FERMILAB-CONF-04-237-TD

# New Facility For Testing LHC HTS Power Leads

R. Rabehl, R. Carcagno, S. Feher, Y. Huang, D. Orris, Y. Pischalnikov, C. Sylvester, M. Tartaglia

***Abstract*—A new facility for testing HTS power leads at the Fermilab Magnet Test Facility has been designed and operated. The facility has successfully tested 19 pair of Pirelli HTS power leads, which are to be integrated into the Large Hadron Collider (LHC) Interaction Region cryogenic feed boxes. This paper describes the design and operation of the cryogenics, process controls, data acquisition, and quench detection systems. HTS power lead test results from the commissioning phase of the project are also presented.**

***Index Terms*—Control systems, cryogenics, power leads, test facilities.**

## I. Introduction

At each interaction region (IR) in CERN's Large Hadron Collider (LHC), high-gradient quadrupole magnets focus the particle beams into collision. The eight magnet cold masses at each IR are powered by HTS power leads integrated into cryogenic end boxes. Twenty pairs of these HTS power leads have been manufactured by Pirelli.

A new facility for testing these HTS leads has been designed, constructed, commissioned, and operated at the Fermilab Magnet Test Facility. The facility includes cryogenics, process controls, data acquisition, and quench detection subsystems. Nineteen pairs of Pirelli HTS leads have been cold tested thus far in this facility. The facility subsystems are described here along with test results from its commissioning.

## II. Facility Subsystems

### A. Cryogenics

The cryogenics system provides liquid helium to cool the power leads and the superconducting bus. Liquid nitrogen is provided to cool the thermal shielding. The HTS leads test facility is a stand-alone facility; cryogenic fluids are not supplied by the 1500 W helium refrigerator of the Fermilab Magnet Test Facility. Liquid helium and liquid nitrogen are both supplied from portable dewars.

The two power leads are mounted in a top plate assembly supplied by CERN. The top plate assembly includes a 2.5 cm thick stainless steel top plate, lead chimneys, baffles to reduce radiation heat transfer from 300 K to the 4.5 K liquid helium bath, penetrations for venting boiloff, and piping for the 20 K gas supply to cool the warm terminals and the copper sections. Temperature sensors, liquid level probes, and voltage taps are mounted after the power leads are installed.

The test dewar, fabricated by Cryofab, has a 51 cm inner diameter and is 107 cm deep. The dewar contains 100 l of liquid helium at normal test conditions. The test dewar also has a thermal shield cooled by a bath of liquid nitrogen.

A 500 l helium dewar supplies the test dewar bath. Helium is transferred from the portable dewar to the test dewar through a flexible transfer line and two U-tubes. The flow rate is controlled with a control valve built into one of the U-tubes. A PI (proportional-integral) control loop uses the test dewar liquid level as the process variable to control the valve and maintain a constant liquid level in the test dewar.

A second 500 l helium dewar supplies the helium flow required to cool and maintain the warm terminals at 50 K. Liquid helium from the portable dewar is pushed into a phase separator. The phase separator is a small, vacuum-jacketed helium vessel. There are six penetrations in the phase separator top plate for the liquid helium supply, the cold helium gas withdrawal, a relief valve and vent, a liquid level probe, a cartridge heater, and a temperature sensor. A 40 W cartridge heater, controlled by a PI loop-driven SCR power controller, is immersed in the phase separator helium bath to maintain a constant 30 cm of liquid in the phase separator. The boiloff produced by this heater has a typical measured temperature of 5 K before being recooled by the accumulated liquid and pushed into the downstream transfer line. The gas is then warmed to 20 K by a heater built into the downstream transfer line. The transfer line heater is a copper block with a 200 W cartridge heater and multiple holes through which the gas flows. Heat is transferred from the copper block to the gas. A PI loop, using the gas temperature as the process variable, interfaces with a second SCR power controller to control the cartridge heater and maintain a measured 20 K gas

Manuscript received October 4, 2004. This work was supported by the U.S. Department of Energy under contract No. DE-AC02-76CH03000.

R. Rabehl, R. Carcagno, S. Feher, Y. Huang, D. Orris, Y. Pischalnikov, C. Sylvester, and M. Tartaglia are with the Fermi National Accelerator Laboratory, Batavia, IL 60510 USA (phone: 630-840-8855; fax: 630-840-6724; e-mail: rabehl@fnal.gov).

temperature just upstream of the power leads.

