

Full Cryogenic Test of 600 A HTS Hybrid Current Leads for the LHC

M. K. Al-Mosawi, S. A. March, C. Beduz, A. Ballarino, and Y. Yang

Abstract—For full cryogenic test of CERN 600 A High Temperature Superconducting (HTS) current leads prior to integration into the Large Hadron Collider (LHC), a dedicated facility has been designed, constructed and operated at the University of Southampton. The facility consists of purpose-built test cryostats, 20 K helium gas supply, helium gas flow and temperature control systems and quench protection system. Over 400 such leads have already been successfully tested and qualified for installation at CERN. This paper describes various design and operation aspects of the test facility and presents the detailed cryogenic test results of the CERN 600 A current leads, including steady state 20 K flow rates.

Index Terms—Accelerator technology, cryogenics, current leads, high temperature superconductors (HTS).

I. INTRODUCTION

THE comprehensive implementation of HTS current leads in the LHC at CERN [1] represents a major breakthrough for large scale practical applications of high temperature superconducting materials. After more than ten years of extensive R&D effort by CERN and several external partners, the production design was adopted by the end of 2003 for three classes of current leads rated at 13000 A, 6000 A and 600 A with different performance specifications. A total of about 3 MA current is to be transported by these current leads using 31 km of HTS conductors. Pre-production current leads of each class, about 15% of the total, were first manufactured and tested at CERN during 2004, and the remainder were contracted for external production. As this paper is being prepared, the manufacturing process has proved to be a successful operation with more than 80% completed. The extensive R&D activities over the last 10 years with meticulous cycles of design, test, and debug of the prototypes and pre-production series laid solid foundations for the smooth progress of the current lead production.

While the current leads are being manufactured, CERN has implemented a parallel qualification programme for full cryogenic test of every current lead prior to installation in the LHC. The full cryogenic test is designed not only to check the robustness of the construction upon cryogenic cycles, but also to en-

sure that each lead satisfies the thermal and electrical requirements [2] under real operating conditions.

This paper reports on the progress of full cryogenic testing of 600 A HTS leads undertaken by the Institute of Cryogenics, University of Southampton. As four individual 600 A leads are integrated as an assembly on a common insulating flange, significant complexities are added to the test-bed for such assemblies compared to those for 12000 A and 6000 A leads, which are tested with two individual leads in tandem. In addition to the double number of recorded instrumentation, the controlled flow of four independent 20 K helium gas streams is considerably more challenging. A detailed description of our 20 K gas generation and delivery/control system, which has been in consistent and stable operation for more than 100 tests at conditions required by the LHC, is given below.

II. TEST-BED SETUP FOR 600 A CURRENT LEADS

The test-bed setup at Southampton for the 600 A leads consists of four major parts: cryostat for current leads, 20 K helium gas generator and distribution system, temperature/flow control system, and data acquisition and protection system. A schematic drawing of the whole test-bed setup including the control circuits is shown in Fig. 1.

A. Cryostat

Two purpose built cryostats were used in order to achieve the required test throughput of minimum four assemblies per week. In addition to the standard double wall vacuum super-insulation, common to liquid helium vessels, the cryostat required further optimization of vapor cooling by He boil-off to reduce the conduction heat leak through the wide straight inner vessel. An overall heat leak of 1 W was achieved so that the helium level could be maintained comfortably within ± 2.5 cm of the required position during the whole test.

B. 20 K Helium Gas Generation and Delivery System

Cooling of the resistive copper section of the current lead by a 20 K helium gas, available to LHC at no extra cooling cost, is the key to design and stable operation of the LHC HTS current leads and is integral to the overall reduction of the heat load achieved. Therefore the full cryogenic test should be carried out with the generation and delivery of 20 K gas in conditions as close as possible to that used by the LHC accelerator.

