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THERMAL TESTS OF 6 KA HTS CURRENT LEADS FOR THE TEVATRON

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ABSTRACT

Prototype current leads incorporating High Temperature Superconductor (HTS) elements have been tested at Fermilab. Fermilab's Tevatron includes about 50 pair of 5 to 6 kA current leads, and Fermilab is investigating the feasibility of replacing some of these conventional leads with HTS leads. The prototype HTS current leads are cooled primarily by a countercurrent flow of liquid nitrogen from the 80 K intercept to the warm end of the leads, but also a small flow of helium gas cools the HTS section from the 4 K level. The HTS current leads carried the design current of 5 kA with good thermal and electrical stability. LN2 flow without current was 0.24 g/sec per lead and with 5 kA was 0.53 g/sec per lead, corresponding to heat inflows to the 80 K intercept of 46 Watts and 101 Watts, respectively. The heat input to the 4 K level was 0.6 W with no current and 0.7 W +/- 0.1 W per lead with 5 kA current, about 1/8 of the heat load via copper, vapor-cooled leads.

INTRODUCTION

Conventional, vapor-cooled power leads carry electric current from room temperature to 4.5 K in order to power the superconducting magnets in the Tevatron at Fermi National Accelerator Laboratory. Over 50 pair of leads each carry 4500 to 6000 amps of current and result in substantial heat loads for the cryogenic system. About 25% to 30% of the total Central Helium Liquefier capacity cools power leads. Reducing the total heat load to the liquid helium temperature level would allow either reduced operational costs or make more refrigeration available for lower temperature and higher energy operation of the Tevatron.

Conventional power leads have a well-known thermal performance limit of about 1.2 W/kA per lead.[1,2] However, with the use of High Temperature Superconductor (HTS), one can reduce the heat transport to the liquid helium level significantly below the limit for conventional, copper leads. Using HTS elements in a combined liquid nitrogen and liquid helium cooled power lead

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design, one can reduce the heat load to LHe through the lead by a factor of ten.[3] The replacement of some of the conventional power leads at Fermilab with more efficient HTS leads is under consideration.

As a first step toward realizing this plan, American Superconductor Corporation (ASC) and Intermagnetics General Corporation (IGC) each developed and built a pair of 5000A HTS current leads. The leads were similar in consisting of parallel tapes of BSCCO-2223 multifilamentary powder-in-tube conductor in a silver alloy matrix soldered to a conventional copper upper section. These leads went through extensive tests at Fermilab. The focus of this paper is on the thermal studies of the IGC current leads.

TEST APPARATUS

The HTS power lead test apparatus is located in the Magnet Test Facility (MTF) at Fermilab. The mechanical system consists of a liquid nitrogen shielded helium cryostat (Figure 1) with a baffle system that includes an 80 K intercept, and the instrumentation necessary to monitor mass

