FERMILAB-TM-2803-TD

	Q1/Q3 Cryostat Assembly and Horizontal Test Final Design Report	**US-HiLumi-doc- 2882** **Date: 15 May 2020** **Page** 1 **of** 99

U.S. HL-LHC Accelerator Upgrade Project

Q1/Q3 Cryostat Assembly and Horizontal Test
Final Design Report

Prepared by:
S. Feher, US HL-LHC AUP L2 Manager
T. Strauss, US HL-LHC AUP Deputy L2 Manager
R. Bossert, US HL-LHC AUP
G. Chlachidze, US HL-LHC AUP L3 Manager
T. Page, US HL-LHC AUP Integration Manager
R. Rabehl, US HL-LHC AUP L3 Deputy Manager
S. Stoynev, US HL-LHC AUP L3 Deputy Manager
A. Vouris, US HL-LHC AUP L3 Deputy Manager
Reviewed by:
S. Feher, US HL-LHC AUP L2 Manager
G. Ambrosio, US HL-LHC AUP L2 Manager
R. Carcagno, US HL-LHC AUP Deputy Manager
Approved by:
G. Apollinari, US HL-LHC AUP L1 Manager

This manuscript has been authored by Fermi Research Alliance, LLC under Contract No. DE-AC02-07CH11359 with the U.S. Department of Energy, Office of Science, Office of High Energy Physics.

Revision History

Revision	Date	Section No.	Revision Description
0.0	2/17/2020	All	Initial Release
0.5	5/1/2020	All	All parts were worked on
0.8	5/16/2020	All	Editing all parts to get references correct and the style uniform

TABLE OF CONTENTS

1. Overview

The Inner Triplet (IT) quadrupoles are the magnetic system for reaching low beta functions around the Interaction Point (IP) [1]. The triplet is made of three optical elements: Q1, Q2, and Q3. The upgrade of the Inner Triplets in the high luminosity insertions is the cornerstone of the LHC upgrade. The decision for HL-LHC heavily relies on the success of the advanced Nb_3Sn technology that provides access to magnetic fields well beyond 9 T, allowing the maximization of the aperture of the IT quadrupoles. A 15-year-long study led by the DOE in the US under the auspices of the U.S. LARP program, and lately by other EU programs, has shown the feasibility of Nb_3Sn accelerator magnets. The HL-LHC is expected to be the first application of accelerator-quality Nb_3Sn magnet technology in an operating particle accelerator.

For HL-LHC, 20 IT Nb_3Sn quadrupoles (16 plus spares) are needed: they all feature 150 mm aperture and operating gradient of 132.6 T/m, which entails 11.5 T peak field on the coils. In addition, HL-LHC will use the same Nb_3Sn technology to provide collimation in the Dispersion Suppression (DS) region, which will be achieved by replacing a number of selected main dipoles with two shorter 11 T Nb_3Sn dipoles (MBH).

Figure 1 shows a conceptual layout of the HL-LHC interaction region, and Figure 2 shows the CERN nomenclature of the IT system.

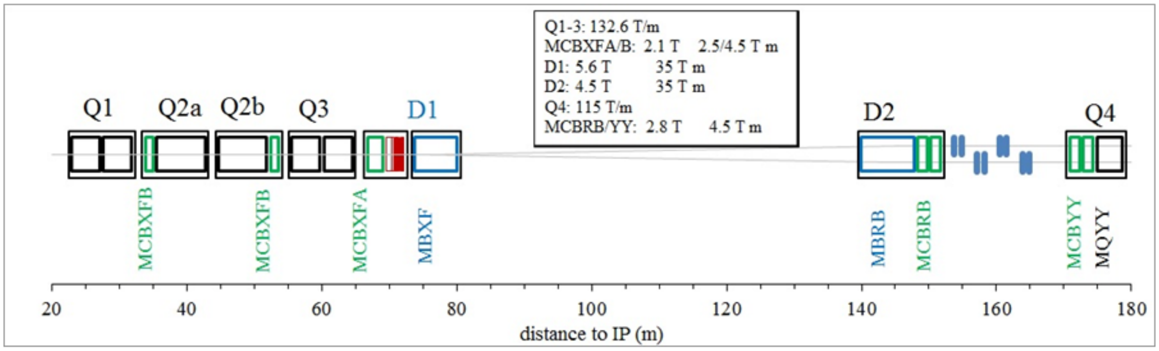


Figure 1: Conceptual layout of the IR region of HL-LHC– thick boxes are magnets, thin boxes are cryostats.

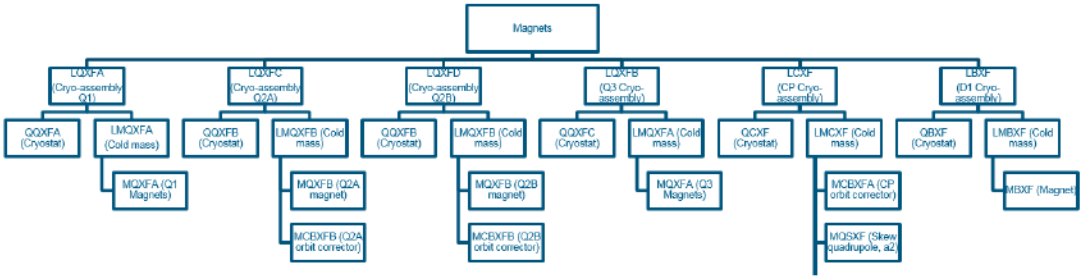


Figure 2: CERN naming conventions for HL-LHC Inner Triplet.

The MQXFA magnet is the quadrupole magnetic element of Q1 and Q3, including the coils and mechanical support pieces to a perimeter defined by the outer shell of the magnets and the end plates of each magnet. Figure 3 shows the LMQXFA Cold Mass cross section (without the LHe SS vessel one obtains the MQXFA magnet cross section). A pair of ~ 5 m MQXFA magnet structures are installed in a stainless-steel helium vessel, including the end covers, to make the Q1 and Q3 Cold Mass (LMQXFA): see Figure 4. Q2a and Q2b each consist of a single unit MQXFB ~ 7 m long. The LMQXFA, when surrounded by the QQXFA or QQXFC cryostat shields, piping, and vacuum vessel, is then the LQXFA Cryo-Assembly for Q1 and the LQXFB Cryo-Assembly for Q3, as installed in the tunnel of LHC.

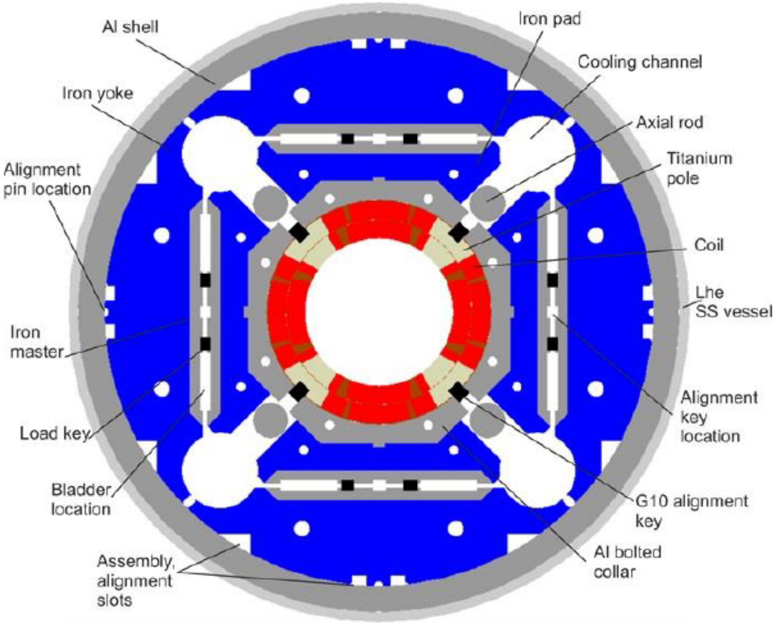


Figure 3: LMQXFA Cross Section. The difference between the Cold Mass LMQXFA and magnet MQXFA is the LHe SS vessel.

The US is responsible for the final design and fabrication of 10 Q1/Q3 Cold Masses (3 pre-series, 7 series production) including final design and fabrication of the Q1/Q3 Cold Mass fabrication tooling. The installation of CERN-provided Q1/Q3 Cryostat tooling and assembling of Q1/Q3 Cryo-Assemblies (2 pre-series, and 8 series production Q1/Q3 Cryo-Assemblies) using CERN provided cryostat kits is also a US responsibility, together with horizontal testing and shipping of the 10 Q1/Q3 Cryo-Assemblies to CERN.

CERN is the Design Authority for the Q1/Q3 Cryostat design. The Q1/Q3 Cryostat tooling procurement is also the responsibility of CERN. The cryostat kit, cryostat tooling, and some Cold Mass parts are provided by CERN including initial inspection of these items at CERN and shipping to Fermilab. The complete list of CERN provided components can be found in [2]. Q1/Q3 Cryo-Assembly installation into the LHC tunnel and commissioning is not in the project scope.

In this Preliminary Design Report, besides the description of the Cold Mass Design and the Horizontal Test Facility, we also give a summary of the CERN Cryostat Design. This helps to better understand the cryostat assembly work execution the US is responsible for in the scope of the AUP project.

2. Cold Mass

2.1. Scope and Design Overview

The scope encompasses the final design and fabrication of 10 Q1/Q3 Cold Masses (3 pre-series, 7 series production) including final design and fabrication of the Q1/Q3 Cold Mass fabrication tooling. Although some Cold Mass parts were designed and will be procured by CERN, Fermilab performed design verification of these components since Fermilab is the Design Authority for the Cold Mass design.

The design was developed to meet the LMQXFA Cold Mass Functional Requirements Specifications (FRS) [3]. The FRS Document identifies 27 Threshold requirements (R-T-XX) and 4 objective requirements (R-O-XX) for the LMQXFA Cold Mass. These requirements will be identified how they apply to the Cold Mass throughout the following sections of the Final Design Report.

The Cold Mass is defined as the helium pressure boundary containing a pair of 4.2-m-long (magnetic length) MQXFA magnet structures. The Q1 and Q3 Cold Masses of the interaction region triplet identified as LMQXFA. The LMQXFA, when surrounded by the QQXFA or QQXFC cryostat shields, piping, and vacuum vessel, is then the LQXFA Cryo-Assembly for Q1 and the LQXFB Cryo-Assembly for Q3, as installed in the tunnel of LHC. With the understanding that the Q1 and Q3 Cold Mass assemblies are identical, the term Cold Mass will refer to both Q1 and Q3 Cold Masses.

A drawing tree with listed drawings can be found in [4]**.** The Cold Mass major components (see Figure 4) consist of:

- Stainless Steel Half Shells per Section 2.2
- Stainless Steel End Covers per Section 2.3
- Heat Exchangers per Section 2.4
- Stainless Steel cold bore tube per Section 2.5
- Bus per Section 2.6
- CLIQ leads per Section 2.7
- kMod (trim) leads per Section 2.8
- Instrumentation per Section 2.11
- Cold Mass Support per Section 2.12

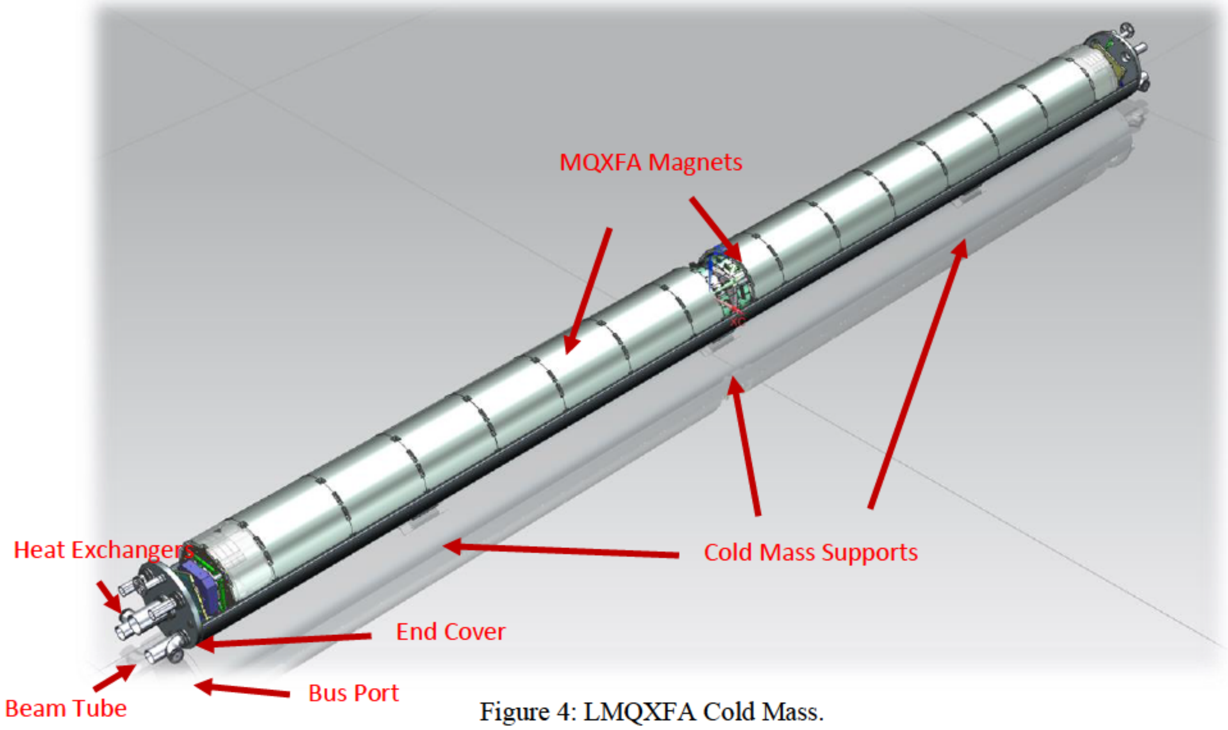


Figure 4: LMQXFA Cold Mass.

2.1.1. Codes and Standards Applied for the Design

To meet the FRS requirement "R-T-26: The LMQXFA Cold Mass assembly must comply with CERN's Launch Safety Agreement (LSA) for IR Magnets" but must also meet all the requirements of FESHM 5031 in order to be pressure tested and operated at Fermilab's Test Stand 4 in Industrial Building 1. The design and fabrication shall follow a specific set of codes and standards to comply with both CERN's LSA and Fermilab's Environment, Safety & Health Manual (FESHM) chapter 5031 which directs design and fabrication to comply with ASME Boiler & Pressure Vessel Code Section VIII [3] [5] [6] [7]. The LSA outlines the path taken to achieve compliance with the 2014/68/EU Pressure Equipment Directive Essential Safety Requirements. The Agreement also describes the use of harmonized codes for design and manufacturing of the Cold Mass as well as the technical documentation required and the appropriate quality controls that must be put in place.

Understanding that all pressure equipment installed and operated at CERN shall be designed in accordance to CERN Safety Rules and the new European harmonized standard EN13445 (Unfired Pressure Vessels), the agreement clarifies that although EN13445 provides a presumption of conformity with EU Directives, ASME Boiler and Pressure Vessel Code Section VIII Div.2 is considered as one of the similar applied construction codes for Cold Masses procured through US HL-LHC AUP.

Per the LSA, ASME Section VIII Div. 2 is approved for use on design but where differences appear on the fabrication side, a few modifications have been outlined.

These include:

- Per LSA Sect. 3.8.1 - ASME B&PV Code Section VIII div.2 is applied to meet the Design by Analysis method requirements
- Per LSA Sect. 3.9.2 table 4 – Austenitic materials allowed for pressure vessel parts include:
    - 316L (lower plates per F10103814)
    - 316LN (End Covers per LHCLMQXF S0002 (CERN) and formed shell plates per F10125550)

  - 317L (weld filler rod)
- Per LSA Section 3.9.1 - Certification of materials and their properties – materials and weld consumables will be procured with traceability to a certified material test report that meets the requirements of ASME B&PV Code material specifications and have an EN 10204:2004 3.1 product control. Materials and their certificates will be reviewed by the engineer as they are received and approved for fabrication process prior to any work commencing.
- Per LSA Sect. 3.8.5 & 3.10.2 - welding procedures qualifications for listed weld types are in accordance to ASME Section IX with additional testing and acceptance requirements per table 5 of LSA Sect. 3.11.2:
  - Longitudinal shell joints
  - Circumferential Shell to End Cover Joints
  - Cold Mass support (lower plate) base joints
  - Circular butt joints on the interconnection pipe joints
- Approval of welders and NDT personnel follow ASME Sect. IX with additional requirements per LSA Sect. 3.11.2
- Definition of the pressure vessel pneumatic test pressure is per ASME Section VIII div.2 with the exception that it is 1.25 x design pressure

To maintain consistency through all the analysis, all design calculations regardless of pressure bearing or otherwise, are per ASME Section VIII div.2 to comply with LSA Sections 3.1.

2.2. Shell

The selection of the shell material and size is in accordance with the FRS requirements. To meet FRS requirement R-T-07, the Cold Mass is designed and documented in accordance with CERN and U.S. HL-LHC Accelerator Upgrade Project safety agreements. As further described in Section 2.1.1, Codes and Standards Applied for the Design and Section 2.14, Cold Mass Pressure Vessel Analysis, the shell thickness is analyzed per ASME Section VIII div.2 to verify that the 8 mm thickness is sufficient for a maximum allowable working pressure of 20 bar differential per the FRS requirement "R-T-09: The LMQXFA provides a 1.9 K helium vessel that must be designed for a Maximum Allowable Working Pressure of 20 bar differential with an applied test pressure of 25 bar differential" and FRS requirement "R-T-10: The LMQXFA Cold Mass assembly must be capable of sustaining loads resulting from up to 20 bar of pressure differential without physical damage or performance degradation". This thickness also satisfies the maximum diameter of the Cold Mass as required per FRS requirement "R-T-02: The LHe stainless vessel outer diameter, including tolerances, must not exceed 630 mm at room temperature". This OD specification limit does not include attachments for interfacing with or mounting to the cryostat.

To meet the FRS requirements R-T-08, LMQXFA pressure vessel material for the cylindrical shell and R-T-24, for LMQXFA components to withstand maximum radiation doses, the material grade used for the shell is Austenitic Stainless-Steel Grade 316LN with Cobalt content lower than 0.1%. This material is procured with traceability to Certified Material Test Reports (CMTR) so that it can be verified to ASME specifications for physical and chemical properties and fulfill traceability requirements. The traceability will be maintained through the Fermilab Cold Mass assembly traveler as described further in Section 2.17.2, Assembly Procedures. The material grade and specification also meet the requirements of the LSA.

The 8 mm (5/16") thick 316LN low Co stainless steel shell will be formed in two 180° half shells with tangents per F10103607 to allow for pre-weld machining per drawing F10125550. To compensate for any weld shrinkage, the shell arc length is machined to a specific length as determined in Section 2.2.1, Shell Tolerance Calculations based on Weld Test Results.

There is no minimum pre-stress requirement for the stainless-steel shell. The stainless-steel skin will have an interference fit between shells after welding. It is completely welded and attached to the magnet via the longitudinal weld seam backing strip.

