Test Results of a 1.5 kA HTS Current Lead for μSMES

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Abstract - A pair of 1.5 kA current leads incorporating a conventional (copper) upper stage, a lower BSCCO stage, and intermediate cooling from a twin-cold-finger GM cryocooler have been designed, fabricated and tested. A lower stage has been fabricated and tested using a stacked-tape sample of BSCCO-2223 material donated by American Superconductor Corporation. Test results characterize the helium boil-off rate, cryocooler power consumed, and joint resistances measured during the base line operation of the current leads at various currents. Additionally, the transient performance of the leads in response to a loss of cooling is reported. Here the temperatures and voltage drops at significant locations on the leads are reported as a function of time for the various operation conditions. Test results show that the most significant factor in determining the allowable operation time subsequent to a loss of cooling is the thermal inertia of the cold bus connecting the current leads to the cryocooler. The current leads are designed for use in a μSMES system and incorporate the necessary lead-to-lead voltage isolation within the body of the cryocooler.

I. INTRODUCTION

Development of HTS leads has matured from the initial excitement of realizing low heat leak operation to the sophistication of including magnet system protection considerations. In particular, it is of great interest to the magnet system designer / operator to know how long a set of HTS leads may be safely operated, without self destruction, in the event of a loss of cooling at the thermal intercept. Such information can determine whether the magnet energy must be immediately dumped, or at the other extreme, whether there is sufficient time to repair or replace the intercept cooler without changing the magnet operating current. Scenarios in between these extremes can involve various emergency modes of magnet operation. In addressing these issues, the report. by Wesche and Fuchs [1] provides a convincing description of the significant advantages in reaction time associated with the use of 2223/Ag HTS elements over what may be obtained using bulk 2212 elements.

Manuscript received August 27, 1996.
This work supported by the U.S. Defense Nuclear Agency under DNA MIPR 92-719, work unit CD:00014, RCC: 7010.

In that report, the time to reach the critical temperature following a loss of cooling at the intercept is predicted to depend inversely on the square of the operating current and somewhat less strongly on the ratio of j_{op}/j_c . The experimental investigation reported here is directed toward the same information and uses a set of HTS current leads for which the intercept cooling is provided by a twin cold-finger GM cooler. Initial operation of the experimental test rig, and the performance of the GM cooler are reported elsewhere [2].

II. EXPERIMENT

A. Equipment description

The experimental test rig for testing HTS current leads at UW-Madison is shown schematically in Fig. 1. Here a standard liquid helium dewar, provided with a liquid nitrogen jacket, provides the main housing for the experiment and is evacuated following the full assembly of the experiment. Within the dewar, the test rig is primarily comprised of a liquid helium vessel of nominal dimensions 0.48 m ID by 0.56 m height, surrounded by a copper radiation shield, two GM cryocoolers - one for cooling the two current leads, and,

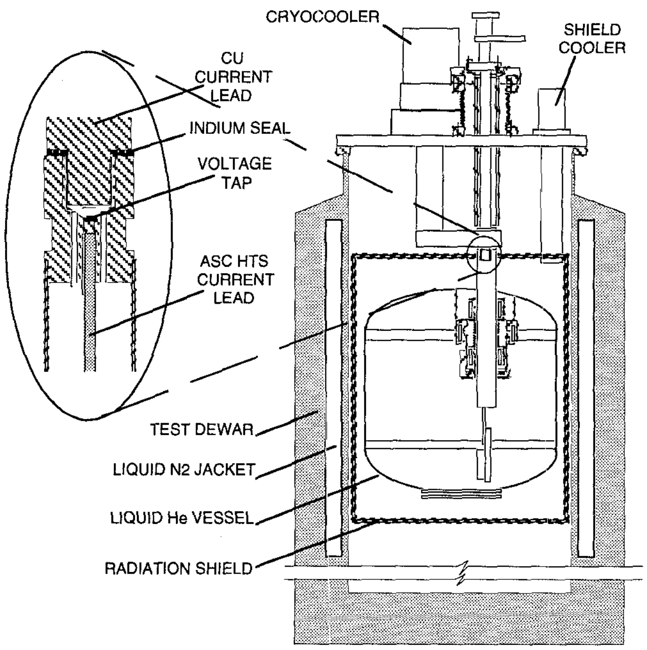

Fig. 1 HTS Current lead test rig.

one for cooling the radiation shield, and the cold copper bus connecting the cold fingers of the cryocooler with the current leads. A single 6 kW compressor drives the two cryocoolers which provide a nominal 200 watts total cooling power at 70 K.

