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AUP first pre-series Cryo-Assembly Design Production and Test Overview

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Abstract— **New high field and large-aperture quadrupole magnets for the low-beta inner triplets (Q1, Q2, Q3) have been built and tested as part of the high-luminosity upgrade of the Large Hadron Collider (HL-LHC). These new quadrupole magnets are based on Nb_3Sn superconducting technology. The US Accelerator Upgrade Project (US-AUP) is producing the Q1 and Q3 Cryo-Assemblies: a pair of ~ 5 m long magnet structures installed in a stainless-steel helium vessel (Cold Mass) and surrounded by cryostat shields, piping, and a vacuum vessel. This paper gives an overview of the design, production, and the results of the horizontal test of the first pre-series Q1/Q3 Cryo-Assembly.**

***Index Terms*—Accelerator magnets, superconducting magnets, Cold Mass.**

I. Introduction

THE main objective of the US Accelerator Upgrade Project (US-AUP) is to produce several Nb_3Sn superconductor based quadrupole magnets built into Cryo-Assemblies and produce bare crab radio frequency cavities [1] for the High Luminosity Upgrade of the Large Hardon Collider (HL-LHC) [2]. The Cryo-Assemblies will ultimately be installed in the LHC tunnel as Q1 and Q3 insertion region quadrupoles. US-AUP is a collaboration among four US laboratories: Brookhaven National Laboratory (BNL), Florida State University (FSU), Lawrence Berkeley National Laboratory (LBNL) and Fermi national Accelerator Laboratory (FNAL). The superconductor strand procurement and test are Fermilab and FSU responsibilities. The cable production is being done by LBNL, the coils are being fabricated at BNL and FNAL, the magnets are being produced in LBNL then vertical tests are conducted at BNL. The Cold Masses containing two successfully cold tested magnets were designed by FNAL. FNAL is also in charge of the production of the Cold Masses. The cryostat design and procurement of the cryostat parts were CERN responsibilities. The final Cryo-Assemblies (Fig. 1 shows the cross section of a complete Q1/Q3 Cryo-Assembly) are tested at FNAL.

The first pre-series US-AUP Cold Mass (LMQXFA01) production was completed in early fall of 2022. Cryostat work including the final pressure and leak test was completed in January 2023. The first Cryo-Assembly (LQXFA/B01) was tested in the newly upgraded horizontal test facility at Fermilab. The commissioning of the test facility with LQXFA/B01 and the cold tests were completed at the beginning of fall 2023. In this paper we give an overview of the design, production, and test of the first Cryo-Assembly.

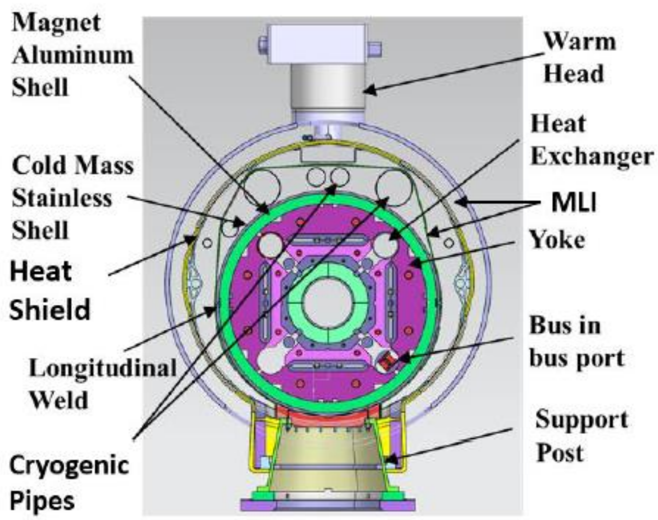

Fig. 1. Each Cryo-Assembly contains two ~5 m long quadrupole magnets, utilizing the key and bladder yoke assembly technique with segmented aluminum shells [3]-[4]. The magnets are installed into a stainless-steel pressure vessel (Cold Mass) that provides alignment for the magnets and a leak tight helium enclosure. Within the Cold Mass is the bus work and the heat exchanger. The instrumentation wires exit at the warm head. The Cold Mass and the cryogenic pipes are thermally insulated with MLI and enclosed by the heat shield. There is another MLI between the heat shield and the vacuum vessel.