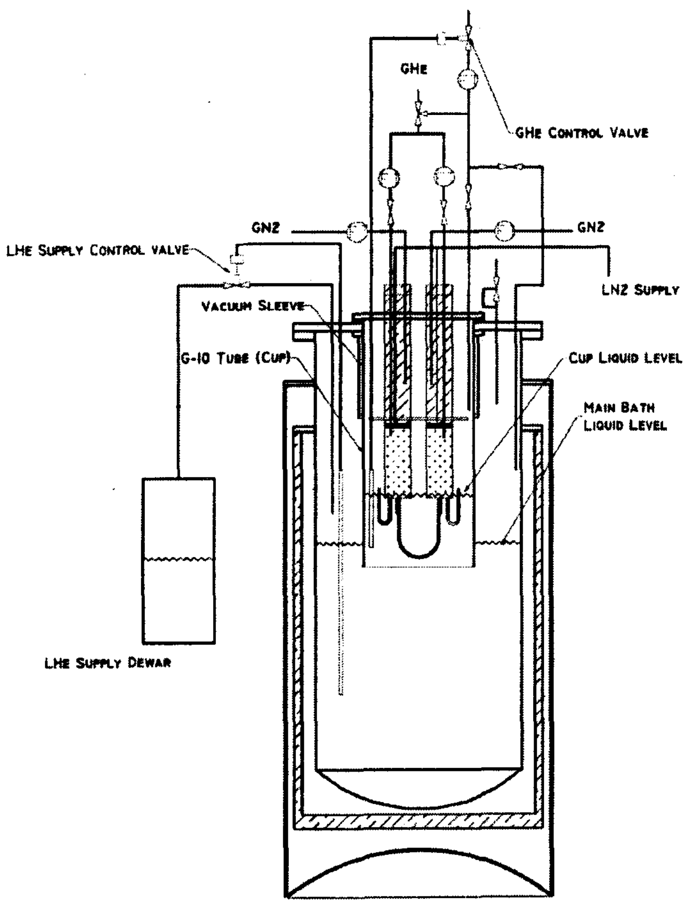

Figure 1. The current lead test schematic.

flow rates, measure and regulate system pressures and liquid level and record system temperatures. The 51 cm diameter by 107 cm long helium vessel is sized to accommodate power lead pairs, which are spaced on a 10 cm center-to-center distance, and are up to 76 cm long. The leads are mounted on a plate that is separate from the main vessel cover plate. This feature allows for power lead removal without complete disassembly of the vessel cover plate. The remaining top surface area of the vessel accommodates fill and vent lines, valves, liquid level sensors, and other instrumentation.

To thermally separate the main dewar helium volume (referred to as the "main bath") from the volume immediately around the power leads, the leads are housed inside a glass/epoxy (G-10) tube (referred to as the "cup"). The cup extends from the cover plate to several centimeters below the minimum operating helium level in the main dewar, and thus the cup contains a separate liquid level around the leads. To further thermally isolate the two volumes, the power lead pair and G-10 tube assembly is mounted inside a vacuum-jacketed sleeve that extends to the depth of the liquid nitrogen cooled intercept. Anticipating differences in pressure due to the different thermal environment in each, the system provides for independent or simultaneous venting of the two volumes. A backpressure regulator, sensitive to 0.3 mbar pressure changes, is installed to help maintain a constant pressure in the main bath, while pressure changes may be occurring inside the G-10 tube.

The calibrated mass flow meters (FT in Figure 1) used in the system were sized to operate effectively over the expected range of flows. The HTS data acquisition (DAQ), and the quench detection and management systems used in this test are adapted and extended from those systems developed at MTF to conduct tests on superconducting R&D magnets.[4] Temperature and voltage measurements from the DAQ scans are monitored by a new software quench detection system[5] that triggers the quench management system to protect the leads from (relatively slow) quenches. An independent hardware backup system protects against ground faults as well as fast resistive voltage growth across the leads. A quench is detected when one of the analog signals or software process variables exceeds a (configurable) threshold or when a scan malfunctions. When triggered, the management system initiates fast quench data logging and slow power supply ramp down.

The quench thresholds were set low. The system tripped for any temperature rise of 5 K above the zero-current baseline temperature profile, HTS voltage greater than one millivolt, or copper section voltage greater than 32 millivolts. Temperature and voltage process variables were monitored and logged by two independent scan systems, which used complementary instrumentation schemes. The carefully wired and isolated sensors delivered typical noise levels of less than 1 K for temperatures, and less than 3 μV for voltage taps at 5000 A.

The Current Lead Test Modes

Thermal tests of the helium-cooled HTS section included three different modes of cooling. In "conduction mode", the HTS section was cooled by only heat conduction from 80 K to 4.5 K (Figure 2). Boil-off from the cup surrounding the leads was measured. In "regular mode", He cooling flow through the leads was adjusted to be 0.006, 0.011 and 0.025 g/sec. The balance of the boil-off from the cup surrounding the leads was vented and measured. In "self-sufficient mode", all boil-off helium inside the exits via the leads, and the flow through the leads was measured.

