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Tevatron HTS Power Lead Test

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***Abstract*—Two pairs of ASC 6 kA power leads developed for the Tevatron were successfully tested at Fermilab at over-current conditions. Stable operation was achieved while operating at a current of 9.56 kA for five hours and while continuously ramping between 0-9.56 kA at a ramp rate of 200 A/s for one hour. The minimum required liquid nitrogen flow rate was measured to be 1.5 g/s at 10 kA. After ramping up to 10 kA at 200A/s, it took only 15 minutes to stabilize the upper copper section of the lead with a flow of 1.8 g/s of liquid nitrogen vapor. Testing under extreme operating conditions – 270-370 kPa liquid nitrogen vapor pressure and over 0.1 T external magnetic field – demonstrated that the HTS part of the lead can safely operate in the current sharing mode and that this design has large operating margin.**

***Index Terms*—Accelerator, Superconducting magnet, HTS leads**

I. Introduction

A NEW Interaction Region (IR) for the BTEV experiment is planned to be built soon at Fermilab. This IR will require new superconducting quadrupole magnets and additional power circuits for their operation. The design of these new "low beta" quadupole magnets will be based upon the Fermilab LHC quadrupole design, and the magnets will operate at 9.5 kA in 4.5 K liquid helium. The use of conventional power leads for these circuits would require substantially more helium for cooling than is available from the cryogenic plant, which is already operating close to its limit. To decrease the heat load and helium cooling demands, the use of HTS power leads is necessary.

Fermilab has both test and operational experience with 5 kA and 6 kA HTS power leads produced by American Superconductor Corporation (ASC) and Intermagnetics General Corporation (IGC) [1]-[2]. A test subjecting ASC HTS power leads to over-current conditions was conducted to evaluate their use in powering the BTEV circuits. The primary goal for the test was to evaluate the operational stability at 9.56 kA with a 5% margin, and at an elevated temperature of the copper-HTS junction (~82K).

HTS leads were tested in two different configurations: i) one pair of leads already installed in a Spool piece; and, ii) a second pair of leads mounted in a test dewar. This paper summarizes the test results.

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II. Test Setup

A. ASC Power Leads

HTS current leads consist of parallel tapes of BSCCO-2223 multifilamentary powder-in-tube conductor in a silver alloy matrix soldered to a conventional copper upper section. The vapor-cooled conventional copper section operates between room temperature and two phase nitrogen temperature, while the HTS section operates between this region and 4 K. The leads are instrumented with voltage taps attached to the copper section (V1-V2) and HTS section (V3-V4) separately. At the HTS and copper section joint embedded into the copper block, platinum based temperature sensor was installed.

B. Spool Piece at Stand 2

Some of the conventional leads in the Tevatron were replaced with HTS leads. Among the several different types of devices which contain high power leads, a multi-purpose cryogenic component of the Tevatron, an "H-spool", was chosen to be retrofitted with HTS power leads. Of twelve H-spools, four have been retrofitted and three of them contain ASC 6kA HTS leads. Since the three spools containing ASC power leads are Tevatron spares, it was possible to use one of them for the test. H-spool TSHH 296 was selected and mounted on Stand 2 (a standard test stand for testing Tevatron components) in the Magnet Test Facility (MTF). Since this stand has limited current and signal readout capability, the power distribution and readout system were borrowed from an adjacent test stand, Stand 3. In order to simulate a "worst case" condition, a permanent magnet was placed on the outside of the spool close to region where the HTS tapes are at their highest operational temperature. The magnetic field close to the HTS tapes was about 0.1 T.

C. Stand 3

Stand 3 was designed to test HTS current leads. It contains a Cryofab dewar, has access to 10 kA and has a readout system specifically designed for monitoring and controlling liquid helium and liquid nitrogen vapor flows, temperatures, pressures and voltages across the leads. Recently this test stand was used to test HTS power leads developed for the LHC. Details of the test stand is described in details elsewhere [3].