Excessive pre-stress of the stainless-steel shell can cause misalignment issues for the Cold Mass but also affect the magnet performance. Per LBNL Technical Note [8], the coil stress increases by ~3.2 MPa / 0.1 mm (0.004") of weld shrinkage in the shell. This translates to 48 MPa coil stress increase to be expected for a 1.5 mm (.05") weld shrinkage. To avoid an unacceptable stress that may damage the coils and affect performance, the developed arc length of the shell is controlled as shown in Section 2.2.1 below.

The shell will be attached to the MQXFA magnets (LBNL drawing SU-1011-0518) physically at each of the two longitudinal seams, 180 degrees apart per sub-assembly drawing F10138328. Each MQXFA magnet has 9 openings per side (18 total/magnet or 36 total/Cold Mass) through the aluminum outer shell that will allow for stainless steel tack blocks to be fastened with bolts to the inner iron yoke and sit flush with the aluminum shell OD. A matching slot through the stainless-steel tack blocks and aluminum shell will allow for fitting a stainless-steel backing bar per drawing F10103774 that will be attached to each of the tack blocks by welding. This backing bar will serve a dual purpose: first, a barrier between the aluminum shell and stainless-steel shell weld seam; and second, to allow for a good root penetration weld that will lock the shell and magnet together. With the exception of four tack blocks per drawing F10125422 located at the mid-points of each MQXF magnet (2 per magnet), the remaining tack blocks consist of a 2-piece design that allows for longitudinal or horizontal sliding motion needed during cooldown and quenching. Of the 34 sliding tack blocks, 30 are the standard wide tack blocks per drawing F10125377 and the 4 which are mounted at the ends are a narrow version per drawing F10129290 to fit the reduced width at the ends of the magnet. See Figure 5 and Figure 6 below.

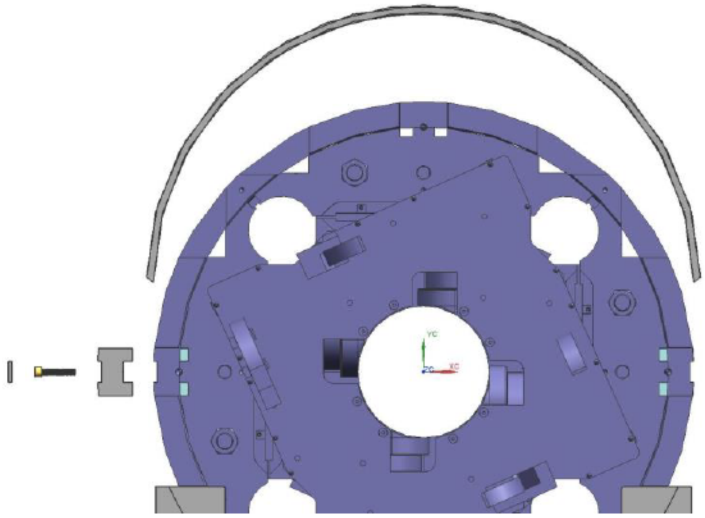


Figure 5: Tack Block Assembly.

The design of the tack blocks is consistent with analysis of the Cold Mass [9] which is designed according the 2017 version of the Boiler and Pressure Vessel Code Section VIII div 2 with some reference to the 2019 version of the code for updated material properties. Low Co 316LN grade material requirements are removed from the tack blocks and will be fabricated using dual certified 316/316L Stainless Steel with a thin hard chrome plating on all sliding contact surfaces. The dual certification will meet the minimum strength requirements of 316 yet meet the chemical properties of 316L material required by the LSA for Cold Mass components.

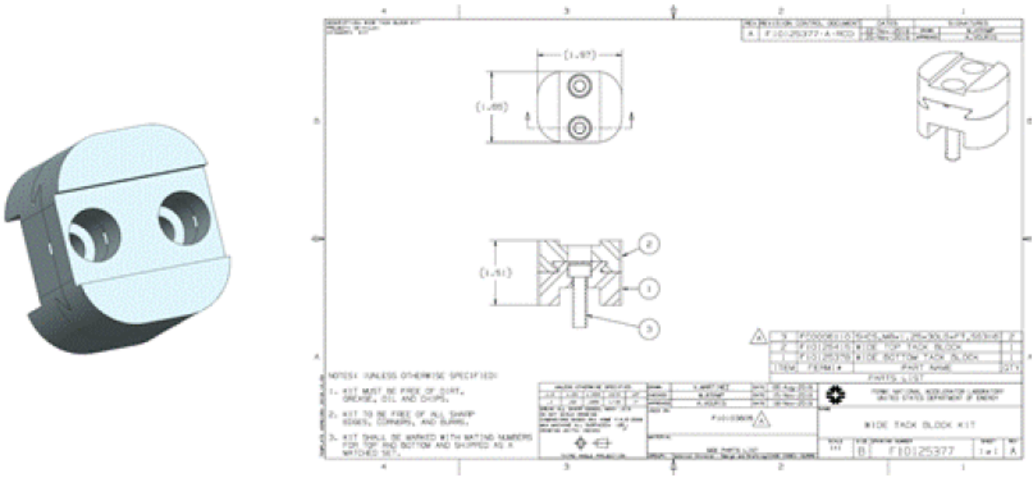


Figure 6: F10125377 Tack Block.

Examining the behavior of the Cold Mass when the shell is not in full contact with the magnet, the tack block design is determined to be sufficiently strong enough to support the magnet although the shell will deform under the load. Due to the intended pre-stress incorporated by the shell design described further in Section 2.2.1, the shell will always be in contact with the magnets and the load is transferred directly through the shell to the lower plates per F10103814 described in Section 2.12, Cold Mass Supports. Testing will also be performed on the tack block to ensure that failure will not occur due to the harsh conditions it is required to operate in and that there will not be wear in the sliding contact. Full details can be accesses in the Engineering Note [10] and Tack Block Test Fixture [11]. The Tack Block Test Fixture document will be updated when the results of the testing are available.

2.2.1. Shell Tolerance Calculations Based on Weld Test Results

To complete the welds, two weld machines have been procured to simultaneously weld on both sides of the Cold Mass (180 degrees apart) and avoid excessive distortion. Parameters have been developed for a GMAW procedure [12] to weld the Cold Mass longitudinal seam in three total passes (1 root & 2 cover passes) using the recently purchased pair of Miller Invision 450P power sources, Miller S-74 MPa Plus wire feeders, water cooled MIG torches and MPD 1000 BUG-O carriages which utilize existing rails in FNAL stock.

From multiple weld sample tests done by FNAL welders, a weld shrinkage of approximately 0.045" (1.3 mm) per longitudinal weld seam using a semi-automatic GMAW process is evident (See FNAL Document, MQXFS1d Shell Preparation [13]). Taking the shrinkage into account, 1 mm or 0.039" of developed arc length is added to each half shell to compensate for the total weld shrinkage between 2 welds. To achieve and consistently maintain warm and cold contact between the outer stainless-steel shell and aluminum shell of the magnet structure, 0.02" (0.5 mm) is removed from the overall developed length. The minimum increase in pre-stress is allowed considering an expected increase in stress on the coil of 3.2 MPa per 0.004" (0.1mm) of reduced shell length. This satisfies the maximum additional pre-stress allowed on the coil [8].

The calculated half shell developed length is shown in FNAL Document, MQXFS1d Shell Preparation [13]. Strain gauge measurements [14] confirmed the process how we calculated the ideal pre-stress on the coil. The MQXFS1d quench test [15] [16] proved that the applied pre-stress will not degrade the magnet performance meeting R-T-22.

A full length empty shell sample weld test was conducted in November of 2018 using SA240 316L stainless steel formed and machined plates per FNAL drawing F10094031 rev.A and 317L filler weld rods. The tests were performed using a prototype of the weld station tooling in Industrial Building 2 (IB2) using 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 which are the same equipment to be used for the actual longitudinal welding. More details and results can be found in [17].

Half shells will be measured from top dead center to distribute an equal amount of developed length on both sides of the center line.

After welding the longitudinal seams, the shell ends will be cut square and beveled using a WACHS model “Dynaprep” MDSF for 22”-28” shell OD cutting and beveling. A boring adapter for the WACHS cutter will also be used to cut a minimum length and depth on the inside surface of the shell ends to match the End Cover ID. This cut will allow the shell and End cover to match ID/OD surfaces and the use of a welding backing strip.

The longitudinal welds on the shell will be full penetration butt joints that will be 100% Ultrasonically tested using a phased array process per the requirements of ASME B&PV Code. Acceptance criteria will meet both, ASME Section VIII div.2 and with CERN and U.S. HL-LHC Accelerator Upgrade Project safety agreement [5] for compliance with the European Pressure Equipment Directive (PED).

2.2.2. Stainless Steel Shell

The shell per F10125550 is designed to allow for one half shell to be fit and tacked in place to backing bar per F10103774 prior to rotating (rolling) the Cold Mass assembly and fit/tack the second half shell. The half shell (see Figure 7 and Figure 8) overall length and weld preps are machined per print with tangents to allow for any weld shrinkage in the stainless-steel shell. Tolerances shall be included to maintain shell straightness and geometry during forming as well as any tangent lengths and weld preps during machining. Installation of the instrumentation, bus, beam pipe, and heat exchangers will be done prior to shell fit up for accessibility.

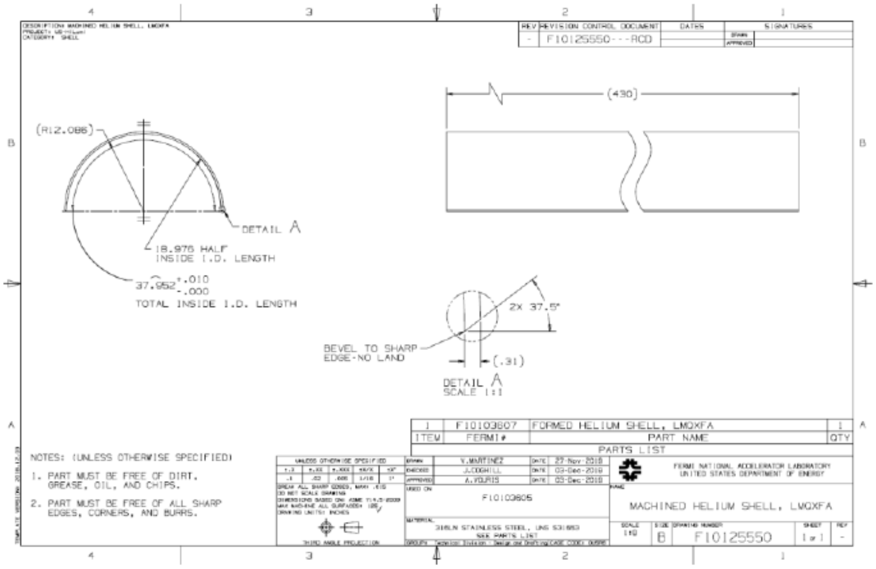


Figure 7: Machined Half Shell drawing.

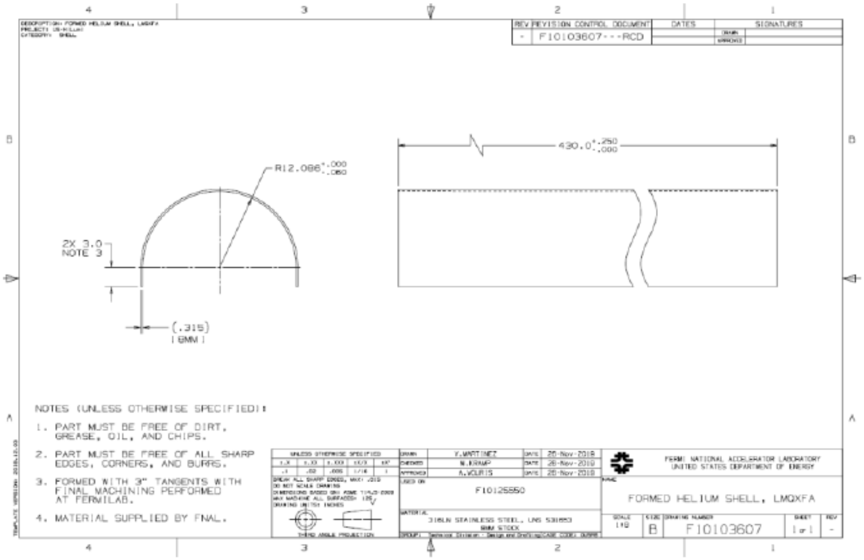


Figure 8: Formed Half Shell drawing.

2.3. End Cover

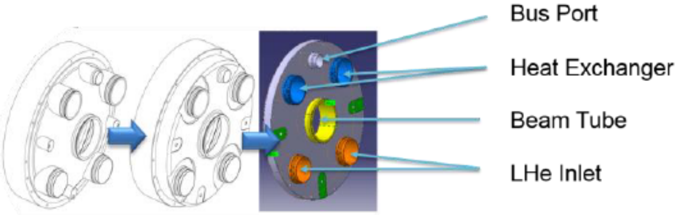
The selection of the end cover material and size is in accordance with the FRS requirements. The end covers are bound by the identical requirement as apply to the shell (See Section 2.2 Shell) for material selection, safety, Codes and Standards, documentation and design parameters. The end cover thickness is analyzed per ASME Section VIII div.2 as done for the shell, to verify that the thickness is sufficient for a maximum allowable working pressure of 20 bar differential at 1.9 K The overall length to the fiducial spot faces on each end of the Cold Mass is maintained per FRS requirements R-T-01, The LMQXFA assembly physical length (end cover to end cover, including tolerances) must be ≤ 10,100 mm. This dimension is at room temperature (296K). This is controlled through trial weld runs to determine weld distortion and shrinkage [17] [18].

Again, as is for the shell, to meet the FRS requirements R-T-08, LMQXFA pressure vessel material for the end covers and R-T-24, for LMQXFA components to withstand maximum radiation doses, the material grade used for the end covers is also made of Austenitic Stainless-Steel Grade 316LN with Co content lower than 0.1%. This material is also procured with traceability to Certified Material Test Reports (CMTR) so that it can be verified to ASME specifications for physical and chemical properties and fulfill traceability requirements as is for the shell and other pressure bearing components. The traceability will be maintained through the Fermilab Cold Mass assembly traveler as described further in Section 2.17.2, Assembly Procedures.

The Cold Mass end cover per CERN drawing LHCLMQXF_S0002 (see Figure 9) design is fabricated stainless steel flat plate and has several openings that serve the functions per FRS requirements R-T-03: The LMQXFA end cover must include piping listed in Table 1 for cryogenic and electrical connectivity purposes and R-T-25: The LMQXFA Cold Mass assembly must meet the detailed interface specifications with the following systems:

- 1x Instrumentation port – used for the main bus bars,
- 2x Heat Exchanger opening – used for the Heat Exchanger connection mounted in the cooling hole of MQXFA
- 1x Cold Bore Connection (Beam Tube)

- 2x LHe inlet – for the liquid Helium to enter to the Cold Mass volume, CLIQ leads and the instrumentation wires (through a reduced side outlet of a tee branch attached to these ports)



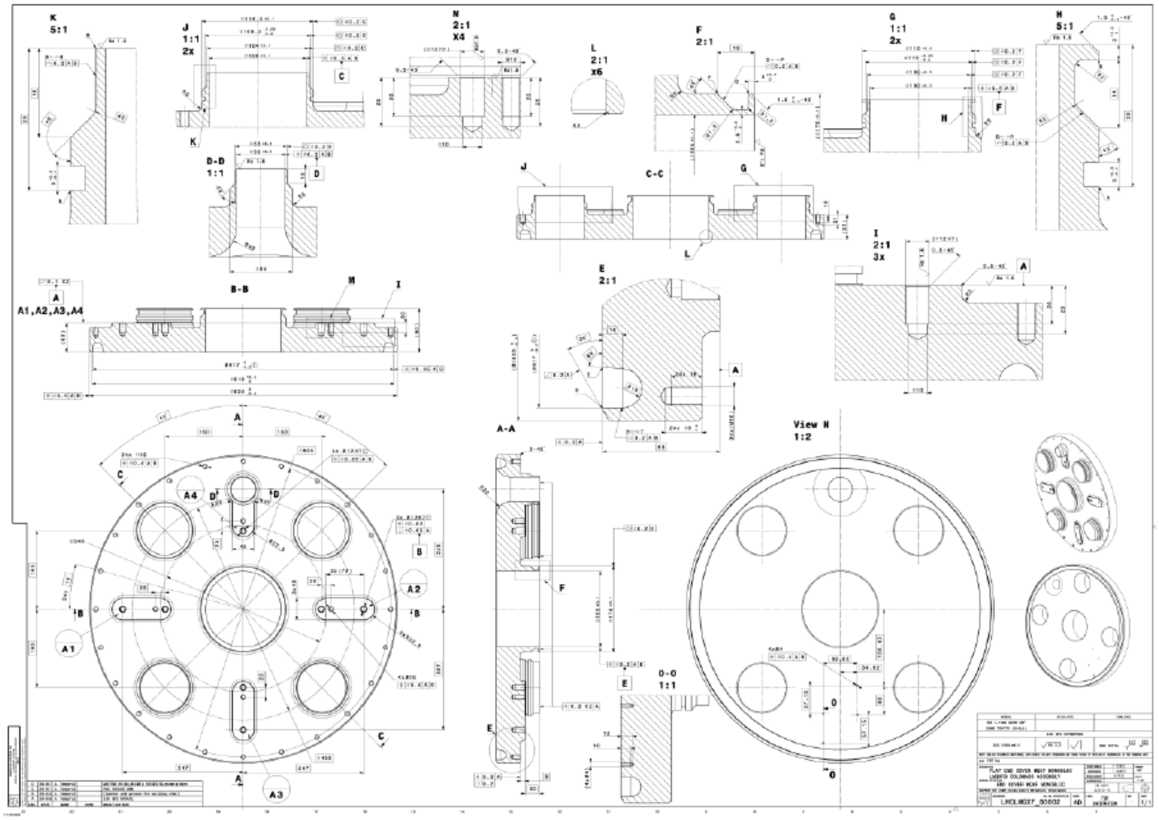


Figure 9: End Cover Design with openings per FRS requirement R-T-03 (CERN drawing LHCLMQXFA_S0002).

The circumferential welds on the shell to end cover will be full penetration groove joints that will be 100% Ultrasonically tested using a phased array process per the requirements of ASME B&PV Code. Acceptance criteria will meet both, ASME Section VIII div.2 and with CERN and U.S. HL-LHC Accelerator Upgrade Project safety agreement [5] for compliance with the PED.

The connections for the Helium heat exchangers, cold bore tube and LHe inlets are designed to align with the MQXFA magnet yoke openings and welding procedures are utilized to minimize twist by tacking sufficiently but also welding three passes with start/stops equally spaced at 120° apart [18].

2.4. Heat Exchanger

The Heat Exchangers per CERN drawing LHCLMQXF_S0022 as shown in Figure 11 will be installed in the two upper 77 mm diameter quadrant cooling channels of the MQXFA yoke and run the length of the Cold Mass without obstructions between the magnets per FRS R-T-04 requirements. The 74 mm OD Heat Exchangers will be installed without supports provide enough annular space to allow adequate flow for maximum heat extraction. The cross-sectional area of the heat exchangers has been analyzed and confirmed that the free area is maintained per the requirement of R-T-23 in [19].

The heat exchangers also have to meet FRS requirement R-T-07, and thus analyzed per ASME Section VIII div.2 to verify the design is sufficient for buckling under maximum allowable working pressure per the FRS requirement R-T-09, for a Maximum Allowable Working Pressure of 20 bar differential with an applied test pressure of 25 bar differential and FRS requirement R-T-10.