During the thermal tests, we tried to maintain the following parameters constant: pressure, liquid helium level inside the cup (directly under the leads), helium gas flow through the current leads, and LN2 flow to the 80 K intercept. Automatic control of the bath pressure and two liquid levels were implemented in order to help maintain steady conditions.

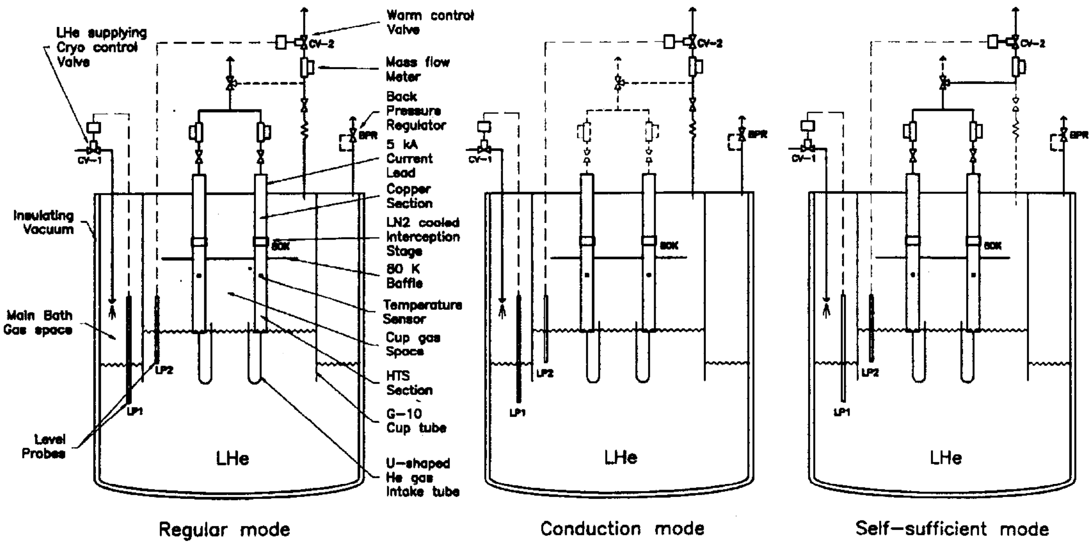

Figure 2. The current lead test modes.

POWER TEST RESULTS

Electrical test results and some preliminary thermal test results for these HTS current leads have been previously reported.[6] The IGC current leads, for which this paper describes the thermal test results, carried over 5000 Amps with stable voltages and temperatures.

THERMAL TESTS OF THE LN2-COOLED COPPER UPPER SECTION

To determine heat inflow to the 80 K intercept, the liquid nitrogen cooling flow was reduced stepwise until the temperature of the nitrogen intercept in the lead started to rise, indicating that all the LN2 supplied was boiled-off. Helium cooling flow was maintained as recommended by the vendor: 0.026 g/sec without current and 0.033 g/sec with 5 kA. It was found that the minimum required LN2 flow without current was 0.24 g/sec and with 5 kA was 0.53 g/sec, corresponding to heat inflows to the 80 K intercept of 46 Watts and 101 Watts, respectively.

Table 1. Liquid helium boil-off rates under different modes (flows are per lead)

Mode	Conduction			Regular					Self-sufficient		
Helium transfer	yes	yes	no	yes	yes	yes	yes	no	yes	yes	no
Current (kA)	0	0	0	0	0	0	7	0	0	5	0
Lead flow (g/s)	0	0	0	0.006	0.01	0.024	0.024	0.025	0.025	0.029	0.059
Total flow (g/s)	0.05	0.058	0.086	0.044	0.035	0.029	0.037	0.035	0.025	0.029	0.059

THERMAL TESTS OF THE HELIUM-COOLED HTS SECTION

The results of the boil-off rate measurements for the HTS leads are shown in Table 1. The boil-off rate measurements were done both when liquid helium was transferred to maintain a constant main bath level and when no helium was transferred, so the main bath level dropped slowly. One can see in Table 1 that the boil-off rate was lower during helium transfer. As we will discuss later, the presence or absence of helium transfer and the venting location (e.g., self-sufficient mode or conduction mode) resulted in different vapor temperature profiles and convection rates on each side of the G-10 cup wall and different rates of heat transfer into or out of the current leads environment. This led to inconsistent results unless one accounts for these background effects.