The 20 K gas helium generator (lower left corner in Fig. 1) at Southampton was effectively a pressure controlled boiler incorporated into a standard liquid helium vessel as a container. An immersed heater was used to generate the boil-off with the heating power regulated by a PID controller to maintain the vapor pressure at a given level (30 kPa gauge in this case). The temperature of the vapor was homogenized and maintained at

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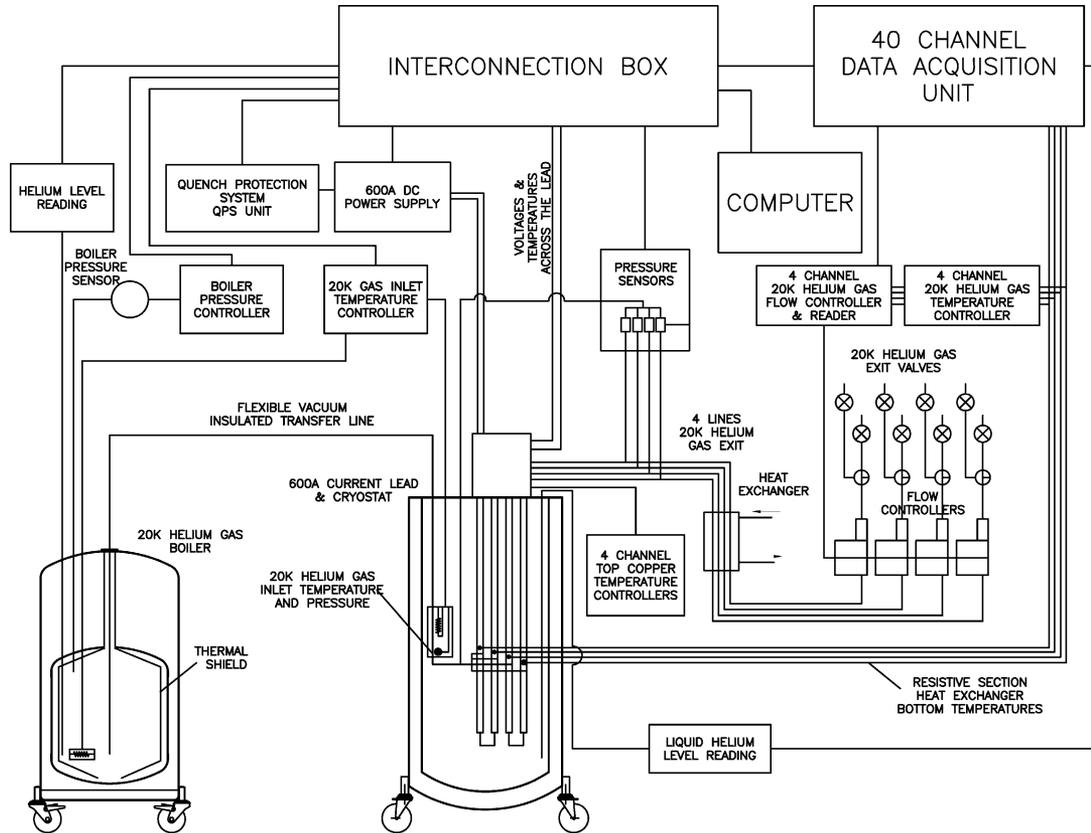


Fig. 1. Schematic of the test-bed including 20 K helium gas generator, test cryostat, instrumentation, and control circuits for temperature and gas flow.

close to the corresponding saturation temperature by a copper screen, which is immersed in liquid helium at one end and extends to the top of the vapor space at the other end. A standard liquid helium transfer line inserted into the vapor space was used to draw cold helium gas to the test rig. The heat leak along the transfer line was reduced by cryo-pumping via a thermal anchor connected to a copper cold finger extended to the liquid helium. With such an arrangement, the exit temperature of helium gas was reduced to below 12 K at the required nominal flow rate.

C. Temperature and Flow Control of the Test Circuit

The cold helium gas delivered through the transfer line from the gas generator was directed to a copper mesh heat exchanger integrated inside the test cryostat (Fig. 1). A PID controlled heater was used to maintain the heat exchanger at a constant temperature of 20 K, at which the cold helium gas was thermalized after passing through the heat exchanger.

The flow rate of 20 K helium gas through an individual lead was set by maintaining a constant temperature of 50 K at the top of the HTS section. For each lead, a PID temperature controller was used to generate the flow rate set point for the corresponding flow controller at the warm exit. The PID flow controllers could settle to the set point within a typical time constant of less than a second.

A shut-off valve and a rough needle valve were also installed at the exit of each leads for the required cut-off/power-down test, and for setting the upper limit of the flow rate during initial cooling down respectively.

