HTS POWER LEAD TEST RESULTS*

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Abstract

R&D High Temperature Superconductor (HTS) power leads were developed and built for Fermilab by American Superconductor Corporation and Intermagnetics General Corporation. Each company provided one pair of 5kA HTS current leads, and these have been successfully tested at Fermilab. This paper summarizes the test results.

1 INTRODUCTION

Conventional power leads carry electric current from room temperature to the superconducting magnets in the Tevatron at Fermi National Accelerator Laboratory. Over 50 pair of leads carry up to 6000 amps of current and result in substantial heat loads for the cryogenic system. Reducing the total heat load to the liquid helium temperature level would allow either savings in operational costs or make more refrigeration available for lower temperature and higher energy operation of the Tevatron. Using a combined liquid nitrogen and liquid helium cooled power lead design, one can reduce the heat load to LHe by a factor of ten. A proposal to replace most 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 and Intermagnetics General Corporation each developed and built a pair of 5000A HTS current leads. These leads went through extensive tests at Fermilab.

2 TEST APPARATUS

The HTS power lead testing equipment is located in the Magnet Test Facility (MTF) at Fermilab. The mechanical system consists of a liquid nitrogen shielded helium cryostat with a baffle system that includes an 80 K intercept, and the instrumentation necessary to monitor mass flow rates, measure and regulate system pressures and liquid level, and record system temperatures. The 20 inch diameter by 42 inch long helium vessel is sized to accommodate power lead pairs, which are spaced on a 4 inch center-to-center distance, and are up to 30 inches 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 volume from the volume immediately around the power leads, the leads are housed inside a glass/epoxy tube that extends from the cover plate to several inches below the minimum liquid helium level in the main dewar. To further thermally isolate the two volumes, the power lead pair and glass 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 1/8 inch of H_2O pressure changes was installed to help maintain a constant pressure in the main bath, while pressure changes may be occurring inside the glass/epoxy tube.

The mass flow meters and rotameters used in the system were carefully calibrated and sized to operate effectively over the range of flows required. A simplified mechanical system schematic is shown in the online overview, Figure 1.

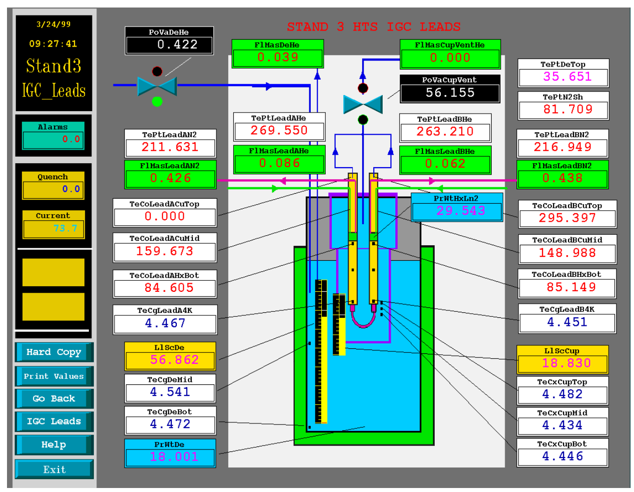

Figure 1: Schematic overview of the HTS test setup.

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 [3]. Temperature and voltage measurements from the DAQ scans are monitored by a new software quench detection system [4] 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.

* Work supported by the U.S. Department of Energy.
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The quench thresholds were set low, for any temperature rise of 5K above the zero-current baseline temperature profile, or HTS (Copper) voltage (imbalance) greater than one(32) millivolt(s). 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 1K for temperatures, and less than 3 μV for voltage taps at 5000A.

3 THE LEADS

American Superconductor Corporation (ASC) and Intermagnetics General Corporation (IGC) developed and built HTS leads following the Fermilab lead specification (see Table 1). Both companies utilized Ag-alloyed sheathed BSCCO-2223 (powder-in-tube) multifilamentary high temperature superconducting tapes between 4K and 80K cooled with helium liquid and vapor. The upper section (80K-300K) of the lead was made from copper cooled with liquid and gaseous nitrogen and helium vapor. The vendors instrumented these R&D leads with RTD temperature sensors and voltage taps across HTS and copper sections.

