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FERMILAB-Pub-98/047-E
D0

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February 1998

Submitted to *Advances in Cryogenic Engineering* and
Published Proceedings of the *Cryogenic Engineering Conference*, Albuquerque, New Mexico, July 12-16, 1993

Operated by Universities Research Association Inc. under Contract No. DE-AC02-76CH03000 with the United States Department of Energy

DESIGN OF THE 2 TESLA SUPERCONDUCTING SOLENOID FOR THE FERMILAB DØ DETECTOR UPGRADE*

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ABSTRACT

A thin superconducting solenoid has been designed for an upgrade to the Fermilab DØ detector, one of two major hadron collider detectors at Fermilab. The original design of the DØ detector did not incorporate a central magnetic field which necessitates a retrofit within the parameters of the existing tracking volume of the detector. The two layer solenoid coil is indirectly cooled and provides a 2 T magnetic field for a central tracking system. To minimize end effects in this no iron configuration, the conductor width is varied thereby increasing current density at the ends and improving field uniformity. This paper summarizes the results of the conceptual design study for the DØ superconducting solenoid.

INTRODUCTION

The DØ detector[1] was officially proposed and approved in 1983 and completed in the spring of 1992. Its prime physics focus is the study of high mass states and large $p_\perp$ phenomena, including a search for the top quark, precision studies of the W and Z bosons, perturbative QCD, b-quark physics, and searches for new phenomena beyond the Standard Model. The detector utilizes a muon detector system, a uranium liquid argon calorimeter system, and a central tracking system for the analysis of particle final states from proton-antiproton collisions at the Fermilab Tevatron. The operation of the liquid argon system in particular has been completely reliable over the year-long physics run[2] .

*Work supported by the U.S. Department Of Energy under contract No. DE-AC02-76CH03000.

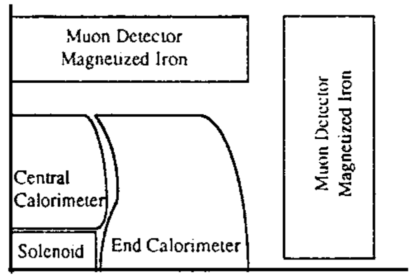

Fig. 1. Quarter section of the calorimeters, solenoid, and Muon detector iron. The calorimeters and solenoid are cylindrical about the horizontal section line.

The luminosity or collision rate of the Tevatron is scheduled to increase substantially in the future, and an upgrade project for the DØ detector has been proposed to allow for the exploration of new physics. This upgrade involves a magnetic tracking system[3] to be installed in the existing aperture of the central calorimeter which requires a 2 T solenoid.

Figure 1 shows the general layout of the detector. An end calorimeter is located on each end of the central calorimeter. These calorimeters are enclosed within a magnetized-iron muon detector. Given this geometry, access to the solenoid for repairs will require a substantial amount of time and effort thus causing an unacceptable delay in the physics program. Therefore, the solenoid system must operate reliably.

The size of the cryostat is limited by the central calorimeter and the required volume of the tracking systems that will be installed in the bore of the solenoid. The support cylinder thickness is determined by the pressure exerted by the coil when at full field. The thickness of the coil is based on two conditions: 1) the number of turns needed for the given current and 2) the amount of aluminum stabilizer required to limit the temperature of the coil to less than 90K if all of the stored energy were absorbed by the stabilizer. This leaves approximately 108 mm radially in which to place the vacuum jackets, cooling tubes, cold mass supports, radiation shields, and multilayer insulation (MLI) (Figure 2).

To minimize the shell thickness, the cold mass supports are attached to the bulkhead and the loads transferred directly to the central calorimeter. To prevent interference between the axial and radial supports, the radial supports are mounted on the end rings of the support cylinder.