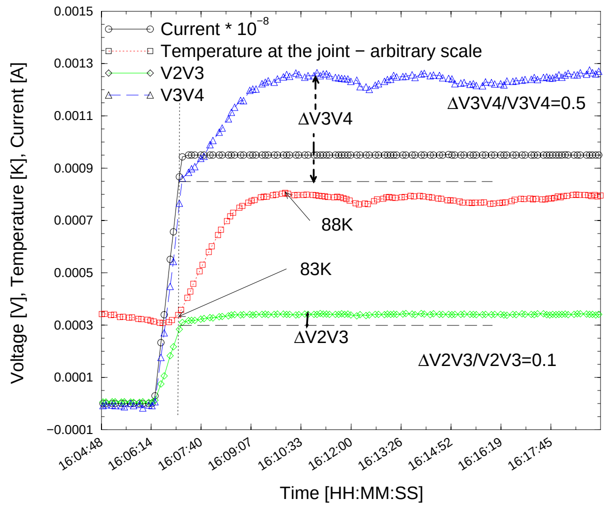

Fig 1. Voltage change of the copper and HTS section is plotted as a function of time. During this time period the current is at 9.5 kA but the temperature of the junction rose from 83 K to 88 K.

III. Test Results

A. *TSHH-296 test*

The test was performed in Spring of 2004. The HTS power leads were operated at 9.5 kA for several hours without observing any sign of instability in either the copper or the HTS section. Test conditions are summarized in Table I. During the test the coolant flows had to be kept steady and voltage drops along the copper and HTS sections were recorded. Clear proof of stable operation is when the voltages are steady. Unfortunately, we were not able to keep the coolant flows steady. Test Stand 2 was not designed to control liquid nitrogen (LN_2) pressure since LN_2 was used only to provide cooling of the thermal shields of magnet (or spool) cryostats. Due to the change of the LN_2 pressure the LN_2 flow fluctuated and with it the coolant temperature and cooling of the copper and HTS section varied as well. The observed correlation among these variables indicated that the change in voltage was not related to lead instabilities. On the other hand, due to large pressure fluctuations, we were not able to establish steady flow rates and consequently we were not able to measure the minimal LN_2 vapor flow required to operate the leads in a steady state condition.

TABLE I
TSHH-296 Spool Test and Test Conditions

Test	Time minutes	LN_2 flow g/s	LHe flow g/s	Current kA	LN_2 pressure kPa
DC	15	1.2	0.03	6	270-370
DC	15	1.4	0.03	7	270-370
DC	15	1.8	0.03	8	270-370
DC	15	2.2	0.03	9	270-370
DC	60	2.4	0.03	9.5	270-370

0.1 T external magnetic field was applied

In Fig. 1. the voltage rise as a function of time is plotted after the current ramped up to 9.5 kA. As the lead stabilizes, the temperature of the junction between the HTS and copper section rises from 83 K to 88 K. This means that the temperature of the copper block and the temperature profile of the HTS section of the lead is changing as well. Relative change of the copper block voltage (V2V3) measured between V1 and V2 voltage taps was 10 % which one would expect if the RRR value is around 100. Since the V3–V4 section contains part of the copper block as well as the HTS tapes, one would also expect a 10 % change in V3V4 voltages. However, we measured about a 50% change. This can be explained by assuming that the HTS section operates in the current sharing mode, so part of the voltage drop is coming from the contribution of the silver matrix of the HTS tapes.