The upper, conventional, stage of the current leads are optimized for 1500 A capacity and include provision for helium vapor cooling, although during this test, they are operated only in a conduction cooling mode; that is, no helium vapors are allowed to pass up through the leads. Two different lower (HTS) sections are designed to be assembled to the upper stage: one using bulk 2212 materials purchased from Hoechst Celenese, and the other a stacked tape of 2223/Ag donated by American Superconductor Corporation. The results presented in this report are for the stacked tape 2223/Ag samples.

Assembly of the HTS section is accomplished by soldering the ends of the stacked tape into machined slots in the copper end caps of a 4.45 cm diameter stainless steel tube. The solder is Indium based and has a melting point of 130°C. During assembly of the current lead into the test rig, the lower stage is screwed together with the upper stage, this joint being sealed with an indium o-ring (see inset of Fig. 1). Surface preparation for this joint is after the recommended procedure of Niemann et.al. [3]. The full current lead is then attached to the dewar cover, voltage isolated penetration through the helium vessel, and to the cold bus connection to the cryocooler. Bellows at the dewar cover and helium vessel penetration allow for differential thermal contraction both in the vertical and horizontal directions.

Instrumentation is provided to measure temperatures along one of the two current leads, including the upper stage (2 platinum thermometers), the thermal intercept joint (1 platinum thermometer), the lower stage (5 platinum thermometers), and the electrical connection bus in the liquid helium vessel (1 carbon glass thermometer). Additional platinum thermometers record temperatures at the cryocooler cold fingers and along the cold bus. Voltage taps encompassing the entire electrical circuit are installed to measure voltages across all the current lead joints as well as the superconducting and conventional sections of the leads. Finally, a superconducting level indicator is used to measure the liquid helium boil-off rate. Positions of the thermometers and voltage taps on the HTS element of the (+) lead are shown in Fig. 2.

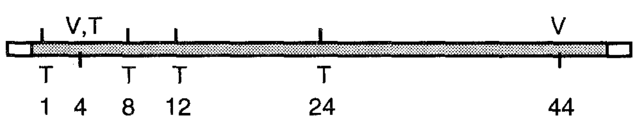

Fig. 2: Instrumentation location on superconducting element. All numbers are in (cm) and are as measured from the right edge of the left end section (non-shaded region). Thermometers numbers from left to right are: T8 (1 cm), T9 (4 cm), T10 (8 cm), T11 (12 cm), and T12 (24 cm).

B. Testing sequence

1) Cooldown: Following full assembly of the current lead test rig, the cooldown process begins by evacuating the dewar, filling the liquid nitrogen jacket, and turning on the cryocoolers. The use of both a nitrogen jacket and the cooled radiation shield minimizes the background heat load to the liquid helium vessel. Finally liquid helium is admitted to the inner vessel.

2) Boiloff measurements: In the first set of measurements, temperatures along the current lead are observed to determine steady state conditions. Helium level measurements are gathered for conditions of 0 A, 500 A, 750 A, 1000 A, and 1200 A. In the last case, steady state conditions were not achieved and the measurement was cut short due to concerns with the temperature at the warm end of the conventional section of the current lead.

Following the initial boiloff measurements, the current leads were subjected to 9 additional electrical cycles between 0 and 1250 A, and a final boiloff measurement at 1000 A was then gathered.

