CONF-810835--18

Lawrence Berkeley Laboratory

UNIVERSITY OF CALIFORNIA

Physics, Computer Science &
Mathematics Division

MASTER

To be presented at the Cryogenic Engineering
Conference, San Diego, CA, August 11-14, 1981

**GAS COOLED ELECTRICAL LEADS FOR USE ON FORCED
COOLED SUPERCONDUCTING MAGNETS**

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August 1981

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INTRODUCTION

The two meter diameter thin superconducting solenoid for the Time Projection Chamber (TPC) experiment at the Stanford Linear Accelerator Center is cooled with two phase helium in forced flow in a pipe.¹ This magnet, which has a design current of 2300 A (the maximum current is 3000 A), required gas cooled electrical leads which would operate directly off the two phase flow circuit.² The primary requirements of the leads were: 1) reasonable efficiency, 2) the ability to operate in the cryostat vacuum, yet withstand internal pressures up to 100 atm, 3) low pressure drop at full gas flow, 4) the ability to operate in a horizontal position with the cold end slightly higher than the warm end, 5) reliability so that the lead can run without gas flow for at least 20 minutes, and 6) restricted length (less than 600 mm).

A simple copper pipe lead permits one to operate directly off a forced flow helium circuit. The copper pipe can be pressurized to 100 atm while the outside of the pipe is in vacuum. A copper pipe electrical lead alone is not very efficient.³ However, if

*This work was supported by the Director, Office of Energy Research, Office of High Energy and Nuclear Physics, Division of High Energy Physics of the U.S. Department of Energy under Contract No. W-7405-ENG-48.

the copper pipe lead has an insert to enhance the heat transfer, the efficiency of the lead can be increased to acceptable levels. The insert also permits the lead to be operated in the horizontal position. Copper pipe leads can be built curved and the pipes can be bundled so that the lead can carry currents up to 10,000 A without increasing the basic copper pipe lead length.

Each TPC magnet lead consists of a bundle of five type L copper pipes which have an outside diameter of 15.9 mm. The leads are 533 mm long and they are curved with a radius of curvature of 1.18 m. All joints in the TPC magnet leads are either hard soldered or welded. The leads are connected directly into the helium flow circuit at their cold end. The helium flow and current flow are separated at the room temperature end. The leads are electrically and thermally insulated from the cryostat and the magnet and they are in the cryostat vacuum space. The current bus bar and the helium gas pipe are separately fed out through the cryostat vacuum wall.

This paper describes the fabrication and testing of a pair of single tube leads which carry one fifth of the TPC magnet current. Since one of the TPC magnet leads is horizontal within the vacuum chamber, the test leads were tested in a near horizontal position. From the tests, one can predict the performance of the composite TPC magnet lead or the performance of other leads built with multiple tube bundles.

THE BASIC THEORY OF ENHANCED HEAT TRANSFER IN COPPER PIPE LEADS

The current carrying part of the enhanced heat transfer lead is a commercial copper pipe. Electrically the copper in commercial pipe is not very good ($RRR \approx 5$). The thermal conductivity of the lead is nearly constant as a function of temperature (around $300 \text{ W m}^{-1} \text{ K}^{-1}$). The leads are operated at relatively low design current densities (less than $1.5 \times 10^7 \text{ A m}^{-2}$). Therefore the leads are resistant to burnout.

Since all of the current carrying capacity in the lead is in the copper tube, one must find a way of increasing the heat transfer coefficient between the helium and the copper. This is done by reducing the boundary layer thickness on the tube wall surface. Flow through a gas cooled lead has a Reynolds number below 2000; therefore, it is laminar. In tubes which are long compared to the annular dimension, the Nusselts number reaches a minimum value of around 4.⁴ The heat transfer coefficient at the tube wall becomes two times the helium thermal conductivity divided by the thickness of the annulus.

The annulus thickness is dictated by a couple of factors. In general, the annulus thickness should be less than 0.6 mm in order to prevent thermal acoustic oscillations in the electrical leads. Practical considerations such as clearances and clogging with dirt suggest that the annulus thickness should be greater than about 0.2 mm. Using the thermal conductivity of helium one calculates heat transfer coefficients at the tube wall of $100 \text{ Wm}^{-2}\text{K}^{-1}$ at 20 K and $620 \text{ Wm}^{-2}\text{K}^{-1}$ at 300 K.⁵ The gas temperature in the lead is therefore within 10° of the copper tube temperature.

THE TEST LEADS AND THE TEST SET-UP TO TEST THE LEADS

The test leads were made from a single copper tube which represented one-fifth of a TPC magnet lead. The length of the test lead was the same as the TPC magnet lead (533 mm). The test lead was straight rather than curved. The test leads were made from a single 5/8 inch OD (15.9 mm OD) copper pipe with 0.040 inch (1.0 mm) walls. The insert was made from 304 stainless steel tube which is 0.50 inch OD (12.7 mm OD). The annular space between the OD of the stainless steel tube and the ID of the copper tube was about 0.023 inches (0.58 mm). The stainless steel tube had metal pieces welded into the ends, and was filled with glass wool, with a small hole in the upper end. It was spiral wrapped with a strip of stainless steel which served as a spacer to center the insert within the copper tube. Figure 1 shows the construction of the straight tube test leads.