In order to check the background heat load, boil-off rate measurements were made without current leads and as a function of main bath (MB) level. The vaporization rate without current leads versus main bath level is shown in Figure 3 in comparison to a current lead heat load

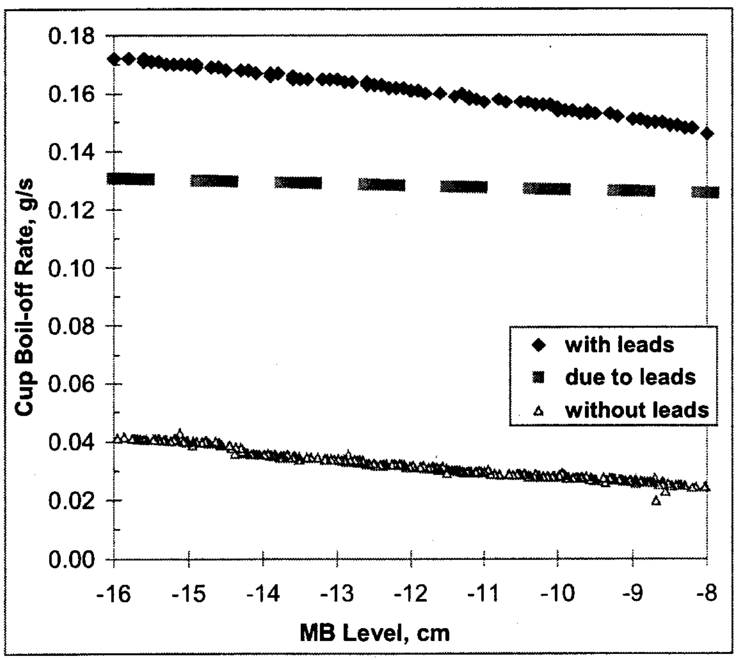

Figure 3. Subtraction of background heat load from conduction mode cooling, no helium transfer, as a function of main bath (MB) level.

measurement versus main bath level. For both this background run and the current lead run, helium exited via the cup vent (conduction mode) and the measurement was made without helium transfer to the main bath. One can see the dependence of boil-off rate on main bath liquid level. A higher main bath level provides more cooling of the cup through the epoxy-fiberglass tube wall. Subtracting the vent rate without current leads from the rate measured with current leads reveals a constant difference, 0.13 g/s, attributable to the pair of current leads in conduction mode.

Conduction mode had the problem that, due to the onset of thermo-acoustic oscillations when the insulated vent pipe was lowered to near the liquid level, the vent pipe entrance had to be raised to nearly the level of the 80 K intercept. The helium vapor then provided some external cooling of the current leads; some heat was still removed from the leads by convection. Thus, conduction mode results cannot be taken to indicate the heat that would be added to a passing forced-flow helium stream by a conductively cooled HTS section.

In order to get a more direct measure of the relationship between heat added to the bath within the cup and cup boil-off rate during helium transfer, measurements using a small electric heater were done while liquid helium was transferred into the main bath to maintain a constant main bath liquid level. The dependence of the liquid helium boil-off rate versus power dissipated in liquid helium in the cup is shown as the lower curve in Figure 4. Unlike the situation without helium transfer described in Figure 3 above, no correlation of boil-off rate with main bath level was noticed. Variation of main bath level and helium transfer rate resulted in some scatter of the results, with the resultant uncertainty shown in Figure 4. It was expected that the dependence of

