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Fermilab's Horizontal Test Stand Upgrade Overview and Commissioning

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***Abstract*—Cryo-assemblies with the Nb_3Sn MQXFA low-beta quadrupoles for the High Luminosity LHC (HL-LHC) upgrade will be tested at Fermilab's magnet test facility. A total of 10 cryo-assemblies will be delivered to CERN within the US HL-LHC Accelerator Upgrade Project (AUP). The horizontal test stand at Fermilab already has been used for testing the existing LHC inner-triplet quadrupoles, but the stand and corresponding electrical and cryogenic sub-systems were not operational for more than a decade.**

In order to restore the test stand functions and meet the design and test requirements for the HL-LHC magnets, the existing horizontal test facility at Fermilab underwent a significant refurbishment of the cryogenic and mechanical components. Most of the upgrades were completed and verified during so called zero-magnet test by late 2020, and then final commissioning of the upgraded horizontal test stand was completed during the first cryo-assembly test in 2023. These tests verified the major cryo-mechanical installations, as well as the basic test stand operations, including controlled cooldown and operation at 1.9 K, magnet protection and process controls.

Overview of the Fermilab's horizontal test facility upgrade and commissioning of these upgrades are presented in this paper.

***Index Terms*—High Luminosity LHC Upgrade, Large Hadron Collider, Superconducting Magnets, Superconducting Magnet Test Facilities**

I. INTRODUCTION

Horizontal Test Stand at Fermilab previously was used for testing the existing LHC inner-triplet quadrupoles in 2001-2006 [1-2]. Refurbishment and new fabrication of test stand components was necessary to meet the High Luminosity LHC (HL-LHC) cryo-assembly design and test requirements [3-4]. 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. The process controls and magnet protection and monitoring systems also were upgraded. Most of these upgrades were completed to support a zero-magnet test in late 2020, with the remainder of the upgrades completed during the first pre-series cryo-assembly test in early 2023. The first pre-series cryo-assembly LQXFA/B-01 is shown in Fig.1.

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Fig. 1. LQXFA/B-01 at Fermilab's Horizontal Test Facility.

II. New Adapter Box

An important addition to the stand is the new Adapter box (see Fig. 2-3), designed and built as an interface between the existing cryogenic feed box and the new HL-LHC cryo-assemblies. The adapter box adapts the piping locations of the feed box to match the piping layout of the new cryo-assemblies. It consists of a vacuum shell and thermal shield, and helium piping. To accommodate thermal contractions when cryo-assembly is cooled down, externally pressurized expansion joints and flexible hose loops are used.

The adapter box allows using of the old components, including the cryogenic feed box, and the feedbox insert with vapor-cooled power flags.

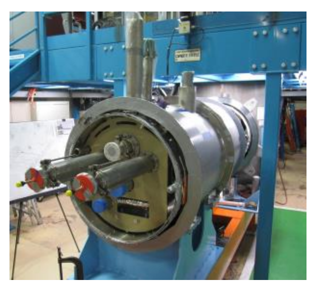

Fig. 2. The Adapter Box at the horizontal test stand.

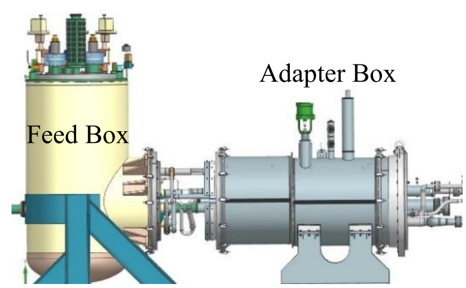

Fig. 3. Model representation of the Feed box and the Adapter box

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III. New Location of the lambda plug

The adapter box also serves as a separation between the 4.5 K and 1.9 K temperature levels. The Lambda plug location was moved from the Feed box to the Feed box-to-Adapter box interconnect, see the 3D model sketch in Fig. 4 (left).

A proven CERN Lambda plug design [5] was modified for the Fermilab's horizontal test stand, accommodating three superconducting busses. With three busses, the two magnets in the cryo-assembly could be powered individually. The plug is made of *Ultem 1000* and resides inside a Stainless-steel housing (see Fig. 4).

Moving the 1.9 K boundary from the Feed box to the interconnect reduces the 1.9 K volume by ~400 liters. This will result in shorter pump-down times and reduced liquid helium usage.

Separating the cryo-assembly from the feed box using the lambda plug will also allow the cryo-assemblies to reach higher pressure after a quench (above 17 bar), reproducing HL-LHC tunnel conditions after a quench.