Table 1: Lead specifications and requirements

Gas cooled power lead operating between 300 - 4.3K
Maximum operating current 5000A
Case leak rate to vacuum $< 2x10^{-8}$ atm cc/sec
Low helium consumption
Thermal intercepts at 80K
Voltage standoff to ground or other lead $>$ 2000V
Magnetic field environment $<$ 100 gauss
Radiation environment $\sim$ 1-5 Rad/hour
Electric current decay time constant = 12 second
Cool down rate from 80k to 4.3K within 60 sec
Robustness, withstand thermal cycles

4 TEST HISTORY

4.1 ASC Lead

The first version of the ASC lead was tested in December, 1997. At recommended helium and nitrogen flow rates, neither section of the lead exhibited stable operation. At 3500A DC operation the voltage across the HTS section rose slowly and exceeded the 1mV threshold limit specified by the vendor. Voltage across the copper section also rose and showed no sign of reaching a stable value. The HTS section of the lead was re-built and was then successfully tested in August, 1998, reaching 5000A stable operation. In October 1998 the lead was tested again, however a leak developed between the helium and nitrogen flow passages making it impossible to continue the test. In the following discussion, we only refer to the second version of the ASC lead [2] and the August, 1998, ASC test results.

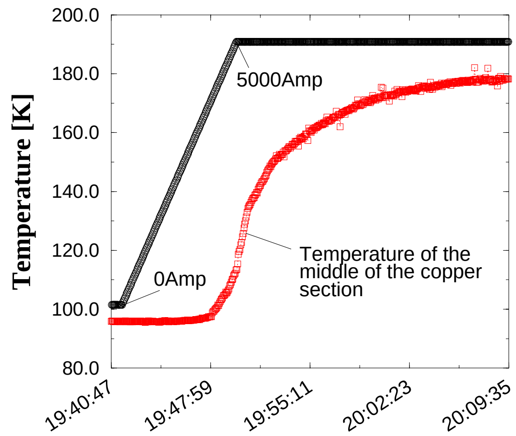

Figure 2: Temperature rise of the middle of the copper section due to 0 to 5000A current ramp.

4.2 IGC Lead

The IGC lead was first tested in March-April, 1998. Unreliable lead temperature sensors made the test difficult and required in-situ calibration. The lead was able to conduct 5000A steadily. In May, 1998, the lead was tested again. In an attempt to quench the HTS section, the current was raised to 7500A. At this current the low temperature superconductor (LTS) cable attached to the bottom of the lead burned out. The lead was repaired with a better transition to the LTS cable. Several successful tests to 5000A have been performed since then.

5 TEST RESULTS

The primary goal of the tests was to verify whether the leads met all the requirements and specifications. First, nominal cooling conditions were established, then the current was ramped up to 5000A. All the lead temperatures and voltages at both sections (copper and HTS) of the lead remained unchanged after equilibrium was reached, indicating steady-state operation. The next test verified that stable operation can be achieved by ramping the current up and down at 350A/sec between 0 and 5000A. Both temperature and voltage values were stable but not constant; temperature showed periodic behaviour correlated with current, as one would expect.

Extensive thermal studies on the copper section, including temperature profiles as a function of nitrogen flow rates and transient effects due to sudden change of the current or nitrogen flow rate, were performed on the IGC lead and the results were compared with calculations [1]. A fast response to transients was found. In Figure 2, the temperature rise of the middle of the copper section as a function of time after ramping the current up to 5000A is plotted. It took 15-20 minutes to reach stable operation.

