Conf-941013--14

LA-UR- 94-3725

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Submitted to: Applied Superconductivity Conference

Los Alamos
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HTS Current Lead Using A Composite Heat Pipe

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***Abstract*—This paper discusses the design and fabrication of HTS current leads being built by Los Alamos to supply power to a demonstration HTS coil which will operate in a vacuum cooled by a cryocooler. Because vapor cooling is not an option for this application the leads must be entirely conductively cooled. In the design of HTS current leads for this type of application, it is desirable to intercept part of the heat load at an intermediate temperature. This thermal intercept or connection must be electrically insulating but thermally conductive, two mutually exclusive properties of most candidate solid materials. To achieve this end we incorporate a composite nitrogen heat pipe, constructed of conducting and non-conducting materials, to provide efficient thermal communication and simultaneously, electrical isolation between the lead and the intermediate temperature heat sink. Another important feature of the current lead design is the use of high Jc thick film superconductors deposited on a non-conducting substrate to reduce the conductive heat leak through the lower portion of the lead. Two flexible electrical conductors are incorporated to accommodate handling, assembly and the dissimilar expansion coefficients of the various materials.**

I. Introduction

The high temperature superconducting (HTS) current leads discussed in this paper are being developed for installation in a prototype high gradient magnetic separation (HGMS) system. HGMS is a powerful technique which can be used to separate widely dispersed contaminants from a host material. Los Alamos is developing HGMS technology for soil remediation and process residue reduction of materials contaminated with actinides such as uranium and plutonium throughout the DOE complex.[1] Other applications of HGMS include purification of drinking water supplies, the removal of heavy metals and other contaminates from waste water and the purification of feed stocks and raw materials. The key objective of the project is to develop a system which can provide bench top demonstrations of the advantages which are possible by combining HTS and HGMS technology.

The prototype HGMS system consists of an outer vacuum vessel which contains an HTS solenoid magnet.[2] The magnet is surrounded by a thermal radiation shield and multilayer insulation (MLI) blankets. The magnet, thermal shield and current leads all operate in a vacuum and are cooled by a cryocooler. Thus the separator is portable and requires no cryogens -- just electrical power. Because no liquid cryogens are used vapor cooling is not an option for the HTS current leads. The design is similar to the Nb_3Sn magnet operating in a vacuum at 11 K with HTS current leads described by Watanabe et. al.[3]

HTS current leads have three major components: a normal metal upper stage, a thermal intercept and the HTS lower stage.[3,4,5,6] We believe the design concept we have developed contains several novel methods of constructing these components. First, a composite heat pipe is used to provide efficient thermal communication and simultaneously, electrical isolation at the thermal intercept. Next, thick film YBCO superconductors deposited on a low thermal conductivity substrate are used in the HTS lower stage. Finally, the design includes flexible electrical conductors to mechanically isolate the heat pipe thermal intercept from both the lower HTS section and the vacuum vessel top plate. Each of these elements is discussed further below.

II. Design Requirements

The major design specifications for the HTS current leads are shown in Table 1. The operating temperature of the lower end of the HTS current leads is determined by the magnet operating temperature. The maximum operating temperature at the upper end of the HTS portion of the current leads is fixed by the thermal intercept, which in turn is cooled by the cryocooler through the thermal shield. The thermal intercept must remove the heat conducting down the copper upper stage and ensure that the warm end of the HTS conductor is adequately cooled. The nominal operating current for the magnet is 75 A at 27 K. The leads, however, have been designed to operate at 100 A. The structural loading specified for the current leads was determined by the demonstration HGMS system specifications.

TABLE I
HTS CURRENT LEAD DESIGN REQUIREMENTS

Parameter	Design Value
Operating Current	100 A
T HTS cold end	27 K
T HTS warm end	80 K
Q thermal intercept (80K)	5.0 W/lead
Q Lead @ magnet (27 K)	0.1 W/lead
Structural Loading	+/- 3 g
Magnetic Field	1000 G

III. GEOMETRY

The current lead assembly is shown in Figure 1. The subassemblies of the current lead are the upper stage, composite heat pipe, flexible link, and HTS lower stage.

