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An upgraded cryogenic test stand for HL-LHC cryo-assemblies

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Abstract. The Fermilab horizontal test stand previously used for testing the LHC inner triplet quadrupoles has been upgraded to test cryo-assemblies for the high-luminosity LHC upgrade (HL-LHC). The test requirements of these new cryo-assemblies required additional capabilities of the test stand cryogenic system, including controlled cool-down and warm-up, helium recovery after a quench, and operation at higher pressures. Most of these upgrades were completed to support a zero-magnet test in late 2020, with the remainder of the upgrades completed to support the first pre-series cryo-assembly test in early 2022. An overview of the design and initial operating experience of the upgraded test stand cryogenic system and associated process controls system are presented in this paper.

1. Introduction

The U.S. is contributing new Nb_3Sn-based superconducting interaction region quadrupole magnets to the CERN High-Luminosity Large Hadron Collider (HL-LHC) upgrade. After integrating two magnets into a cold mass and installing the cold mass in a vacuum vessel, this cryo-assembly will be horizontally tested at the Fermilab Industrial Building 1 test facility. These tests will be conducted in 1.9 K, 1.3 MPa helium II at currents up to nearly 17 kA.

An existing test stand [1], originally used for testing first-generation LHC interaction region quadrupole magnets, has been upgraded to support this new test program. These upgrades include an Adapter Box that interfaces the feed box to the cryo-assembly and allows the cryo-assembly to reach higher pressure after a quench. New piping supports the added capability of controlled cool-down and warm-up. The process controls system has been modernized with improved automation capabilities to implement controlled cool-down and warm-up.

A zero magnet test was successfully conducted in late 2020 to verify the functionality of test stand systems in preparation for the beginning of cryo-assembly production testing in early 2022.

2. Adapter Box

The Adapter Box was designed and built by Fermilab as an interface between the existing cryogenic feed box and the new cryo-assemblies. It has a 0.91 m diameter vacuum shell, an 0.83 m diameter LN2-cooled thermal shield, and helium piping ranging from 1-1/2 NPS to 3 NPS. The Adapter Box adapts the pipe locations of the feed box to match the piping layout of the new cryo-assemblies. The Adapter Box also includes externally pressurized expansion joints and flexible hose loops to

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accommodate thermal contractions when an installed cryo-assembly is cooled down on the test stand. The Adapter Box at the completion of fabrication is shown in figure 1.

Figure 1. The Adapter Box is shown at the completion of fabrication. During intermediate fabrication steps, it was suspended from the framework shown. Externally pressurized expansion joints are seen at the left end of the Adapter Box.

The Adapter Box also serves as the new separation point between the 4.5 K and 1.9 K temperature levels. This was previously occurred in the feed box, where the upper section operated at saturated 4.5 K to support the vapor cooled power leads and the lower section operated at subcooled 1.9 K. This lower volume was a common volume with the magnet. These two volumes were separated by the feed box lambda plate. The separation of temperature levels is now accomplished using a lambda plug at the feed box-Adapter Box interconnect, as shown in figure 2.

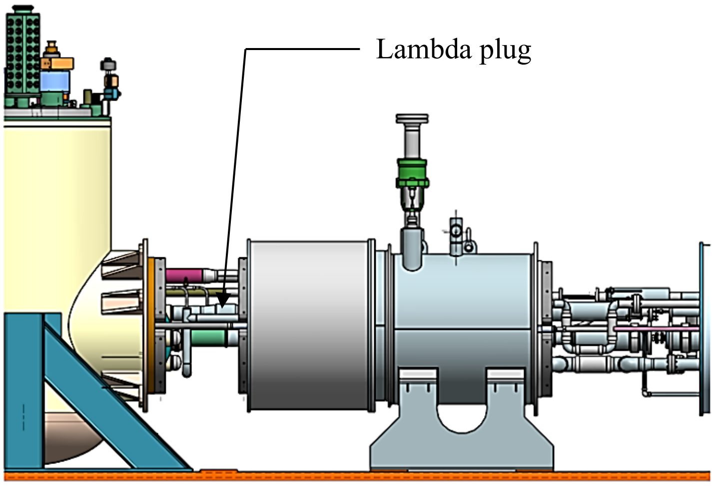

Figure 2. Model representation of the Adapter Box installed on the horizontal test stand. The location of the lambda plug is indicated. The sliding vacuum sleeve is shown in its resting position on the Adapter Box. To the right of the Adapter Box is the interconnect to the cryo-assembly.