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II. Design

A. Cold Mass Design

The pre-series Cold Mass design (see in detail [5]) is a Stainless-steel pressure vessel made from two half shells and two end covers welded together. Since the Cold Mass contains two 4.2 m magnetic length MQXFA Nb_3Sn quadrupoles [3] the Cold Mass design takes into account the following: the alignment of the two MQXFA magnets, the bus work that connects the two magnets and provides the through bus, the heat exchangers, the beam tube, and the magnet instrumentation wiring from the magnets all the way to the cryostat ports (see Fig 1 and Fig 2).

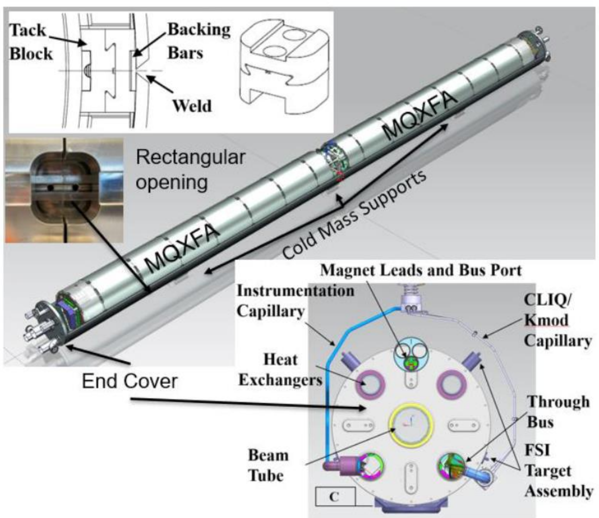

Fig. 2. Cold Mass made of two MQXFA magnets. Some of the design features are shown.

The shell and the end cover material are made of low cobalt content 316LN Stainless Steel (SS). The magnet aluminum segmented shells have shallow longitudinal channels designed to hold the backing bars horizontally on both sides along the magnet. The center of each aluminum shell has a wider rectangular opening with two screw holes to be able to mount the tack blocks. At the center aluminum shell of each magnet the tack blocks are fixed to the iron yoke. The rest of the tack blocks are sliding tack blocks to compensate for the differential shrinkage between the SS outer shell and the magnet. Tack blocks also have machined rectangular channels for the backing bars. Backing bars made of 316L SS provide the mating surface with the two half shells and providing the backing material for the shell longitudinal welds.

The end covers provide an opening for the beam tube and for the two heat exchangers. There are two more openings for the liquid helium passage (150 mm^2 free area) and one more opening for bus bars (including the auxiliary corrector bus bars).

On the top of the CM shell two pipes are attached for the purpose of holding the corrector bus bars initiated from Q2. At each end on both sides of the Cold Mass there are capillary assemblies to provide passage of the instrumentation wires (Voltage taps, Temperature sensors, warm up heaters) and for the Coupling Loss Induced Quench (CLIQ) leads and trim (k-modulation) buses from the magnets to the warm heads that are attached to the vacuum vessel. At the bottom of the Cold Mass there are three supports (made of 316 L SS) that interface with the cryostat. At 12 locations for the Cold Mass position monitoring system, frequency scanning interferometry (FSI) supports are installed for the reflectors.

The Cold Mass components are welded together. The Cold Mass design includes the weld design that follows ASME Section VIII div.2 pressure vessel code requirements. The pressure vessel design analysis, besides dealing with the pressure related forces, also must take into consideration the shipping related forces.

The primary purposes of the 10.1 m long SS shell surrounding the two 4.2 m long magnets are:

- To provide adequate mechanical support for the magnets, during transportation and during cold testing (cool down and pressure wave related forces)
- To maintain magnet alignment relative to each other; ± 0.5 mm deviation from the common magnetic axis.
- To provide a pressure boundary for the Cold Mass at room temperature and cryogenic temperatures

To satisfy the above listed design features the SS shell needs to compress the magnet with some pre-load to generate the required friction between the aluminum and SS shells. Alternatively, due to the fragile nature of the Nb_3Sn magnets, there is a limit of a 3.2 MPa increase in pre-stress on the coils generated by the SS shell welding.