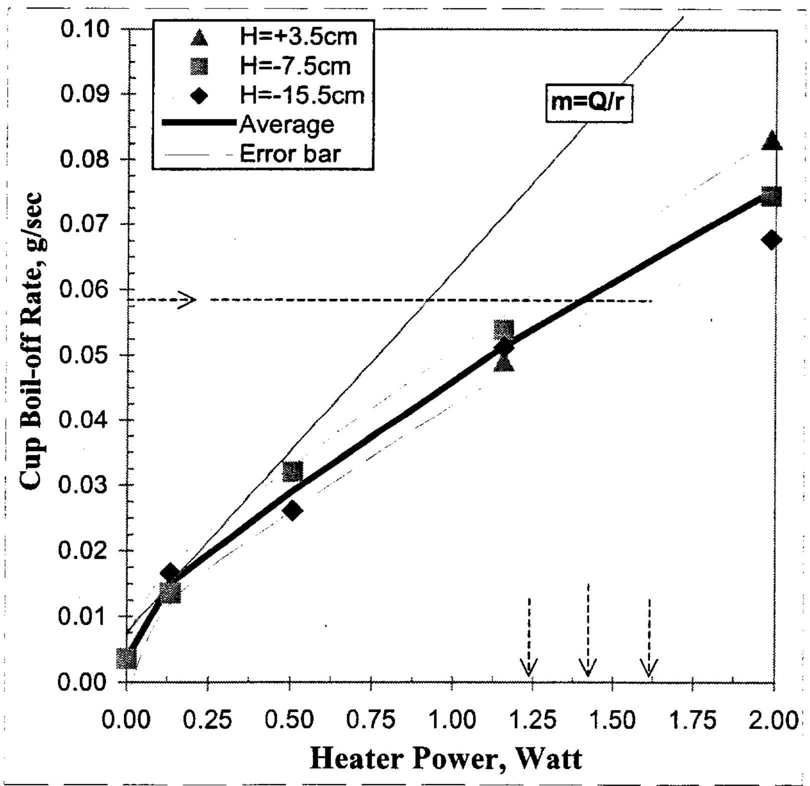

Figure 4. Evaporation from under the cup (both leads) versus heater power with liquid helium transfer

LHe boil-off on the dissipated heater power should be linear (m=Q/r) starting from a background value at 0 Watts. However, the amount of increase in measured mass flow from the cup was less than that corresponding to the additional heat from the heater. The difference is probably due to the extra cooling of the cup volume through the G-10 cup wall.

One can see by comparing heater results with current lead boil-off measurements that in the self-sufficient cooling mode, with liquid helium transfer, the total current lead boiloff for the pair of leads of 0.050 g/s with no current corresponds to 1.2 W of heat input via the current leads. At 5 kA the vent rate of 0.058 g/s corresponds to 1.4 W +/- 0.2 W of heat input via the current leads. In a well-insulated environment, this would result in a self-cooling flow of 0.035 g/s +/- 0.005 g/s per lead.

DISCUSSION

A problem during these tests was that the G-10 tube, the "cup", was not a good thermal insulator, and heat flowed across the tube walls depending on the amount of turbulence-induced convection and the temperature difference between the vapor spaces above the main bath and in the cup. Helium transfer into the main bath affected the vapor flow rates and temperature distribution in the vapor space around the outside of the cup. With helium transfer, the vapor outside the cup over the main bath was colder and more turbulent, so some cooling of the cup volume occurred and resulted in a lower boil-off rate from the leads. Without helium transfer, the vapor temperatures increased to levels above the nominal lead temperature at the corresponding height, and significant heat was transferred to the current lead. Hence the higher lead flows with no helium transfer in Table 1.

