ANL/ET/CP-91949

CONF-970758--

HIGH-TEMPERATURE SUPERCONDUCTOR COIL SYSTEM FOR A PARTICLE DETECTOR ANALYZING MAGNET*

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*Work supported by the U.S. Department of Energy, Energy Efficiency and Renewable Energy, as part of a program to develop electric power technology, under Contract W-31-109-Eng-38.

Submitted to CEC/ICMC Conference, July 28-August 1, 1997, Portland, Oregon.

DISCLAIMER

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ABSTRACT

The high energy physics experiment known as the Main Injector Neutrino Oscillation Search (MINOS), which is intended for the study of neutrinos, will incorporate a large particle detector system. The detector employs an analyzing magnetic field generated by magnetizing an array of steel plates, called absorbers, with a current-carrying coil. We have evaluated the feasibility of a high-temperature superconductor coil system that provides a 25,000 A-turn magnetizing force. An equivalent conventional coil system (i.e., water-cooled copper) was also designed for comparison.

INTRODUCTION

The feasibility of using high-temperature superconductor (HTS) coils for high energy physics (HEP) detector magnets has been evaluated. The detector magnet type is that planned for the Main Injector Neutrino Oscillation Search (MINOS) experiment.[1]

The MINOS experiment is designed to determine if one kind of neutrino (electron, mu, or tau) can change into another, as it can if neutrinos have mass. This is not only a fundamental question in its own right, but bears directly on two major unresolved issues of contemporary physics and cosmology, the missing matter problem and the solar neutrino deficit. The MINOS collaboration has more than 100 participants from more than 20 institutions around the world. Magnet technology that would improve the MINOS experiment, or similar experiments, is clearly relevant to HEP.

Three benefits of using an HTS coil are foreseen. First, the HTS option allows operation at higher currents and thus provides insurance against two major uncertainties in the magnet design, i.e., the possible inability to achieve the design B-H curve of the magnet iron, and the possibility that the gaps within each lamination, or the field reduction due to the gaps, may be larger than anticipated. (Gaps in the laminations are unavoidable because of assembly constraints.)

Second, because the coil can operate at higher currents, the magnetic fields in the iron can be higher and more uniform. More of the detector iron will be at fields above 1 T. (Because the inner portion of the steel is already saturated, the field there will not increase much.)

Third, the use of a superconducting coil leads to savings in energy and operating costs. The location of an experiment in a mine deep underground (760 m [2500 ft] below the surface), as in the MINOS experiment, may increase the importance of these savings.

The application of HTS coils to HEP detectors will benefit from innovation in several technical areas. Among these are HTS conductors that perform effectively and reliably at the applied detector field; low-loss, reliable electrical junctions to and between HTS conductors; low-loss, reliable, field-assemblable cryostats; and effective, efficient, and reliable cryogenic refrigeration systems.

THE MINOS DETECTOR

Figure 1 is an overview of the far detector. The total length of the detector is 36 m and total mass is 10,000 metric tons. The iron will be magnetized toroidally by running a coil through a hole in the center of the absorber plates to produce a reasonably uniform field. The magnetization allows measurement of high-energy muon momenta. The detector will have 600 octagonal cross-section steel absorbers.

The active detector elements consist of planes of streamer tubes. The total area of active detector planes to be instrumented is 32,000 m^2. The total number of instrumentation channels to be read out is 480,000.

The steel absorbers for the far detector consist of octagonal plates that are 4 cm thick and 8 m across from flat to flat on the sides of the octagon. The gap between plates is nominally 2 cm. Each steel plate has a total mass of 16.8 metric tons. The steel plates will be fabricated from AISI 1010 or equivalent steel; such steel is relatively inexpensive and provides good magnetic permeability.

The steel portion of the detector will have a central hole through which a current-carrying coil runs in order to magnetize the steel plates toroidally. Figure 2 shows the strength of the magnetic field as a function of position within a portion of one steel plate. For example, with 10^4 ampere-turns running through the coil, the average field in the steel is 1.5 T and the field near the center is $\approx$2.0 T; average field 50 cm from the edge of the detector is $\approx$1.1 T. The field changes relatively smoothly and slowly across the face of the detector.

The magnet coil will be installed in three separate sections along the length of the detector, each section serving 200 plates of steel. Figure 3 shows conceptually how the coil will run around the ends of the detector segments. Sufficient gaps will be allowed between the steel plates at these locations to allow access for servicing the coil if necessary. Installation of the coil in sections will allow the first sections of the detector to begin normal data acquisition while the remainder of the detector is being completed.