We also measured the minimum liquid nitrogen flow rates required to keep the upper part of the HTS section at

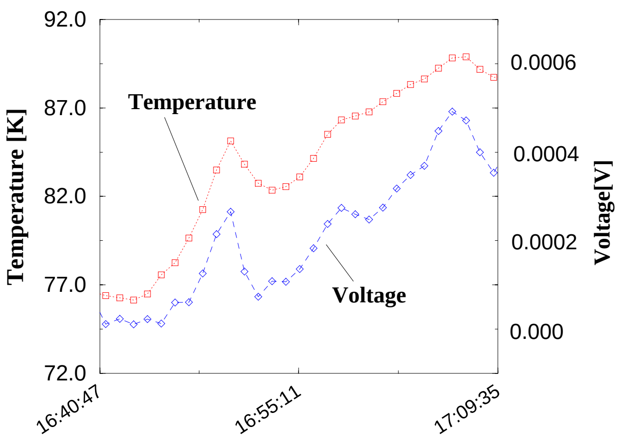

Figure 3: Voltage of the HTS section and temperature at the top of the HTS section are plotted as a function of time.

80K (see Table 2). All of the measured values show good agreement with calculations [1]. Both current leads were able to operate with no helium flow through the lead. The current flag temperature was kept close to 300K by using a water heater-chiller attached to the flag. There was no need to regulate the coolant flow rate as a function of current; no freezing at the top of the lead was observed even at 0A applied current and nominal coolant flow rates.

Table 2: Minimum liquid nitrogen mass flow rates at nominal liquid helium mass flow rates (IGC lead).

Vendor recommended (g/sec)	measured (g/sec)	Applied current (Ampere)
0.30	0.24	0
0.83	0.53	5000

Voltages across the HTS section, across the HTS-copper joints, and across the HTS-LTS joints were measured. Both IGC and ASC had low joint resistances (ASC: 80-100nΩ, IGC: 12 nΩ) and low voltages ($\sim$ 25μV) across the HTS section at 5000A and nominal coolant flow rates.

A quench performance study of the IGC lead was carried out at 5000A DC: the voltages across the entire HTS section were monitored as the temperature of the upper part of the HTS section was increased, by varying the nitrogen flow rate. The voltage-based quench detection threshold was set to 1mV. The voltage change was highly correlated with the temperature change (see Figure 3). There was no sign of any instability even if the HTS was forced to operate in current sharing mode. The temperature at the middle of the copper section also rose and stabilized around 300K. It seems that protection of the copper section of the lead would be sufficient for protection of the entire lead, since loss of cooling would be seen in the copper section first. It was hard to do further quantitative analysis of the HTS section since the temperature values were not accurate.

The IGC lead went through several thermal cycles (see Table 3) and was then power tested successfully. There was no performance degradation observed.

Table 3: Thermal cycles.

HTS upper section from 300K to 80K and HTS lower section from 300K to 4K	x5
HTS upper section from 300K to 80K and HTS lower section from 300K to 80K	x22
HTS upper section from 200-300K to 80K and HTS lower section from 50-150K to 4K	x8

The heat leak to the cold (4K) end of the lead was estimated by measuring the evaporation rate through the lead while keeping the helium liquid level constant and high enough to reach the bottom of the current lead. The LTS part of the lead was completely immersed in liquid helium. The liquid level was controlled by adjusting the outgoing helium gas flow rate through the lead. Due to background effects we were able to estimate only the upper limit of the heat load. ASC and IGC helium boil-off rates were less than or equal to 0.045 g/sec and 0.050 g/sec, respectively.

6 CONCLUSIONS

Two pairs of HTS current leads (from ASC and IGC) were successfully tested at Fermilab. Stable steady-state operation was observed at nominal cooling conditions and at nominal 5000A current. The transient effect recovery time in the copper section of the IGC lead was fast ($\sim$15 min). Low joint resistances (ASC: 80-100nΩ, IGC: 12 nΩ) and low voltages ($\sim$ 25μV) across the HTS section were measured at nominal current and cooling conditions. There was no sign of any instability even if the HTS was forced to operate in current sharing mode. There was no performance degradation observed due to thermal cycles. The upper limit on the heat leak to the helium bath was estimated (ASC: less than 0.045 g/sec; IGC: less than 0.050 g/sec).

7 REFERENCES

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