A proven CERN lambda plug design [2] used in the LHC was modified for the test stand. The plug is made from Ultem 1000 and resides inside a stainless steel housing. Belleville washers push on a retaining plate to ensure that the end of the lambda plug maintains a good seal against the housing after cool-down. The plug accommodates three superconducting busses, which allows the two magnets housed in the cryo-assembly to be powered individually or simultaneously. The lambda plug is 51 mm in diameter and 62 mm long. As can be seen in figure 3, there are three slots 20 mm wide and 7.2 mm high for the buswork. Each bus is potted into the lambda plug using Stycast 2850FT.

Figure 3. To the left is the lambda plug itself. The slots for accommodating three superconducting busses can be seen as well as access ports for injecting potting material. The center photo shows an end view of the lambda plug as it sits in the housing. The end shown faces the cryo-assembly. In the right photo, half of the retaining plate is shown. The retaining plate provides a force on the lambda plug and forces it to seal against the other end of the housing.

A prototype lambda plug was fabricated and tested to verify its performance before it was installed at the test stand. After being cooled to 80 K in a liquid nitrogen bath, the end of the lambda plug that will face the cryo-assembly was pressurized with 80 K helium gas. The leak rate was measured, which allowed calculation of the leakage area and the expected superfluid heat leak at 1.9 K. The expected 1.9 K heat load due to leakage at the lambda plug is 35 mW.

In addition to providing a very low heat leak transition from 4.5 K to 1.9 K, moving the 1.9 K boundary from the feed box to the interconnect reduces the 1.9 K volume by 400 liters. Operationally this will result in shorter pump-down times and less liquid helium usage. Separating the cryo-assemblies from the feed box using the lambda plug will also allow the cryo-assemblies to reach higher pressure after a quench. During the original LHC IR quadrupole test program, pressure was limited to the 0.69 MPa(g) rating of the feed box liquid helium vessel. The lambda plug will allow the 20-bar rated cryo-assemblies to reach 16 bar and simulate HL LHC tunnel conditions after a quench.

3. Piping upgrades

The test stand upgrade also included piping system upgrades. This included new U-tubes connecting the feed box to the cryogenic distribution system, but also new piping required to meet the test requirements of the HL-LHC cryo-assemblies.

One such requirement is controlled cool-down and controlled warm-up of the cold mass. The maximum temperature difference between the ends of the cold mass is 50 K. The test stand upgrade was designed to accomplish this in two stages: temperatures of 80 K and above, and temperatures below 80 K.

To supply helium gas to the cold mass at temperatures of 80 K and above, up to 20 g/s of purifier compressor discharge flow are taken. Based on an energy balance calculation, using a mass flow controller a specified fraction of this flow is cooled to 80 K in a liquid nitrogen bath. A second mass flow controller is operated with a temperature control loop to mix 300 K helium with the 80 K helium to achieve the required cold mass supply temperature. This mixing and the mixed flow temperature measurement take place in the supply piping outside the feed box.

To supply helium gas to the cold mass at temperatures below 80 K, 4.5 K liquid helium is mixed with 80 K helium gas. The larger of two feed box fill valves is fully opened to flow liquid helium from the test facility's 10,000 liter liquid helium storage dewar. This is mixed with 80 K helium gas using a mass flow controller with a temperature control loop. The mixing and mixed flow temperature measurement occur in the feed box internal piping. The total flow rate in this mode of about 6 g/s is somewhat lower than the 20 g/s in the higher-temperature mode because of storage dewar operating pressure limitations and the small size of the feed box internal piping. Figure 4 shows the new piping associated with controlled cool-down/warm-up.

