AUP first Pre-Series Cold Mass Installation into the Cryostat

R. Rabehl, S. Feher, D. Ramos, T. Strauss, and M. Struik

Abstract— **For the HiLumi LHC Upgrade (HL-LHC), new high field and large-aperture quadrupole magnets for the low-beta inner triplets (Q1, Q2, Q3) are being built. These new quadrupole magnets are based on Nb_3Sn superconducting technology. As part of the US-HiLumi Accelerator Upgrade Project (AUP), ten Cryostat Assemblies (LQXFA) for Q1 and Q3 replacement will be built, tested, and delivered to CERN. The first LQXFA was assembled and tested at Fermi National Accelerator Laboratory (FNAL) during fall 2022 and spring/summer 2023, respectively. This paper summarizes the assembly process and experience of the first LQXFA Cryostat Assembly at FNAL.**

***Index Terms*—LQXFA, cryostat**

I. Introduction

FINAL assembly of LQXFA Cryostat-Assemblies is performed at FNAL under the US-HiLumi AUP. These Cryo-Assemblies are the Q1 and Q3 quadrupoles of the HiLumi "inner triplets" to be installed on either side of the ATLAS and CMS collision points. The LQXFA was designed by CERN and incorporates the LMQXFA Cold Mass.

II. Cryostat Tooling

The cryostat tooling was manufactured by Applus+ of Barcelona, Spain and provided to FNAL via CERN. The tooling is located is the FNAL Industrial Center Building Addition (ICBA) fabrication facility where the Cold Masses are also produced. The tooling provides both cryostating and decryostating capabilities in the event that repair of a Cryostat-Assembly or Cold Mass is required.

The tooling was installed in February 2021. Due to COVID-related travel restrictions, a team of only two Applus+ personnel were on-site at FNAL to lead the installation. FNAL mechanical technicians and a third-party contracted alignment specialist completed the installation crew. Use of a Hololens system allowed for effective, remote, real-time audio-visual communication between FNAL, CERN, and Applus+ during tooling installation.

The completed tooling is shown in Fig. 1 and Fig. 2. It has overall dimensions of 27.9 m long and 3.1 m wide. Fig. 1 shows the decryostating winch, assembly table, and work platform.

Fig. 1. The cryostat tooling, showing the decryostating winch, work platform, and assembly table.

Fig. 2. The cryostat tooling, showing the cryostating winch, alignment tables, mechanical screw jacks, and stabilizer frames.

The assembly table is where the Cold Mass, thermal shield, cryogenic piping, and multilayer insulation (MLI) are integrated into a Cold Mass assembly before being introduced into the vacuum vessel. The platform allows this work to be performed at a comfortable height on both sides of the assembly table. The decryostating winch is used to pull the Cold Mass

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Fig. 3. Stabilizer installed on the end of the Cold Mass.

Fig. 4. Mechanical screw jack.

assembly out of the vacuum vessel, if necessary. During normal cryostating operations, it used to remove a rail system that is installed for pulling the Cold Mass assembly into the vacuum vessel. It is also used to pull the rail system out of the cryostat during normal cryostating operations. Fig. 2 shows the cryostating winch, alignment tables, mechanical screw jacks, and stabilizer frames. The cryostating winch is identical to the decryostating winch. The alignment tables provide a 3-point support system for the vacuum vessel and allow the vacuum vessel to be properly positioned relative to the Cold Mass. The stabilizer frames, when used in conjunction with a stabilizer bolted to each of the Cold Mass as shown in Fig. 3, ensure that the Cold Mass cannot roll off the jacks.

A mechanical screw jack is shown in Fig. 4. The three jacks are mechanically synchronized to lift the Cold Mass assembly within the vacuum vessel to allow proper alignment of the vacuum vessel relative to the Cold Mass assembly. Support posts are also installed while the Cold Mass assembly is supported by the screw jacks. The three jacks have sufficient capacity to lift the 15,900 kg Cold Mass assembly and have a 200 mm stroke.

III. Cold Mass Assembly

Fig. 5 shows a Cold Mass being transported to the cryostating tooling.

Fig. 5. The Cold Mass being transported to the cryostat tooling.

