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High Current Composite Superconductor Electrical Power Lead*

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ABSTRACT

We have developed and tested a nominal 100A lead to conduct electrical current between room and helium temperature. The lead affords considerable savings in refrigeration costs by incorporating elements made of high transition temperature superconductors, (HTSC). The lead was designed to operate both in the conduction mode and in the vapor cooled mode. Several leads have been combined to make a high current composite electrical conductor which carries currents up to 1200A.

KEY WORDS: High temperature superconductor, composite, electrical lead

INTRODUCTION

One of the major costs in the operation of a superconducting high current device, such as a superconducting magnet, is the heat transmitted by conduction and that developed in joule heating in the electrical lead going between room and helium temperatures at which conventional superconducting magnets operate. The refrigeration cost, work consumed to transfer a unit of heat from a low temperature, T_l, to a high temperature which in this case is the ambient, T_h, goes approximately as the ratio of those temperatures, T_h/T_l. One thus gains a factor of 18 if one removes the heat at 77K, Liquid nitrogen temperature, as opposed to 4.2K, liquid helium temperature.

Conventional electrical leads which conduct current between room temperature and helium for the purpose of energizing superconducting magnets are designed so as to optimize the heat conduction to the helium bath at the operating current[1,2]. However, there are many occasions where the current is less than the maximum current and some occasions where the current is zero. In those instances most of the heat loss comes because of conduction. In those instances as well as those of full current application it is of great importance to minimize the heat conduction. An ideal material for the construction of such a lead is the HTSC material which has low thermal conductivity together with a vanishing electrical resistance.

Figure 1 shows the thermal conductivity of copper and $Y_1B_2C_3O_7$, (YBCO). Note that the YBCO thermal conductivity is multiplied by a factor of 100. The figure also shows the electrical resistivity of copper multiplied by a factor of 5×10^6. It is obvious that even if the area of the YBCO were to be increased by a factor of 10 from that of copper, due to the low critical current density in the YBCO, the reduction in the helium loss due to conduction would be decreased by more than a factor of 10.

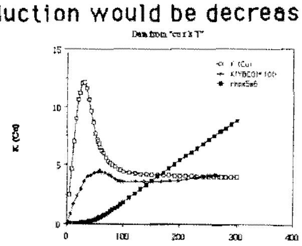

Fig. 1 The thermal conductivity of copper, K(Cu), that of YBCO*100, K(YBCO)*100, and electrical resistivity of Cu multiplied by 5×10^6 as a function of temperature.

Our lead was designed to reduce the heat input to the helium bath, with the HTSC section inserted between the temperatures of 70K and 4.2K, although the optimum upper temperature is 50K as will be shown below.

DESIGN

The design[3] incorporates several features which enhance the operation of the lead. Figure 2 shows the details of the lead construction.

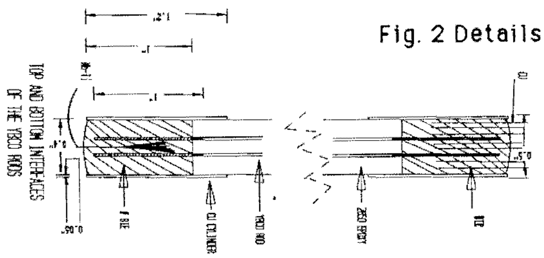

Fig. 2 Details of the composite lead construction.

The lead is composed of several YBCO filaments which are encased in plastic to form a composite. The thermal expansion coefficients of the plastic material and YBCO have to be matched so as to avoid thermal stresses upon cooling. The composite is much stronger than YBCO itself and results in a rugged construction. The filamentary structure enhances the reliability of the composite in that if one of the filaments becomes normal the other filaments can take up the current load.

The top of the YBCO filaments is electrically and mechanically bonded to copper wires coming from room temperature by means of silver pads and solder applied in a proprietary process by the ZerRes Corp., which give reliable contacts with a resistance of less than 10^{-6} ohms per square centimeter at 50K. For further safety the contacts are encased in a brass envelope and then covered by epoxy.

The lower portion of the YBCO filaments is joined by a similar process to a low temperature superconductor such as a niobium titanium copper clad wire. The copper cladding of the wire is stripped in order to expose a greater area of the superconducting NbTi filaments. In this way contact resistance of less than 10^{-9} ohm per square centimeter is achieved between the low and the high temperature superconducting components at 4.2K. Again this contact area is encapsulated in a brass envelope and sealed with epoxy.

PERFORMANCE

The leads were operated continuously for two weeks and warmed and cooled from room temperature to that of liquid nitrogen over 50 times without any change in characteristics. The mode of operation was that the bottom junction between the YBCO and the low temperature superconductor was kept below 5K while the temperature of the YBCO-Copper junction was varied.