3) Transient measurements: After a single thermal cycle to room temperature, the test rig is recooled by the cryocoolers and liquid helium, and steady state thermal conditions are achieved. At each of the currents of 500 A, 750 A, 1000 A, and 1250 A, a 1 hour wait is used to allow thermal equilibration along the current lead. After this time, power to the cryocoolers is turned off and the temperatures and voltages along the current leads are observed in real time on the data acquisition computer. In all cases a voltage runaway near the upper end of the HTS element is used to by the operator as an indication to initiate a manual trip of the power supply. Shortly thereafter, the cryocoolers are turned back on, and the thermal equilibrium waiting process is repeated for the next current level.

III. Results and Discussion

A. Helium boiloff heat leak measurements

The total heat leak from the combined sources of the dewar structure, thermal radiation, and the current leads is shown in Fig. 3 as a function of the operating current. A reliable value for the boiloff from the rig without the current leads has not yet been obtained and this is due to the long thermal equilibration times for the thermal radiation shield which have been discovered during the course of the measurements. The values displayed in Fig. 3, except for the lower value at 1000 A, have all been gathered in a span of 2 hours, while the lower value at 1000 A was taken 1.5 hours later, following the 9 electrical cycles, but perhaps significantly also after the radiation shield had been further cooled. In spite of this uncertainty, and the fact that a background heat leak has not been subtracted from these numbers, the heat leak realized for

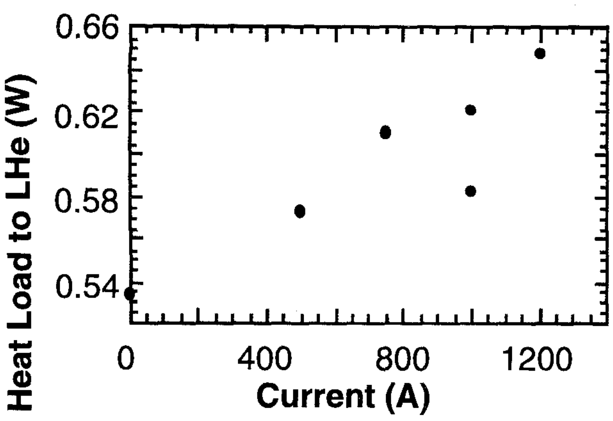

Fig. 3 Heat load from current lead to liquid helium bath as determined from rate of change of liquid level.

the 1.5 kA leads, operating at 1250 A is at most only 25% of the theoretical best value for a pair of 1.5 kA conventional vapor cooled leads operating at the same current.

B. Contact resistance

Values of the contact resistance both at the indium sealed joint between the upper and lower stages, and between the copper end caps and the superconductor are known from the voltage measurements across these joints. In that thermal dissipation and warming occurred at these joints during the thermal equilibration process, the data affords a temperature dependence to these contact resistance values. For purposes of scaling these types of joints to other applications, note that the contact area between the upper and lower stages is 22.6 cm^2, while that between the upper copper end cap and the superconductor is 12.35 cm^2. The contact resistance values are shown in Fig. 4. These values are combined from results gathered at each of the operating currents.

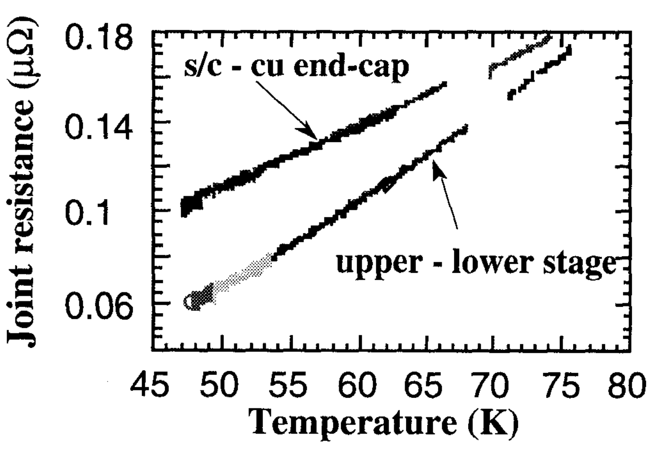

Fig. 4. Measured resistances at the joints between the upper and lower stages of the current lead, and between the upper copper end cap and the HTS superconductor.