Mass flow controllers regulate flows of up to 0.8 g/s of 20 K helium gas to each power lead. For each lead, a PI loop uses the warm terminal temperature as the process variable and then sends the appropriate command signal to the mass flow controller. The minimum pressure drop across these mass flow controllers is 0.69 bar (10 psid), but the upstream pressure is limited by the relief valve setting on the 500 l helium dewar. Therefore, the pressure downstream of the mass flow controllers is reduced using two Edwards ED660 mechanical vacuum pumps with 39 $m^3$/hr (23 cfm) displacement apiece. These pumps were sized to maintain the pressure drop across the mass flow controllers at the expected 20 K helium flow rate.

Fig. 1 shows the insert with a pair of installed power leads. The insert is being readied to be set into the test dewar, which can be seen behind and to the right of the insert. The instrumentation panel and Edwards ED660 mechanical vacuum pumps can be seen behind and to the left of the insert.

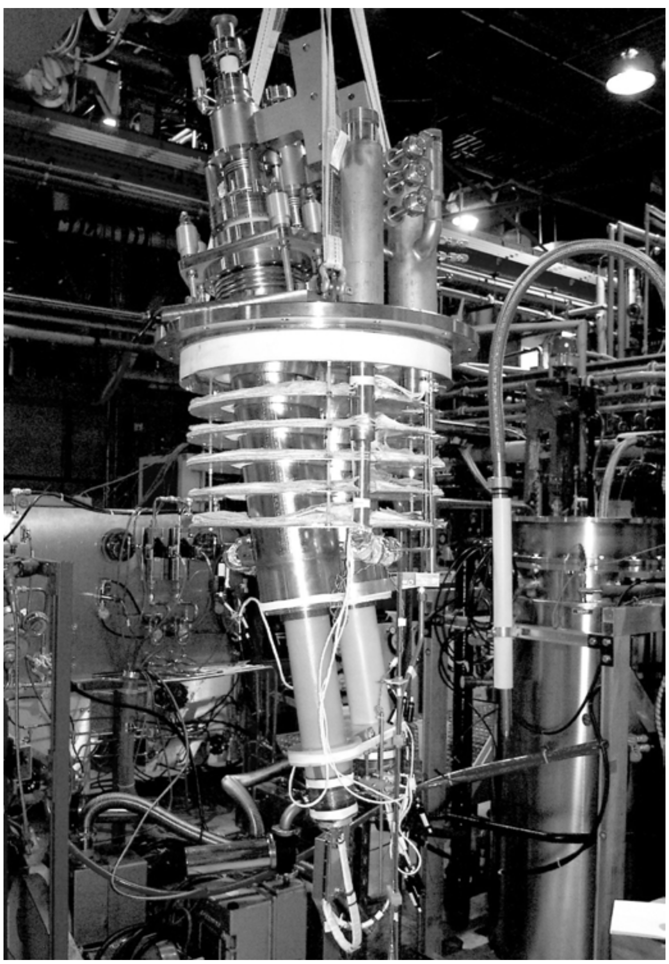

Fig. 1. The test dewar insert with two installed LHC HTS power leads.

### B. Process Controls

The test facility control system follows the architecture of the Magnet Test Facility (MTF) 1500 W refrigerator control system [1]. However, the test facility control system has a separate programmable logic controller (PLC) and shares a supervisory control and data acquisition (SCADA) node with an LHC quadrupole horizontal test stand. As a stand-alone facility, operation of the test facility is therefore unaffected by refrigerator operations. The test facility control system is also completely independent from the data acquisition (DAQ) and quench management systems. This is important in order to maintain cryogenic operability of the test facility in the event of reconfiguration or failures of these systems. Operators can easily navigate between refrigerator control displays and test facility control displays. Real-time and historical trending are available. An alarm management system and first-fault diagnostics logic help to quickly identify and troubleshoot problems. A software link allows two-way communication between the test facility control system database and the DAQ system. Table I shows hardware and software components of this industrial control system.