The heat exchangers are inserted through the upper quadrant openings of the aligned MQXFA magnets prior to fitting/tack welding of the stainless steel shells to allow for access during assembly and verify there are no obstruction or interferences between the magnet pairs and through the full Cold Mass length as required by FRS requirements R-T-04: The LMQXFA Cold Mass assembly must not have any obstructions or interferences that will prevent insertion along the entire LMQXFA length of the 74 mm OD heat exchangers. Weld details for the heat exchangers have been established and are as shown in Figure 10 below. A flared flange per CERN drawing LHCLMQXF_S0013 is first welded to the neck of the heat exchanger, fit and aligned prior to final welding to the end cover port. The location and end connections of the heat exchanger will remain compliant to FRS R-T-25.

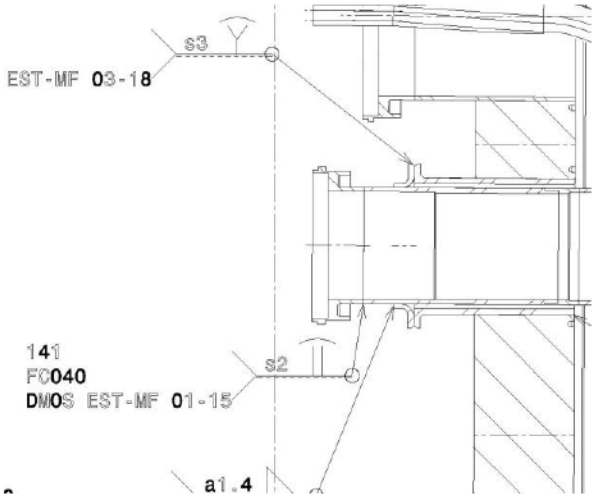


Figure 10: Heat Exchanger weld details.

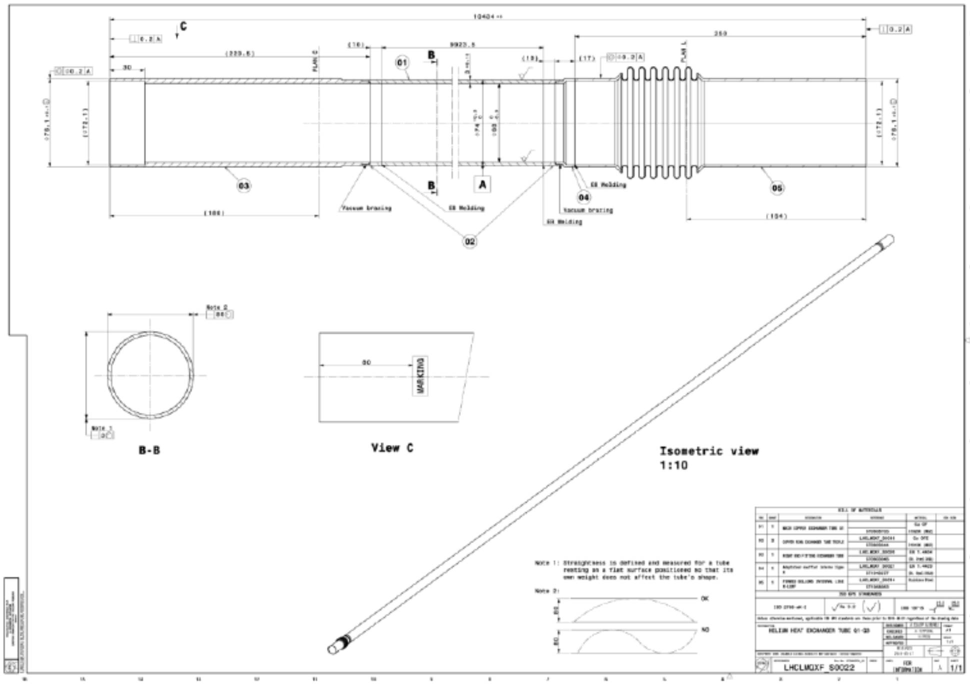


Figure 11: Heat Exchanger design.

2.5. Beam Pipe

The selection of the beam pipe, also known as the cold bore tube, material and size is in accordance with the FRS requirements. The beam tube is another pressure bearing component of the Cold Mass that meets or exceeds the FRS requirements that apply to all other Cold Mass components that are identified in Section 2.2 for the shell. The beam pipe or cold bore tube thickness is analyzed per ASME Section VIII div.2 to verify that the thickness is sufficient for a maximum allowable (external) working pressure of 20 bar differential per the FRS requirement R-T-09, and FRS requirement R-T-10.

The material grade for the beam tube is Austenitic Stainless-Steel Grade 316LN with Co content lower than 0.1% to meet the requirements of R-T-24. The beam tube is one of the components that is also considered to be part of the containment vessel and thus the material is procured with traceability to Certified Material Test Reports (CMTR) and maintained as it is for the shell, end covers and other pressure bearing components as stated in Section 2.2 and further explained in Section 2.17.2 The insulated Beam pipe per CERN drawing LHCLMQXF_S0026 is sized to be installed and centered in the MQXFA magnets by contact between insulation on the outside of the Beam Tube and the coil ID bumpers. The Beam Pipe is trimmed to length after all testing is complete on both ends and provided to meet interface documents per FRS R-T-25.

Weld details and attachment procedures for the beam tube are similar to the heat exchangers shown in Figure 12. Flared flange fittings per CERN drawing LHCLMQXF_S0012 are used for the beam tube also to maintain proper alignment after welding. The beam tube is inserted through the center bore of the aligned MQXFA magnets prior to fitting/tack welding of the stainless steel shells to allow for access during assembly and verify there are no obstruction or interferences between the magnet pairs and through the full length as required by FRS requirements R-T-04: The LMQXFA Cold Mass assembly must not have any obstructions or interferences that will prevent insertion along the entire LMQXFA length of the cold bore.

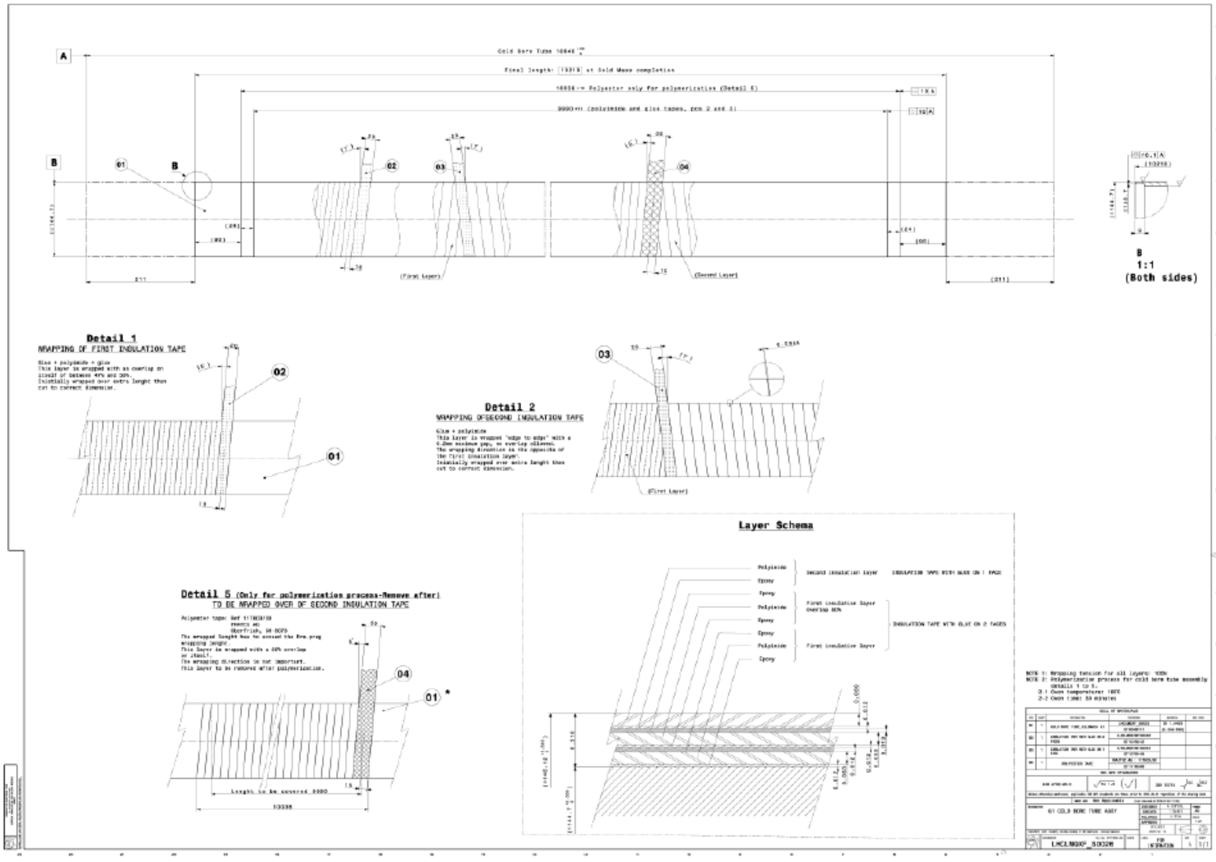


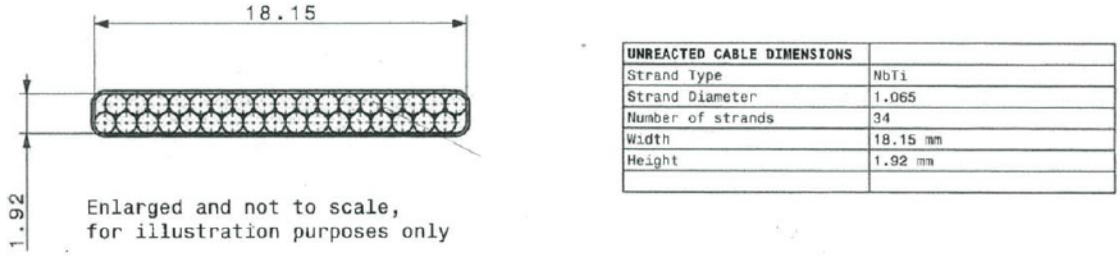
Figure 12: Insulated Cold Bore Beam Pipe.

2.6. Bus Work

2.6.1. Bus Design

The through bus is similar to the design used for the MQXB (LHC IR triplet) magnets in the current IR triplet. It consists of two pairs of special rectangular NbTi cable used for busses and coil leads as shown in Figure 13 and CERN drawing number LHCMQXFB0079, consistent with requirement R-T-12. Each pair is soldered together and wrapped with Kapton. The pair will be wrapped together as shown in Figure 14 and placed into a bus housing made of G-11 (Figure 21). The assembly drawing of the bus is FNAL #F10119849.

The amount of Kapton between each bus is 995 µm. 50 µm (2 mil) Kapton will withstand 6100 V/mil. 125 µm (5 mil) Kapton will withstand 3900 V/mil. The bus insulation can therefore withstand a total electrical resistance of 131 kV, which far exceeds the High Voltage withstand requirement of 4600 V (at room temperature).



UNREACTED CABLE DIMENSIONS	
Strand Type	NbTi
Strand Diameter	1.065
Number of strands	34
Width	18.15 mm
Height	1.92 mm

Figure 13: LMQXF Bus Cable.

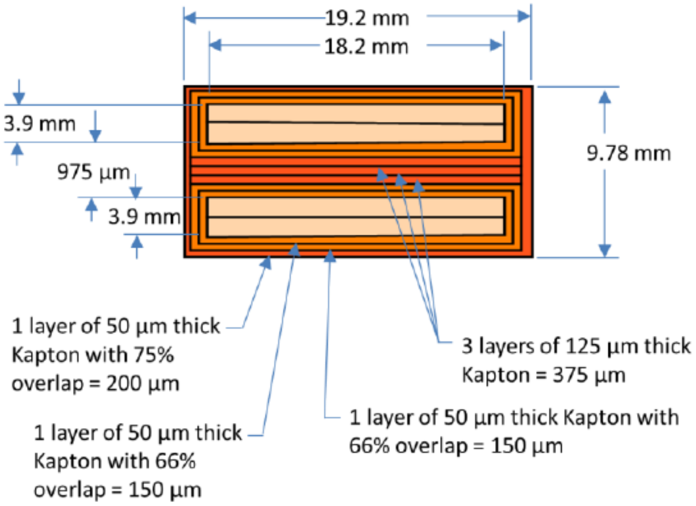


Figure 14: Cross section of Through Bus.

2.6.2. Bus Manufacturing

Solder used for the busses as well as the splices between the local busses and the A leads are the materials approved by CERN (R-T-14). Solder is 96% tin / 4% silver and is pre-rolled into strips which are 0.25 mm (0.010 in) thick and the same width as the cable (see dwg FC0073209). Two pieces of solder strip are placed between the cables and enclosed in a full-length fixture (dwg F10119961), then heated to 240 degrees C for 10 minutes. The flux used is Solder Gel MOB 39. The solder joint for the busses and splices were tested in a short model (MQXFS1e) [15]. Similar splices with NbTi cable and the same solder were also previously tested during the fabrication of the MQXB magnets used for the existing LHCIR quadrupoles and showed resistances well under 1.0 nano-ohm (R-O-03) [20].

Testing of strands at operating temperature and field after being heated to the temperatures to be used during soldering is being done to ensure that the soldering temperatures being used will not damage the NbTi cable [21].

Busses are wrapped with layers of 50 µm thick Kapton as shown in Figure 14. Wrapping is done on a device designed at Fermilab for this purpose (FNAL assembly drawing #F10095440).

2.6.3. Bus Expansion Loops

The expansion loops for the LMQXFA Cold Mass will be similar in style to the design implemented on the previously built MQXB Cold Masses. Each Q1 and Q3 include a power lead which soldered to the next magnet (practically it is lead B), a local bus that is soldered to lead A, a through bus, and 4 CLIQ leads. Each will include two K-mod (trim) leads on the "Qa" end only. The bus port through the magnet iron will contain the power leads while the CLIQ leads and K-mod leads will exit at their respective ends as shown in Figures Figure 15 and Figure 16, then proceed into either the CLIQ/K-mod or IFS capillaries as shown schematically in Figure 17. The magnet leads, as they exit the magnet, will have two "loops" on each end, an upper loop going to the next magnet, and a lower loop going to the local bus. The bus is fixed to the shell of the Cold Mass at the center point between the Q1a/Q3a and the Q1b/Q3b.

The configuration of the Q1 will be identical to that of the Q3. Both Q1 and Q3 Cold Masses contain two MQXFA magnets; Qa and Qb (see Figure 15). The Qb is "flipped" horizontally with respect to the Qa to provide the appropriate field rotation necessary between the Qa and the Qb. Since the Qb is flipped horizontally with respect to the Qa, the bus work on the face of the Qb will be somewhat different in shape to that of the Qa.

Figure 15 shows an illustration of an entire string with the Cold Masses connected. Busses, CLIQ leads, K-mod leads, exterior voltage taps, and a special lead for testing at Fermilab (MTF lead) are shown. Figure 16 shows the configuration of a single Q1/Q3 Cold Mass. Figure 16 is identical to the area inside the dotted box in Figure 15. The voltage taps shown (blue lettering) are added during the Cold Mass assembly. Figure 15 and Figure 16 are consistent with the triplet schematic, CERN drawing number LHCLMQXF E000 and Functional Requirements specification R-T-11.

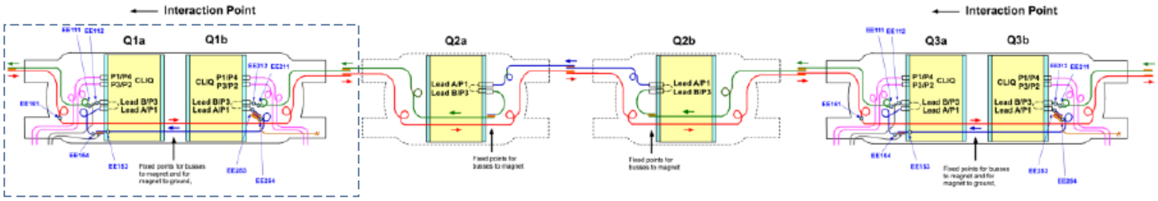


Figure 15: Bus work (entire string shown). Green lines represent lead B, blue lines represent lead A, red lines represent the through bus, purple lines represent the CLIQ leads, gray lines represent K-mod leads, and the tan line represents an extra lead used during testing to allow each magnet to be tested individually on the horizontal test stand at Fermilab (MTF lead). This lead will be terminated before shipment to CERN and will not be used during operation at CERN.

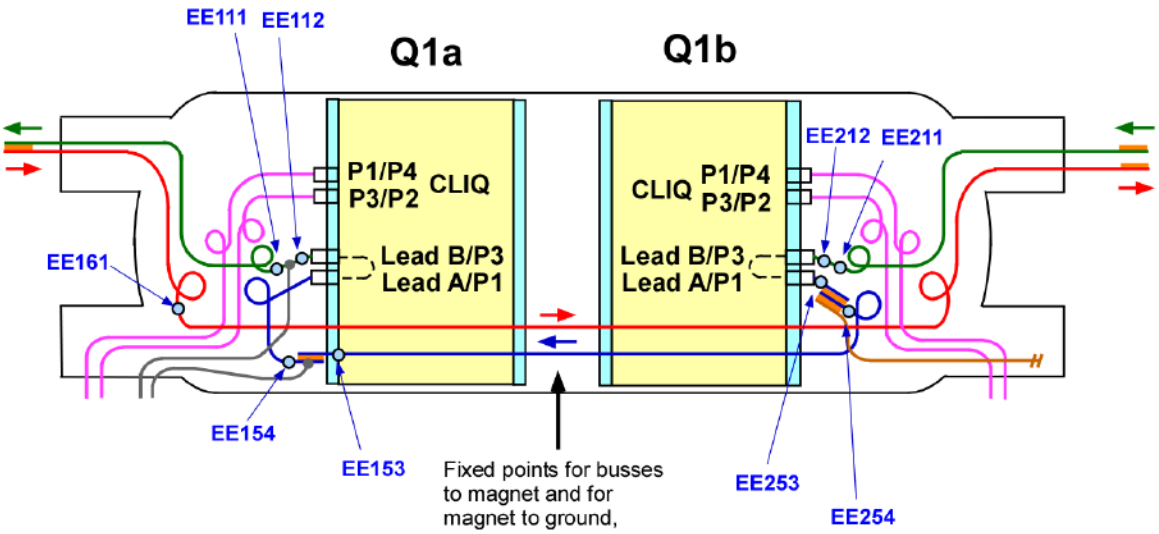


Figure 16: Bus work of a single Cold Mass. Positions of the voltage taps added during Cold Mass assembly are shown by the light blue dots.

Figure 17 shows a top view of the entire triplet, describing where the various instrumentation wires exit the Cold Mass. Coil voltage taps, Quench Protection heater wires, Cold Mass voltage taps, temperature sensors, and warmup heaters wires will exit through the IFS capillary. CLIQ leads and Kmod leads will exit through the CLIQ/KMod capillary. The configuration is shown in more detail in Cold Mass assembly drawing F10103605 and associated subassemblies.