TABLE II
L2576 (-) & L2585 (+) Test and Test Conditions

Test	Time minutes	LN_2 flow g/s	LHe flow g/s	Current kA	LN_2 pressure kPa
DC Stability	300	(-) 2.7-3.0 (+) 2.2	0.03	9.56	190
AC Stability	60	(-) 3.0 (+) 2.2	0.03	0-9.56 200A/s	190
Minimum Flow	~15	(-) 2.5 (+) 1.5	0.03	10	190
Minimum Flow	~15	(-) 1.9 (+) 1.3	0.03	8	190
Minimum Flow	~15	(-) 1.5 (+) 1.1	0.03	6	190
Minimum Flow	~15	(-) 1.2 (+) 1.0	0.03	4.4	190
Minimum Flow	~15	(-) 1.0 (+) 0.9	0.03	0	190
Coolant loss	~15	0	0.03	10	190
Transient AC => DC	50	(-) 2.8 (+) 1.8	0.03	10 200 A/s	190

No external magnetic field was applied

The HTS section of the lead was operated clearly in the current sharing mode (see Fig. 1.). This was expected since the LN_2 pressure was kept high, between 270-370 PSIA which corresponds to ~86-89 K and the external 0.1 T magnetic field also contributed to drive the HTS into current sharing mode. These conditions were extreme since the lead will never be exposed to LN_2 temperatures higher than 83 K and stray magnetic fields higher than 0.01 T in the Tevatron On the other hand this test was useful to show that the lead has a huge operational margin. This test also demonstrated that HTS current leads could be designed using a smaller amount of HTS tapes since one can achieve stable operation of the HTS part in current sharing mode.

B. *HTS Power lead test at Stand 3*

In August of 2004 another pair of ASC 6 kA HTS power leads were successfully tested at Fermilab. This test was performed in a dewar at Stand 3, discussed above. This time controlling the LN_2 pressure and flow rates was not difficult. The test and the test conditions are summarized in Table II.

1) DC and AC stability test

The leads were operated for five hours at 9.56 kA. Lead voltages and the junction temperature were stable. The HTS section resistance was dominated by the copper resistance – voltage taps were soldered to the copper blocks and not directly to the HTS tapes – and it was well below 1 mV. The current sharing mechanism this time was much smaller. During AC operation – ramping the current between 0-9.56 kA at a rate of 200 A/s – the voltages have to change, however, they changed periodically which means no average

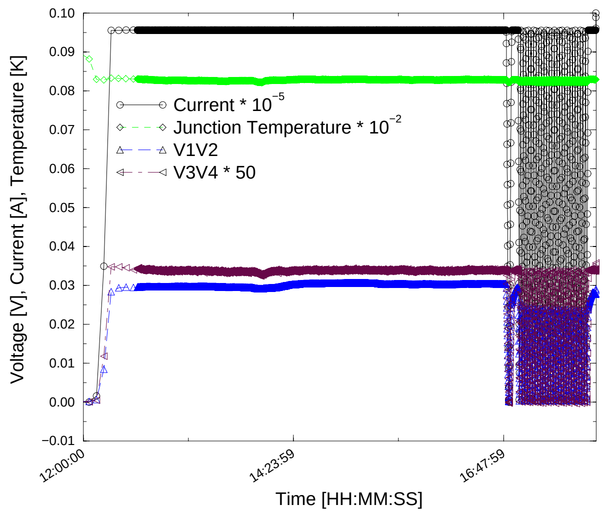

Fig 2. DC and AC stability test. The power supply was operated for 5 hours and no sign of instabilities were observed. Right hand side of the plot shows a high, 200A/s ramp rate test of the lead.

voltage growth was observed. This also means that stable operation was achieved (see Fig. 2.).

We also noticed that the two leads were not symmetric. The negative lead (L2576) required much more cooling to keep it stable (see Table II) and its copper section was more resistive. Once the higher flow rate was applied the lead exhibited the same stable operation than the other one. This asymmetry might be related to fabrication differences. If the copper material properties are different or if the solder joint at the bottom end of the copper section was not properly made, it would result in higher copper section resistance. At high (over 6 kA) current operation the HTS-copper joint temperature of the negative lead was few Kelvin higher than that of the positive lead. This is an indication that there must be a heat source close to the junction where the temperature sensor is located. Based on this fact the primary suspect for the cause of this asymmetry is a high resistive solder joint.