The coil and iron will be assembled underground.

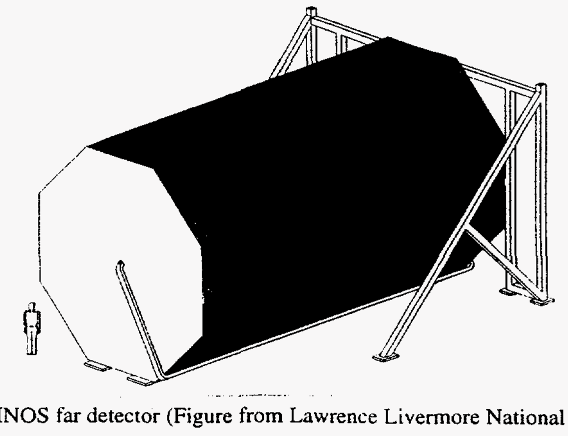

Figure 1. Overview of MINOS far detector (Figure from Lawrence Livermore National Laboratory, used by permission).

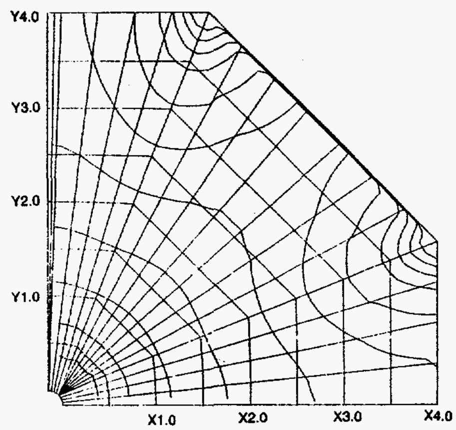

Figure 2. Magnetic field contour map of octagonal plates with 2.5 10^4 ampere-turns. Innermost field contour is 1.8 T, and outermost is 0.8 T (Figure from Lawrence Livermore National Laboratory, used by permission).

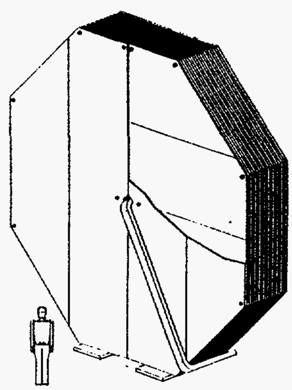

Figure 3. Magnet coil installation on the steel absorber plates will be in three separate segments along the detector.

COIL ASSEMBLY SPECIFICATION

Geometry

The general layout of the coil is shown in Figure 4. Installation constraints include maximum cryostat OD = 0.30 m (12 in.) (outermost cryostat wall/flange), and maximum cryostat extension beyond detector end plates = 0.91 m (36 in.).

Cryogenics

The working fluid is liquid nitrogen, and the coil will operate at 66 K +2/-0 K in single-phase fluid.

Electrical

The magnetizing current is 25 kA-turns (DC). The power supply ripple ≤ 1%. A low ramp rate is employed during magnet charging.

Magnetic

The coil will operate in an applied field generated by the magnetized steel plates. The applied field at the coil, as subdivided for magnetic field analysis, shown in Figure 5, assumed to be 10 × 10 cm square, is given by Table 1. Maximum Lorentz force on the coil is 670 N/m (≈4 lb/in.), occurring at the bends between the central and radial sections. The force is normal to the coil and is in the plane of the coil.

Assembly/Installation

The three detector modules will be built sequentially and will operate independently of each other. Thus, there will be three separate coil assemblies, each with its own power supply, cryogenic system, and controls.

Because the coil will be assembled underground, components must fit within the mine shaft elevator, i.e., 1.2 m × 1.8 m (47 in. × 71 in.) cross-section; 8 m (315 in.) length; and 5442 kg (12,000 lb) maximum load.

HTS COIL/SYSTEM

Design Assumptions

Conductor. The basic conductor element is HTS tape, grouped in either monolithic or transmission-line format. Operation is in the detector applied field.

Coil. The total number of coil turns is determined by the cryogenic load control, including current lead heat gain and joint ohmic heating, as well as assembly considerations. Joints are used at only one location, on the perimeter.