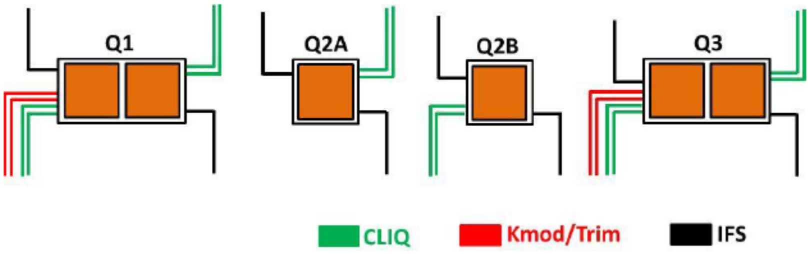


Figure 17: Top view of the entire Triplet.

The general configuration of the LQMXFA expansion loops is shown below in Figure 18. Q1a/Q3a is shown to the left and Q1b/Q3b is shown to the right. Note that both views are shown looking into the lead end of the respective magnet and are therefore viewed from the opposite direction. The magnet is rotated horizontally, providing the appropriate field rotation between the Qa and Qb. As above, power leads are shown in green, local busses are shown in blue, and through busses are shown in red. Local bus splices are shown between the splice box and the first magnet iron lamination on the Qa side and on the face of the splice box on the Qb side.

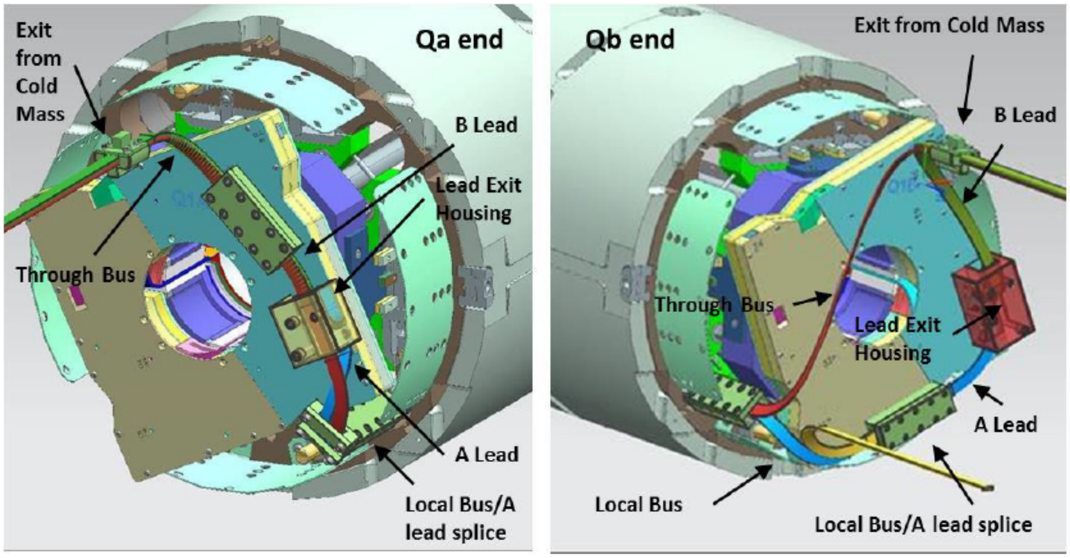


Figure 18: 3D model of the MQXFA Q1/Q3 expansion loops Q1a/Q3a is shown to the left and Q1b/Q3b is shown to the right.

The maximum axial travel needed for any loop is expected to be no more than +/- 18 mm. Thermal contraction calculations shown in [22] describe the criteria in detail for both upper and lower loops. The total space allowed for the loop (between the inside surface of the end cover and the front surface of the splice box) is 75 mm +/- 1mm. Figure 19 shows models similar to those shown in Figure 18, except that the side views are shown so the room for expansion can be seen. The loops are shown in the "home" position (when constructed at room temperature), which is approximately in the middle of the space allowed. A full-scale mockup was constructed ([23]) and has demonstrated that the loops as designed satisfy the travel requirements (R-T-13).

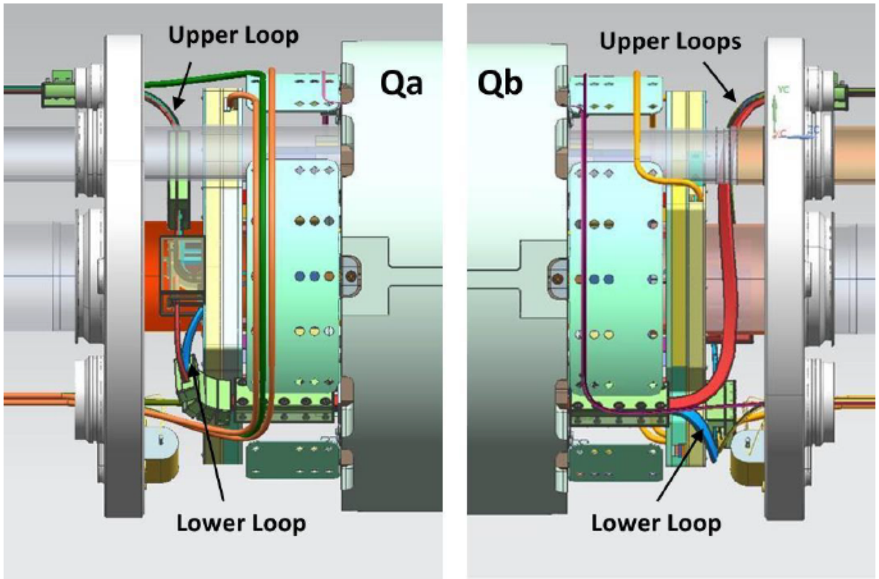


Figure 19: Side view of the expansion loops. Q1a/Q3a is shown on the left and Q1b/Q3b on the right. Loops are shown in their room temperature position, which is approximately in the middle of the space available.

2.6.4. Bus Support

A single bus housing, made of G-11, will be placed within the designated bus port at the position shown in Figure 20. A cross section of the bus housing is shown in the right side of the figure. The housing will be supported by aluminum clips at fixed positions within the bus port as shown in Figure 20 and Figure 21.

.

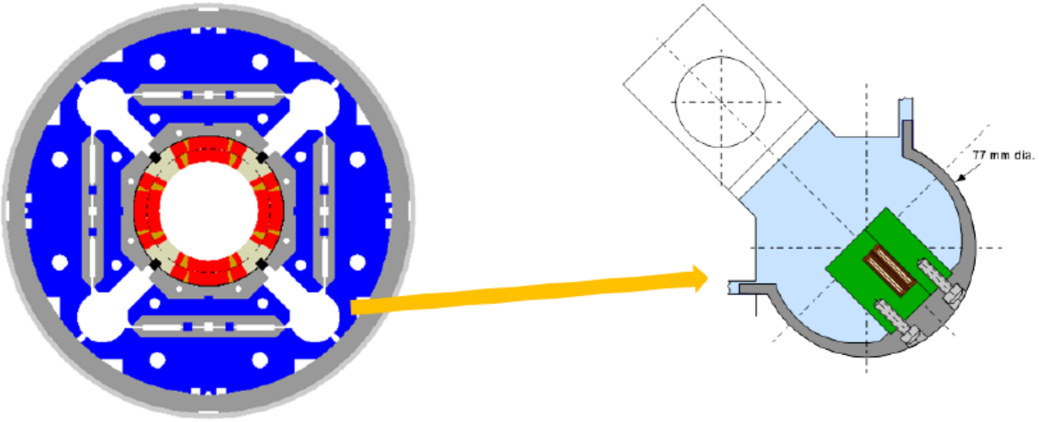


Figure 20: Cross section of bus housing in position.

The bus housing assembly takes up space within the bus port but must not unduly impede helium flow. The bus system is designed to take up as little area as reasonably possible. A calculation of the minimum area for helium flow and the space taken by the bus housing assembly is given in [19].

Figure 21 shows the bus and bus housing assembly (drawing #F10129998). The assembly shows the positions of the supporting clips (item #4) along the length of the Cold Mass. The clips spring slightly outward to position the bus at the desired position.

The bus is inserted into the Cold Mass manually. While inserting, the clips are squeezed to allow insertion, then spring out after insertion to provide support. The bus housing and assembly procedure were demonstrated in short model MQXFA1e [15].

The bus is positioned at an angle which results in the minimum magnetic forces from the magnet. Structural analysis of the bus assembly [24] as well the test results of MQXFA1e demonstrate that the bus housing assembly can withstand the magnetic forces from the operating current.

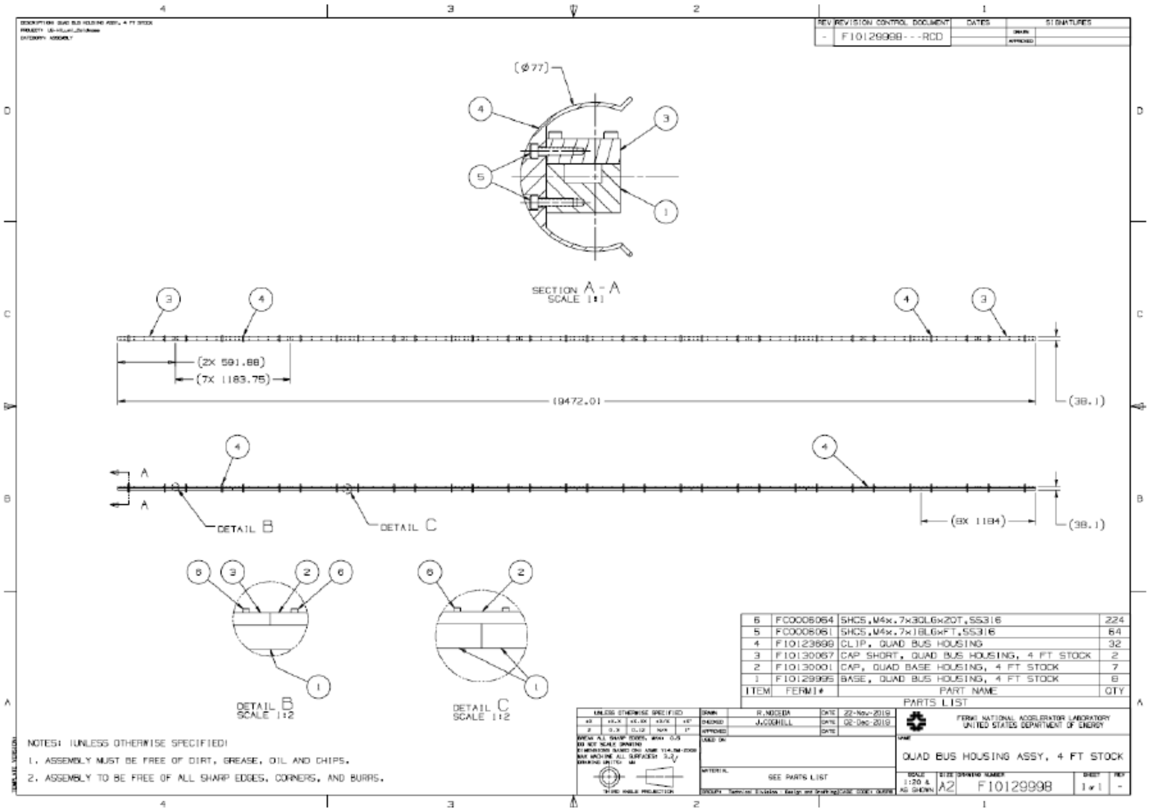


Figure 21: Completed Engineering Drawing of the MQXF Bus Housing Assembly.

2.7. CLIQ Leads

The CLIQ Quench Protection system is described in [25]. Two CLIQ leads extend from the lead end of each magnet. The CLIQ leads consist of 35 A copper cables (non-superconducting) with a 10 mm cross section. They are described in the manufacturer's specification shown in [26] (R-T-11 and R-T-15).

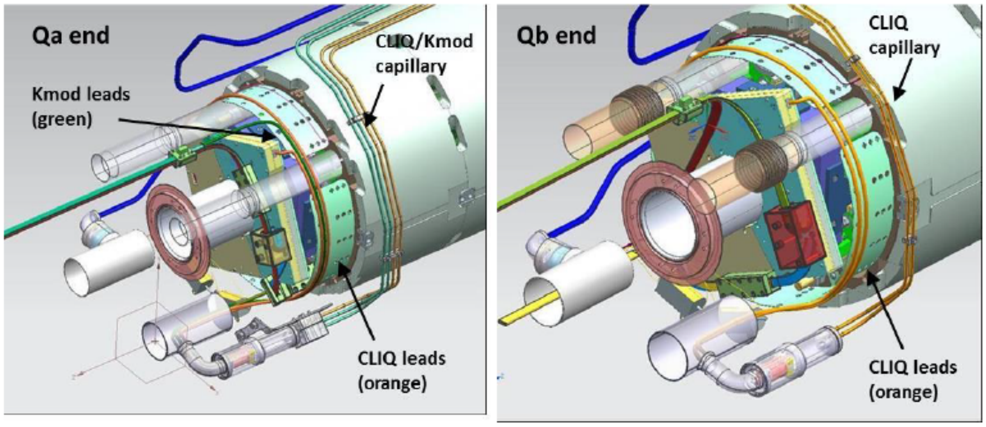


Figure 22: CLIQ and Kmod lead configuration on Cold Mass face.

The CLIQ leads exit the splice box as shown in Figure 22. They are attached to the connector skirts for support as they exit the Cold Mass. They will exit each end of the Cold Mass at the CLIQ/Kmod exit port (requirement R-T-11) and proceed to the CLIQ/Kmod capillary (CERN dwg. #LHCQQXF_DQ0001) in the cryostat. They will be soldered to the lead from CLIQ/Kmod capillary at the exit port during the cryostat stage of construction.

2.8. Kmod (trim) leads

Two Kmod (trim) leads exit the splice box only on the Qa end as shown in Figure 22. The Kmod leads are 30A copper cables (non-superconducting) with a 10mm cross section and are described in the manufacturer's specification shown in [26] (identical to the CLIQ leads) (R-T-11).

They are attached to connector skirts for support as they exit the Cold Mass. They will exit the Qa end at the CLIQ/Kmod exit port, and proceed to the CLIQ/Kmod assembly in the cryostat (R-T-11). Like the CLIQ leads, they will be soldered to the lead from CLIQ/Kmod assembly at the exit port during the cryostat stage of construction.

2.9. MTF (Magnet Test Facility) Lead

One special lead made of standard NbTi bus cable (as shown in Figure 13) is needed during horizontal testing at Fermilab. This lead is needed to allow individual testing of either magnet within the Cold Mass if a reason to do so is determined. The MTF lead will be soldered onto the magnet "A" lead at the Qb end with the local-bus-to-"A"-lead splice as shown schematically in Figure 16 and pictorially in Figure 23. After testing, the MTF lead will be terminated inside the end dome flange and capped. The MTF lead will not be used during operation in the LHC.

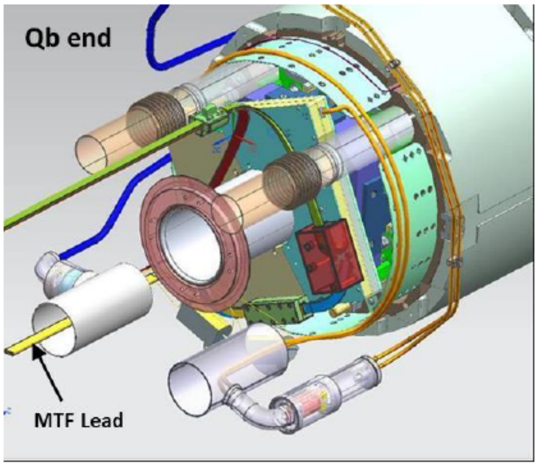


Figure 23: MTF lead configuration.

2.10. Q2 Bus

In addition to the Q1/Q3 bus, Fermilab is responsible for the design of the bus and expansion loop hold down parts for Q2a and Q2b. The Q2a and Q2b are identical. The Q2 bus is designed and fabricated by Fermilab but installed by CERN personnel. The bus design must be approved by CERN before fabrication can take place. The same is true for the expansion loop configuration and hold-down parts. A general configuration of the Q2 components is included in Figure 15 and is consistent with the triplet schematic, CERN drawing number LHCLMQXF E000

2.10.1. Q2 Bus Design

The Q2 bus and housing are designed in a manner almost identical to the Q1/Q3 bus. There are two exceptions. The length of the bus is slightly shorter, commensurate with the length of a Q2 Cold Mass. Also, the Q2 bus includes a twist at the lead end of the magnet. The twist takes place over a distance of approximately 15 cm. The twist is made so that the bus on the lead end of the magnet exits at an angle that is adequate to proceed to the lead exit of the Q2. The twist takes place completely within the confines of the bus housing and is surrounded by a G-11 tube filled with Stycast.

The bus cross section is shown in Figure 14. The placement and angle of the bus within the Cold Mass cross section is shown in Figure 20. The assembly drawing of the Q2 bus is F10135129 and is shown in Figure 24. A pictorial view of the bus as it twists within the bus housing is shown in Figure 25.

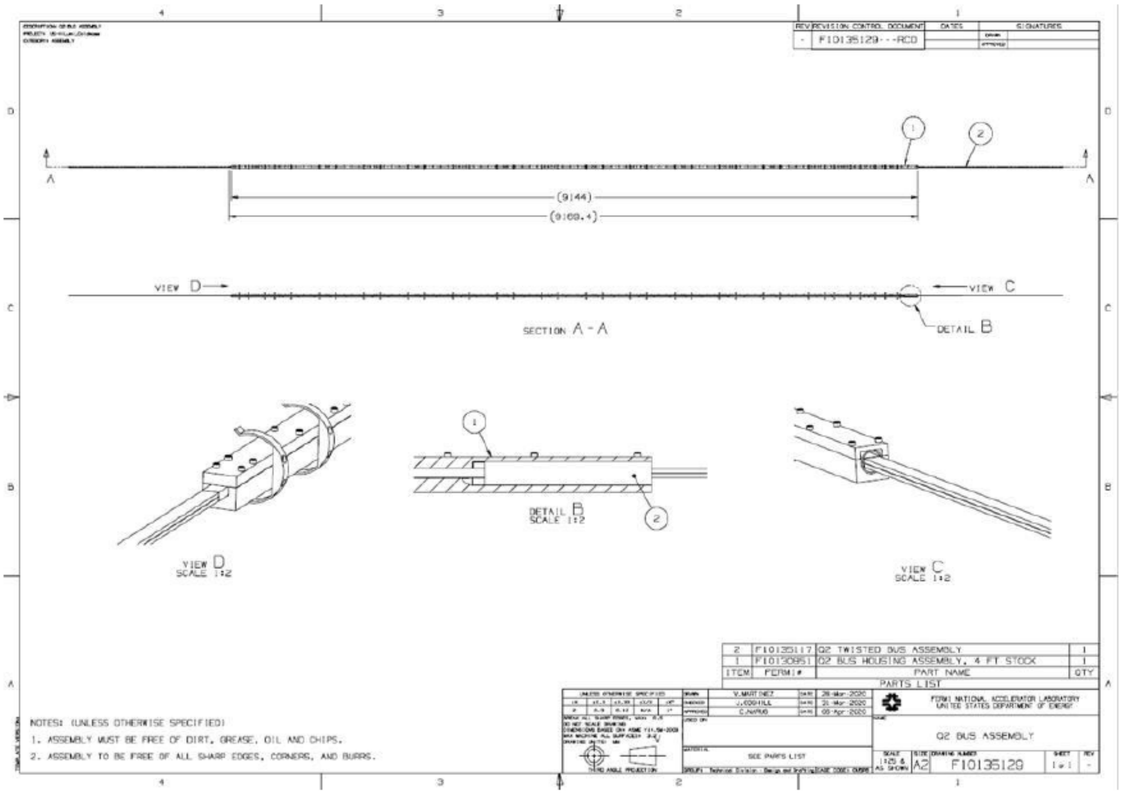


Figure 24: Q2 bus assembly.