TABLE I
TEST FACILITY PROCESS CONTROL SYSTEM

| Subsystem | Choice |
|---|---|
| Programmable logic controller (PLC) | Siemens 505-454 PLC |
| Input/output (I/O) cards | Siemens 505 series |
| Control network | Ethernet with TCP/IP in a routed network |
| PLC programming language | FasTrak 505 Workshop |
| Operator interface software | FIX32 from GE/Intellution |
| Electrical loops | 24 VDC for discrete I/O, 4-20 mA or 0-5 VDC for analog I/O |
| Temperature sensors | Lakeshore Cernox RTDs with Model 234 temperature transmitter cards and platinum RTDs with Model 231P cards |
| Liquid helium level probes | American Magnetics superconducting level sensors and Model 135 liquid helium level monitor |
| External interface | ODBC interface to FIX32 real-time database |

### C. Data Acquisition

The test facility DAQ system follows the standard MTF DAQ architecture. Its main function is to provide accurate 4-wire measurements of devices such as temperature sensors. Fast sampling of these devices is not typically required, so this system is designed for relatively low sampling frequency (~8 Channels/sec). As an example of the DAQ system accuracy, assuming that all temperature sensors in a current chain are at around 4.5 K the absolute measurement error introduced by the DAQ system is approximately ±4 mK. Details of the DAQ system have been described elsewhere [2].

### D. Quench Detection

The quench management system performs the following tasks: it monitors/controls the power lead protection hardware, provides permits for the power system to turn on, and it monitors the power leads for resistive voltages (quench detection) [3] above the threshold. Typical thresholds are 100 mV on the copper section and 1 mV on the HTS section. In the event of a quench, it carries out the necessary actions in order to shut down the power supplies while logging power lead voltage data at a fast rate in order to characterize the quench.

## III. Facility Commissioning

Commissioning of the test facility began in March 2003 with the first pair of production current leads. There were a number of problems resolved and systems improvements made during the commissioning phase. A 30 cm superconducting liquid level probe used to control the liquid helium level in the test dewar was found to be not operational due to broken insulation on the lead wires. It was replaced, and an additional 76 cm liquid level probe was added so that the entire filling process of the test dewar could be monitored. A carbon resistor assembly meant to read the temperature of the 20 K helium gas supplied to the warm terminals had fallen apart and was giving erroneous results as it touched the pipe wall. It was replaced by two Cernox sensors.

A significant problem encountered was that the temperature of the nominally 20 K gas supplied to the HTS warm terminals was very unsteady, oscillating by 10-15 K. The oscillations disappeared when the portable helium dewar supplying the lead flow went empty. This indicated that two-phase flow was the source of the oscillations. The stinger was raised above the liquid level so that only cold gas would be pushed through the transfer lines. This made the system control somewhat labor intensive, but the lead flow supply temperature was much steadier. Designing a phase separator and incorporating it into the system in time to test the third pair of production leads in June 2003 solved this problem. The phase separator allows helium gas over a wide temperature range to be supplied to the power lead warm terminals. Lead flow supply temperatures as low as 6-8 K have been achieved by shutting off the transfer line heater and increasing the mass flow rate.

An important finding from the commissioning of the test facility was that the elevation at which helium boiloff was vented from the test dewar had a significant impact on power lead performance. The vacuum-jacketed bayonet for venting helium boiloff initially extended to the elevation of the warm terminals. From the top portion of Table II, each power lead required 0.50 g/s of helium to maintain a 50 K warm terminal with no current. While powered at 7500 A, over 0.6 g/s was required by each power lead to maintain 70 K at the warm terminal. A 50 K warm terminal temperature could not be maintained. The Edwards mechanical vacuum pumps were struggling to maintain the required pressure differential across the mass flow controllers. This limited the achievable lead flow rates, and the warm terminal temperature rose to 70 K as a result. It was expected that 0.4-0.5 g/s through each power lead would be required at 7500 A to maintain 50 K at the warm terminal. The vacuum-jacketed vent bayonet was shortened by 20 cm so that boiloff was removed at a higher elevation. The resulting lead flows at zero current were greatly reduced, from 0.50 g/s to 0.14 g/s per lead. Similarly, at 7500 A, the lead flows were reduced to 0.44 g/s per lead. A 50 K warm terminal temperature could also be maintained under these conditions. Additional thermal studies need to be performed to understand the effect of the vent elevation.

Reduced lead flows had the additional benefit of eliminating frosting of the upper ends of the leads. This was especially evident during standby operation at zero current. With the longer vent bayonet, the upper ends of the leads became frosted even with the flag heaters continuously powered. The lower lead flow rates that accompanied the shorter bayonet allowed the flag heaters to operate with a 33% duty cycle while keeping the upper ends of the leads frost-free and dry.