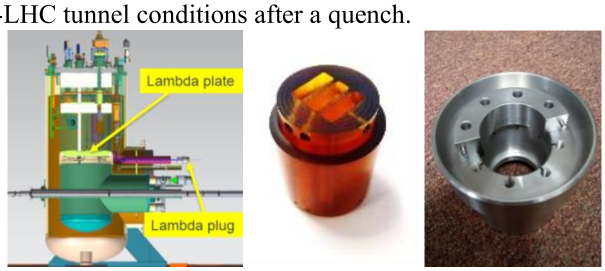

Fig. 4. New Lambda plug location (left). The Lambda plug insert and case (right)

A. Feed Box insert.

The old Feed box insert is used for horizontal cryo-assembly testing. Three vapor cooled power leads will allow testing of two magnets in the cryo-assembly individually or together connected in series. Copper flags were silver-plated for a better connection with the flexible leads. New current limiting resistors were installed. The low conductivity water system (LCW) for cooling the solid copper bus and the flexible power leads was fully refurbished to provide an adequate water flow. The water flow rate in the flexible power leads at the Feed box after this upgrade was increased from ~15 l/m to ~36 l/m in each 1500 MCM water cooled cable.

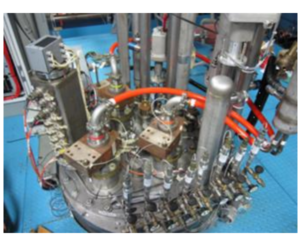

Fig. 5. The Feed box insert.

III. Quench protection and monitoring

A Quench Protection and Monitoring (QPM) system was developed for protecting and monitoring the SC magnets at Fermilab [6]. The quench system was designed for a high level of dependability and long-term continuous operation and is based on three tiers: Tier-1 is a primary FPGA based Digital Quench Detection (DQD) system, Tier-2 - secondary Analog Quench Detection (AQD) system, and Tier 3 - Quench controls and Data Management system.

High reliability is achieved with two independent and fully redundant Tier-1 and Tier-2 systems. The Tier-3 system is based on National Instruments (NI) cRio and provides the user interface for quench controls and data management.

Fig. 6. QPM racks (left), HFU and CLIQ racks (right) at Fermilab's horizontal test stand.

Coupling Loss Induced Quench (CLIQ) system [7] is included in the magnet protection along with the protection heaters. CERN designed CLIQ units were manufactured by the same vendor both for CERN and Fermilab. Quench protection heaters are located on the outer coil surface. Heater firing units (HFU) for powering and controlling the protection heaters were provided by CERN. All HFUs were modified to make them compatible with the Fermilab's magnet protection system. Our goal was to provide magnet protection at Fermilab as close as possible to the operating conditions at CERN. The QPM and HFU racks, as well as the CLIQ unit for a single magnet in the cryo-assembly is shown in Fig. 6.

IV. zero-magnet test

Major cryo-mechanical and electrical upgrades at Fermilab's horizontal test stand were verified during the shorted bus (zero-magnet) test in late 2020. All superconducting leads were shorted at the return end by solder splicing. Without a cryo-assembly installed, turn-around piping spools were used to complete the helium circuits. The insulating vacuum space was closed with the same return end vacuum shell that was used later for the pre-series cryo-assembly test. The upgraded test stand in the zero-magnet test configuration is shown in Fig. 7.

Functionality of the various test facility upgrades were successfully verified during the zero-magnet test, including new Adapter box, the Feed Box-Adapter Box interconnects, insulating vacuum, new Quench Protection and Monitoring systems, automated cooldown, and warmup procedure. Of course, without a cryo-assembly installed, it was not possible to validate 1.9 K cooldown or quench recovery. Although, 1.9 K was reached in the pumping line and a small return end reservoir vessel.

Main vapor cooled power leads were verified at currents up to 18500 A, providing sufficient margin for testing the HL-LHC cryo-assemblies at 16530 A, the nominal current plus 300 A, which is set as an acceptance test current.

A zero-magnet test demonstrated successful operation of completed upgrades. But there were remaining test stand upgrades to be completed in time for the first pre-series cryo-assembly test, including the controlled cooldown and warmup capability, the production interconnect piping, the warm bore (anti-cryostat) assembly for the magnetic measurements, etc.

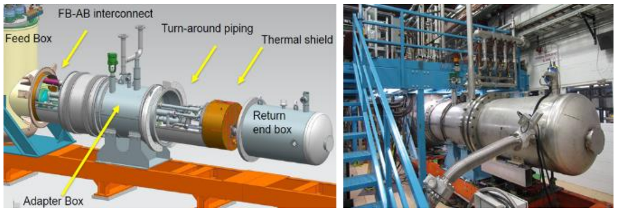

Fig. 7. Upgraded horizontal test stand for the zero-magnet test configuration.

V. Controlled cooldown and warmup

To prevent excessive stresses in the magnet structure during the cool-down and warm-up, the maximum temperature difference between the ends of each magnet should not exceed 50 K. At the test stand, a maximum operating temperature difference of 80 K across the cold mass (two magnets) is used. The temperature gradient during cool-down and warm-up in the LHC tunnel is expected to be less than this upper limit.