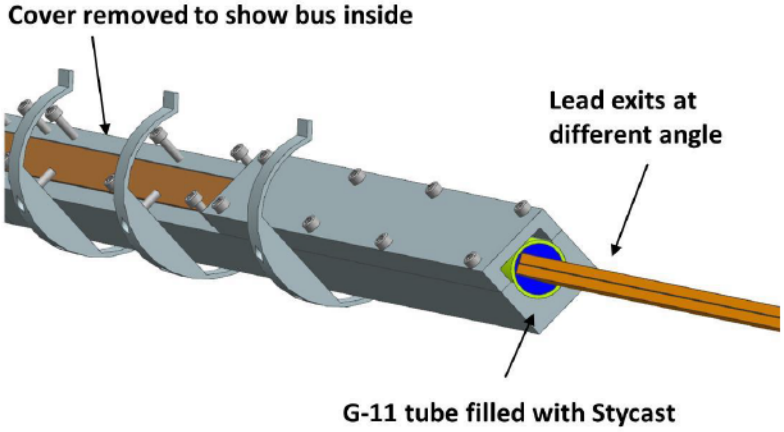


Figure 25: Q2 bus twist configuration.

2.10.2. Q2 Expansion Loop and Parts Design

The expansion loop positions, and orientation are designed by Fermilab in collaboration with CERN personnel. Figure 26 shows the general configuration and parts used in the present design. Expansion loop travel requirements are given in [27]. Parts have been designed and installed on a mockup at Fermilab. There is one splice, at the lead end, with a configuration the same as the splices on the Q1/Q3. The design of the expansion loop parts is still in process. Model and drawings are done, with the configuration shown currently being studied by CERN personnel before being considered complete.

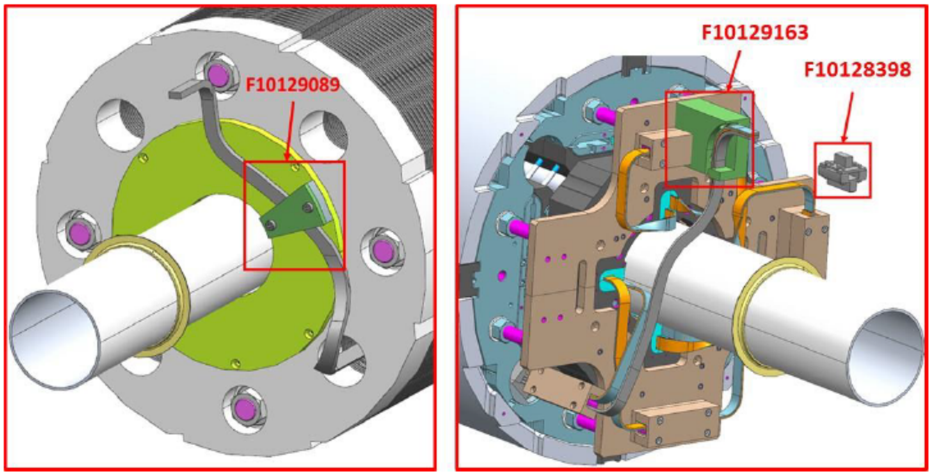


Figure 26: Expansion loop configuration of Q2. Return end is shown at left and lead end at right.

2.11. Instrumentation

The Cold Mass is instrumented with temperature sensors, warm up heaters and voltage taps. In addition, there are Quench Protection heater wires and several other voltage taps that are mounted on the MQXFA magnet coils that will be routed out of the Cold Mass through the instrumentation port to the IFS capillary (R-T-19). Table 1 consists of a list of the all instrumentation wires which exit the end dome (R-T-18). The instrumentation wiring diagram is shown in Figure 71 in Section 3.4, as well as CERN drawing number LHCLMQXF E0001.

Table 1: Leads and wires exiting the end dome.

Lead or Wire	Qty per end	Exit port	Notes
Quench Protection Heater Wires	16	IFS Capillary	From the Quench Protection heaters bonded to the coils Total of 4 wires from each coil. Jumpered on the return end of magnets during magnet construction. 18 AWG polyimide coated wire.
Magnet Voltage Taps	16	IFS Capillary	Voltage taps which extend from the end of the coils. 4 taps from each coil. 26 AWG polyimide coated wires.
Cold Mass Voltage Taps	4 or 5	IFS Capillary	5 on Qa end and 4 on Qb end. 26AWG polyimide coated wires.
Temperature Sensor Wires	8	IFS Capillary	Four wires from each temperature sensor. 30AWG polyimide coated wire.
Cryo Heater Wires (Warmup Heaters)	4	IFS Capillary	Two wires from each Heater. 18 AWG polyimide coated wire.
Temperature Sensor for MTF Wires	2	IFS Capillary	Two wires from each temperature sensor. 36AWG quad-twist polyimide + Tefzell single strand wire, used only for MTF testing.

All wires on production Cold Masses are sufficiently long to be routed to the “warm head” of the cryostat without splices. All wires are insulated with polyimide insulation (Kapton), a CERN approved material with high insulating properties and high radiation resistance.

2.11.1. Quench Protection Heater Wires

There are 16 Quench Protection heater wires coming from the lead end of each magnet, 4 wires from each coil, as shown in Figure 27 and LBNL magnet assembly drawing su-1011-0518. Quench Protection heater wires are designated as PH in Figure 27. They are secured by attaching to the “magnet connector skirts” (LBNL dwg. 27L062) and ultimately routed out through the IFS port into the IFS capillary. Quench Protection heater wires are attached to the coil at the coil assembly stage. They are 4.5 meters long and will not be spliced at the IFS port but extend through the IFS capillary on each lead end to be terminated at the warm head during the cryostat construction.

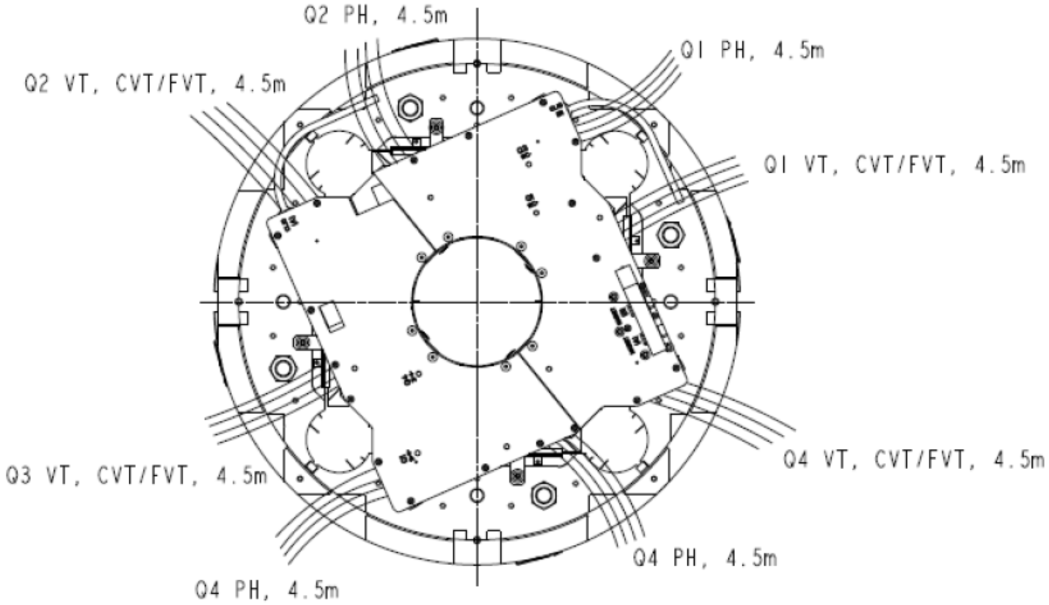


Figure 27: Quench Protection Heater wires and Magnet Voltage Taps.

2.11.2. Magnet Voltage Taps

Each MQXFA magnet assembly includes voltage taps attached to the coil turns for Quench Detection. There are 16 voltage taps on each magnet (4 on each coil), installed during the coil assembly (R-T-17). These 16 wires exit the lead end of each magnet as shown in Figure 27 and LBNL magnet assembly drawing su-1011-0518. Coil voltage tap wires are designated as CVT/FVT in Figure 27. They are secured in the same manner as the Quench Protection Heater wires, by attaching to the “magnet connector skirts” (LBNL dwg. 27L062) and ultimately routed out through the IFS port into the IFS capillary. As are the Quench Protection Heater wires, Magnet Voltage Taps are 4.5 meters long, and will not be spliced at the IFS port but extend through the IFS capillary to be terminated at the warm head during the cryostat construction.

2.11.3. Cold Mass (Quench Detection) Voltage Taps

The LMQXFA Cold Mass assembly includes a total of 9 voltage taps for Quench Detection. There are 5 taps on the Qa end and 4 on the Qb end. These wires are attached to the leads during the Cold Mass fabrication. The wires are soldered to the leads as shown in Figure 28 and are secured in the same manner as the Quench Protection Heater wires and coil voltage taps, by attaching to the "magnet connector skirts" (LBNL dwg. 27L062) and ultimately routed out through the IFS port into the IFS capillary. As the other instrumentation wires, they are 4.5 meters long, and will not be spliced at the IFS port but extend through the IFS capillary to be terminated at the warm head during the cryostat construction.

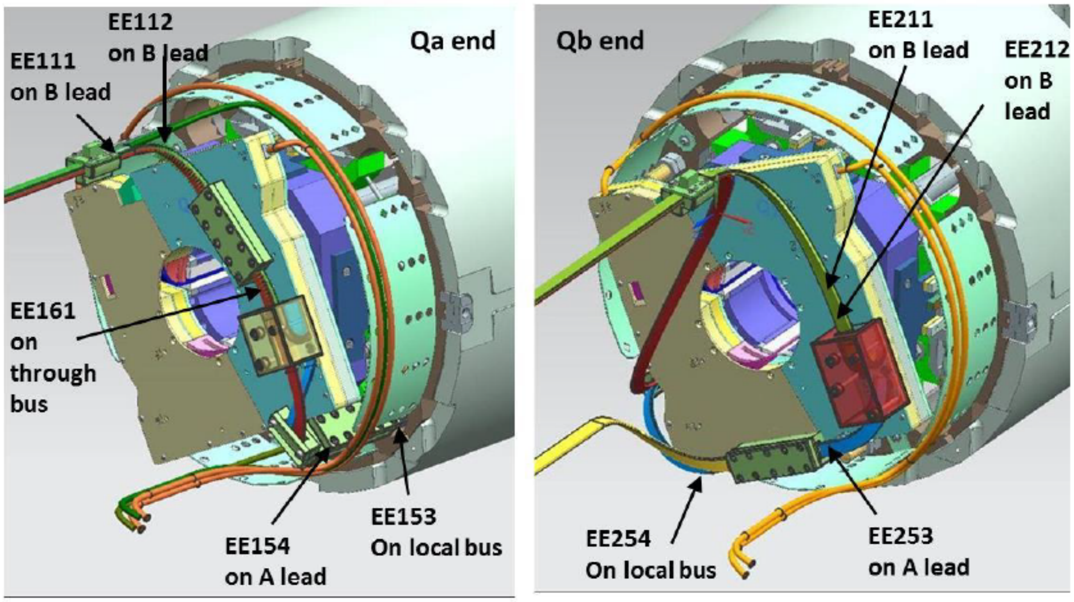


Figure 28: Cold Mass voltage tap configuration.

The Quench Detection voltage taps are doubled consequently they meet the MQXFA redundancy requirements (R-T-17).

2.11.4. Temperature Sensors

Two temperature sensors (thermometers) are attached to the Cold Mass of each MQXFA magnet assembly in the manner shown in Figure 29. The sensors are described in CERN drawing LHCLMQXF_E0029 (R-T-16). They do not exist on the magnet during individual magnet testing at BNL but are installed during the Cold Mass assembly. They are supplied by CERN.

Each temperature sensor has 4 wires so there are a total of 8 wires exiting each end of the Cold Mass. They are routed to the IFS port in the same manner as the other instrumentation wires, as shown in Figure 30. As all other instrumentation wires, they extend beyond the IFS port into the IFS capillary. Qa end is shown, but a similar configuration is used on the Qb end. As the other instrumentation wires, they are 4.5 meters long from the end of the Cold Mass and will not be spliced at the IFS port but extend through the IFS capillary to be terminated at the warm head during the cryostat construction.

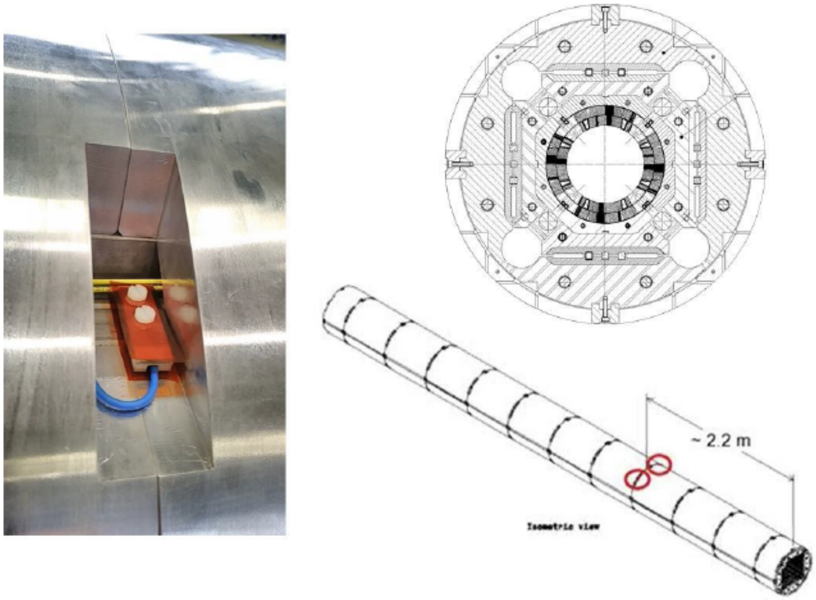


Figure 29: Installation of Temperature Sensors.

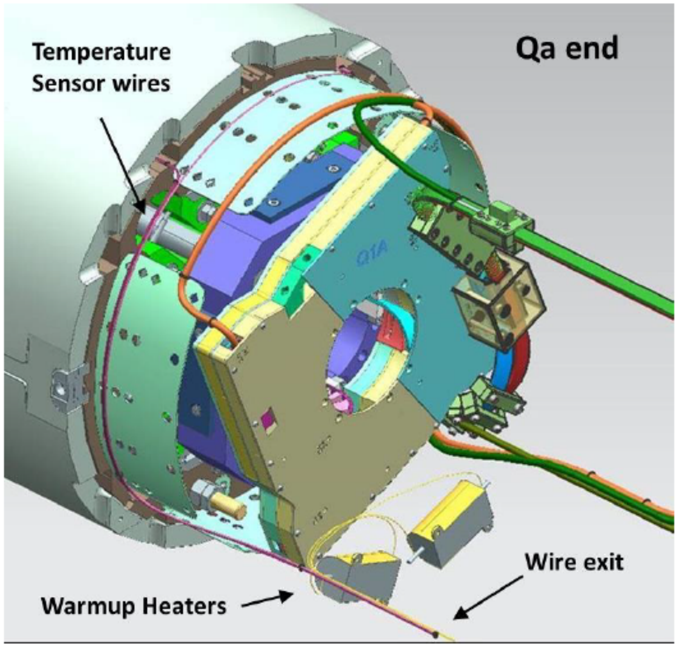


Figure 30: Routing of Temperature Sensor and warmup heater wires.

2.11.5. Cryo Heaters (Warmup Heaters)

Two Warmup heaters (VISHAY part number RH100) will be attached to the inside surface of each of the LMQXFA end covers at the positions shown in Figure 30 (Qa end is shown, but the position is the same on both ends). These heaters are independently powered. CERN will supply the Warmup heaters.

Each heater has 2 wires, so there are a total of 4 wires exiting the lead each end of the Cold Mass. They are routed to the IFS port in the same manner as the other instrumentation wires. (The Warmup heaters in Figure 31 appear to be floating in mid-air, because they are attached to the end cover, and the end cover is not shown in the figure.) A view facing the Cold Mass end is shown in Figure 31. As all other instrumentation wires, they extend beyond the IFS port into the IFS capillary. As the other instrumentation wires, they are 4.5 meters long from the end of the Cold Mass and will not be spliced at the IFS port but extend through the IFS capillary to be terminated at the warm head during the cryostat construction.

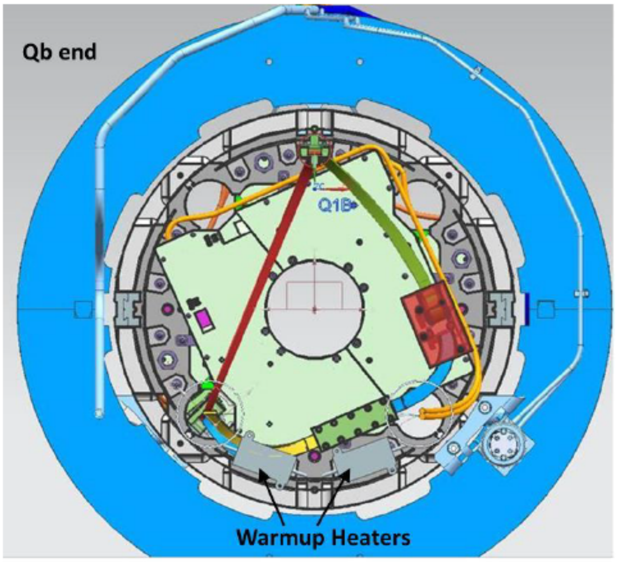


Figure 31: Warmup Heater positions.

2.12. Cold Mass Supports

The LMQXFA Cold Mass supports (Lower Plates) design per drawing F10103814 is shown below in Figure 32 Low Co 316LN grade material requirements are removed from the supports and thus material and machining will be procured by FNAL using dual certified 316/316L stainless steel. The dual certification will meet the minimum strength requirements of 316 yet meet the chemical properties of 316L material required by the LSA for Cold Mass components. A 14mm bolt hole pattern has been included to accommodate shipping restraints. The lower plates are the interface between the Cold Mass assembly and thus designed to meet CERN interface requirement R-T-25. Tooling has been developed to comply with accurate placement of the plates and meet the specified angular tolerances of w/in +/- 0.5 mrad and coplanar w/in 0.02”.

The analysis of the lower plates complies with FRS requirement R-T-07, the Cold Mass and each of the components are designed and documented in accordance with CERN and U.S. HL-LHC Accelerator Upgrade Project safety agreements. As described in Section 2.1.1, Codes and Standards Applied for the Design and Section 2.14, Cold Mass Pressure Vessel Analysis, the support plates are analyzed per ASME Section VIII div.2 to verify that the thickness and welds are sufficient to withstand shipping conditions as well as structural loads under operating conditions.