D. Instrumentation and Protection

As specified in the test schedule, there were thirteen monitored instrumentation for each current lead including four thermometers (two on the copper connection block at room temperature and two on the top of the HTS section), five voltage drops (two along the resistive section, two along the HTS section, and one across the low temperature superconducting (LTS) link between two current leads), the flow rate of 20 K helium cooling gas for the resistive section and the corresponding pressure drop. In addition, the liquid helium level, the 20 K gas inlet temperature and pressure were also recorded. The protection of the current leads would be activated by immediately reducing the current to zero when either any one of the HTS or LTS voltage exceeded the specified level, or one of the four 20 K helium gas flow was below a minimum level.

III. RESULTS AND DISCUSSION

A. Procedure for Full Cryogenic Test

The full cryogenic test consisted of both mechanical and thermoelectrical assessments prior to, during, and after cooling down to helium temperature.

The mechanical tests on the leak tightness of the envelope cryostat and the 20 K helium gas circuit of the current lead were carried out using a standard helium leak detector. The thermoelectrical tests were performed to assess the performance of 20 K heat exchanger at the top of HTS section, the operation of

HTS section under superconducting conditions, the high voltage insulation of each assembly in normal conditions, and individual instrumentation connections.

Of all the leads tested so far (> 400), no important failures were found. This paper will focus on the thermoelectrical behavior given by the recorded instrumentation.

B. Operation and Performance of the Test-Bed

After mechanical and electrical test at room temperature, each assembly of four current leads was cooled down by transferring liquid helium to the test cryostat. A transport current of 5 A was injected into the four current leads connected in series so that the electric resistance of the copper and HTS sections could be recorded during cooling down. When the helium reached about 50% of required level, 20 K gas flow was introduced to each lead to assist the cooling down of the resistive section. The flow is regulated so that a set temperature of 48 K was obtained at the inlet heat exchanger located at the top of the HTS section. Once the flow and temperature were stabilized, the current was ramped up at 40 A/s to 600 A, which was kept for two hours. Then the 20 K gas flow was interrupted and the current was ramped down exponentially in ten seconds. The data acquisition and protection were fully automated while operating in parallel with the autonomous temperature/flow control system. No manual intervention was required during the two hours of full current test.

For all the full current tests so far, the 20 K gas generator has worked flawlessly without experiencing significant fluctuation, loss of temperature, or blockage. We are satisfied that the 20 K gas was delivered as required by the LHC.

C. Key Instrumentation and Typical Test Results

As mentioned above, the key instrumentation for the thermoelectrical assessment are the resistance/voltage of the resistive copper section (R_{Cu} and V_{Cu}) and HTS section (R_{SC} and V_{SC}), the temperature of the 20 K inlet heat exchanger (T_{HEX}) at the top of the HTS sections and the 20 K gas flow rate (m_{He}) in each leads.

1) *Cool Down Behavior:* Fig. 2 shows the key instrumentation results as function of time during cool down. In the upper pane, the temperature at the top of the HTS section T_{HEX} and the 20 K gas temperature before entering the inlet T_{He} are plotted against the left vertical axis, together with the 20 K gas flow rates and the liquid helium level H_{He} against the respective vertical axes on the right. The origin of H_{HE} is at bottom of the HTS section. The resistance of the HTS section and copper section are shown in the lower pane against the left and right axes respectively. It should be noted that the thick line for T_{HEX} contains all the readings of all four thermometers, one from each current lead. Even at the initial cooling stage without any 20 K gas, all the current leads showed a consistent cooling behavior.

The dynamics of the initial cooling stage during liquid helium transfer to the cryostat can be found in the resistance of HTS section. While recording started at time zero, stable delivery of liquid helium into the cryostat was established after about 6 min, when a sharp reduction in R_{SC} occurred (marked as I in Fig. 2). For the next 15 min or so, R_{SC} continued to reduce as the lower