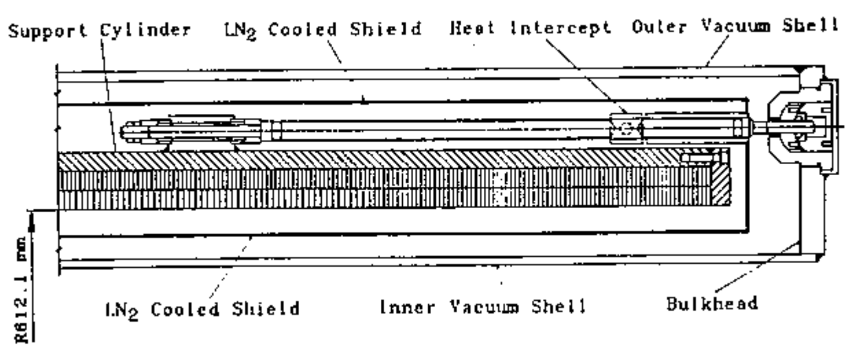

Fig. 2. Cross section at the end of the cryostat showing axial support.

Table 1. Radiation (X_o) and absorption (λ_o) lengths for normal incident particles at the center of the solenoid

Component	Material	Thickness		
		mm	X_o	λ_o
Inner Vacuum Shell	Al	6.4	0.07	0.017
Inner Shield	Al	1.6	0.02	0.004
Conductor	Al	27.2	0.31	0.073
	Copper + NbTi	2.8	0.18	0.019
Coil Insulation	G-10/Kapton	4.4	0.02	0.01
Outer Support Cylinder	Al	15.0	0.17	0.04
Outer Shield	Al	1.6	0.02	0.004
Outer Vacuum Shell	Al	7.9	0.09	0.021
Totals			0.88	0.188

Since charged particles must pass through the superconducting coil and cryostat before entering the calorimeter, it is desirable to minimize the thickness of material in terms of radiation and absorption lengths. Table 1 lists the radiation and absorption lengths for this design. Additional parameters for the coil and cryostat are given in Table 2.

COIL AND SUPPORT CYLINDER DESIGN

The new central tracker for the detector upgrade requires a central field of 2 T for the desired momentum and energy resolution of charged particles. To reach the require field, two layers of conductor operating at a current of 4825 A are used. Because of the detector geometry, there is no iron yoke and the field will drop off rapidly at the end of the solenoid. To improve the field uniformity inside the tracker, the current density is increased toward the ends of the coil by using a narrower conductor. The transition locations are staggered in the two layers with the inner one closer to the end of the coil. Figure 3 shows the calculated field.

Table 2. Cryostat, coil, and conductor parameters

GENERAL		CONDUCTOR	
Cryostat Inner Diameter	1134 mm	Superconductor	Cu/NbTi
Cryostat Outer Diameter	1450 mm	Stabilizer	Al(99.996%) RRR=300
Cryostat Length	2750 mm	Dimensions	
Design Central Field	2 T	TI 5.125 X 15 mm	TII 3.82 X 15 mm
Peak Field at Conductor	2.2 T	Al:Cu:NbTi ratios	
Total Mass of Coil/Cryostat	2550 kg	T1: 19.3:1.3:10	TII 13.8:1.3:1.0
COIL			
Inner Diameter	1224.2 mm	Operating Current	4825 A
OD of Support Cylinder	1319.6 mm	Inductance	0.48 H
Number of Turns	1010	Stored Energy	5.6 MJ