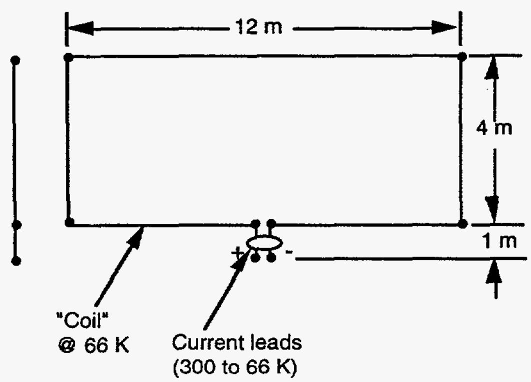

Figure 4. Coil assembly geometry.

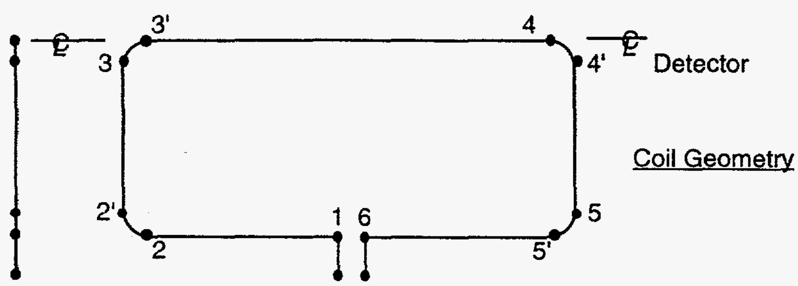

Figure 5. Coil subdivisions for magnetic field analysis.

Table 1. Applied field (in gauss) at conductor for NI = 25 kA-turns.

Coil Section	Along Coil	Normal to Coil in Coil Plane	Normal to Coil Normal to Coil Plane	Magnitude
Return (1-2) & (5-6)	0.1	223	413	413
Radial (2-3) & (4-5)	3	670	448	747
Central (3-4)	108	770	710	850
Outer Arc (5-5')	20	175	618	618
Inner Arc (4-4')	18	662	825	852

Cryostat. Transmission line geometry is used, together with a single junction/current lead box.

Cryogenics. The working fluid is liquid nitrogen at an operating temperature of 66 K +2/-0 K. The coil will operate in single-phase fluid.

HTS Coil

The coil consists of multistrand BSCCO-2223 multifilamentary cable. The operating current can be selected by grouping the individual cables together for a one-turn coil or grouping into several bundles for a multiple-turn coil. The coil will have only one joint, at the junction/current lead box.

To meet the 25 kA turn requirement for the specified conditions (assuming a 50% packing factor over the whole conductor cross section), the conductor must have an operating current density of at least 500 A/cm^2. The standard BSCCO-2223 for the given conditions of ≈66 K with a peak radial field of ≈0.85 T and peak axial field of 0.67 T can meet and exceed this requirement.

The forces on the cable are modest and occur only at the bends between the central and radial sections.

The conductor shown in Figure 6 comprises an annealed, perforated copper channel with the HTS conductor laid in lengthwise and soldered into one monolithic cable. Each coil consists of ≈250 cables packed into the total available coil cross section (≈10 × 10 cm). The annealed copper channels will facilitate handling and bending of the cable.

Because the conductor runs in DC mode, there is no need to helically wind the HTS conductor with pitch. The added benefits here are that the properties of the conductor can be maintained by avoiding a cabling operation and that less tape (length) is required.

If the piece lengths are limited to ≈40 m, each coil turn can be wound and delivered on a 1-m-diameter spool.

Each of the 250 cables will support the requisite 100 A plus a 10% margin between this operating current and the cable critical current.

Installation will not be a significant problem. As long as each turn can be assembled in the cryostat on site without making joints or having to bend the conductor around a radius of <0.5 m, the HTS conductor properties will be maintained.

Experiments[2] indicate that silver-sheathed HTS composite conductors are not prone to quench as low-temperature superconductors do, but rather exhibit current-sharing over a wide range of temperature and current. Consequently, for a conductor driven by a constant-current power supply, a local temperature perturbation or other triggering event would most likely lead to a detectable increase in power supply voltage. If the perturbation then disappeared, the voltage would decrease with no consequences. If the voltage continued to rise, the power supply could be programmed to shut down in an orderly manner, with no additional forces placed on the conductor. In a power failure at the site, the current in the conductor would decrease rapidly, but because there are no nearby current paths for inductive current transfer, there would be no additional forces on the conductor.

Cryostat

The cryostat cross section is shown in Figures 7 and 8. The stainless steel inner line will contain the conductors surrounded by single-phase, subcooled liquid nitrogen. The annular space between the inner line and the surrounding tube will be filled with boiling two-phase liquid nitrogen. The wall between the two fluid streams provides a heat exchange surface to allow heat to be removed from the single-phase fluid along the entire length of the line.