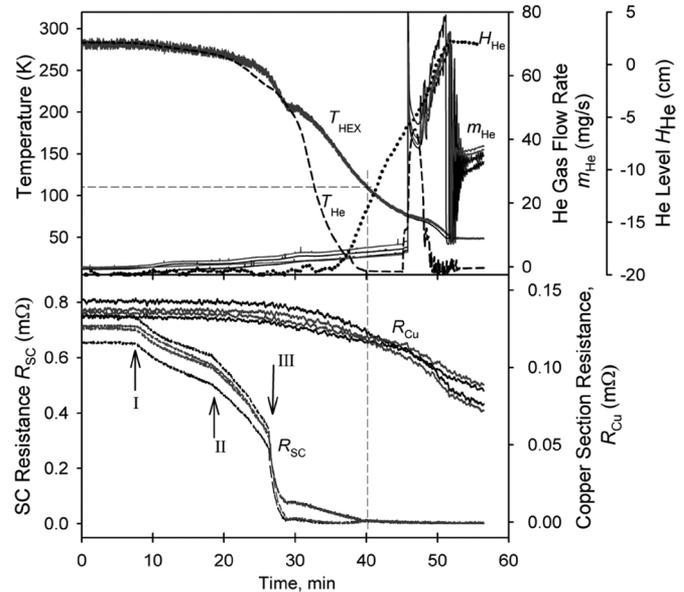


Fig. 2. Cool down time series of 20 K gas flow rate, resistive-HTS junction temperature T_{HEX} , 20 K inlet temperature T_{He} , and liquid helium level H_{He} in the upper pane and resistance of the resistive copper section R_{Cu} and HTS section R_{SC} in the lower pane.

section was cooled by cold helium vapor, boiled off immediately after entering the warm cryostat. During this period, very little temperature reduction took place in T_{HEX} and T_{He} . Prior to commencing the 20 K gas flow, the latter is a rather good approximation of the ambience temperature in the lower region of the cryostat. At about 20 min, a further steep drop in HTS resistance developed at II, corresponding to the start of liquid helium collection at the bottom of the cryostat. At the same time, T_{He} also started to decrease significantly, followed later by T_{HEX} . It should be noted that the helium level at more than 20 cm below the bottom of the HTS section was beyond the length of the level sensor, as shown as a constant -20 cm in Fig. 2. After another 5 min at III, R_{SC} fell suddenly as the liquid helium reached the LTS links between the current leads, extending about 15-20 cm from the bottom of HTS. The high thermal conductivity of the LTS wires led to a rapid cooling of bottom section of HTS conductors. As the liquid helium level continued to rise, the ambient temperature inside the cryostat represented by T_{He} decreased quickly. In contrast, the temperature T_{HEX} at the top of the HTS fell at a significantly slower rate due to the large thermal mass of the copper section, which was almost in adiabatic condition without the flow of 20 K gas. The HTS section remained partially normal with a slowly diminishing resistance as a large temperature difference remained between the upper (T_{HEX}) and lower (T_{He}) regions of HTS conductor. At about 40 min, T_{HEX} finally reached ~ 110 K where the whole HTS section became superconducting at 5 A, as indicated by the short-dashed lines. The liquid level also rose to about 13 cm from the bottom of HTS section.

The flow of the 20 K gas was switched on at 45 min when the liquid helium level climbed to within 5 cm of the bottom of the HTS section and the top of the HTS was cooled down to 70 K. As it took some time for the transfer line of the 20 K gas to cool down, the inlet gas temperature T_{HE} initially increased sharply

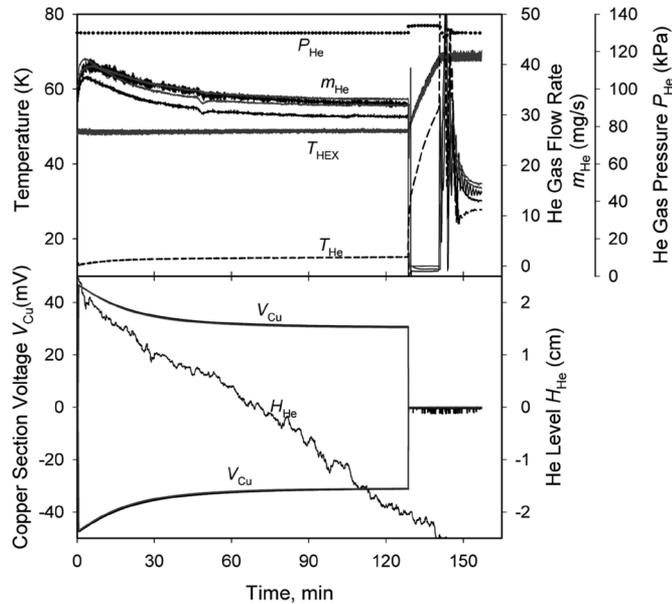


Fig. 3. Full current and standby time series of 20 K gas flow rate, resistive-HTS junction temperature T_{HEX} , 20 K inlet temperature T_{He} and pressure p_{He} in the upper pane and voltage drop V_{Cu} along the resistive copper section and liquid helium level H_{He} in the lower pane.

then quickly fell back to become settled at about 20 K in about 5 min. The 20 K gas flow was limited to 80 mg/s while T_{HEX} was brought down to 48 K. The flow was then cut back automatically by the temperature controller and gradually settled down to about 30–35 mg/s.