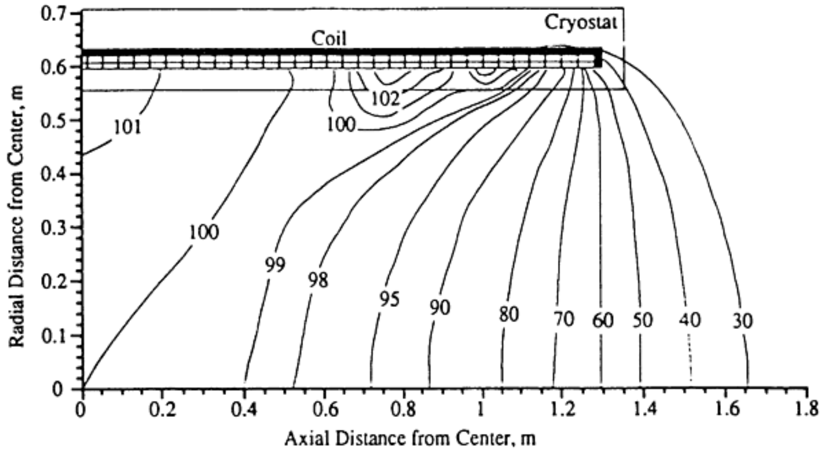

Fig. 3. Axial magnetic field as a percentage of axial field at center (2T). The two regions of higher field near the end of the coil are due to the changes in the current density.

The conductor is chosen such that the maximum field operating point is 55% along the load line to the critical current at 5.0 K. The conductor consists of a 16 strand Rutherford superconducting cable in high purity aluminum stabilizer (Figure 4).

The radial forces on the coil are supported with a 15 mm outer support cylinder, of 5083 aluminum alloy. This support cylinder also induces quench back heating.

Heat is absorbed by 4.6 K pressure fed two-phase helium flowing through a 15 mm ID aluminum tube welded to the outer support cylinder. The single serpentine path is routed longitudinally on the outer surface of the support cylinder with 18 straight sections and has a total length of 60.4 m. The cooling tubes are laid out such that they pass close to the support brackets. The steady-state heat load includes thermal radiation through the insulation system and conduction through the cold mass supports. Additional heat is generated by joule and eddy current heating in the support cylinder and coil while charging, discharging, or quenching the coil. To reduce the heat load on the coil, both the coil and the radiation shields are coated with aluminum tape (3M no. 425)[4] . The calculated heat loads are summarized in Table 3.

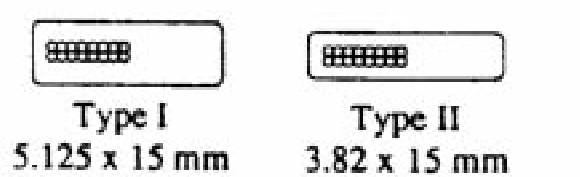

Fig. 4. Cross section of the two sizes of conductor used for the solenoid.

Table 3. Summary of thermal heat loads

	300 to 85K W	85 to 4.7 K W
Cryostat		
Radiation	130	9.3
Conduction		
Shield Standoffs	12	–
Six axial supports	6.6	0.5
Twelve radial supports	16.7	2.7
Eddy Current in support cylinder (charging)	–	20 W
Chimney	108	1.5
Control Dewar	8.2	3.9 + 29 l/hr

The radiation load includes a contingency based on experience. The charging rate used for the transient calculation is 12 A/s.

The maximum temperature in the coil was studied using 3-D finite element models to calculate the temperature profiles near the support brackets. To lower the coil temperature near the radial supports, most of the heat load from the radial supports is intercepted by connecting high purity aluminum straps to the helium cooling tube. To ensure good thermal contact between the support cylinder and the end rings, an indium ring is inserted before bolting on the end ring. The analyses indicate that the maximum temperature in the coil occurs near the axial support blocks (Figure 5) and is 4.9 K for steady current and 5.1 K while charging at 12 A/s. The maximum steady state coil temperature away from the supports was determined to be within 0.1 K of the cooling tube wall temperature of 4.7 K.