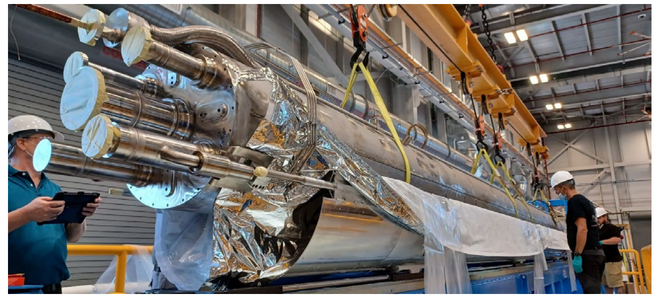

Fig. 6. The Cold Mass being lowered into the thermal shield lower shell assembly.

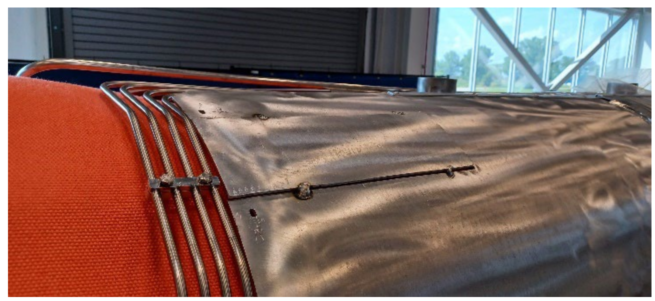

Fig. 7. Modification to the thermal shield upper end shell to prevent a thermal short to the cryogenic piping.

When the Cold Mass arrives at the cryostat tooling, it is set into the thermal shield lower assembly which has been previously placed on the assembly table along with one 30-layer MLI blanket. An interference was found between the thermal shield cooling tubes and the Cold Mass capillary systems, which can be seen in Fig. 5 and Fig. 6. For future Cryostat-Assemblies, this cooling tube will not be attached to the thermal shield lower shell assembly until the Cold Mass has been set in place. This was followed by completing the Cold Mass MLI installation, and installation of the thermal shield upper shells. Modifications to the thermal shield upper end shells were required as shown in Fig. 7. Portions of the shells were cut out and retacked at a larger radius to gain clearance and prevent thermal shorts to the cryogenic helium piping. For future Cryostat-Assemblies, the thermal shield upper shells have been rerolled to pull the thermal shield lower shell assembly into shape and eliminate this issue.

Installation of the Frequency Scanning Interferometry (FSI) Cold Mass position monitoring system cold heads followed, as shown in Fig. 8. These delicate, 3-D printed parts must be installed very carefully and integrated with the Cold Mass MLI in order for them to be maintained at a slightly elevated temperature once the Cold Mass reaches the 1.9 K operating temperature.

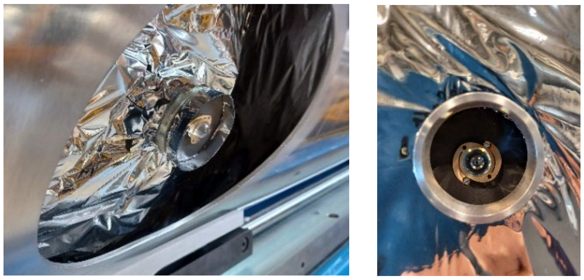

Fig. 8. FSI insulated reflector after installation on the Cold Mass and integration with the Cold Mass MLI.

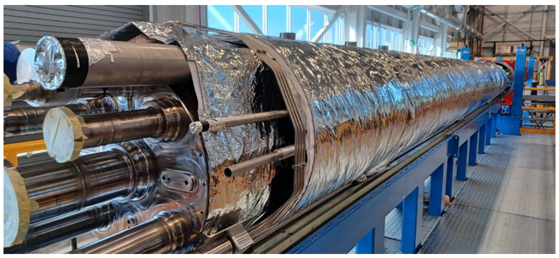

Fig. 9. Completed Cold Mass assembly ready for cryostating.

Covers were placed with help of the metrology group and tack-welded in place. Careful integration with the thermal shield MLI blankets is required to ensure that the targets remain visible and do not become obstructed or out of alignment after the Cryostat-Assembly reaches operating temperature.

After installation of the thermal shield MLI is completed, the Cold Mass assembly is ready for cryostating. This is shown in Fig. 9. The two small pipes at the center of the photo are a thermal shield/beam screen supply pipe (top) and a thermal shield cooling line (bottom). The large pipe to the upper left is one of the two pumping lines for supporting 1.9 K operation after installation in the HiLumi LHC. The pipe immediately below is one of the two heat exchangers required for the Cold Mass to reach subcooled temperatures. The flange on the end of this pipe is required to interface with the FNAL horizontal test stand. It will be removed from the Cold Mass before delivery of the Cryostat-Assembly to CERN.