A pair of test leads were installed in a vacuum tight test box which was connected to the TPC magnet pumped two phase cooling system. At the upper end of each lead, the warm helium gas was separated from the current carrying bus. The current bus and the tube carrying helium gas passed through the vacuum wall separately. The cold ends of the leads were connected into a common pipe which carries two phase helium from the TPC magnet cryogenic system. Figure 2 is a schematic diagram of the electrical lead experiment in a two phase helium circuit supplied by a helium pump. The cold ends of the lead were connected to the common two phase helium carrier. A "U" shaped piece of superconductor was extended from three quarters of the way up one lead to the common helium carrier then three quarters of the way up the other lead. This superconductor, which allows the lower portion of the lead to become superconducting, effectively shuts off the heat leak into the lower portion of the leads. Figure 3 shows the experimental set up with both leads connected to a common helium carrier.

Fig. 1. The construction of a single tube enhanced heat transfer lead.

Fig. 2. Helium flow circuit for the gas cooled lead experiment.

Fig. 3. The location of temperature diodes on the electrical lead experiment.

Fig. 4. Total experiment heat lead as a function of lead current at lead angle of zero.

Five silicon diode thermometers were used in the experiment. One diode was attached to the downstream leg of the helium circuit. The other four diodes were evenly spaced along one of the leads. Figure 3 shows the location of diode thermometers. In addition to the silicon diodes, there was a pressure tap on the manifold between the leads so that the pressure drop across either lead could be measured while helium flowed through the leads. The rate of gas flow through the leads was measured using rotometer type flow meters which operated at room temperature.

The lead experiment was powered by the 3000 A, 10 V power supply to be used with the TPC magnet. The voltage drop across the leads could be measured from the gas pipe at the room temperature end of each lead to the pressure tap into the manifold between the leads.

RESULTS OF THE LEAD EXPERIMENT

During the course of testing, the total heat load into the system was measured using gas boil off. (Note: The flow through the leads was included in this measurement.) In addition to total heat load into the system, the temperature profile along the lead, the pressure drop across the lead, and the voltage drop across the lead pair were measured.

The total heat load into the experiment as measured by helium boil off comes from several sources. They are: 1) the heat leak into the control dewar, 2) the heat leak into the transfer line and lead box, 3) helium pump work, and 4) the heat leak down the leads themselves. The heat leak into the control dewar varied from 2 to 5 W depending on the liquid level. The transfer line heat leak was estimated to be between 14 and 16 W. The helium pump work was a function of pump speed, pump stroke and pressure rise across the pump (see Ref. 6). When the pump speed was 24 RPM with a pressure rise of 0.1 to 0.2 atm and a stroke of 2.54 cm, the mass flow through the circuit was around 18 gs^{-1} . Most of the experimental work was done at a pump speed of 24 RPM and a stroke of 2.54 cm. The pump work under these conditions was estimated to be 15 W.

When no gas or current flowed through the leads, there was a 15 W heat leak down the leads. Without current, gas flows as little as 0.02 gs^{-1} shut the heat flow off into the helium circuit. If the lead gas flow was sufficient, powering the leads did not add heat to the helium system (see Figure 4). Increasing the current in the leads did change the temperature profile in the lead (see Figure 5), but there was no change in the heat flow into the helium circuit.

Fig. 5. Measured temperature profile versus position along the lead for various currents.

Fig. 6. Total experiment heat load versus lead angle.

Most of the lead tests were done with the leads in the horizontal orientation (the cold end and warm end are at the same level). The lead angle could be adjusted from +22 degrees (the cold end is down) to -10 degrees (the cold end is about 10 cm above the warm end). There was little or no system heat load dependence with angle when the current in the leads was zero or 383 A. (See Figure 6) From the results of this experiment, we found that the enhanced heat transfer lead can be operated directly from a two phase flow circuit in a variety of orientations.

The experiments showed that the test leads operated well at 460 A with gas flows as low as 0.044 g s^{-1} through the leads. The leads ran stably at currents up to 800 A with increased gas flow. Experiments with leads of this type in a liquid bath suggest these leads can be operated at currents above 1000 A.

At 460 A (equivalent to the design current of the TPC magnet), the lead current density in the copper was 10^7 Am^{-2} . We calculate that these leads should operate at least 10 minutes without burnout at this current density using an adiabatic theory. The test leads were tested with the gas flow shut off for 27 minutes at a current of 460 A. The maximum temperature measured in the lead was 360 K. The temperature profile in the leads during operation without gas flow is shown in Figure 7. During the 27-minute test without gas flow, the heat load into the helium circuit increased from 33 W to 63 W. The resistance across the lead pair increased from $140 \mu\Omega$ to $450 \mu\Omega$. The voltage drop across the lead is a good indication of changes in lead gas flow.

The lead experiment showed that stable performance could be obtained at 460 A when the gas flow was maintained at 0.044 g s^{-1} . The pressure drop across the leads was less than 0.03 bar. The measured resistance across the lead pair was around $140 \mu\Omega$. There is no apparent need for an active control system for the leads at this current. If a control system is desired, the voltage drop across the lead is a good control criteria.

ACKNOWLEDGMENTS

The idea of enhanced heat transfer leads is an old one. The first leads of this type were built at LBL by R. Hintz or W. Chamberlain in the late 60's. This is the first application of these types of lead to our knowledge in any position other than vertical. The authors thank H. Van Slyke, C. Covey, E. Lee, and P. Harding for their efforts. P. Eberhard is thanked for his advice and encouragement.

Fig. 7. Temperature profile in the lead with no gas flow versus time at a current of 460 A.

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