The SS shell-generated stress (or preload) is controlled by selecting the proper SS shell inner circumference value relative to the magnet outer circumference value. The Stainless-Steel shell pre-load is calculated using FEA from the difference between the Stainless-Steel shell ID circumference and the magnet OD circumference. To prevent an excessive preload, the design incorporates a 2 mm thick x 6” wide Stainless-Steel shim fit and tacked to the inside surface of the Cold Mass stainless shell located at top center (12 o’clock) and bottom center (6 o’clock) and runs the full length of the magnets. This shim allows the Stainless-Steel shell to bend at the gaps versus stretching during the longitudinal welding and thus reduces the preload on the shell resulting in a lower preload increase on the coils (see [6]).

At room temperature, the prestress on the coil will not exceed the 3.2 MPa increase limit, and at cold the prestress will not drop below the chosen minimum preload of 0.1 MPa (see [6]). This low prestress value was chosen to assure that the frictional force between the magnet and the SS shell is sufficient to hold the magnet in position by the SS shell in case of a pressure wave occurrence which could generate a force of 62 kN acting on one magnet face.

In the Cold Mass design, to assure adequate and redundant mechanical support, high strength certified screws were chosen for the fixed tack blocks, and the sliding tack blocks are being strategically offset.

The bus bar (two LHC cables soldered together and insulated with polyimide) was designed to be able to carry the ultimate current (17.5 kV) with a large current and temperature margin and to operate safely using high, up to 0.8 V quench detection voltages [7].

B. Cryo-Assembly design

The Cryo-Assembly design contains a Cold Mass surrounded with pipes for the thermal shield, beam screen, quench recovery, bus work, and superfluid pumping (see Fig. 3). The Cold Mass is supported within the Cryo-Assembly on conical monolithic glass fiber reinforced epoxy (GFRE) support posts.

The cryostat design developed by CERN has a lot of similarity with the design that has been produced for the LHC main quadrupole and dipole magnets. The main difference is the Cold Mass size, which has increased from previous Cold Masses. The design takes into consideration optimizing the heat load to the helium system and accommodating the structural loads imposed on the cryostat systems from static weight, shipping and handling, quench loads, and ambient ground motion.

The vacuum vessel, the outermost cryostat component, has a 914 mm outer diameter with 12 mm wall thickness (sufficient for the designed differential pressures); the overall length is 9345 mm. The overall width and height are 1055 mm and 1388.9 mm, respectively. The weight of the vacuum vessel without cover plates or instrumentation wiring housings is 4,941 kg. It is made of low carbon steel with certified resilience down to -50 °C for pressure applications. The vessel is designed for 1 bar external pressure differential and 0.5 bar internal pressure differential. The end flanges are made from 304L forged rings. There are over 20 openings on the vacuum vessel shell, including 3 ports for the support system, 1 port for the relief valve, 2 ports for the instrumentation feedthrough wiring, 2 ports for the feedthrough of CLIQ leads, 1 port for the feedthrough of trim leads, and 12 ports for Cold Mass positioning/monitoring. There are several attachments to the vacuum vessel: survey monuments, support system reinforcement rings, and lifting lugs.

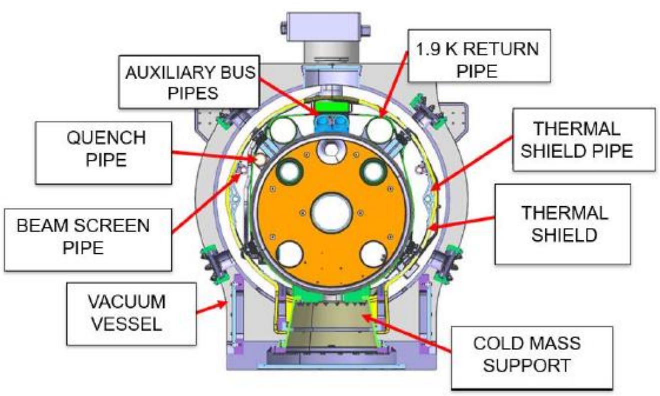

Fig. 3. Cryostat cross section is shown.