III. Cryostating

The cryostating winch of Fig. 2 is used to pull the Cold Mass assembly into the vacuum vessel. Each winch includes a load cell to shut down the winch if the pulling force exceeds 28.6 kN, which load becomes excessive. Using this load cell, the measured pulling force was 24.3 kN as the Cold Mass assembly was pulled into the vacuum vessel.

This pull-in must be done slowly and with multiple people providing visual monitoring to ensure that the capillary tubes clear the vacuum vessel end flange and that the capillary system warm heads do not become stuck before reaching their intended penetrations, as illustrated in Fig. 10.

To operate the tooling, the control system uses a hand-held controller and a local control box shown in Fig. 11. The local control box allows selection of winch or mechanical jack operation, the winch is to be operated, and winch speed (50 mm/min or 800 mm/min).

Fig. 10. Capillary tube clearance and warm head position must be visually monitored during cryostating of the Cold Mass assembly.

Fig. 11. Local control panel, allowing selection of winches or jacks and providing a readout of winch pulling force or jack elevation.

Fig. 12. Each alignment table includes provisions for lifting the support feet into the vacuum vessel.

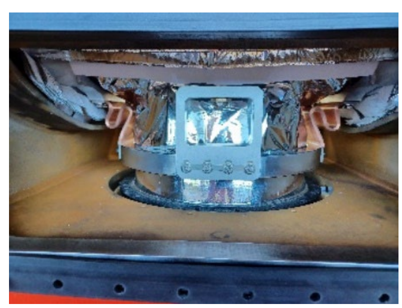

Fig. 13. Installed Cold Mass support post showing the thermal intercept ring and flexible copper straps.

Once the Cold Mass assembly is in the vacuum vessel and supported by the mechanical jacks, three glass fiber reinforced epoxy (GFRE) support posts are lifted into place as shown in Fig. 12. The center post is bolted to a lower support ring and serves as the fixed point for the Cold Mass. The outboard posts slide along keys and act as sliding supports to accommodate the thermal motion of the Cold Mass. Each support post includes a thermal intercept ring cooled by the thermal shield via flexible copper straps as shown in Fig. 13.


Fig. 14. The first HiLumi LHC Cryostat-Assembly after completion of assembly operations on the cryostat tooling.

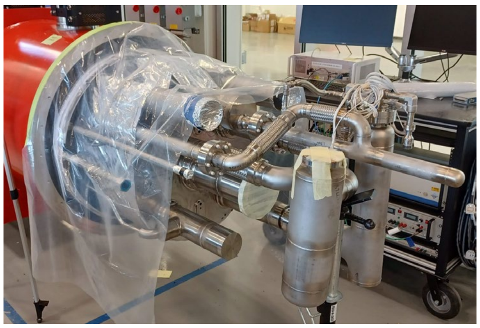
Fig. 15. Cryogenic piping installed on one end of the Cryostat-Assembly in preparation for the horizontal testing.

This is the last operation required on the cryostat tooling, and the Cryostat-Assembly appears as shown in Fig. 14. The Cryostat-Assembly is removed from the cryostat tooling and set on floor-mounted I-beam stages for the final assembly steps.

IV. Final Assembly Steps

Piping spools are mounted to both ends of the Cryostat-Assembly as shown in Fig. 15, allowing one end to interface with the FNAL horizontal test stand while the cryogenic circuits are completed at the other end. All seals are made using annealed copper gaskets between either knife-edge flanges or face-seal fittings.

Vacuum vessel warm connections are also completed at this stage. Fig. 16 shows an FSI measurement head with its fiber optic cable are mounted to the vacuum vessel using elastomer O-rings and vacuum claw clamps. The Instrumentation Feedthrough System (IFS) is wired, and the IFS, Coupling Loss Induced Quench (CLIQ), and K-modulation (Kmod) systems are welded as shown in Fig. 17 and Fig. 18. Lastly, Fig. 19 shows the warm interface boxes mounted.

V. Conclusion

Assembly of the first HiLumi LHC Cryostat-Assembly has been completed at FNAL. Experience gained from this first unit will feed forward into assembly of the remaining nine units.

Fig. 16. FSI measurement head installed on the exterior of the vacuum vessel with a connected fiber optic cable.


Fig. 17. Wiring of the IFS system, and after the IFS warm head assembly has been welded into place.

Fig. 18. CLIQ (left) and KMOD (right) warm head assemblies after being welded onto the vacuum vessel.


Fig. 19. The warm interface boxes of an IFS (left) and a CLIQ (right).

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