Controlled cooldown is accomplished in two stages: for temperatures above and below 80 K. For cool-down from 300 K to 80 K, helium gas is cooled in a liquid nitrogen bath and then mixed with the 300 K helium to achieve the required cold mass supply temperature. For further cooldown, 80 K helium gas is mixed with the 4.5 K liquid helium. A PLC script is implemented to automatically control the temperature of the helium supplied to the test stand.

Pumping for cooldown from 4.5 K to 1.9 K is provided by two sub-atmospheric warm pumping skids, each with a pumping capacity of 2.5 g/s of helium at 16 mbar.

VI. Warm finger (anti-cryostat)

A vacuum jacketed “warm finger” or anti-cryostat was fabricated for the field quality measurements. It will allow insertion of a stretched wire or a rotating room temperature measurement probe into the cold mass aperture during the horizontal cryo-assembly test.

The “warm finger” with 100-mm inner diameter is equipped with temperature sensors and heaters. Heaters are required to prevent ice buildup inside the bore. Temperature sensors are installed at both ends and in the middle of the “warm finger”.

During the cooldown, as well as between the magnetic measurements, the “warm finger” is under vacuum to reduce the heat load to 1.9 K.

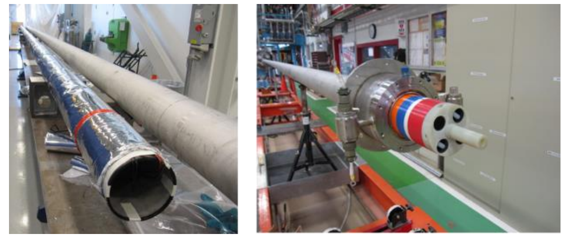

Fig. 8. “Warm finger” assembly and test with a rotating magnetic measurement probe

VII. Test facility improvements

Various test facility improvements have been made to achieve high reliability of the cryogenic plant, test facility and power systems operation at Fermilab.

A new liquefier from *Air Liquide Advanced Technologies* will increase total liquid helium make rate to 600 liter/hour and total liquid storage volume to 14000 liters. New liquefier was installed in 2022, and commissioning was completed in 2023. Full stream purification system helps to control contamination level.

New Helium compressor skids include four Kinney pumps providing sufficient pumping speed for Fermilab’s vertical and horizontal test stands.

Fig. 9. New liquefier at Fermilab’s magnet test facility.

VIII. First cryo-assembly test

The first pre-series cryo-assembly LQXFA/B-01 was assembled and then delivered to Fermilab’s magnet test facility in January 2023. First cooldown started on March 15th, and 1.9 K was successfully reached on April 3rd. The temperature change at the longitudinal midpoint of two magnets during the cooldown is shown in Fig. 10. The first cooldown process was delayed due to adjustment of automated cooldown process parameters, as well as due to the cold box trip. Cooldown from 4.5 K to 1.9 K requires about 3 hours. The 300 K warmup time was just over 1 week.

LQXFA/B-01 test results in two thermal cycles are presented elsewhere [8-9].

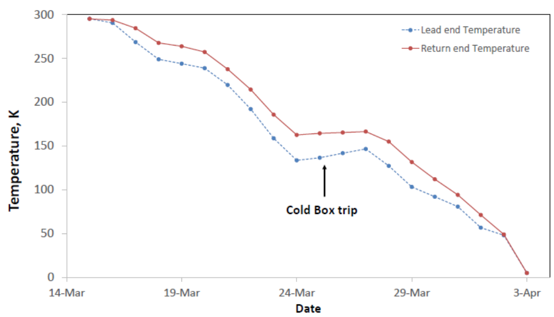

Fig. 10. LQXFA/B-01 cooldown at Fermilab

IX. Summary of Horizontal Test Stand Commissioning

After more than a decade of shutdown, the horizontal magnet test stand at Fermilab is fully operational again. Refurbishment of the cryogenic and mechanical components were required to restore the test stand functions and meet the design and test requirements for the HL-LHC inner-triplet quadrupole magnets.

Functionality of the upgraded systems, including new piping systems, the cooldown return, relief manifold, new adapter box and new lambda plug were successfully verified during the zero-magnet test in late 2020. The insulating vacuum of the stand reached ~10^{-7} mTorr. The return end piping was successfully pressurized up to 17 bar, demonstrating acceptable vacuum sealing of the lambda plug and interconnects. The main vapor cooled leads were verified at currents up to 18500 A.

The remaining test stand upgrades and commissioning were completed during the first pre-series cryo-assembly test in 2023. Controlled cooldown and warmup have been successfully demonstrated, and the required temperature of 1.9 K has been achieved. Quench pressures over 19 bar have been safely handled, and the helium recovery capabilities were successfully demonstrated.

New Quench Protection and Monitoring systems provided reliable protection of magnets. As a last step in commissioning of the completed upgrades, LQXFA/B-01 magnets were held at the nominal current of 16230 A for 5 hours.

Acknowledgment

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