The cryostat has a single thermal shield cooled by helium gas between 60 K and 80 K. The shield intercepts heat radiated from the 300 K surface of the vacuum vessel and is conducted through the support system. The thermal shield is comprised of 4 mm thick, high thermal conductivity Aluminum 1050 rolled shells riveted and welded to two aluminum extrusions. The shield itself is a formed shell attached to the cryostat at the support structure made of high thermal conductivity 4 mm thick Aluminum 1050. The thermal shield assembly is anchored to the thermal intercept of the central (fixed) Cold Mass support foot but is free to move axially at the other two (sliding) Cold Mass support feet to allow for thermal contraction.

The multi-layer insulation system is modeled after the insulation system of LHC magnets. The thermal shield is wrapped in two 15-layer multi-layer insulation system (MLI) blankets, and the Cold Mass is wrapped in one 10-layer MLI blanket.

C. LMQXFA01 Production

Cold Mass production (described in detail [8]) started with the inspection (electrical and mechanical integrity) of the two previously cold tested magnets: MQXFA03 and MQXFA04 [9] which were then placed on the alignment table. Magnet transporting requirements were stringent, had to keep the deflection of the magnets to less than 0.25 mm. To achieve this accuracy, a specially designed self-leveling lifting fixture has been used. During the entire activity of lifting the Cold Mass, moving it, and placing it on the alignment table, the total (measured with dial indicators) deflection was 33 µm.

Prior to placing the magnets on the alignment table, the precision SS clamps siting on rollers were aligned to 100 µm accuracy allowing to achieve the goal of maintaining the ±0.5 mm tolerance value on the magnetic axis of the two magnets relative to the common magnetic axis. The alignment of the magnets was checked by survey and with Single Stretched Wire based magnetic measurements.

The beam tube, heat exchanger installation was followed by the bus bar and instrumentation wiring installation. After every critical step an electrical check out including continuity and High Voltage withstand measurements, was performed to assure the electrical integrity of the magnets during the entire production and to be able to debug any non-conformities if they occurred.

The tacking block installation (paying attention to offset the sliding tacking blocks correctly) was followed by the installation of the backing bars. The developed length of the SS Shells prior to installing them onto the magnets were precisely measured (optical survey method) and the results showed that no shims were needed to be used since the dimensions of the shells enlarged with the tolerance values were within the requirements. After the first shell was lowered onto the magnet it was carefully aligned with the magnet utilizing the machined marker on the backing strips. Prior to rotating the top shell-magnet assembly the shell was tack welded to the backing bars. Then the second shell was lowered onto the magnet, aligned and tack welded.

To ensure the shells were ready for welding circumferential measurements were performed using pi tape and an optical survey. It was found that the values before welding were consistent with expectations. Prior to moving the assembly to the welding station optical fiber-based strain gauges were installed onto the shell [10].

Welding used a GMAW 4 procedure with a DC pulse mode, a pair of Miller Invision 450P power sources, Miller S-74 MPa Plus wire feeders, water cooled MIG torches and MPD 1000 Bug-o carriages and rails. The CERN proposed filler wire was 317L(MOD). Two welding machines were used simultaneously at both sides of the magnet controlled by two ASME certified welders. After every pass (three altogether) the weld shrinkage was measured to assure the obtained value is consistent with previously determined values from practice runs. Both strain gauge results and survey measurements of the circumference are assured that the additional stress that the welding generated was less than the maximum allowed value.

The assembly was moved back to the alignment station where shell cutting, and weld prep activities were performed. Then the end covers were fitted, and tack welded. These activities were supported by optical survey to be able to meet the stringent tolerance requirements. The end cover weld utilized the same GMAW 4 procedure and the same equipment used for the longitudinal welding except in this case the torch was stationary, and the Cold Mass was rotating while the three weld passes were executed.