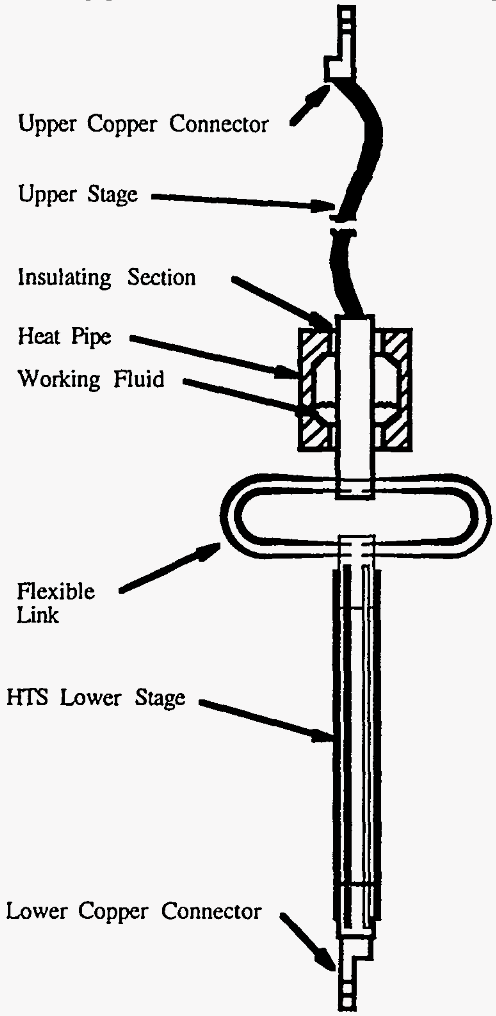

Fig. 1. Schematic view of HTS current lead incorporating composite heat pipe thermal intercept.

A. *Upper Stage*

The upper stage consists of an insulated copper wire braid. The bottom end of the wire is soldered into the heat pipe and the top end has a standard solder connector. The wire length and diameter have been sized to minimize heat leak and Joule heating.[7] This flexible electrical conductor simplifies assembly because both current leads can be connected to a standard vacuum feed through. It also accommodates differential thermal expansion and enables the lead to better withstand transportation and handling loads.

B. *Composite Heat Pipe*

The composite heat pipe is both electrically insulating and thermally conductive. The current flows through the copper center section which is the evaporator of the heat pipe. The copper outer annulus is thermally connected to the first stage of the gas cycle refrigerator and is the condenser of the heat pipe. The working fluid in the heat pipe is nitrogen which gives the heat pipe an approximate operating temperature range between 67K and 120K. The heat pipe is filled with high pressure gaseous nitrogen at room temperature. After the heat pipe is cooled down to between 63.1 K and 126.2 K the nitrogen becomes a two-phase system. Heat is transferred from the current carrying center by evaporation and to the condenser by condensation. Electrical isolation between the condenser and evaporator is provided by an epoxy joint. The epoxy joint is designed to provide 2 kV electrical isolation and withstand the stress caused by the high pressure of the nitrogen gas at room temperature, and cool down stresses. The dimensions of the heat pipe are determined by the heat load of the upper stage of the current leads and the stresses due to the pressure of the room temperature nitrogen gas.

C. *Flexible Link*

The flexible link provides mechanical isolation and an electrical connection between the heat pipe and HTS lower stage. The link is constructed of thin strips of copper shim stock bent into a "U" shape and soldered to the heat pipe evaporator and HTS leads. The mechanical connection allows for different thermal contractions and for vibration isolation. The size and number of copper strips are determined by Joule heating and by the flexibility required.

D. *HTS Lower Stage*

The HTS lower stage minimizes heat conduction and heat generation while maximizing electrical conductivity. The lower stage consists of copper end caps and two HTS elements with insulating substrates enclosed in a G10 tube providing mechanical support and electrical insulation. The HTS is thick film YBCO pulse laser deposited on a yttrium stabilized zirconia (YSZ) substrate. The thick film YBCO is sized to operate at 25% of critical current density for the design current of 100 Amps. The two HTS elements are used to provide redundancy in the design. The YSZ substrate is 1 cm wide, .05 cm thick and provides mechanical support for the YBCO film. The YSZ has very low thermal conductivity thus minimizing heat conduction. The YBCO is electrically connected to the copper end caps by sputtering a layer of silver on the YBCO, annealing the silver layer, and soldering to the copper end cap with indium solder.