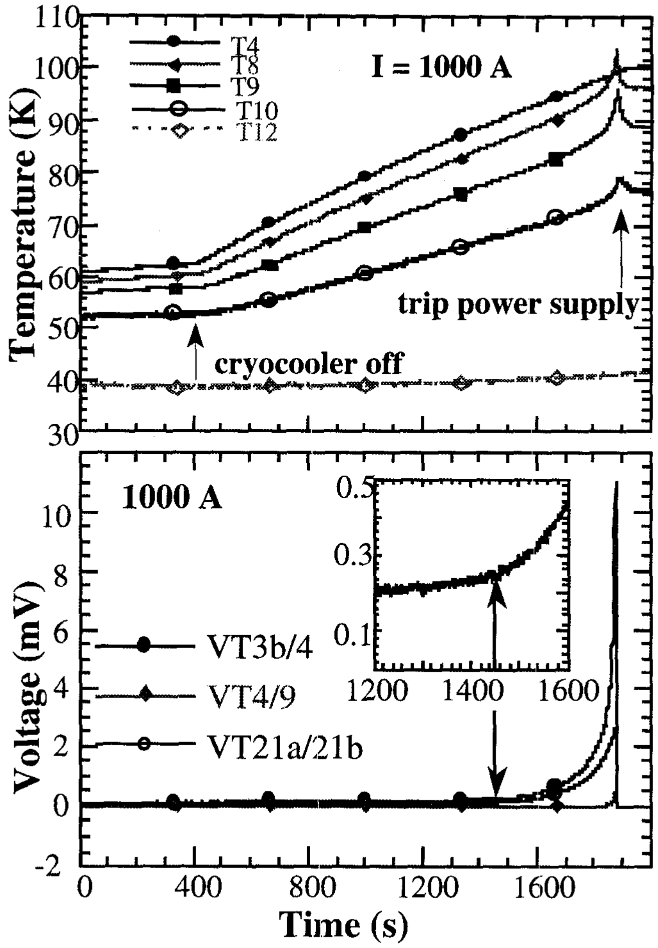

Fig. 5. Transient response of temperatures and voltages to loss of cryocooler power. Temperature data correspond to transducers identified in Fig. 2 . In addition, T4 measures temperature at upper stage - lower stage joint. Voltage tap data VT3b/4 measured across upper end cap - superconductor joint, VT4/9 across the (+) HTS lead, inside of any joints, and VT21a/21b across the (-) HTS lead.

C. Transient operation measurements

A typical data set describing the behavior of the current leads following a loss of cooling from the cryocooler is shown in Figs. 5a and 5b. Here a voltage and temperature runaway are clearly evident. Thus, one can easily argue the need for a protection circuit in the use of these current leads.

For each of the operating currents similar behavior is observed in the temperature and voltage data. With the definition of t = 0 corresponding to that when the cryocooler power is turned off, times for the appearance of the superconductor - normal transition, and the times when the power supply is tripped are defined as Δt_{crit} and Δt_{trip} respectively. These times are plotted in Fig. 6. The steady state intercept temperature for the 1250 A case is above Tcs, therefore no value for Δt_{crit} is given for 1250 A. As a byproduct of the same data, one can identify a current sharing temperature corresponding to each of the operating currents, and these are listed in Table 1.

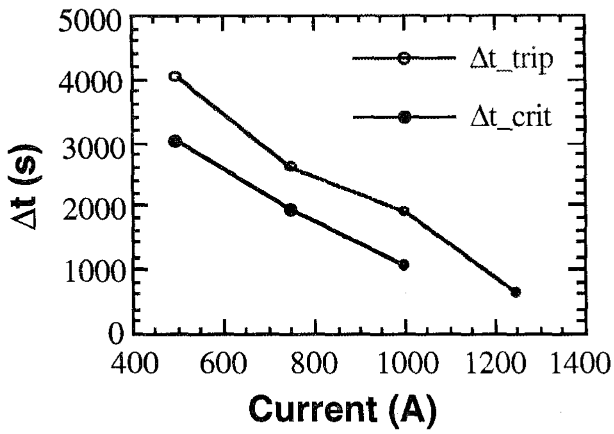

Fig. 6. Transient operation time as measured from the time when the cryocooler is turned off.