This material is procured with traceability to Certified Material Test Reports (CMTR) so that it can be verified to ASME specifications for physical and chemical properties and fulfill traceability requirements. The traceability will be maintained through the Fermilab Cold Mass assembly traveler as described further in Section 2.17.2, Assembly Procedures. The material grade and specification also meet the requirements of the LSA.

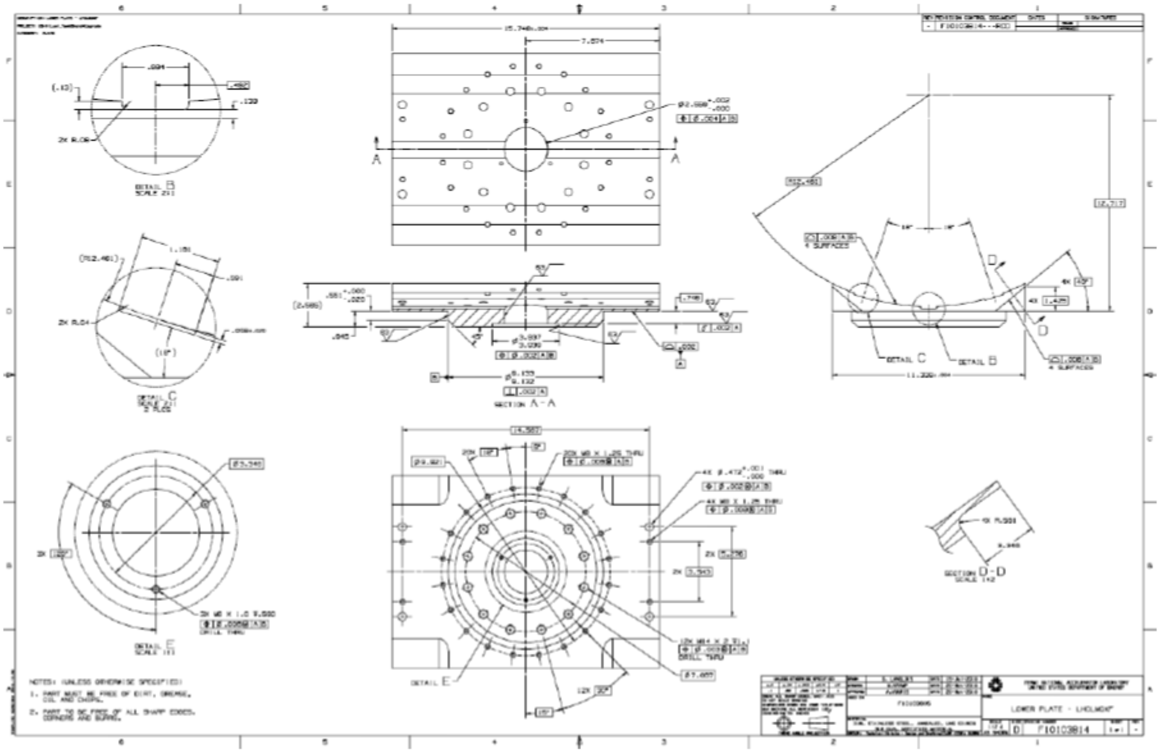


Figure 32: Cold Mass Lower Plate Support design F10103814.

2.13. FSI Components

2.13.1. Survey Targets

The FSI Components are a set of alignment targets that will be installed on the external surfaces of the stainless-steel shell for surveying purposes. Through this system, the actual position of the Cold Mass inside the cryostat can be monitored in real time. Each Cold Mass will have 12 mirror targets attached by GTAW tack welds and arranged per Figure 33 as required per FRS R-T-21 positioned in groups of 4, in the mid-point and towards the Cold Mass ends, at 45°, 135°, 225°and 315°. This layout scheme is presently being developed at CERN. The target component CERN drawings include the Triplet Reflector Short Support, LHCGIOFV0010 and the Triplet Reflector Long Support, LHCGIOFV0011. The long supports are welded on the upper quadrants of the Cold Mass and the short supports are welded on the lower quadrants prior to the ASME final pressure testing of the Cold Mass.

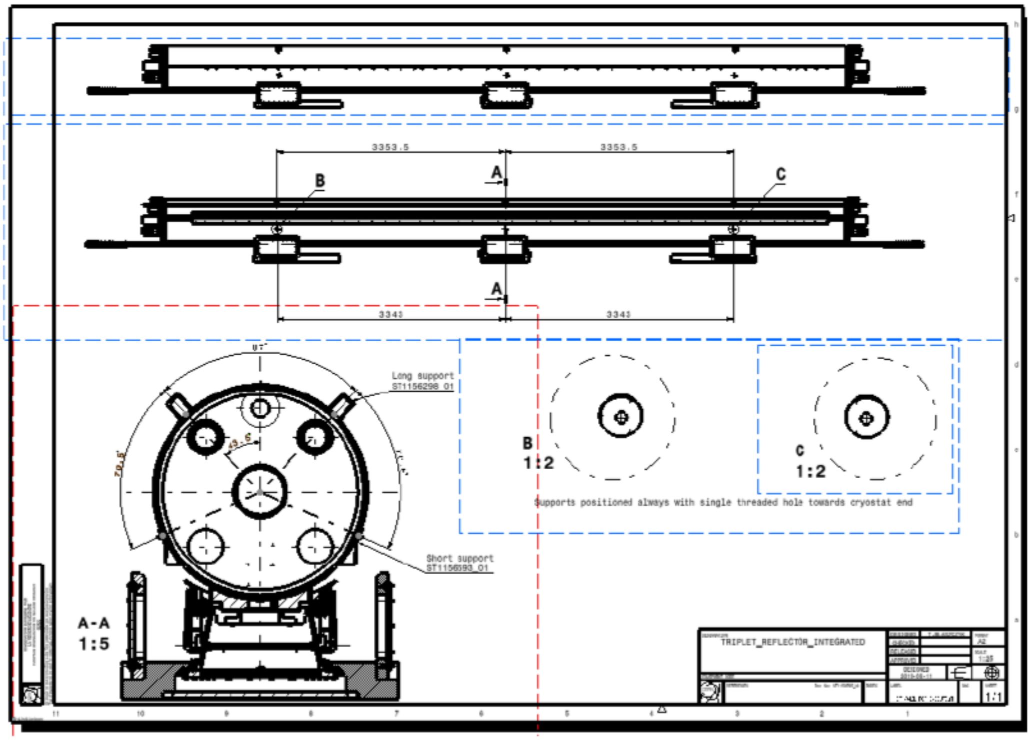


Figure 33: Cold Mass FSI Target layout.

2.14. Cold Mass Pressure Vessel Analysis

Analysis use a Maximum Allowable Working Pressure (MAWP) of 20 bar differential pressure at 1.9 K He as per requirement R-T-07. The vessel shall also be capable of sustaining loads up to 20 bar of pressure differential without physical damage or performance degradation from asymmetrical axial forces due to quenches as per requirement R-T-10.

ASME B&PVC calculations per Section VIII Division 2 and FESHM 5031 can be found in [9]. The analysis used elastic-plastic material conditions to determine if an acceptable amount of strain occurred during loading. A summary of the analysis results can be seen in Table 2. The analysis concluded that the behavior of the Cold Mass under MAWP conditions, pressure test conditions at 25 bar, quench conditions, shipping conditions, and under external pressure were safe and meet the FRS R-T-09. Additional analysis was performed on sub-models of the assembly to determine if individual components would fail, buckle, and to determine the minimum number of operational cycles before additional design analysis was needed. The results of the additional analysis can be seen in Table 3.

Table 2: Cold Mass analysis summary.

Loading Condition	Peak Result	Value	Acceptance
MAWP	Equivalent Stress, ksi (MPa)	47.2 (325.4)	Convergnce
	Total Deformation, in (mm)	0.086 (2.184)	N/A
	Limiting Strain Ratio	0.04	< 1
Pressure Test	Equivalent Stress, ksi (MPa)	59.6 (410.9)	Convergnce
	Total Deformation, in (mm)	0.177 (2.972)	N/A
	Limiting Strain Ratio	0.22	< 1
Quench	Equivalent Stress, ksi (MPa)	44.3 (305.4)	Convergnce
	Total Deformation, in (mm)	0.063 (1.600)	N/A
	Limiting Strain Ratio	0.02	< 1
Shipping (X-Axis)	Equivalent Stress, ksi (MPa)	117.6 (810.8)	Convergnce
	Total Deformation, in (mm)	0.292 (7.417)	N/A
	Limiting Strain Ratio	0.28	< 1
Shipping (Y-Axis)	Equivalent Stress, ksi (MPa)	117.6 (810.8)	Convergnce
	Total Deformation, in (mm)	0.234 (5.944)	N/A
	Limiting Strain Ratio	0.60	< 1
External Pressure	Equivalent Stress, ksi (MPa)	19.7 (135.8)	Convergnce
	Total Deformation, in (mm)	0.042 (1.073)	N/A
	Limiting Strain Ratio	6.40E-05	< 1

Table 3: Cold Mass component analysis.

Model	Loading Condition	Peak Result	Value	Acceptance
Endcover	Pressure Test	Equivalent Stress, ksi (MPa)	57.7 (397.8)	Convergnce
		Total Deformation, in (mm)	0.074 (1.880)	N/A
		Limiting Strain Ratio	0.16	< 1
	Quench	Equivalent Stress, ksi (MPa)	56.4 (388.9)	Convergnce
		Total Deformation, in (mm)	0.046 (1.168)	N/A
		Limiting Strain Ratio	0.10	< 1
Beamtube	Pressure Test	Minimum Load Factor	3.24	> 2.605
Heat Exchanger	Tube, Pressure Test	Minimum Load Factor	10.57	> 2.605
	Bellows, Pressure Test	Equivalent Stress, ksi (MPa)	65.7 (453.0)	Convergence
		Total Deformation, in (mm)	0.069 (1.753)	N/A
Fatigue Screening Criteria	MAWP	Number of Cycles	610	N/A

2.15. Tooling

2.15.1. Alignment-Rolling Station

Tooling for the first step in the assembly process of the Cold Mass will include the alignment and rolling fixturing. A pair of weld tables are aligned, levelled and anchored to support the weight of the Cold Mass. Additional supports were added to the tables to minimize deflection [28]. The fixtures are mounted on the table and pinned after Metrology has verified positions of the tooling. Any adjustments done were re-verified by Metrology. The tooling will support each magnet at fixed locations to support, level and aligning the pair of magnets prior to assembling the backing strip and tack welding the half shells in place. The work station clamp centers are aligned w/in 0.003" per drawing F10121933 to maintain spacing between magnets and overall concentricity. This station will be used to install the bus, instrumentation, Heat Exchangers and Beam Pipe prior to fitting and tack welding the top half shell.

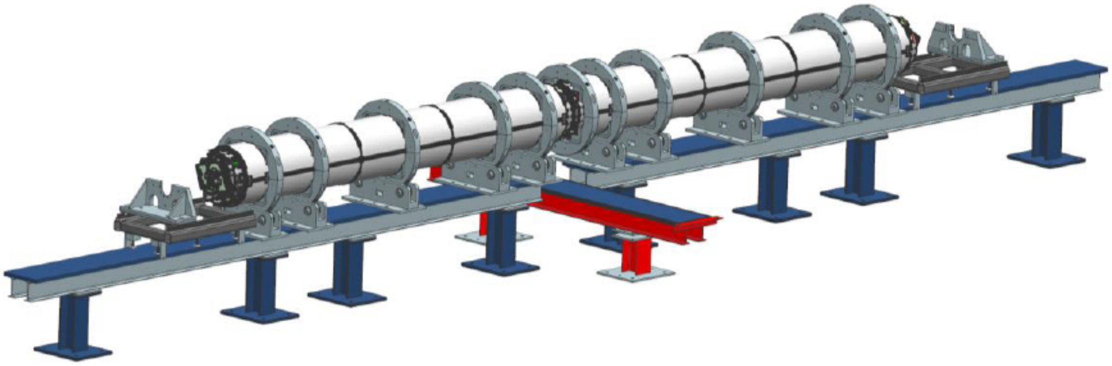


Figure 34: Alignment Tooling, F10104699.

The clamp and roller sub-assemblies are shown below in Figure 35 and Figure 36. For alignment purposes, an insert is used to contact flat surfaces on the magnet yoke as shown on the bottom half of the clamp in the figure below. After the Cold Mass magnet pairs are aligned and fitted to one half of the stainless steel shell, the top portion of the clamp will be installed with a second insert utilizing adjustable rods to center the Cold Mass for rolling but also to assist in forcing the stainless steel shell into position for tacking to the Cold Mass.

The roller design incorporates a set of indexing holes at 180 degrees to locate and lock positions for the shell fit-ups (see Figure 36). Prior to the second half shell being fit up and after the Cold Mass is rotated 180 degrees, installation of the bus, instrumentation, heat exchangers and beam pipe will be done.

During the rolling operation, the Cold Mass will be supported in 10 positions total / 5 positions per magnet (see Figure 34) and located based on the analysis [29] (see the lifting points in Figure 37). All handling, fixturing and shipping will be per FNAL MQXFA Magnet Handling & Shipping Requirements [12].

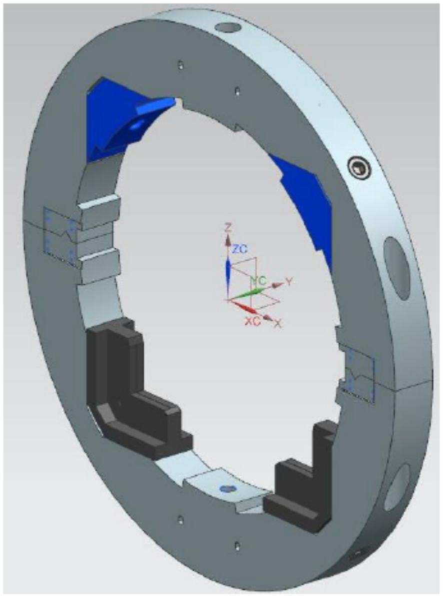


Figure 35: Rolling/Welding Clamp & Fixture, F10072149.

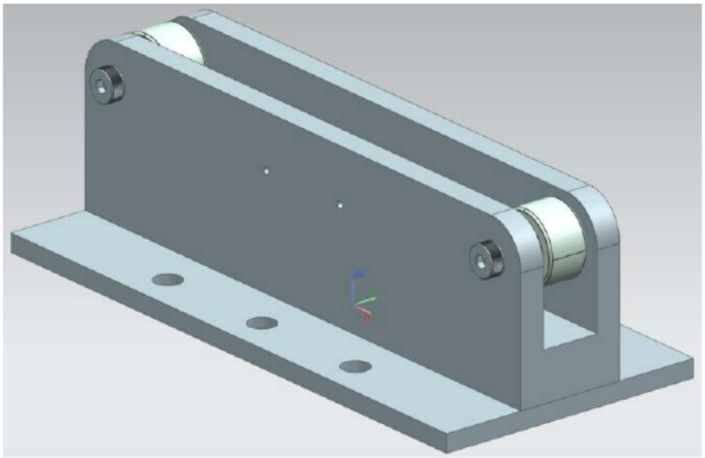


Figure 36: Rollers, F10106130.

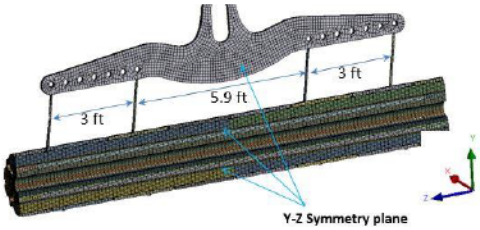


Figure 37: Support locations.

2.15.2. Lifting Fixture

Below-The-Hook (BTH) custom lifting fixtures or spreader bars are required to safely lift each MQXFA magnet, LMQXFA Cold Mass and LQXFA/B cryostat at various stages during the assembly process. First, a lifting fixture (Caldwel 102273-02) per Figure 38 will be used to lift each MQXFA magnet individually to the alignment workstation. After the MQXFA magnets are inspected, aligned and tacked to both half shells, a similar 8-point pick lifting fixture (Caldwel 102273-03) is utilized to lift and lower the set of aligned magnet pairs for at the welding station for the longitudinal welding operation. Once longitudinal welding of the shells is complete, the LMQXFA Cold Mass will be lifted with a 4 point pick lifting fixture (Caldwel 102273-04) per Figure 39 and staged for final end cover welding or cryostat supports welding back at the alignment station. After all Cold Mass welding and testing is complete, the Cold Mass will be lifted and staged for cryostat assembly at the cryostating station. When final assembly and insertion to a vacuum vessel is complete (cryostat), a fourth lifting fixture (Caldwel 102273-01) will be used to lift the LQXFA/B cryostat assemblies for packaging or transport to and from Industrial Building 1 for horizontal testing. All lifting shall follow written procedures per [30].

The design of the fixtures is based on the existing CERN lifting fixture [31]. A procurement specification was distributed to various vendors for a market analysis and awarded to a competent and competitive vendor for design and fabrication. This document can be found at [32].

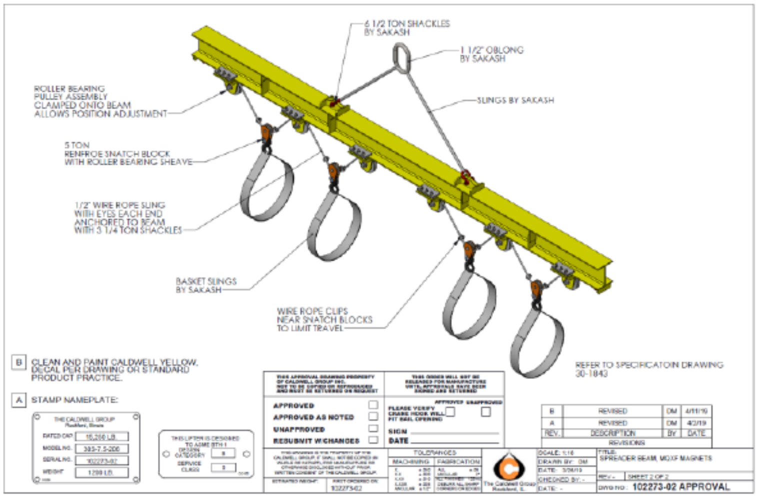


Figure 38: MQXF Magnet Lifting Fixture.

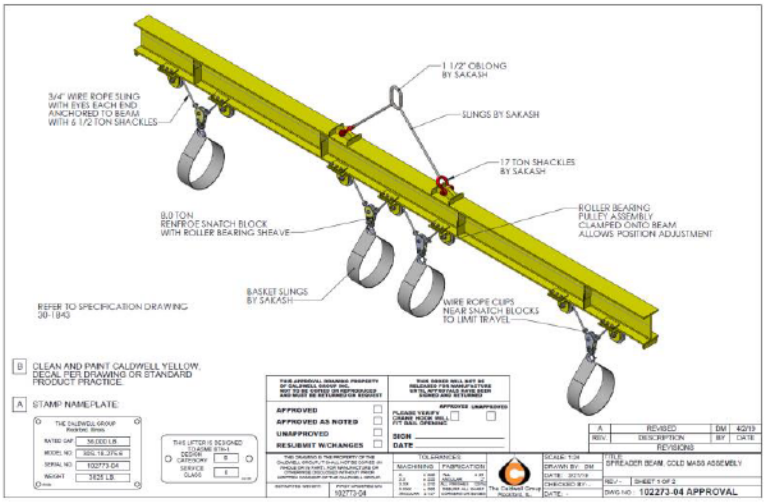


Figure 39: Cold Mass Assembly Lifting Fixture.