2) Coolant loss test

In order to prove that the lead is robust we performed a coolant loss test by closing the valve of the liquid nitrogen flow and waiting for the quench detection system to detect the abnormal situation and to ramp down the power supply. Both the HTS and copper section voltages were rising, however the copper section was the first to pass the threshold which was set by the manufacturer. We did not observe any irregular behavior of the lead operating them after the coolant loss test.

3) Minimum LN2 flow rate measurement

The minimum LN_2 vapor flow rate was measured by lowering the flow rate up to the point when the HTS-copper joint temperature started to rise above the LN_2 coolant temperature. Proper operation of the ASC HTS lead design requires fixed temperature at the joint. Once the temperature start to rise, both the copper and the HTS sections become unstable. It was important to determine the minimum LN_2 vapor flow rate value since based on this value one can set the flow rate just above the minimum flow rate where the lead exhibits stable operation and is not exposed to over-cooling

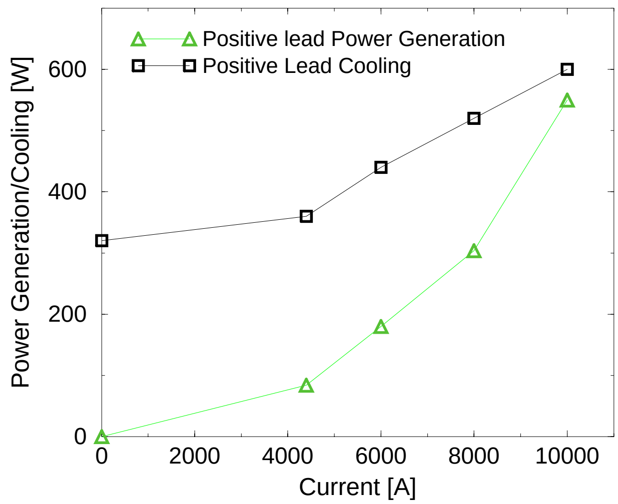

Fig. 3. Power generation and cooling power is plotted as a function of the applied current for those cases when the flow rates of the liquid nitrogen were kept at minimum.

conditions. The measurement results are summarized in Table II. At fixed DC values the LN_2 flow rates were adjusted in 0.2 g/s increments giving about ±0.1 g/s error to each data point.

The voltage drop along the copper section was also measured making it possible to calculate the power generation within the lead. Converting the LN_2 vapor flow into cooling power by assuming that the lead warms the vapor to 300 K at

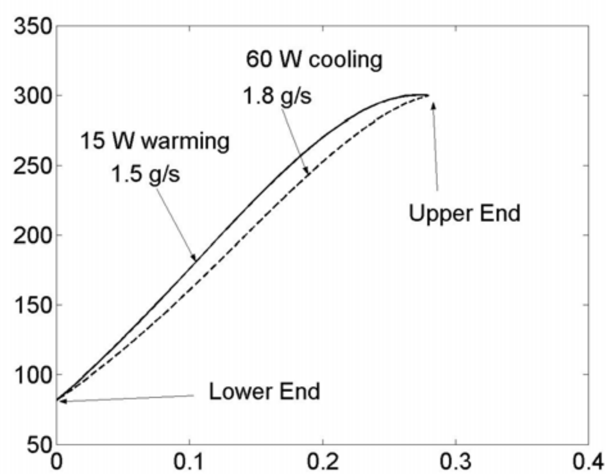

Fig. 4. Power lead upper section temperature profile operating the lead at 10 kA. Upper end of the lead is kept at 300 K and lower end is kept at 82 K. Applying 1.5 g/s LN_2 cooling at 10 kA the heat flow at the upper end is pointing outside of the lead.

the outlet of the lead, the power generation can be compared with the cooling power (see Fig. 3.). From Fig. 3. one can readily see that the lead was definitely not optimized to 6 kA. A well optimized lead at the operational current should generate heat equal to what it is carried away by the vapor passing through the lead. For the ASC upper section, the generated heat is much less than the cooling power used at 6 kA. On the other hand around 10 kA the lead seems to operate closer to the optimum case. Since we did not measure the outlet LN_2 gas temperature we do not know how cold the outlet gas was. If it was much colder than 300 K we might have introduced a significant error in translating the flow rate into cooling power; but the tendency is clear, the optimum operation of the lead is around 10 kA.