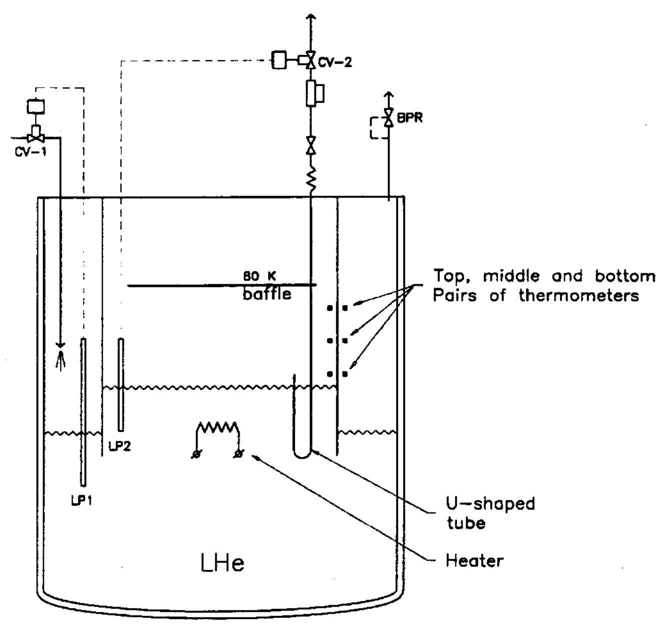

Figure 5. Background heat load measurement schematic.

After we understood the impact of the background heat leak on our head load measurements, we added some thermometry to the dewar (Figure 5). We measured temperature profiles with three pairs of thermometers installed at the same elevations inside and outside cup. The lowest pairs of sensors are at the elevation of the vent tube edge in order to measure the temperature at the vent gas level. The highest sensors are at the elevation of a thermometer embedded in the middle of the HTS section in order to measure the temperature difference between the lead and surrounding gas.

The additional thermometry confirmed that temperature distribution in the space inside the cup was affected by the mode of lead cooling. In conduction mode, cold vapor entered a vent above the HTS lead section, at about the 80 K intercept level (at this level to avoid oscillations), so the cup vapor was colder and was not stagnant. This vapor both cooled the leads and cooled the cup walls, affecting boil-off rate measurements. Our conduction mode results, therefore, are of questionable value. Self-sufficient mode, with all cooling through the leads, left the vapor above the leads largely undisturbed and provided probably the most reliable results.

To make the background boil-off measurements more like a current lead measurement in terms of vapor stratification, vapor temperatures, and background heat load, we inserted a vent tube at the current lead level with features to prevent oscillations (shown in Figure 5). This setup was used in making the heater tests described in Figure 4.

CONCLUSIONS

The focus of this paper is on the thermal studies of current leads supplied by Intermagnetics General Corporation consisting of parallel tapes of BSCCO-2223 multifilamentary powder-in-tube conductor in a silver alloy matrix soldered to a conventional copper upper section. The HTS current leads carried the design current of 5 kA with good thermal and electrical stability. LN2 flow without current was 0.24 g/sec per lead and with 5 kA was 0.53 g/sec per lead, corresponding to heat inflows to the 80 K intercept of 46 Watts and 101 Watts, respectively. Due to the effects of helium transfer and vapor flow on the current lead environment and background heating, the best 4 K heat load results were obtained in self-sufficient mode with a continuous transfer of liquid helium to the test dewar. In self-sufficient mode, the helium boiloff rate was about 0.03 g/s, corresponding to a heat input to the 4 K level of 0.6 W with no current and 0.7 W +/- 0.1 W per lead with 5 kA current, about 1/8 of the heat load via conventional copper leads.

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REFERENCES

1. J. M. Lock, Optimization of current leads into a cryostat, *Cryogenics*, 9 (1969), 438-442.
2. G. Citver, E. Barzi, A. Burov, S. Feher, P. Limon, T. Peterson, Steady state and transient current lead analysis, *ASC'98*, Palm Desert, CA (1998).
3. R.C. Niemann, Y.S. Cha, and J.R. Hull, Perfomance measurements of superconducting current leads with low helium boil-off rates, *IEEE Trans. Appl. Superconductivity* 3(1):392 (1993).
4. M. Lamm, et. al., A new facility to test superconducting accelerator magnets, *PAC'97*, p. 3395, Vancouver, B.C., Canada (1997).
5. J. Nogiec, et. al., Architecture of HTS leads software protection system, *PAC'99*, New York, NY, (1999).
6. G.Citver, S. Feher, P.J. Limon, D. Orris, T. Peterson, C. Sylvester, M.A. Tartaglia, J.C. Tompkins, HTS power lead test results, *PAC'99*, New York, NY, (1999).