TABLE II
Test Facility Commissioning Results

| With Long Vent Bayonet | |
|---|---|
| **Test** | **Result** |
| Zero current, 50 K warm terminal | Negative lead flow: 0.50 g/s<br>Positive lead flow: 0.50 g/s<br>24 K/1.5 bar coolant supply |
| 7500 A current, 70 K warm terminal | Negative lead flow: 0.63 g/s<br>Positive lead flow: 0.61 g/s<br>18 K/1.5 bar coolant supply |
| **With Short Vent Bayonet** | |
| **Test** | **Result** |
| Zero current, 45 K warm terminal | Negative lead flow: 0.14 g/s<br>Positive lead flow: 0.14 g/s<br>24 K/1.5 bar coolant supply |
| 7500 A current, 50 K warm terminal | Negative lead flow: 0.44 g/s<br>Positive lead flow: 0.44 g/s<br>10 K/1.5 bar coolant supply |

Commissioning of the new test facility was concluded with a successful cold test of the first pair of production power leads. A detailed description of the test plan and production test results for the LHC HTS power leads are described elsewhere [4]. After seven weeks, commissioning was completed in late April 2003. Seventeen 500 l helium dewars were used to commission the test facility.

Fig. 2 shows the test facility in operation. At the left are two 500 l liquid helium dewars and one 240 l liquid nitrogen dewar. At the center are two personal computers for monitoring and controlling the facility. The test dewar is behind the computers, and the power buswork and flexible power leads can be seen overhead. The instrumentation rack to the right contains power supplies, liquid level instrumentation, quench detection hardware, PLC system hardware, temperature transmitter cards, and heater controllers.

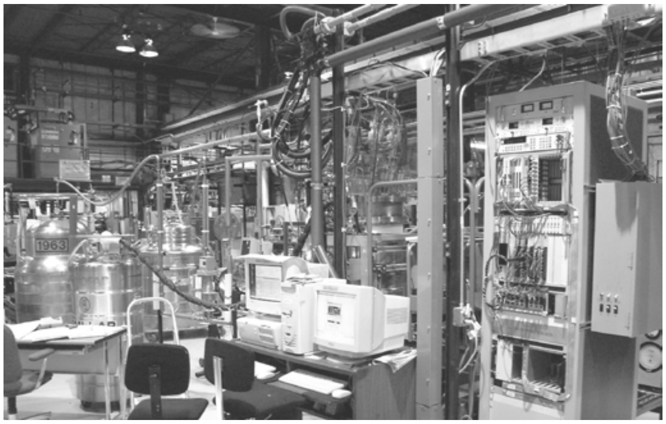

Fig. 2. A view of the LHC HTS power lead test facility in operation.

## IV. Conclusion

A new facility for testing LHC HTS power leads is in operation. The cryogenics system maintains a 4.5 K bath for the LTS while providing the necessary 20 K flow to control the HTS warm terminal temperatures. The process controls system allows an operator to control the facility from a personal computer while a number of PI control loops provide stable, long-term operation. The data acquisition system collects operating data used in determining lead performance. The quench detection system protects the current leads. These subsystems comprise the newest production test facility at the Fermilab Magnet Test Facility.

## References


[1] R. Carcagno, and R. Rabehl, "Controls Upgrade of the Fermilab Magnet Test Facility 1500 W Helium Refrigerator," in *Advances in Cryogenic Engineering* 45B, Plenum, New York, 2000, pp.1795-1802.

[2] R. Carcagno and D. Orris, "A Modular and Extensible Data Acquisition and Control System for Testing Superconducting Magnets," IEEE Particle Accelerator Conference (PAC2001), Chicago, Illinois, June 2001.

[3] Orris, D.F., Feher, S., Lamm, M.J., Nogiec, J., Sharonov, S., Tartaglia, and Tompkins, M. J., "A Digital Quench Detection System for Superconducting Magnets," Proceedings of the 1999 IEEE Particle Accelerator Conference, New York, New York, Vol. 5/5, p. 3191-3193.

[4] M.Tartaglia, R.Carcagno, S.Feher, Y.Huang, D.Orris, Y.Pischalnikov, R.Rabehl, C.Sylvester, J.Zbasnik, "Production LHC HTS Power lead Test Results," submitted for publication.