The cryostat will incorporate a junction/current lead box that serves the dual purpose of containing all the necessary valving, instrumentation, and power leads, and of containing the single field joint.

Cryogenics

The cryogenic system is shown schematically in Figure 9. Pumped pool boiling liquid nitrogen was chosen for simplicity, economy, and function. The heat load on the system is estimated to be 1700 W, due mostly to heat input from the power leads; 30 W has been budgeted for cryostat heat leakage. During operation, liquid nitrogen will be consumed at the rate of 8 g/sec. About 45 cfm of nitrogen gas will be vented into the tunnel or up a stack.

Liquid nitrogen will be purchased for this application and will be supplied to the cryostat from a storage vessel located outside the mine. The liquid nitrogen vessel will probably be located at ground level and the fluid can either be piped down or transported to the detector in dewars.

The vacuum pump will be located in a convenient area near the cryostat and will be sized to handle two cryostats in order to provide redundancy.

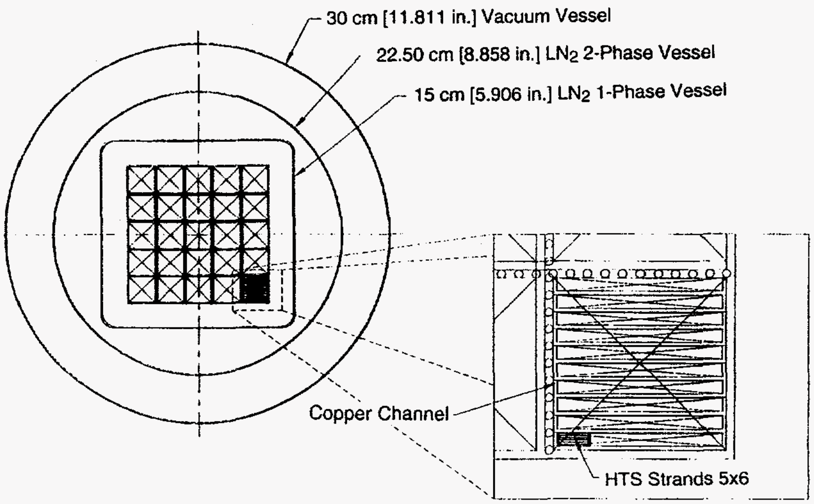

Figure 6. HTS conductor arrangement.

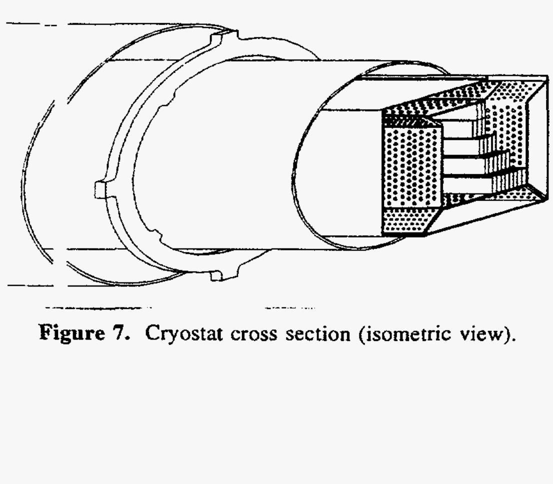

Figure 7. Cryostat cross section (isometric view).

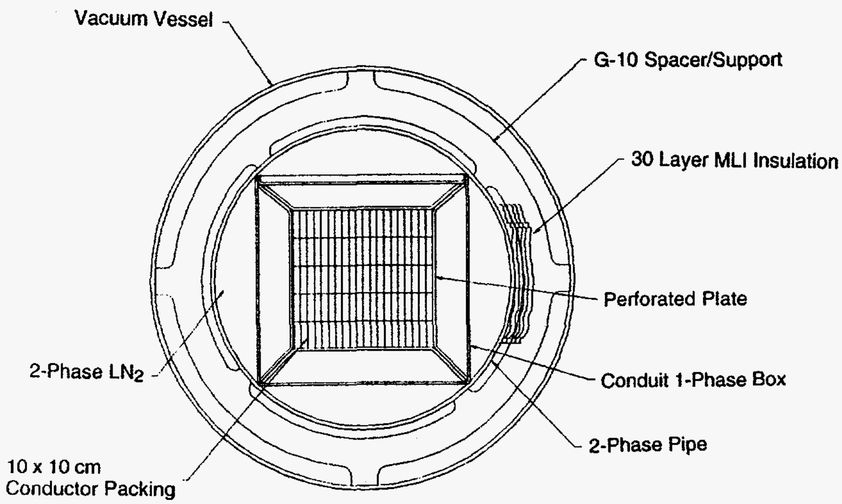

Figure 8. Cryostat cross section.

