Physica C 209 (1993) 291–294
North-Holland

PHYSICA C

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 temperatures. 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 of up to 1200A.

INTRODUCTION

New discoveries lead to new technologies, new technologies lead to new ideas and products. When high transition temperature (HTSC) materials were first discovered, there was an expectation that superconducting devices would immediately become available to the consumer market and that our lives would be the better for it. That was six years ago, and before it was discovered that the nasty physical characteristics of HTSC materials were not so easily overcome. Six years after the discovery, many of us are still struggling with the improvement of the materials and the attempts to put the materials to use.

The superconductivity industry has been in its infancy since 1911 when Kamerlingh-Onnes discovered superconductivity. Today, 81 years later, superconducting devices are used only in cases where the desired results either can not be achieved by means of other materials, or when the cost of achieving those results would be overwhelmingly high. Today, the uses of superconductivity are in the achievement of high magnetic fields for particle accelerators, laboratory magnets, and MRI magnets, all of which require a relatively large magnetic field in a large volume. Other promising uses of superconductivity are in superconducting magnetic energy storage devices (SMES) which would provide power to steady a power grid, magnetic propulsion both on ground and water, and general electric power generators and electric machinery where a higher magnetic field would lead to more power in a smaller volume.

In the above, I mentioned only high current applications. In addition to these, there are many superconducting film device applications which are currently under investigation and close to production.

The application of superconductivity was heretofore hampered by the high cost of refrigeration, reliability, and the connection between the superconducting devices and conventional systems. HTSC materials can be of great benefit in the alleviation of all of the above problems. A reliable connection between room temperature devices and helium temperatures, where most of the current superconducting devices operate, and which saves on refrigeration costs, will be a catalyst to the development of superconducting high power applications. In closed systems, with present techniques, the liquid helium losses can be kept to as low as one liter per day. If the refrigeration loss due to connections to systems which need a continuous current input can also be made negligible then we will be well on the way to the practical application of high current superconducting devices.

In a Carnot cycle, the work which has to be done to remove a quantity of heat Q from a low temperature, T_l, to a high temperature, T_h, is :

$$W=Q(T_h/T_l-1)$$

* Also ZerRes Corporation, Boston, MA.

Since T_h is typically 300K and T_l is 4.2K, their ratio is 71.4 , and one can neglect the 1 in the parentheses. Although in practice the costs are proportional to the square of the temperature ratio, we will confine the discussion to the ideal case. For T_l=50K the quantity in parentheses is 5, and for T_l=77 it is only 2.8.

A conventional 100A optimized power lead between 300K and 4.2K delivers about 0.1 W to the 4.2K reservoir[1]. We have designed a power lead which cuts this heat delivery by a factor of 5.

DESIGN

There have been several designs for power leads which incorporate HTSC material[2]. Our design, however, incorporates several unique features. The design[3] incorporates several unique features which enhance the operation of the lead. Figure 1 shows the details of the lead construction.

The lead is composed of several YBCO filaments which are encased in plastic (epoxy) to form a composite. The thermal expansion coefficients of the plastic material and YBCO have to be matched so as to avoid thermal stresses as well as a slight compression upon cooling. The composite is much stronger than the YBCO itself and its use 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 tops of the YBCO filaments are electrically and mechanically bonded to copper wires, coming from room temperature, by means of silver pads and solder applied in a proprietary process by ZerRes Corp. This process yields reliable contacts with a resistance of less than 3×10^{-5} ohms at 70K and 2×10^{-6} at 50K. For further safety the contacts are encased.

The contact resistance seems to be limited by flux creep as evidenced by Fig. 2 which shows the voltage across one of the components as a function of the current at 77 K. That curve can be fit to a power law,

The lower ends of the YBCO filaments are joined by a similar process to a low temperature superconductor, such as a niobium titanium copper clad wire. In this way a contact resistance of less than 10^{-9} ohm-cm^2 is achieved between the low and the high temperature superconducting components at 4.2K. Again, this contact area is encapsulated.