CRYOSTAT DESIGN

The support system is designed to support the gravitational, magnetic, and thermal contraction loads associated with the cold mass. The design loading requirements are listed in Table 4. The support system consists of axial members (axial supports) to provide longitudinal stiffness and nearly tangential members (radial supports) to provide radial stiffness. The members connect the outer support cylinder to the flat annular bulkheads of the vacuum vessel. Figure 6 shows the general layout of the supports. Six axial tension-compression

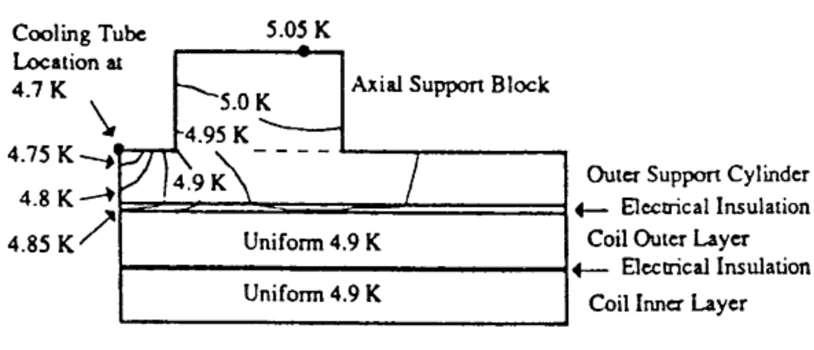

Fig. 5. Temperature profile near an axial support during steady current.

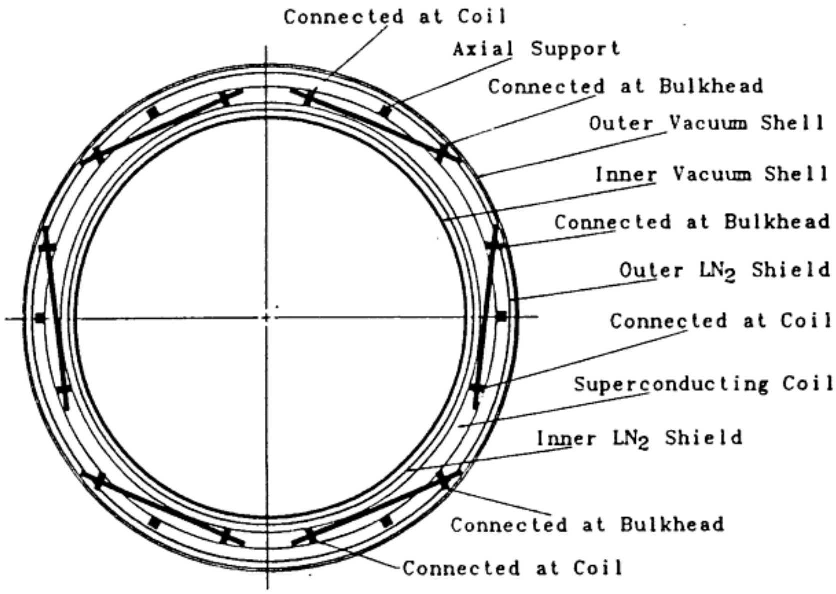

Fig. 6. Chimney end of the solenoid showing placement of axial and radial supports.

supports are located on the chimney end of the cryostat only. Six radial tension supports are located on each end. Both types of members are fabricated of Inconel 718 and have a minimum design safety factor of 4 on the ultimate strength at 300 K. The axial supports are also designed for a buckling safety factor of 4 for the operating loads. Shipping stops will be installed to prevent the axial supports from going into compression during transportation.

All supports members have thermal intercepts which operate near 87 K and the radial supports have a thermal intercept below 10 K. Axial and radial contraction of the coil support cylinder is accommodated by spherical bearings on both ends of each support member.

Table 4. Loading constraints for the support system

Condition	Radial Loading kN	Axial Loading kN
Shipping	57.2	85.8
Coil at 4.6 K	28.6	14.3

The heat load from the radiation shields and support intercepts is absorbed by pressure fed two-phase nitrogen flowing through tubes welded to the radiation shields and thermal intercepts. There are two nitrogen cooling circuits: One cools the shields and the other the intercepts. Eighteen layers of MLI at a density of 10 layers/cm is placed between the shield and vacuum jacket. The maximum shield temperature is calculated to be 84 K. The shield is broken electrically in the circumferential direction to eliminate eddy currents induced by charging/discharging of the coil. The nitrogen heat loads are listed in Table 3.