2.15.3. Welding Station

The weld station (see Figure 40) is also levelled and anchored with saddle supports to fit the length of the Cold Mass. Additional supports were added to the tables to minimize deflection [28]. The saddle fixtures will support the Cold Mass with both half shells fit and tacked in place and host the longitudinal welding sequence. A semi- automatic modular drive system on rails is used to simultaneously weld on both sides of the Cold Mass using a gas metal arc welding (GMAW) process. Supports and mounting brackets are designed and fabricated to support the welding equipment.

The longitudinal weld station components and design were reviewed in a Production Readiness Review (PRR) and approved for procurement in December of 2018. See FRS and analysis documents [33] and [34].

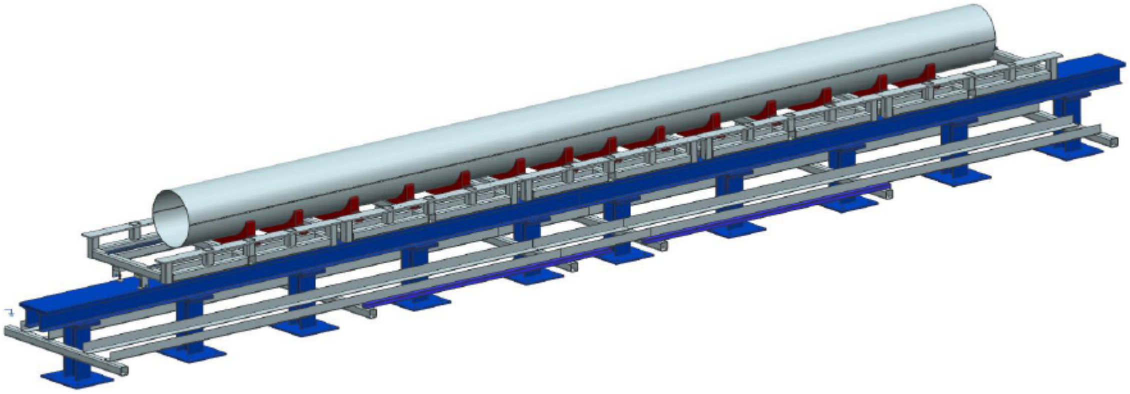


Figure 40: Saddle Welding Station, F10094322.

2.15.4. Bus Soldering Fixture

The approximately 11-meter-long busses for both the Q1/Q3 and the Q2 Cold Masses are soldered in a single full-length fixture (see Figure 41).

The fixture has been previously used to solder busses for the MQXB magnets currently used in the LHC interaction regions. The previous busses were 8 meters long, so the fixture has been extended to 11 meters for the MQXF busses, and the groove made to accept the MQXB bus cable has been modified to accept the MQXF bus cable. Heating is done with a single 11-meter-long electric heating element (Chromalox part #PRN234392).

More information about the fixture, the thermal cycle and solder configuration are shown in [35] [36]

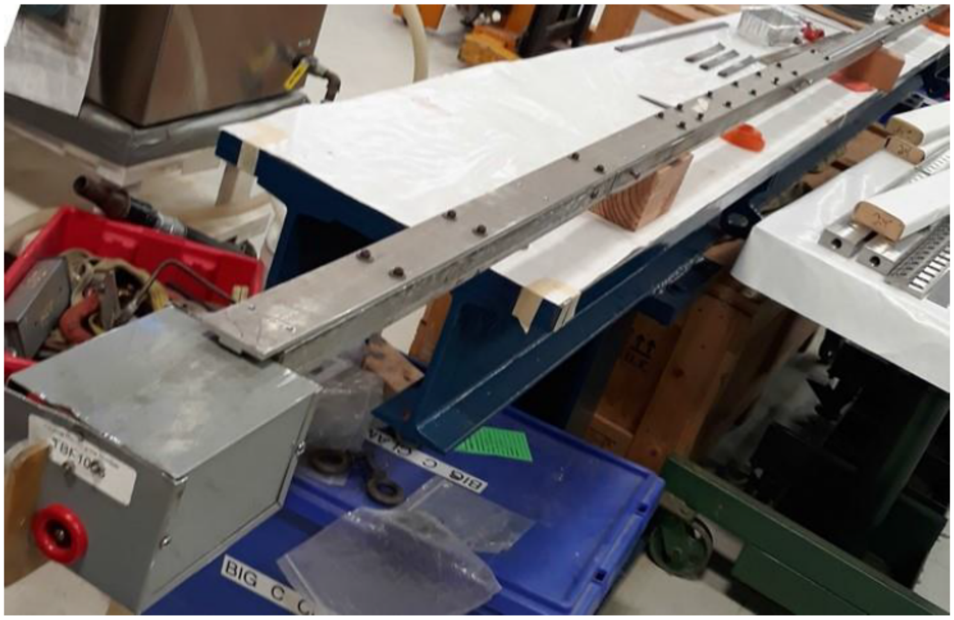


Figure 41: Bus Soldering Fixture for Q1/Q3 and Q2 busses (located in ICBA).

Assembly drawing for the fixture (F10119961) is shown in Figure 42.

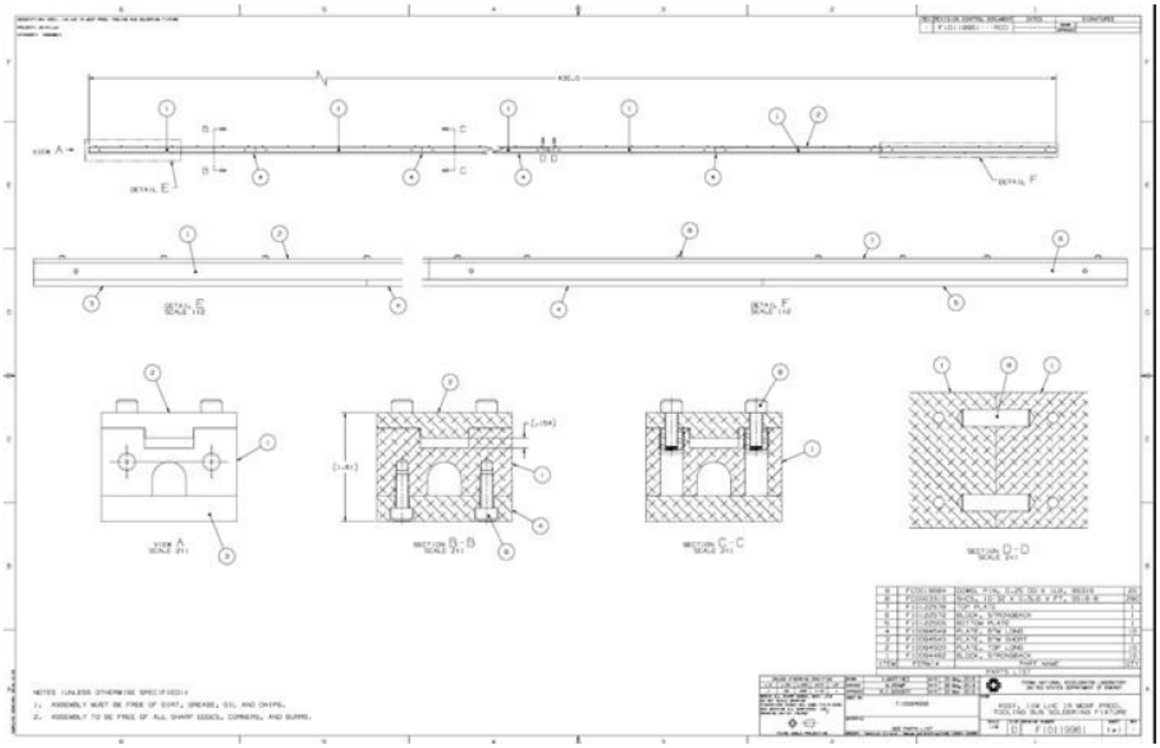


Figure 42: Bus Soldering Fixture for Q1/Q3 and Q2 busses.

A sample of a solder joint made with the fixture is shown in Figure 43. Solder between the busses consists of two strips of 96% tin /4% silver solder, each 0.25mm thick. See also the “Bus Manufacturing” Section 2.6.2 of this report.

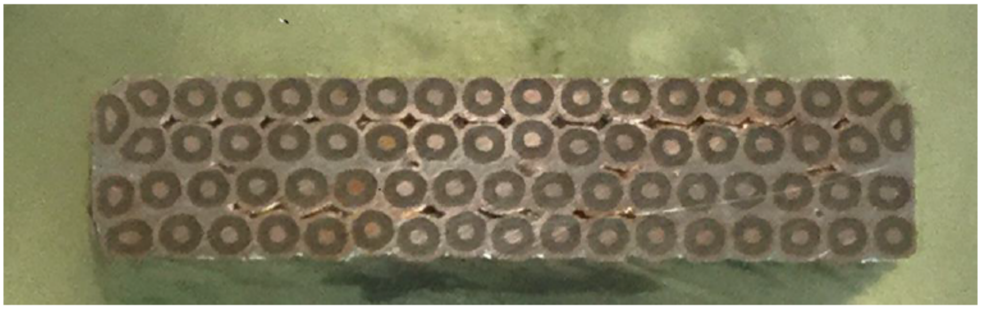


Figure 43: Cross section of soldered bus.

Three bus assemblies have been soldered to date, each containing two busses. Two Q1/Q3 and one Q2 bus assembly have been soldered.

2.15.5. Bus Wrapping Fixture

After soldering, the individual full-length busses are each wrapped with two layers of spiral wrapped Kapton (2/3 overlap). Then the assembly is wrapped with an additional layer at ¾ overlap as shown in Figure 14.

The bus wrapping fixture design is based on a wrapping device previously used to wrap cable for the CLAS12 magnets manufactured for Jefferson Lab in the U.S. It was made adjustable, so it could be used for the LMQXF busses as well as for bus wrapping on the Mu2e project at Fermilab. Busses were wrapped for the Mu2e solenoids before transporting the fixture to ICBA for use on the LMQXF busses.

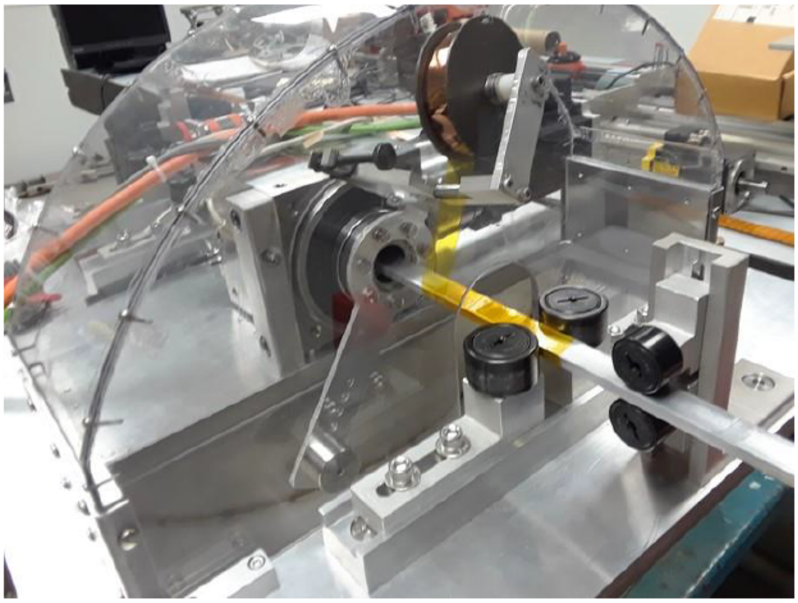


Figure 44: Bus Wrapping Fixture.

The engineering drawing of the bus wrapper is F10095440 and is shown in Figure 45. One complete bus for a Q1/Q3 assembly has to date been wrapped. Also see "Bus Manufacturing" Section, 2.6.2 of this report.

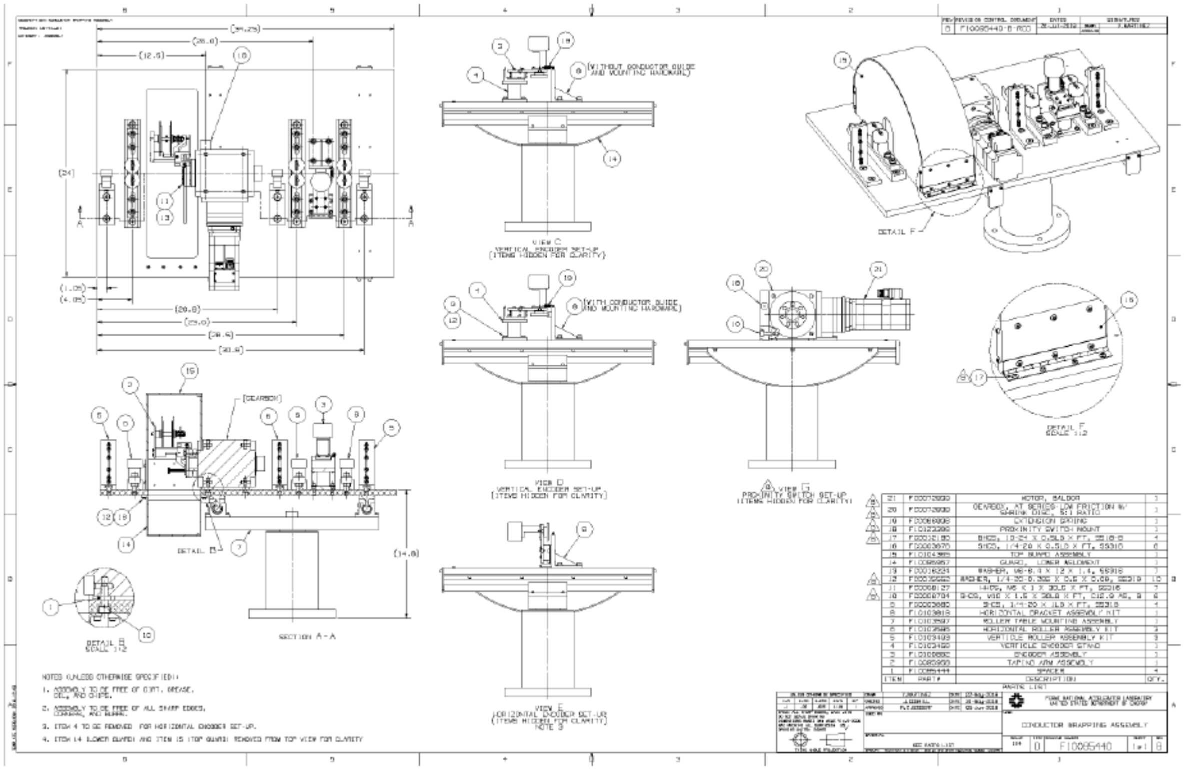


Figure 45: Bus Wrapping Fixture assembly drawing.

2.15.6. End Cover Alignment Station

Once the shells are fully welded, the Cold Mass will return to the alignment station for the final assembly steps where the shell ends will be trimmed square, beveled and ID bored to true up the shell end for proper alignment with the backing strip and end covers. This work will be done in ICBA using a purchased WACHs cutter with specific attachments for completing the beveling and boring. Once this step is completed, The End Cover alignment tooling can be used to align, fit and tack weld the end cover to the shell ends (see Figure 46). The End Cover Tooling has features to adjust and center the end cover with the Cold Mass while supporting it such that it can be tacked in place. After sufficient tacks are made to secure the end cover, the Weld torch can be fixed at the 12 o'clock position and the Cold Mass rotated for a 1-G welding process on the circumferential welds. The circumferential welds will be completed in 3 passes (1 root pass and 2 cover passes). Each pass will be shifted to start 120 degrees away from the previous pass with no start/stop of a weld pass beginning at the same location. A trial run of the circumferential welding process was completed recently. Measurements were made and documented in [18].

The End Cover Tooling was reviewed in a Production Readiness Review (PRR) along with the other alignment tooling and approved for procurement in February of 2019. See FRS and analysis documents [37] and [38].

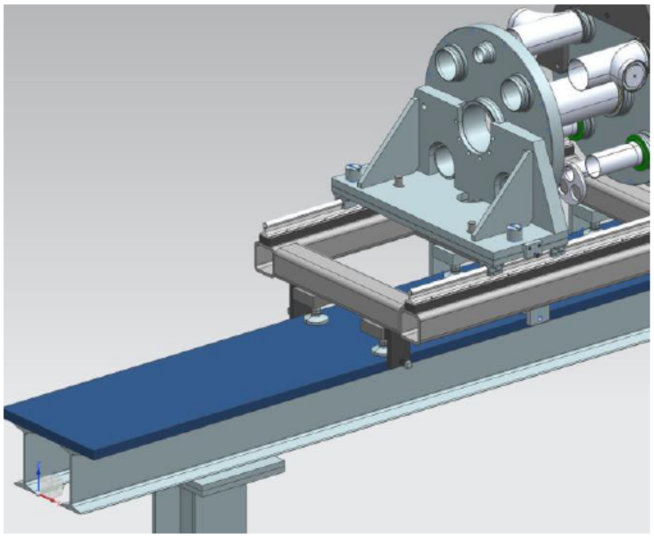


Figure 46: Alignment Rolling Station, End Cover Alignment.

2.15.7. Inspection Table

The final steps in the assembly of the Cold Mass include the lower plates which are the interface mounting features with the cryostat. The lower plates must maintain a clocking position of +/- 0.5 mrad to the vertical magnetic center line. After the vertical centerline is determined through magnetic field measurements, a set of indexing clamps per drawing F10133489 are mounted to the Cold Mass and aligned with the brackets, F10130414 which have been previously indicated in to align with the vertical centerline of the Cold Mass as it rests in the station tooling to indicate the 6 o'clock position. The Cold Mass is lifted from the alignment station and moved over to the inspection table where a matched set of brackets per F10129520 will align and lock the 6 o'clock position once again. The brackets on the inspection table have slots that are slightly wider but within the allowed rotational tolerance for ease of assembly. The mounting surfaces on the table consist of 3 support post that lock in the lower plates and aligned on center with the indexing brackets. The lower plates will be mounted to the posts and inspected for concentricity and coplanarity. Shims can be used to make fine elevation adjustments for any variations in the lower plate machining tolerance. The bolt pattern in the posts is machined with minimum clearance. The inspection table itself has been ground flat to within 0.002" over the full length (24 ft.). After mounting the lower plates and confirming alignment, the Cold Mass is lowered using the 40 T overhead crane slowly aligning the pins in the indexing clamps with the slots in the brackets until the Cold Mass comes to rest in the saddle feature of the lower plates. See Figure 47 and Figure 48. Once the Cold Mass alignment and dimensions are confirmed, the lower plates can be welded per drawing F10103605. After Ultrasonic testing is complete, all final nozzles, capillary tubes, external tube/pipe mounting brackets and FSI target welding can be completed at this workstation.