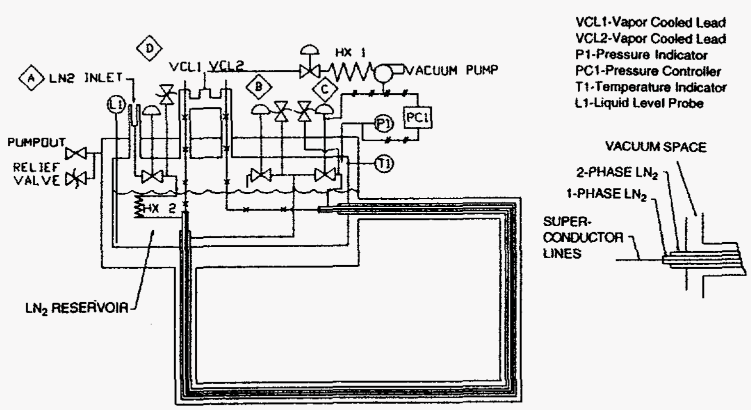

Figure 9. Schematic diagram of cryogenic system.

CONVENTIONAL COIL ASSEMBLY

An equivalent conventional coil assembly was designed for comparison. The conductor is water-cooled copper, with a 2.54 cm (1 in.) square cross section and a 1.27 cm (0.5 in.) circular hole. The coil cross section is shown in Figure 10. The coil has 32 turns and operates at 781 A, with a 32 V drop. The cooling requirement is 24.2 kW/coil and requires 8 gpm cooling water flow.

COST COMPARISON

The coil assembly acquisition costs and operating power requirements were estimated and are compared in Table 2.

CONCLUSIONS

The specified magnetizing current of 25 kA-turns can be produced by both the HTS coil system and the conventional coil system with existing materials and technology.

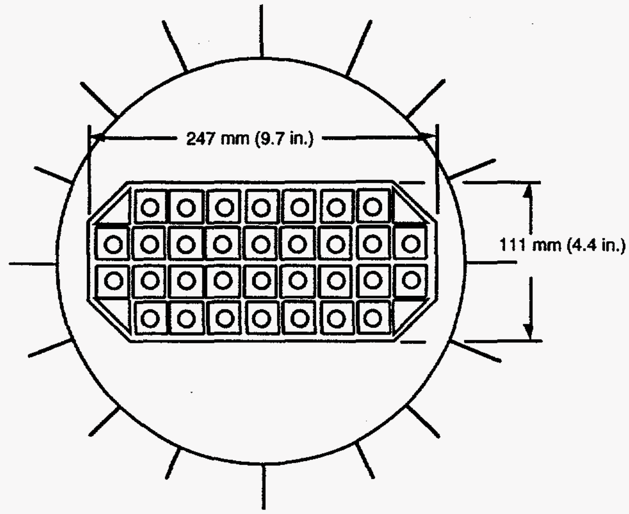

Figure 10. Conventional coil cross section.

Table 2. Coil assembly comparisons.

Characteristic	HTS	ANL Conventional
Coil assembly acquisition cost[a,b] ($$10^3$)		
* Conductor	1475	82
* Tooling	45	50
* Components/hardware	85	77
* Assembly	86	80
	1691	289
Electrical power[c]	4 kW	24 kW

[a]Cost for a single-coil system.
[b]1997 cost.
[c]For a single-coil system.

The estimated 1997 acquisition cost of an HTS coil assembly (one of three required for the detector assembly) of $1691K is significantly higher than that for an equivalent conventional coil system of $289K.

The cost driver in the HTS coil assembly ($1691K) is the conductor cost ($1475K). Projected conductor cost reductions do not result in a cost-competitive coil option in the near future.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the engineering contributions of J. M Jagger and K. Thompson. The authors gratefully acknowledge the manuscript preparation skills of J. A. Stephens and editorial contributions of C. A. Malefyt. Work at ANL was supported by the U.S. Department of Energy, Energy Efficiency and Renewable Energy, as part of a program to develop electric power technology, under Contract W-31-109-Eng-38.

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