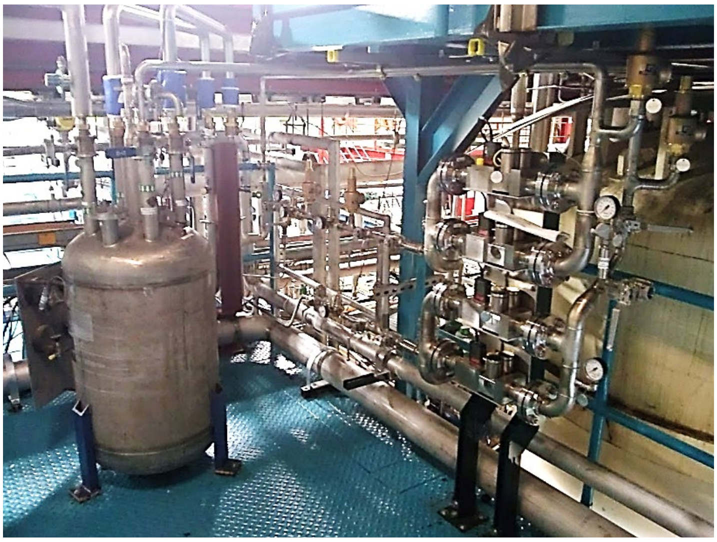

Figure 4. The piping associated with controlled cool-down and warm-up is shown. The vessel containing the liquid nitrogen bath is to the left, and the mass flow controller manifold is to the right.

Figure 5 shows additional piping upgrades integrated with the test facility through the Adapter Box. The cool-down return, relief manifold with outdoor vent line, and quench recovery line are seen. To recover helium vaporized when a magnet quenches, one of the cryoplant's 114 m^3 helium gas storage tanks is reconfigured to serve as a quench tank. The recovered helium is then processed by a purifier compressor and charcoal bed purifier before being returned to the facility's helium gas inventory. The new horizontal test stand quench recovery line ties into the existing quench recovery system that has successfully operated for many years with the Vertical Magnet Test Facility (VMTF) [3].

Figure 5. The Adapter Box is shown installed on the test stand. The uppermost pipe is the cool-down return. Below this are the relief valve vent and supply headers. The lowermost pipe is the quench recovery line.

4. Process controls system

The original process controls system for the test stand was installed over 20 years ago, shortly after the completion of the cryoplant process controls upgrade [4]. The test stand process controls system was now replaced to provide additional automation capabilities as well as to improve its reliability.

The original test stand Siemens 545 PLC was replaced with a Siemens S7 PLC to monitor and control the cryogenic system and manage the cryogenic condition interlocks. The cryogenic system PLC interfaces with the cryogenic power supply PLC. It provides one bit of cryogenic permit that allows the power supply system to start when cryogenic conditions are acceptable. These conditions include feed box liquid helium level and helium flow rate through the vapor-cooled current leads. Loss of this permit signal causes a slow ramp down of the power supply.

There is a total of 65 analog input and 16 digital input signals to the PLC, and 14 analog output and 20 digital output signals from the PLC. Thirty-one of the analog input signals are temperature readouts from Lake Shore Cryotronics 240 modules. Cernox, carbon ceramic, and platinum sensors are used, selected based on the required temperature measurement range and the sensor mounting method. At the test stand, carbon ceramic sensors and platinum sensors are typically surface-mounted while Cernox sensor are immersion-mounted. Additional instrumentation includes process pressure transducers, superconducting liquid level probes, and insulating vacuum transducers.

Human-machine interface/supervisory control and data acquisition (HMI/SCADA) for the test stand cryogenic system is accomplished using the iFix software platform (GE Digital), which interfaces to the PLC using IGS (Industrial Gateway Server, GE Digital) connectivity software. Figure 6 shows the test stand overview iFix screen as it was configured during the November 2020 zero magnet test.