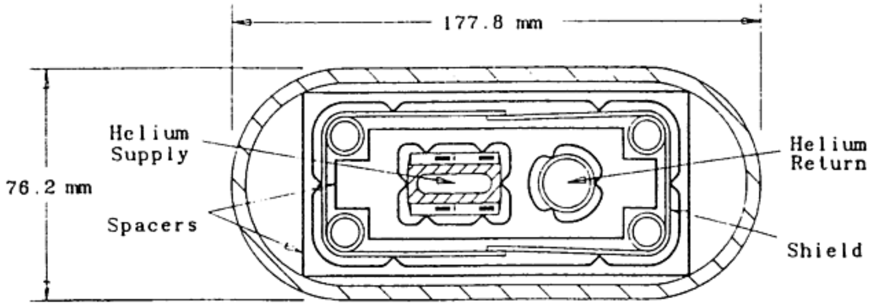

Fig. 7. Chimney cross section in gap between the central calorimeter and the end calorimeter.

CHIMNEY AND CONTROL DEWAR DESIGN

One of the more challenging aspects of the project is the connection of the magnet to the utilities. The chimney supplying cryogens and current to the solenoid must pass through the 80 mm gap between the central calorimeter and an end calorimeter. A cross section of the chimney in this area is shown in Figure 7. Once outside the gap, a conventional circular chimney is utilized with a vacuum jacket fabricated from 219 mm OD x 3.76 mm pipe (8 inch schedule 10s). The overall length of the chimney from the solenoid to the control dewar is approximately 14 m. The conductors, insulated with B-stage Kapton tape, are cooled in the chimney by attaching them to the liquid helium supply tubing. The nitrogen supply and return tubing are used to cool the shield.

The chimney is also used for two other functions: 1) to evacuate the cryostat vacuum and 2) to provide a path for relieving the cryostat in case a cryogenic line ruptures. The use of MLI would significantly reduce the vacuum pumping speed and the relieving capacity. Therefore, MLI is not used. Instead, all surfaces are covered with aluminum tape to provide low emissivity surfaces.

The control dewar is the interface between the building piping and the cryostat. It contains a LHe subcooler for the supply helium, a supply LHe J-T valve, two 6 kA vapor-cooled current leads, and instrumentation and is mounted on the outside of the detector platform. The building piping is connected to the control dewar via removable u-tubes. The high current bus connects to vapor cooled leads extending out the top of the control dewar. The solenoid can be operated in either the assembly or collision halls.

ELECTRICAL CONSIDERATIONS

The coil is powered by a 5 kA, 30 V DC power supply and is protected by a 0.048 Ω resistor in the event that a quench is detected (Figure 8). The current is regulated using an external reference located downstream of the ripple filter and the dump resistor. Quench detection is provided by a programmable logic controller (PLC). When a quench is detected, the dump switch opens and the power supply is turned off. The power supply contains freewheeling diodes that will maintain the circuit when the power is off. A remote controlled motorized reversing switch is provided to change the polarity of the solenoid which may occur many times a week. In the event the reversing switch opens while the solenoid is powered, a shunt diode system (crowbar) is provided that will engage when the voltage

