

The effective time constant for the quench was 26 s which is in good agreement with that obtained by fast dumping the coil. The 263 MIITS deposited into the conductor during the discharge implied a hot spot temperature of ~67 K.

After this quench the helium flow rate was increased to 20 g/s and no further quenches were observed during charging.

Quench #2 - 4.6 kA quench during discharge. A quench also occurred following the manual initiation of a slow dump with the coil operating at 5 kA with a 20 g/s flow rate. Switch SW1 was opened manually causing the coil to discharge through R_S and R_B. The initial discharge rate was 650 A/min; the rate decayed exponentially with a time constant of 460 s. Eddy current heating in the support cylinder caused a pressure rise in the control dewar which substantially reduced the helium flow rate through the cooling circuit. Although the automatic control loop attempted to correct this condition by opening EVMF the response time was too slow and the coil quenched at 4.6 kA. The quench behavior was essentially identical to that observed in quench #1. Slow dumps initiated at 4.6 kA did not produce quenches. For the balance of this run the coil was discharged by turning down the current set point, with the magnet current decaying through the power supply and free wheeling diode. When the magnet current reached ~4 kA a slow dump was initiated. The long term solution is to reduce the value of the slow dump resistor to enable slow dumping from 5 kA without quenches.

Quenches #3 & #4. Both of these quenches occurred due to control system errors during 5 kA steady state operation. They were caused when microprocessor reboots commanded EVMF to close. When this happened the helium flow interlock started a slow dump. However, because of eddy current heating and no helium flow, the coil quenched at 4.4 kA and the quench protection system initiated a fast dump.

Quench Recovery

All the quenches behaved similarly: The relief valves on the helium circuit would typically open for 10-15 seconds expelling the 60-L cooling tube inventory and the control dewar pressure would reach ~0.19 MPa (27 psig). The recovery time to operating conditions was about 2 hours and was routinely performed by cryotechnicians.

Preliminary Magnetic Field Mapping

The magnetic field inside the solenoid was measured using three orthogonal search coils. The results of this measurement are described in detail elsewhere[7]; the axial field uniformity appears quite satisfactory.

CONCLUSION

The successful test and first operational run of the CDF refrigerator-magnet showed the system to be both safe and reliable. Modifications are presently underway to permit slow dumping from full excitation without a quench and to improve the response of the refrigerator to quenches. The counters for the detector are now being installed around the magnet cryostat. The detector will run for preliminary $\bar{p}p$ studies in the fall of 1985. For this run the magnet cannot be energized because both the Tevatron and conventional accelerator beam pipes pass through the detector. The collider experimental program will commence in mid-1986 with all detectors and the magnet operational.

ACKNOWLEDGMENTS

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