PERFORMANCE

The leads were operated continuously for two weeks. Since March, 1992, they have been warmed and cooled from room temperature to that of liquid helium numerous times without any change in characteristics. The mode of operation was to keep the bottom junction between the YBCO and the low temperature superconductor below 5K, while varying the temperature of the YBCO-Copper junction.

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 is a strong function of temperature and becomes negligible below 50K. This curve can be fit to an exponential which is also indicative of flux creep limitation. Therefore the recommended operating temperature of the top portion of the composite is 50K. Since the temperature of the bottom cap was held constant during that time, 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 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 that the heat input to the helium bath is 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, 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 as a function of time during this failure 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].

There is still the question of the cooling of the conventional leads from 50K to 300 K. An optimized conventional copper lead attached to the upper end of our composite can be cooled by helium gas from the 4.2K bath, in which case the flow will be reduced by about 17%. However, if a system is attached to a helium liquefier, one could bleed off some of the helium gas at 50 K and return it at 80 K where the cooling is taken over by liquid nitrogen. In this way refrigeration costs can be cut to 20% of the present conventional lead.

REFERENCES

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2. See literature since 1988.
3. Parts of this work were reported at the 5th International Symposium on Superconductivity, November 1992, Kobe, Japan, and will be published in the proceedings by Schpringer Verlag, in print.
4. J.R. Hull, Applied Superconductivity Conference, Chucago, IL. USA,1992, unpublished.

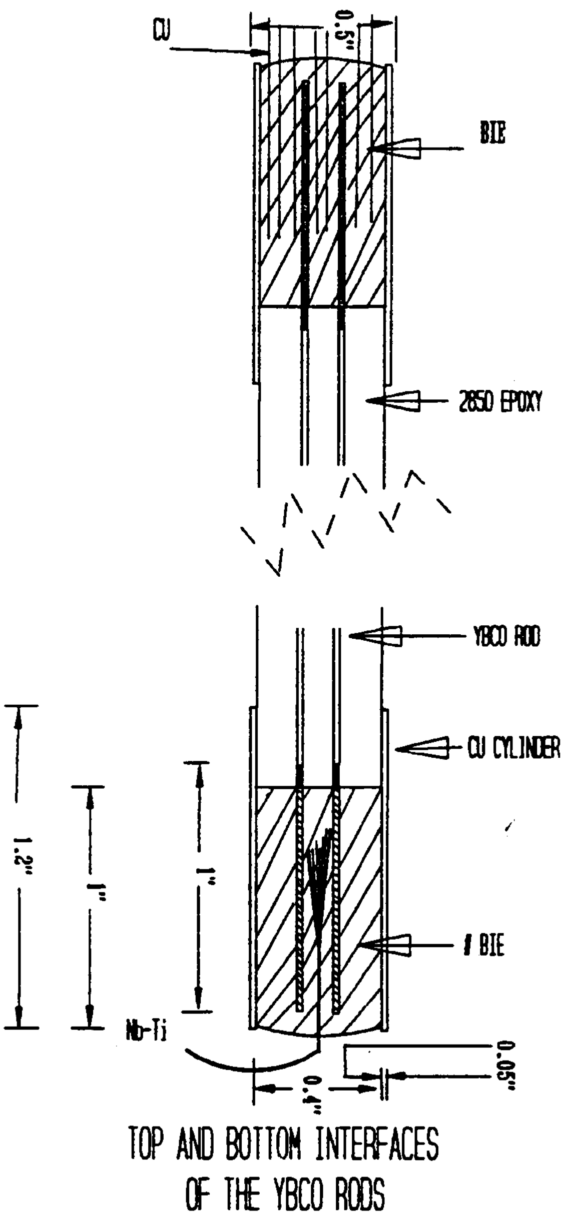

Fig. 1 Details of the composite lead construction.