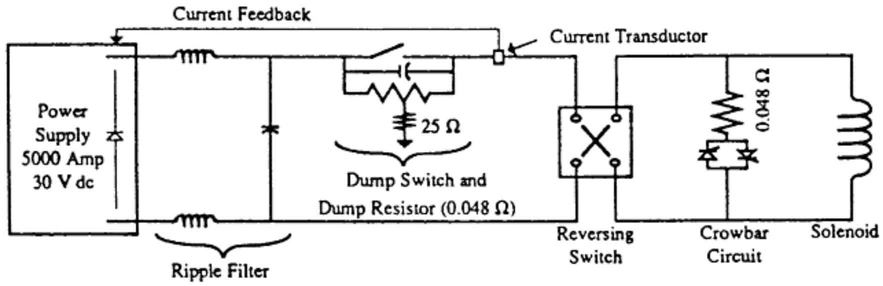

Fig. 8. Schematic of DC circuit. Circuit resistance with the dump switch open is 0.05 Ω.

across the crowbar reaches 300 V. The crowbar is completely self contained and does not require auxiliary power. An uninterruptible power supply is provided to maintain critical control electronics during a power outage and a hard-wired quench detection chassis, set for thresholds slightly higher than those of the PLC, ensures coil safety in the event of failure of the PLC.

REFRIGERATION SYSTEM

The solenoid will be cooled by a 600 W, 58 g/s refrigerator that is shared with another system[5] in the detector (Figure 9). The refrigerator consists of a two-stage screw compression system, counterflow shell and tube heat exchanger, and dry and wet reciprocating expansion engines. To provide flexibility in total system operation, the cool down will be performed in two stages. The first stage cools the solenoid down to 90 K with a separate LN_2 to helium heat exchanger. In this stage, the cool down is limited to 2 K/h and a maximum temperature difference in the cold mass of 100 K to limit thermal stresses. The second stage cools the solenoid from 90 K to 4.7 K with liquid helium provided by the LHe storage dewar. Since the majority of the thermal contraction has occurred by 90 K, the second stage cool down does not have temperature constraints. Cooldown from 300 K to 4.7 K is estimated to take 4.6 days. The estimated temperature of the coil after a quench is 42 K. Recovery uses liquid helium from the LHe storage dewar and will take about 35 minutes. A summary of some of the refrigeration and cool down parameters is listed in Table 5.

Table 5. Summary of helium refrigeration parameters

Liquid Temperature on Support Cylinder	4.6 K
Coil Cooling Mode	Indirect
Steady State Heat Load on Cold Mass	12.5 W
Minimum Required Helium Flow for Solenoid	5 g/s
Length of Cooling Loop on Support Cylinder	60.4 m
Inner Diameter of Cooling Tube	15 mm
Mass of Cold Mass	1460 kg
Maximum Cool Down Rate from 300 to 90 K	2 K/h
Cool Down Time from 300 K	4.6 d
Estimated Temperature after a Quench	42 K
Estimated Recovery Time after a Quench	35 min

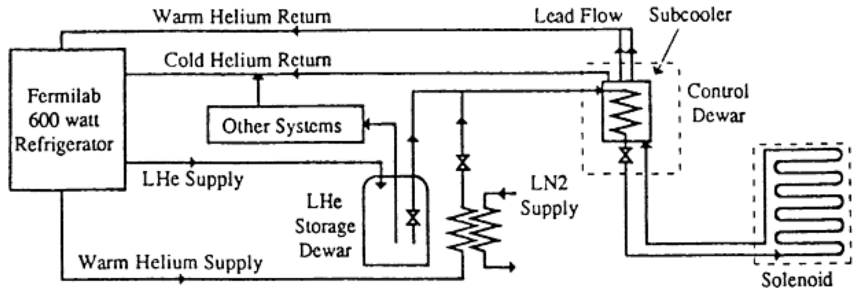

Fig. 9. Helium flow schematic for the superconducting solenoid.

SUMMARY

The upgrade for the DØ detector includes a 2 T iron-free superconducting solenoid. It must fit inside the bore of the central calorimeter and be thin in terms of radiation and absorption lengths. The chimney must pass through the 80 mm gap between the central and end calorimeters. The magnet system must be highly reliable and have a short quench recovery time. The results of the conceptual design study show that such a solenoid is feasible.

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