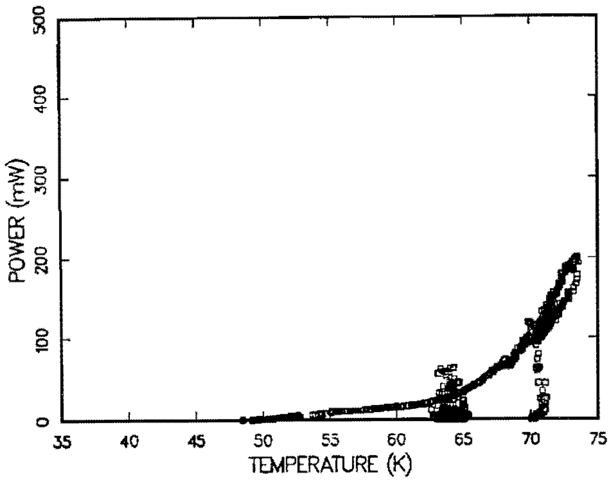

Fig.3 Experimental measurement of the power dissipation of the composite power lead as a function of the temperature of the upper end.

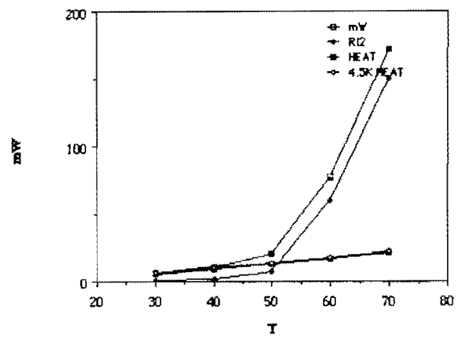

Fig. 4 Total power dissipation as calculated from the measurements and the power delivered to the He reservoir, straight line.

Figure 3 shows the power dissipation of one of our composites as a function of the upper cap temperature. The power was computed from the measured voltage across the composite and the current through it. The graph is for a current of 100A. One notes that the power dissipation becomes negligible below 50K. Therefore the recommended operating temperature of the top portion of the composite is 50K. Since during that time the temperature of the bottom cap was held constant, one concludes that most of the power dissipation occurs at the high temperature junction. The current through the lead with the top junction at 50K can be increased to 150A without a catastrophic failure. During the operation the current was ramped at 30A/s without any deleterious effects.

Because of the low heat conductivity and the power dissipation only at the high temperature end of the lead, we calculate the heat input to the helium bath to be less than 20 mW. That is at least a factor of 5 lower than that of conventional vapor cooled leads. Figure 4 shows the heat generation due to the lead as a function of the top cap temperature. The straight line is the heat conduction down the composite to the helium bath. The line through the small squares is the heat generated at the top cap due to joule heating while the line through the large squares is the total heat generated. One notes that if the top cap is held below 50K then the total heat input due to the lead is below 20mW.

In order to test the extreme performance standards of our lead we induced a catastrophic failure in one of our leads by heating the upper portion of the lead with an external heater while a 100A current was flowing. The power vs. time sequence is shown in Fig. 5. One observes that the time between the onset of a runaway situation and the catastrophic failure is over two minutes. One has therefore ample time to take corrective action. Times of this order of magnitude were predicted by Hull[4].

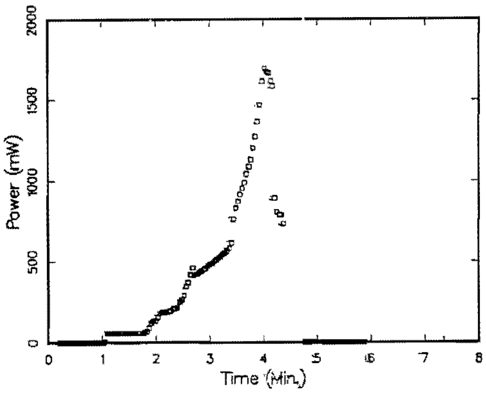

Fig. 5 Illustration of a run away situation sh-- -- that it takes over two minutes to reach a catastrophic point.

CONCLUSIONS

We have constructed a power lead, whose optimum operation is between 50K and 4.2K, which affords considerable savings in power delivered to the low temperature bath. The lead is of rugged construction and at a current of 100A has at least a 50% safety margin. Several leads were constructed and were tested and cycled hundreds of times. There was no perceptible change in performance during the cycling and therefore the lead is judged to be operationally reliable. We believe that the refrigeration savings afforded by this lead should further the development of high power superconducting applications such as superconducting motors and generators which will lead to lower power consumption and the accompanying pollution.

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