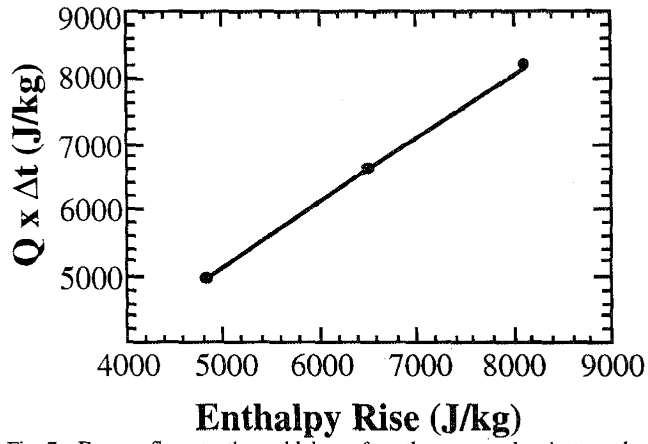

Fig. 7. Energy flow to the cold bus after the cryocooler is turned off compared with the enthalpy rise of the same point in rising to the current sharing temperature.

D. Factors determining duration of transient operation

Three factors in addition to the superconductor critical temperature may be identified as key in determining the duration of the transient operation time. These are 1) the heat load to the cryocooler during normal operation (as determined by the heat conduction and heat generation from the upper stage), 2) the cooling characteristics of the cryocooler, and 3) the thermal mass of the cold bus connecting the cryocooler to the current leads. As regards the second of these factors, one should recall that the operating temperature of the cryocooler is determined by the temperature at which the cooling capacity is equal to the thermal load. In the present experiments, the steady state operating temperature of the cryocooler as a function of the current is given in Table 1. Thus, with the lower heat loads associated with the smaller currents, the system operates at a lower thermal intercept temperature. This behavior in turn influences the heat conduction to the intercept point, so that the first two factors are interrelated.

The third factor determining the transient operation time is clearly recognized by examining the enthalpy rise of the cold bus during this time. When the cryocooler is shut off, the heat which had been extracted by the cryocooler continues to flow to the thermal intercept point of the current leads. Fig. 7 displays the product of that heat flow (Q being determined from the cooling capacity of the cryocooler at the steady state intercept temperature) and the duration Δt_{crit}, vs. the enthalpy rise associated with the mass of the copper cold bus, and adjoining copper pieces on the cryocooler and current lead

TABLE 1

Current (A)	Tcs (K)	T_ss (K)	Q_ss (W)
500	92.9	49.1	38.0
750	89.2	55.8	48.0
1000	85.6	62.5	66.3
1250	64.5	69.3	91.8

over the temperature difference between Tcs and the steady state operation intercept temperature. The relationship is linear with a slope of unity. The same relationship is found to be true calculating the time and temperatures between the point when the cryocooler is turned off and the point when the power supply is tripped.

Aside from the above observations, one may be tempted to search for a relationship between the transient operation duration and the operating current of the lead. However, in that both the heat flow to the cold bus during steady state operation, and the enthalpy rise following loss of cooling are dependent on the steady state temperature at the thermal intercept (T_ss), and this in turn is intimately tied to the cooling characteristics of the cryocooler, one know the steady state intercept temperature to predict the safe transient operation duration. Beyond this observation, one may see that a generous thermal mass at the intercept point provides an easy method for allowing long transient operation.

Summary

A pair of 1.5 kA HTS current leads have been tested under steady state and in transient operation, following loss of cooling at the thermal intercept. Heat loads to the liquid helium are less than 25% of the conventional heat load. The duration of the transient operation is determined by three factors: the heat load realized at the thermal intercept, the cooling characteristics of the cryocooler, and the thermal mass at the intercept.

References

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