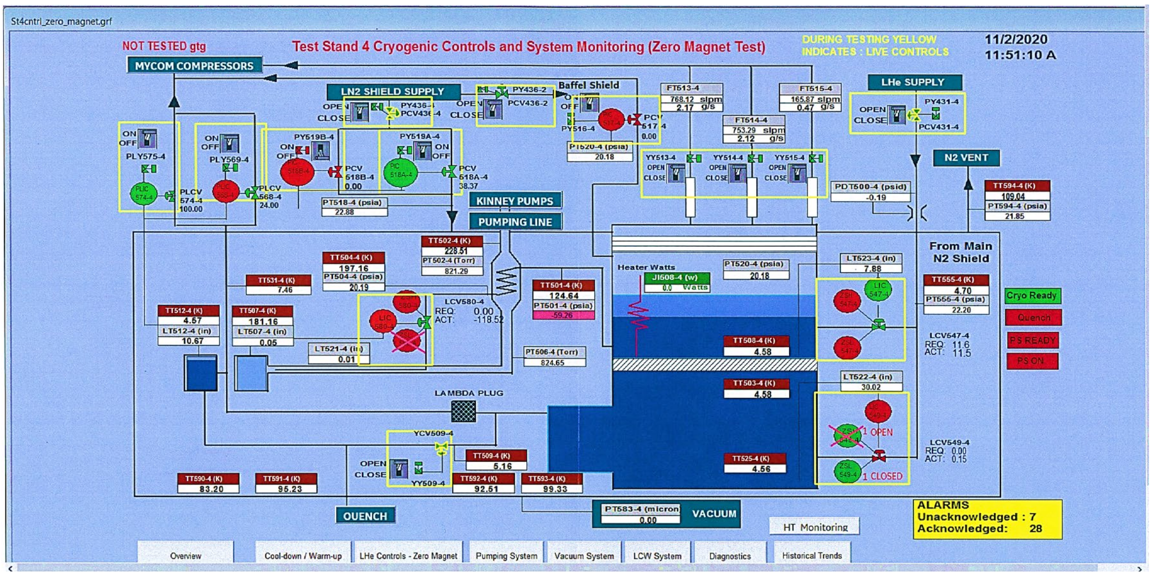

Figure 6. The test stand overview screen shows the test stand in operation in the zero magnet test configuration. The dark color in the feed box (right) and return end (left) indicates liquid helium level as measured by superconducting liquid level probes.

5. Zero magnet test

A zero magnet test was conducted to verify functionality of the upgraded systems. All buswork was shorted at the return end by solder splicing. Without a cryo-assembly installed, piping spools were required to complete the helium circuits where the Adapter Box – cryo-assembly interconnect would normally be installed. The total liquid helium volume during the zero magnet test was 840 liters. The insulating vacuum space was capped off with the same return end vacuum shell that will be used for production testing. The upgraded test stand in the zero magnet test configuration is shown in figure 7.

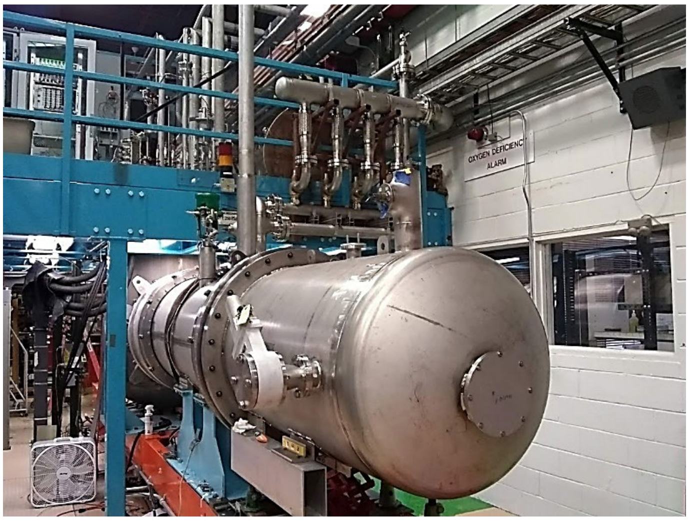

Figure 7. In the zero magnet test configuration, a return end vacuum vessel was attached to the Adapter Box. Helium circuits were completed using turnaround piping spools. The thermal shield circuit was completed using an end cap reused from the original LHC interaction region quadrupole test program.