2) *Full Current Test:* With both T_{HEX} and m_{He} stabilized with a liquid helium level no more than 2.5 cm above the bottom of the HTS section, full current test was ready to commence. A typical example of the test data collected during a full current test is shown in Fig. 3. It can be seen that the temperature T_{HEX} at the joint between the resistive and HTS sections was kept constant at 48 K for all four current leads during the two hour long test. The corresponding 20 K gas flow rates gradually decreased to steady state after an initial increase at the injection of 600 A full current. The time constant for reaching the steady state was about 90 min, as also manifested in the voltage drop V_{Cu} along the resistive section. As shown in the lower pane, the steady state $V_{Cu} \sim 32$ mV (\pm with the four leads connected in series) was 25% lower than the initial ± 45 mV. In accordance to the test specification, the liquid helium level fell less than 5 cm during the test while the 20 K gas pressure p_{He} was kept constant at 30 kPa gauge. When the 20 K gas flow was switched off after two hours, the current was ramped down exponentially in 10 sec. No noticeable increase in T_{HEX} was detected.

3) *Standby Condition:* Following the full current test, the temperature controller regulated the flow of 20 K gas to achieve the standby condition of $T_{HEX} = 70$ K. This was typically

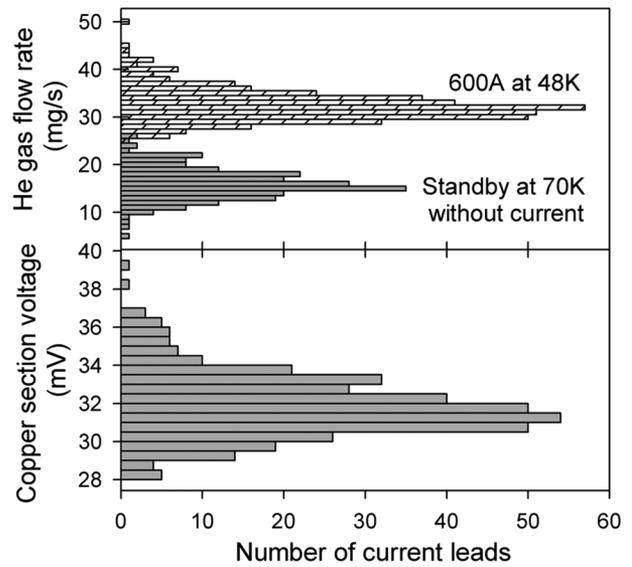


Fig. 4. Distribution histograms of steady state 20 K gas flow rate at full current and standby (upper pane) and voltage drop along the resistive section at 600 A (lower pane).

obtained in 20 min as shown in the upper pane of Fig. 3 with a lower $m_{He} \sim 15$ mg/s.

4) *Conformity Assessment:* Fig. 4 shows the performance of the 385 current leads which have been tested by June 2006. In the upper pane the histogram distribution of steady state 20 K gas flow rate at full current and the standby flow rate are plotted. The average flow rates were 32 mg/s and 15 mg/s respectively, with a spread of about ± 5 mg/s for both cases. The distribution of the steady state voltage drop along the copper section is given in the lower pane. The average voltage drop was about 32 mV. These values are fully within the specification of the current leads. During testing, no humidity nor ice were detected at the top of the leads during cool-down, stand-by, and nominal conditions.

IV. CONCLUSION

The full cryogenic test of 600 A current leads has shown that the expected performance has been verified in the mass manufactured assemblies of the contractors. Excellent consistency has been found in all the key performance indicators, such the steady state 20 K gas flow rate and voltage drop of the resistive section. The current leads also exhibited the required stability upon interruption of 20 K flow. No mechanical failures have been found so far.

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