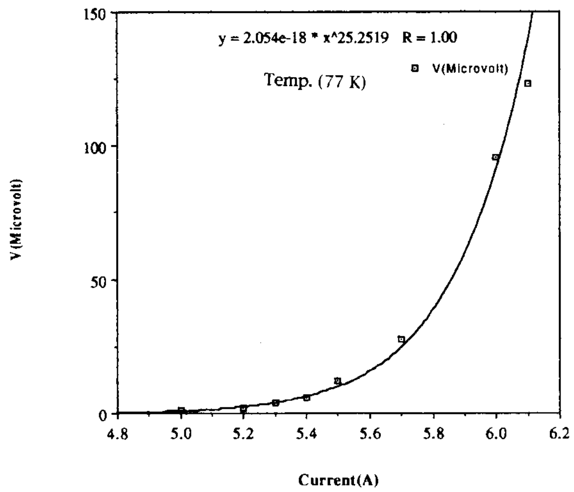

Fig. 2 Characteristic IV curve of one component in the region above the critical current

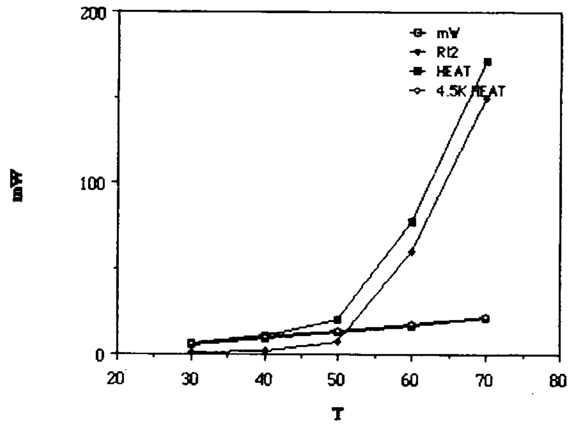

Fig. 4 Total power dissipation as calculated from the measurements and the power delivered to the He reservoir, straight line.

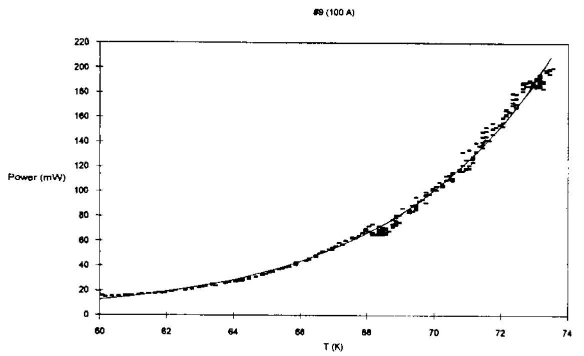

Fig. 3 Experimental measurement of the power dissipation of the composite power lead as a function of the temperature of the upper end.

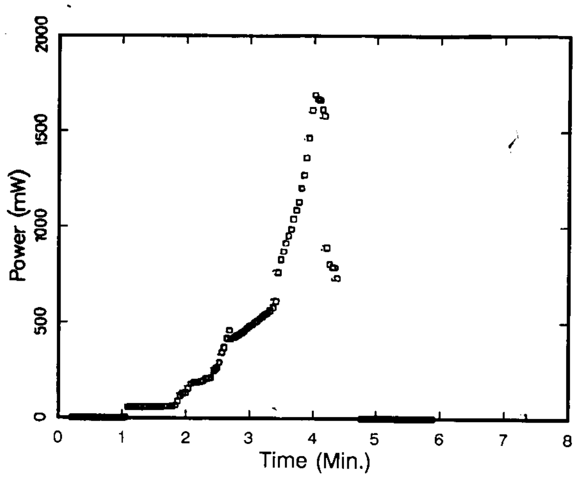

Fig. 5 Illustration of a runaway situation which shows that it takes over two minutes to reach a catastrophic point.