The first portion of the zero magnet test focused on 4.5 K operations and power testing. All three of the feed box 15 kA vapor-cooled current leads and associated busses were successfully powered to the required current level. Control loops for feed box liquid helium level, return end liquid helium level, feed box pressure control, and thermal shield pressure control were tuned. Based on the rate of change of feed box liquid helium level during boil-off tests, the calculated heat load to the feed box was X W. This was in good agreement with expectations.

The second portion of the zero magnet test focused on 1.9 K operation and controlled cool-down and warm-up. Without a cryo-assembly and its two heat exchangers built into the cold mass, there was no way to achieve subcooled operation in the zero magnet test configuration. The only circuit where 1.9 K saturated superfluid was possible was the pumping line and a small return end reservoir vessel. Figure 8 shows the temperature at the return end of the pumping line going below 1.9 K.

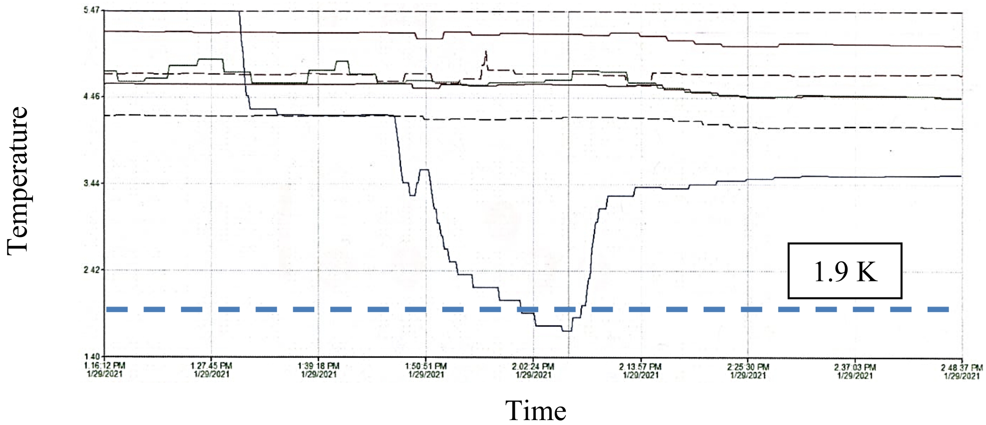

Figure 8. Historical data was collected during the zero magnet test. On the plot, the pumping line return end reservoir temperature is shown going below 1.9 K. Each increment on the horizontal axis is roughly 10 minutes, and each increment on the vertical axis is roughly 1 K. The 1.9 K temperature line is indicated.

6. Production testing

Production testing of HL-LHC cryo-assemblies will begin in early 2022. This will be the first opportunity to operate the upgraded horizontal test stand at the 1.9 K, 1.3 MPa design conditions using the two heat exchangers built into the cryo-assembly cold mass.

The test stand will be supported by two subatmospheric warm pumping skids [5] with a Roots blower backed by a liquid ring pump. Each skid has a pumping capacity of 2.5 g/s of helium at 12 Torr. After accounting for pressure drop between the test stand and the pumping skids, the system is capable of handling a maximum 1.9 K heat load of 84 W.

The estimated test stand 1.9 K operating heat load including the Adapter Box, warm bore, interconnect piping, and return end piping is 27 W. The warm bore accounts for 70% of this heat load, but this heat load is present only when the warm bore is warmed and opened in preparation for magnetic measurements. The expected 1.9 K heat load for a cryo-assembly operating with an 80 K thermal shield (higher than the 40-60 K shield temperature of HL-LHC) is 24 W. The total 1.9 K heat load of 51 W is 61% of the system capacity.

7. Conclusion

The Fermilab horizontal test stand has been upgraded to support U.S. contributions to the CERN HL-LHC upgrade. Upgrades allowing the cryo-assemblies to reach higher pressures after quench and to implement controlled cool-down and warm-up strategies were required to meet the test requirements of the new HL-LHC cryo-assemblies. An upgraded process controls system addressed automation and reliability of the test stand.

A zero magnet test was completed, demonstrating successful operation of completed upgrades. Remaining test stand upgrades will be completed in time for the first pre-series cryo-assembly test in early 2022.

8. References

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Acknowledgments

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