IV. THERMAL MODEL

We modeled the steady state performance of the current lead by solving the one-dimensional conduction equation with internal heat generation (Joule heating) using a commercial finite difference code. The boundary conditions were 300 K at the warm end, 80 K at the heat pipe condenser, and 27 K at the cold end. The heat pipe conductance was a variable parameter, and temperature dependent thermal conductivity and electrical resistivity was used.

Figure 2, which presents the heat leak to the 80 K and 27 K stages of the lead, illustrates the results of the model for a current of 100 A. A thermal conductance through the heat pipe of at least 1 W/K is necessary to obtain near optimum performance (minimum heat leak) of the lead. Such a high thermal conductance is difficult to achieve without heat pipe technology. The heat loads to the 80 K and 27 K stages of the cryocooler are 4.4 W and 0.042 W for a heat pipe conductance of 1 W/K. Our 80 K heat leak compares well with a value of 4.2 W/100A given by McFee[7] for an optimized conduction cooled copper lead. At the 27 K Stage the calculated heat leak for our HTS lead is about 20 times lower than for an optimized conduction cooled copper lead.

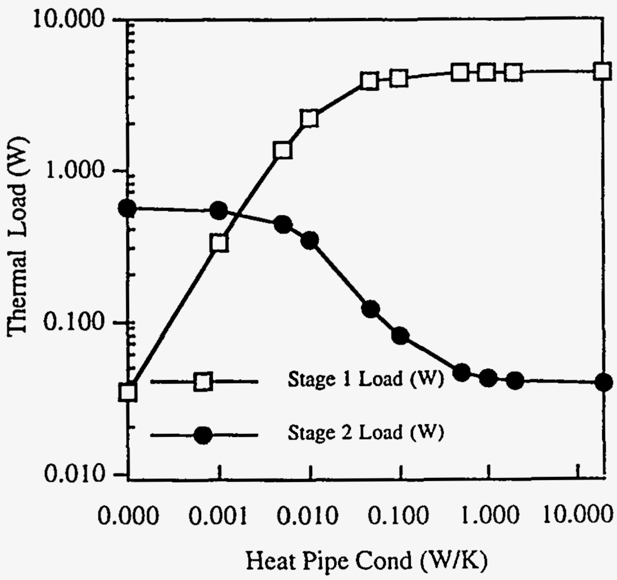

Fig. 2. Thermal load for a 100 A HTS lead with a cold end temperature of 80 K at the first stage and 27 K at the second stage.

V. HTS Stability

In order to investigate their stability, the HTS elements in the lower stage were modeled using the finite difference code SINDA. A network of 50 nodes each in the axial direction for the substrate and the superconductor was used for a total of 100 nodes. Because the volume of the superconducting film is much smaller than that of the YSZ substrate the heat capacity and thermal conductivity of the superconducting nodes were negligible. Heat generated in the superconductor was imposed as a surface heat flux on the YSZ substrate. Temperature dependent heat capacity and thermal conductivity were used for the YSZ substrate.

A three part curve was used to determine the resistivity of the YBCO superconducting film following the method of C. Levillain et. al.[8] Above the critical temperature (T_c) the resistivity of the normal state was calculated as:

$$\rho_N(T) = 5 \times 10^{-9}\, T(K) + 5 \times 10^{-7} \quad (\Omega\, m) \qquad (1)$$

Between the flux flow temperature T_{ff} and T_c the resistivity was defined by the following linear relation:

$$\rho(T,J,\mu_o H) = \frac{[\rho_N(T_c)-\rho_{flux\ creep}(T_{ff})]T+T_c\,\rho_{flux\ creep}(T_{ff})-T_{ff}\,\rho_N(T_c)}{T_c-T_{ff}} \qquad (2)$$

where T_{ff} is defined as the temperature at which:

$$\rho_{flux\ creep}(T_{ff},J,\mu_o H) = 0.2\,\rho_N(T_c) \qquad (3)$$

Below T_{ff} the flux creep regime occurs. In this region the resistivity is calculated as:

$$\rho_{flux\ creep}(T,J,\mu_o H) = \rho_o \exp[-U_o(T,J,\mu_o H)/T] \qquad (4)$$

with

$$U_o(T,J,\mu_o H) = [A/\mu_o H]\ \log(Jo/J)\ [1-(T/T_c)^2]\ [1-(T/T_c)^4]^{1/2} \qquad (5)$$

where $T_c = 92$ K, $\rho_o = 10^{-3}\ \Omega m$, $A = 7.2 \times 10^3$ KT, Jo = Jc (T=77K, $\mu_o H$ = 0T) = 1×10^{10} Am^{-2} and $\mu_o H = 0.1$ T.