Prior to moving the assembly to the inspection table, the rotation of the magnets with respect to gravity was checked and indexing clamps were used to be able to maintain alignment during the movement. Then at the inspection table the saddles were pre-aligned. The final weld inspection using Ultrasonic testing was performed by an external company to assure that the weld meets ASME code requirements. Then capillary assemblies for the instrumentation wires, trim, and CLIQ leads were installed followed by welding the 12 FSI supports for the reflectors. The final step of the Cold Mass installation was the pressure test up to 25 bars (design pressure is 20 bar the test pressure is 1.25 x 20 bar) and the leak test of the longitudinal weld seams at 20 bar nominal pressure.

D. LQXFA/B01 Production

Cryostat activities are described in detail here [11]. The CERN provided cryostat kit was delivered to Fermilab well in advance of the fall 2022 installation. Also, the cryostat tooling was a CERN procurement provided to Fermilab.

The first step was to move the Cold Mass from the inspection table to the cryostat staging area where the lower half of the heat shield assembly and the MLI blankets were already prepositioned. After the Cold Mass MLI was installed the upper heat shield assembly was placed onto the Cold Mass.

The FSI Cold Mass position monitoring system cold heads installation was the next step. Special attention was required during integration of the cold head parts with the Cold Mass MLI to satisfy the slightly elevated temperature requirement once the Cold Mass is at 1.9 K temperature. Optical survey was needed to precisely locate, and tack weld the thermal shield covers (which include the optical window). It was also important to assure that the MLI blankets would not obstruct the view of the target due to the thermal motion of the targets during cooldown from room temperature to 1.9K.

Once the MLI installation was completed, the Cold Mass was pulled into the cryostat utilizing the winch and the sled-on-rail system of the cryostat tooling. Then Cold Mass was transferred from the sled to the mechanical jacks, and the support posts were lifted into place. 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.

The final assembly steps were performed on floor-mounted I-beam stages. For horizontal testing, piping spools were mounted to both ends of the Cryo-Assembly. Warm connections to the vacuum vessel were completed: FSI measurement heads with fiber optic cables; instrumentation, CLIQ, and trim head assemblies; and instrumentation port wiring.

III. Acceptance Tests

Once the Cryo-Assembly was completed an additional combination pressure and leak test was performed. That required all the helium lines and the two ends of the cryostat to be closed to establish the insulating vacuum space. Return end and lead end cans were installed. Finally, the warm bore was installed to be able to perform cold magnetic measurements at the test facility. During the leak test we were not able to reduce the helium background to a level to meet the 10^{-9} torr-liter/sec requirements. On the other hand, pressurizing the Cold Mass up to 20 bars showed no signs of any increase of the leak rate from the achieved $3\text{x}10^{-9}$ torr-liter/sec background level. New, more efficient pumping system is planned to be used for leak tests of future Cryo-Assemblies.

The Cryo-Assembly was moved to the recently upgraded horizontal test facility [12]. The upgraded test facility was successfully tested without a superconducting magnet (zero magnet test) being attached to it two years ago. Therefore, the Cryo-Assembly test and commissioning of the test facility were done at the same time making the test last a lot longer than it would have lasted with a fully commissioned facility.

The test was successful, and the test results were presented in this conference [13]-[14]. Here we summarize some of the essential results that are relevant for the acceptance of the Cryo-Assembly for LHC tunnel operation and some of the non-conformities that we observed:

- The Cryo-Assembly thermal heat leak was measured, and it had a good agreement with the design value.
- Quench performance of the magnets met the requirements.
- Bus bars performance was validated, and the Cold Mass bus splices resistance values were well below the required 1 nΩ value.
- Field harmonics of each magnet were within the expected values.
- Magnet alignment relative to the magnetic axes was met on the horizontal direction and was slightly off in the vertical direction.
- During Cold Mass installation 1 voltage tap wire (out of 42) and one strip heater wire lost connection. Time-domain reflectometry results showed that the location of the discontinuity of the heater wire is close to the magnet coils.
- One additional strip heater was lost during the HV test.

The observed non-conformities are being addressed.

IV. Conclusion

US-AUP has completed the first Q1/Q3 Cryo-Assembly design and fabrication. Successful cold tests have been conducted utilizing the newly upgraded horizontal test facility at FNAL. The Cryo-Assembly exhibited excellent performance, validating the design and the production processes. Few non-conformities have been observed and they are being addressed to improve the production of the Cryo-Assemblies.

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