The temperature profile of the upper copper section of the ASC lead was estimated by using a mathematical model developed for analyzing R&D current leads at Fermilab [4].

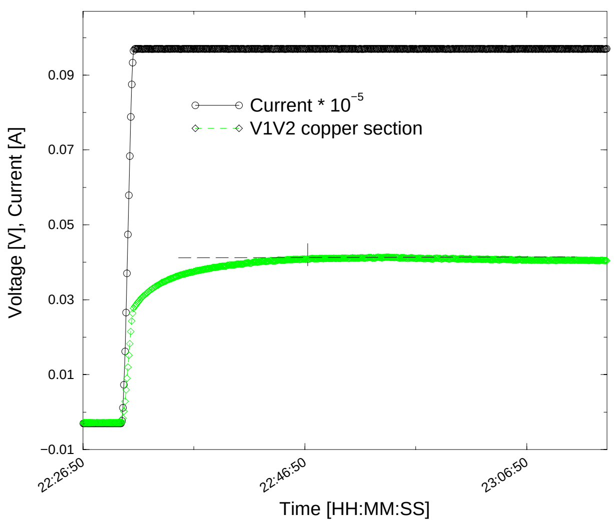

Fig. 5. Transient behavior of the upper section of the lead at 10 kA. The ramp rate was 200 A/s.

Once the temperature profile is available the resistance of the lead can be calculated and the voltage drop across the lead can be compared with measurements. Resistance measurements at room temperature were used to determine the effective cross section of the lead; then using the lead model, the voltage drops were estimated for different current and cooling conditions. The values for the positive lead were in good agreement with the measurements. However, applying the same method for the negative lead, a large difference was observed. This difference can be explained by introducing a large solder joint resistance at the colder end of the copper section which will not scale properly with the cross section.

In Fig. 4. two temperature profiles are plotted using two different flow rates at 10 kA. By differentiating the temperature profile we were also able to calculate the heat flow at the upper end of the lead. At 1.5 g/s flow rate, the temperature change at the upper end of the lead is almost flat and the heat flow is even slightly negative. This means that the power lead flag has to be cooled in order to keep the upper end at 300 K. This calculation also shows that for this lead design the optimum current value is close to 10 kA. For 1.8 g/s flow rates however, the flag has to be heated to keep it at 300 K. The amount of heat needed is not too large, only ~60 W.

4) Transient Test

Once the minimum LN_2 vapor flow rate was determined we adjusted the flow rates of the leads 0.3 g/s higher than the minimum value and retested the leads at 10 kA. The primary purpose for this test was to verify that the leads will become stable after a sudden current change. Sudden current change was achieved by ramping up the current to 10 kA at a rate of 200 A/s. In Fig. 5. the current and voltage profile are shown as a function of time. After about fifteen minutes the lead voltages of the upper section were stable: the lead reached steady operation.

IV. Conclusions

Two pairs of ASC 6 kA HTS leads were successfully tested at Fermilab in two different configurations – one pair was tested in a spool piece and another pair was tested in a dewar. All leads exhibited stable operation at 9.5 - 10 kA. The leads were also successfully operated at 200 A/s ramp rate between 0-9.56 kA showing no sign of instabilities.

Optimum operation of the upper section of the lead favors 10 kA rather than its designed 6 kA current value around 1.5 g/s $\mathbf{LN_2}$ flow rate. The HTS section was tested under extreme operational conditions where temperatures were elevated to 86-89 K and a ~0.1 T external field was applied. Although the HTS was operating in current sharing mode, it was stable.

The ASC designed 6kA HTS current leads are capable of operating at 9.56 kA required to power the LHC type quadrupoles for the BTEV interaction region.

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