The maximum stable operating temperature for the top node was determined with the model as a function of the flux ratio (J/Jo). The results are shown in Figure 3. The HTS portion of the leads are unstable at all temperatures (above 27 K) for a ratio above 0.9 in the applied field of 0.1 T. As the flux ratio drops below 0.8 an appreciable margin develops between the 80 K nominal operating temperature and the maximum stable temperature for the top of the HTS element. Based on these results it was decided to construct the HTS portion of the current leads from two parallel HTS elements each operating at a flux ratio of 0.25. In the event either element fails or quenches the remaining element will be able to safely carry the full current with an acceptable stability margin at a flux ratio of 0.5.

To estimate the stability margin of the HTS elements a series of transient runs were made to determine the maximum energy per unit volume which could be added to the top node without the lead becoming thermally unstable (burning up). The energy was input as a series of three square waves with durations of 0.1 ms, 1.0 ms and 10 ms. For each duration the maximum total energy from which the HTS element recovered was calculated for flux ratios of 0.25, 0.50 and 0.75. The results are shown in Table 2.

In addition, a set of runs was made to determine the stability margin if the energy were uniformly distributed along the entire element. Due to the low thermal conductivity of the substrate these results are essentially the same as when the energy was only added to the top node.

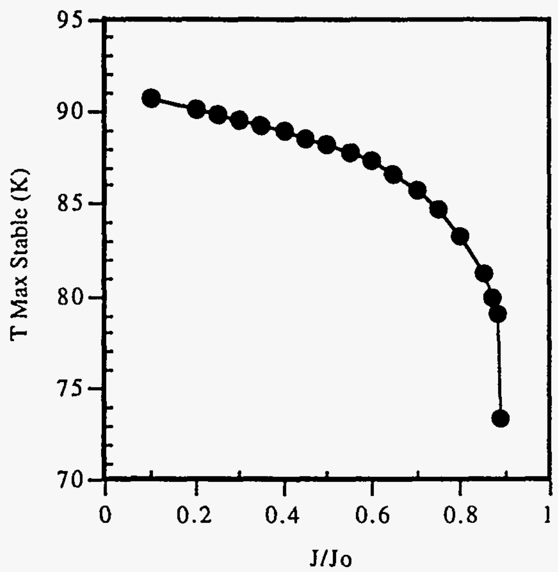

Fig. 3. Maximum stable temperature for the top end of the HTS elements with the bottom end fixed at 27 K.

These results are shown in the last column of Table 2. Time steps in these runs were typically 1000 times smaller than the pulse duration to ensure numerical stability. The sensitivity of the results to the time step was checked by dividing the time step by 10 and ensuring that the results were unchanged.

TABLE II
STABILITY MARGINS (J/cm^3)

Pulse Duration	Flux Ratio 0.25	0.5	0.75	.25[a]
0.1 ms	15.16	12.78	7.69	15.16
1.0 ms	15.18	12.80	7.70	15.15
10.0 ms	15.52	13.06	7.86	15.20

[a] All nodes heated.

VI. Conclusions

The goal of this design is to provide a rugged and stable conductively cooled HTS current lead for operation in a vacuum. The composite heat pipe allows for effective heat transfer combined with electrical insulation in a compact element. By operating at a relatively low flux ratio ample stability margins should be possible. Finally, the flexible electrical conductors accommodate thermal expansion differences and reduce the impact of shocks and vibration on the lead.

Acknowledgments

The authors gratefully acknowledge the assistance of Heinrich Boenig in electrical design and verification, Xin Di Wu, Steve Foltyn, and Jeff Willis in HTS element development and characterization and Claude Conner in mechanical fabrication.

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