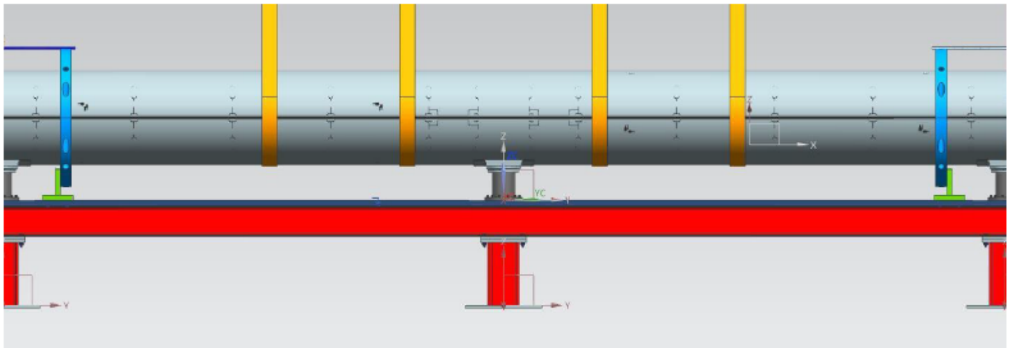


Figure 47: Inspection Table, Lower Plate welding.

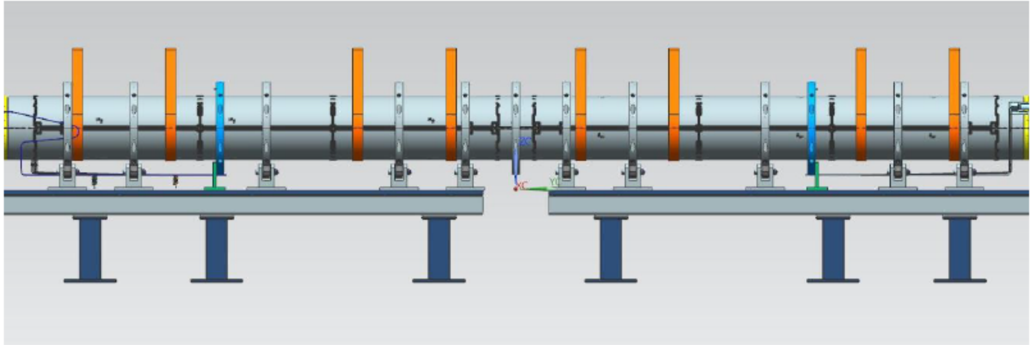


Figure 48: Alignment Rolling Station, Indexing Tooling.

2.16. Production Plan and Infrastructure

The production of LMQXFA Cold Masses & LQXFA Cryostats will be fabricated in the new Industrial Center Building Annex (ICB-A) shown in Figure 49, transported to Industrial Building 1 (IB1) for testing and then transported back to ICB-A for packaging and shipping to CERN. .

The floor plan includes dedicated space for five workstations plus a rework station, component and shipping container storage. All workstations, containers and component storage will be accessible by the main overhead 40 Ton crane.

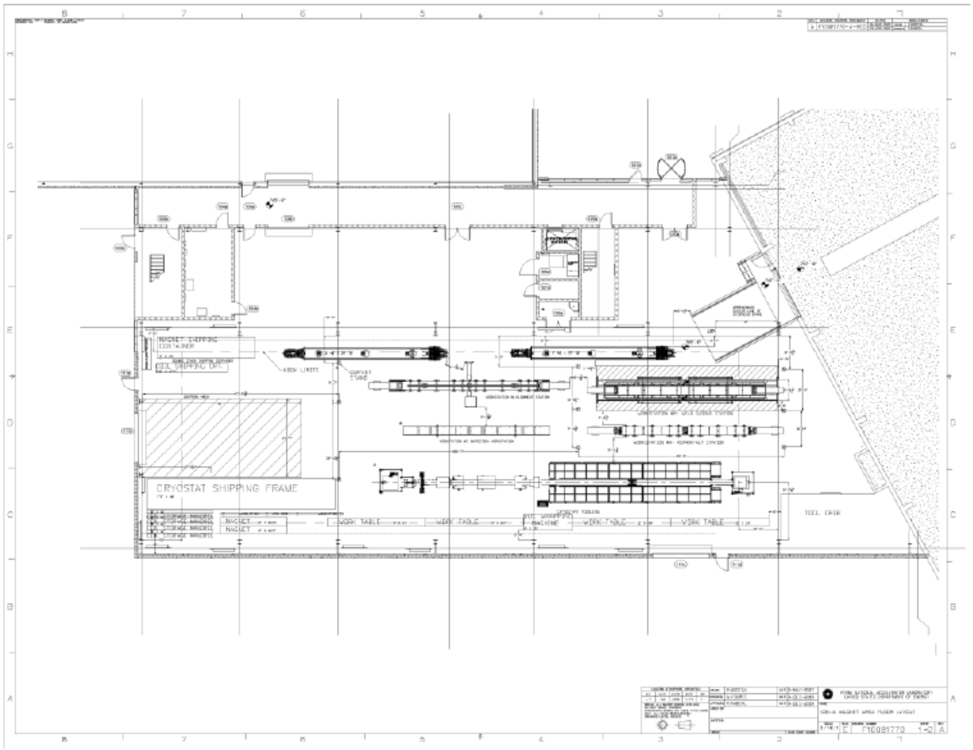


Figure 49: ICB-A Fabrication floor plan.

2.17. Fabrication

The Cold Mass assembly process flows through the workstations described above in Section 2.15: Tooling, utilizing travelers described in Section 2.17.2: Assembly Procedures. Hazard Analysis have been written to alert personnel of all hazards while using the tooling.

The Cold Mass shell plates will be identified, and specific IDs will be recorded in the assembly traveler prior to shipping to vendor for forming the shell described in Section 2.2. Forming will be inspected and approved prior to shipping to a second vendor for machining also described in Section 2.2.

The shells are formed and machined with extra length on the ends. They are fit and tack welded to the magnet pair after insertion of the beam tube, heat exchangers, instrumentation and bus assembly. Spare aluminum magnet structure shells will be used on the ends of the Cold Mass to support the stainless shell and prevent excessive deformation during welding. The stainless-steel shells will be trimmed back to length with the WACHS cutter to achieve squareness and proper weld bevel details. A boring bar attachment for the WACHS cutter will allow for cutting the ID of the shell near the ends to achieve internal ID tolerances and match up to the end cover dimensions.

Utilizing Stretch wire measurements, the Vertical Centerline can be identified and using our indexing clamps and fixed table brackets as described in Section 2.15.7: Inspection Table, the Cold Mass can be transferred from the alignment station to the inspection table orientated correctly to locate and weld the lower plates.

2.17.1. Component Procurement

A list of major components that will need to be procured through outside vendors:

- Shell… forming & machining
- Flat Bar for weld backing … materials
- Tack Blocks… materials & machining
- Fasteners for Tack Blocks…materials
- Cold Mass supports…materials & machining
- Busbar housing and hold-down fixtures….materials and machining

2.17.2. Assembly Procedures

Assembly of each Cold Mass begins with receipt of the first MQXFA magnet and continues until the Cold Mass is tested and ready for installation into a cryostat. There are 3 travelers created within Vector for the Cold Mass assembly.

First in series is the HL-LHC AUP MQXFA Incoming Inspection and QA Traveler No. 464574.This traveler accounts for all incoming inspection including dimensional and electrical checks after it is received from BNL and prior to routing in for the assembly process.

The second is the HL-LHC Magnet Bus Traveler No. 464507. This traveler is for the assembly of the Cold Mass bus.

The third is the HL-LHC AUP Q1 Q3 Cold Mass Assembly Traveler No. 464525. This includes all the assembly steps and QC holds for the proper assembly of the Cold Mass per drawing F10103605.

The sections in the Cold Mass traveler are listed below and are meant to include quality checks and hold points along the fabrication process to assure the quality is consistent and meets the requirements of the FRS and safety documents:

1.0 General Notes
2.0 Parts Kit List
3.0 Q1/Q3 Magnet Inspection & Alignment
4.0 LMQXFA Cold Mass Tack Block and Backing Strip Mounting
5.0 MQXFA (a) Magnet Placement (Cold Mass Alignment Tooling)
6.0 MQXFA (b) Magnet Placement (Cold Mass Alignment Tooling)
7.0 MQXFA (a/b) Magnet Alignment
8.0 Bus & Instrumentation Connection and Assembly
9.0 Electrical Inspection
10.0 LMQXFA Cold Mass Assembly - Fit/Slide HT-X in Through Top 2 Ports
11.0 Beam Tube Insertion
12.0 Top Shell Installation and Welding
13.0 End Cover Installation
14.0 Cold Bore & HT X
15.0 Lower Plate Installation (Saddles)
16.0 Electrical Inspection
17.0 Non Destructive Exam
18.0 Pressure Testing
19.0 Weigh the Cold Mass
20.0 Review/Approval by the Coldmass L3
21.0 Production Complete

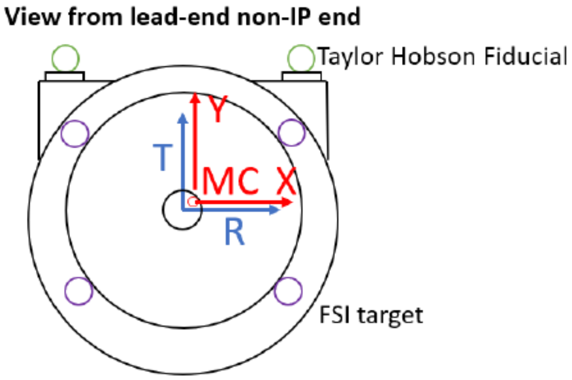
2.17.3. Tests

During assembly of the Cold Mass, various tests are performed to confirm quality of the welds and to verify performance tolerances. Tests included are:

- Mechanical tests
    - In process dimensional inspection on machined/formed components
    - Visual weld inspection. Acceptance per CERN HSE/US HL-LHC AUP agreement [5]
    - Phased Array Ultrasonic testing (UT) of longitudinal seams (100%) and Circumferential weld (Spot)
    - Pneumatic Pressure test to 25 bar – 1.25x Design Pressure (1.25 x 20 bar) w/ nitrogen gas
    - Combination Pressure/He mass spectrometer leak test – Pressurize Cold Mass internal surfaces to operating pressure (20 bar) w/ He gas and draw vacuum on external weld surfaces (Vacuum side connected to Helium Mass Spectrometer)
- Electrical Tests
    - Dielectric voltage standoff test of the Cold Mass
    - V-tap continuity measurements
- Warm magnetic measurements for alignment purposes
    - Magnetic length measurement using small rotating coil probe
    - Stretched wire axis measurements for each magnet upon insertion
    - Subsequent measurements as necessary during fine adjustment of magnet position

2.17.4. Alignment

The 'LMQXFA Functional Requirements' [3] defines the alignment requirements, and the 'Definitions of Survey and Magnetic Data for the inner triplet system at IR1 and 5' [39] replace with "specifies the coordinate system used and shown in Figure 50.



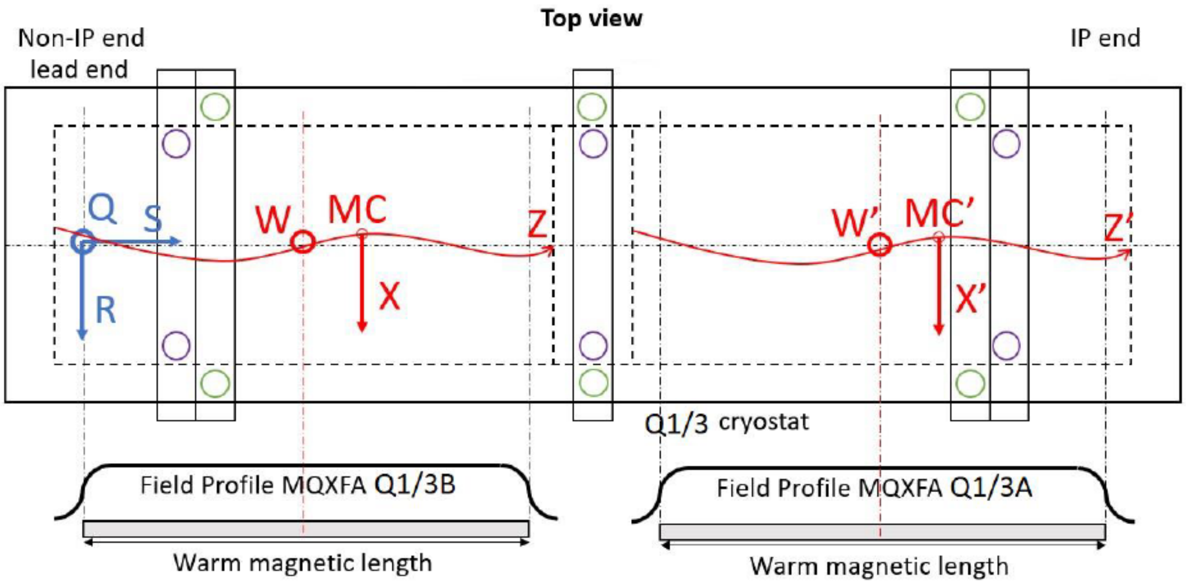


Figure 50: Definition of the reference frame for magnetic and alignment data of Q1/3. The fiducials positions on the cryostat are shown schematically. The position of points Q, the origin of the RST frame, W and W', the origins for magnetic data, is determined in warm conditions.

During the individual MQXFA magnet assembly and testing, the magnetic measurements are tied to the magnet iron as fiducial. This includes measurements like Single Stretch Wire (SSW) to determine the magnet axis, rotating coil probe (RCP) measurements to determine the magnetic length and field harmonics. The SSW is performed as part of the magnet integration at LBNL and data can be found in "HL-LHC: Quality Manufacturing and Inspection Plan - MQXFA Magnet Fabrication (LBNL) Traveler, vector master number 464478" in Section 7.5. The RCP measurements are part of the 'MQXFA vertical test' at BNL. The data is stored in the "HL-LHC AUP MQXFA Vertical Testing Interface Traveler, vector master number 464573" in Section 5.0. Upon approval of a MQXFA series magnet for proceeding into a Cold Mass, the magnet is received at FNAL and undergoes incoming inspection including a survey of the magnet fiducials. The data is uploaded to the "HL-LHC AUP MQXFA Incoming Inspection and QA Traveler, vector master number 464574" in Section 5.0. The SSW and RCP measurements are also used to confirm to the MQXFA Functional Requirement Specification [54] and the LMQXFA interface specification [40] to satisfy R-T-05 of [3]. The alignment station (see Section 2.15.6) is surveyed to ensure all roller clamps are perfectly aligned, such that upon transferring the MQXFA magnets onto the station the location of the MQXFA magnets are fixed with respect to each other. Each individual magnet's axis, and nodal point location is pre-'known' using all the three travelers to be within tolerance, and by design thus should be placed within tolerance to fulfil the alignment requirements below

[3] R-T-06 Nodal point distance between the MQXFA is 4806 ± 5 mm (at 1.9 K)

[3] R-O-01 Maximum deviation of each MQXFA magnet axis to common axis must is within ± 0.5 mm in both horizontal and vertical direction.

[3] R-O-01 Maximum deviation of each MQXFA field angle to common magnetic field angle is within ± 2 mrad.

[3] R-O-02 The common magnetic axis w.r.t. to the Cold Mass fiducials is determined with an accuracy of 0.2 mm to both nodal points.

[3] R-O-02 The common average MQXFA field angle w.r.t. to the Cold Mass fiducials is determined with an accuracy of 0.5 mrad.

[3] R-O-02 The magnetic length and the nodal points of each of the two MQXFA magnets in the Cold Mass is known within ±1 mm accuracy w.r.t the Cold Mass fiducials.

To ensure the requirements can be made survey will be done several times during the assembly process to assure proper alignment of the magnets relative to the Cold Mass vessel (and each other) and relative to the Cold Mass end cover piping.

- Survey effort will be combined with warm magnetic measurements to find the magnet axis and the centers of the magnets relative to each other and relative to the shell (outlined below). The survey activity will be performed before and after the welding of the shell.
- Survey effort will be combined with warm magnetic measurements to find the field angle of the Cold Mass before and after welding the end cover to the shell

Alignment of the magnets with respect to each other and to external fiducials will be performed using a Single Stretched Wire (SSW) system with the magnets powered at 10 A AC current. The AC current is used to enhance sensitivity by frequency 'lock-in', allowing these low current measurements to have high resolution and accuracy, as well as to suppress background field effects. Each magnet is powered and measured separately to determine X/Y-offset in addition to yaw, pitch, and roll angles relative to the SSW system. These techniques have been used previously for the LQX magnets with wire lengths up to 18 m and offset determination better than 20 um, and are documented in detail in [41].

The alignment involves the following:

1. The precision SSW stages are set up at each end of the two magnets as they sit on the assembly station, and their cabling connected to the SSW data acquisition cart.
2. The distances from each stage to the ends of the magnets are measured.
3. The stages are adjusted to be parallel to each other in yaw within 5 mrad using the base plate of each stage unit. This will be done with optical survey or with respect to tooling that is adequate for that precision.
4. The stage units are adjusted for roll angle within 10 μrad with respect to gravity using a precision level. The precision level is also used for a similar stage pitch adjustment, though less accuracy is actually required.
5. AC current is applied to the first magnet.
6. A measurement determining calibration for removal of sag effects based on the magnet and stage geometry is made.
7. Measurement sequences are made to determine the wire offset from average center including any sag compensation. The wire is then moved to this average position.
8. Measurement sequences are then made to determine the pitch and yaw angles of the magnet with respect to the wire axis, again compensated for sag, and the wire is then moved to be coincident to this determined 'true axis'.
9. The sequence of measurements is repeated so as to determine reproducibility and/or to iterate on the approach of being within alignment error limits.
10. Average roll angle measurements of the magnet are then made with another series of wire measurements.
11. When the alignment as outlined in the steps above is completed, the stage positions are recorded and the stage coordinate system preserved.
12. Power is then switched to the second magnet and the sequence of alignment steps performed on the first magnet is repeated to place the wire on the axis of this second magnet.
13. The positions of the axes and the roll angles of the two magnets are reported in the common coordinate system of the SSW, showing the displacements from ideal alignment, and evaluated to determine whether they are within requirements.
14. Adjustments to magnet positions and/or roll angles are applied as needed.
15. Measurements are repeated as needed to adjust and confirm that magnets are properly aligned before next assembly step.
16. Survey will be performed as needed to facilitate and meet requirements of Cold Mass/cryostat assembly.
17. Confirmation of final alignment will be made by repeating the measurements after the weld.

The LMQXFA Cold Mass fiducials are located on the End Cover (F1013796) and Cold Mass Support (F10103814). As these are among the last pieces of the fabrication process (step 13.0 in Section 2.17.2) temporary targets will be placed on the shell (see 1.1.3 in [42]) to ensure the MQXFA SSW and RCP data is consistently traceable to the LMQXFA Cold Mass. The LMQXFA SSW measurement will be stored in the "HL-LHC AUP Q1 Q3 Cold Mass Assembly Traveler, vector master number 464525" in Section 7.0 (pre shell welding) and 12.10 (after shell welding). An extensive summary of the final survey and measurements can be found in [42], including survey for the Cold Mass support feet, the cold bore tube flange and extremity flanges as well as the Cold Mass fiducials on the End Cover. Shown in Figure 51 is the measurement instruction for the extremity flanges. Upon insertion into the cryostat an additional survey of the cold bore tube is required, as described in [42] and in more detail in Section 3.3.4.

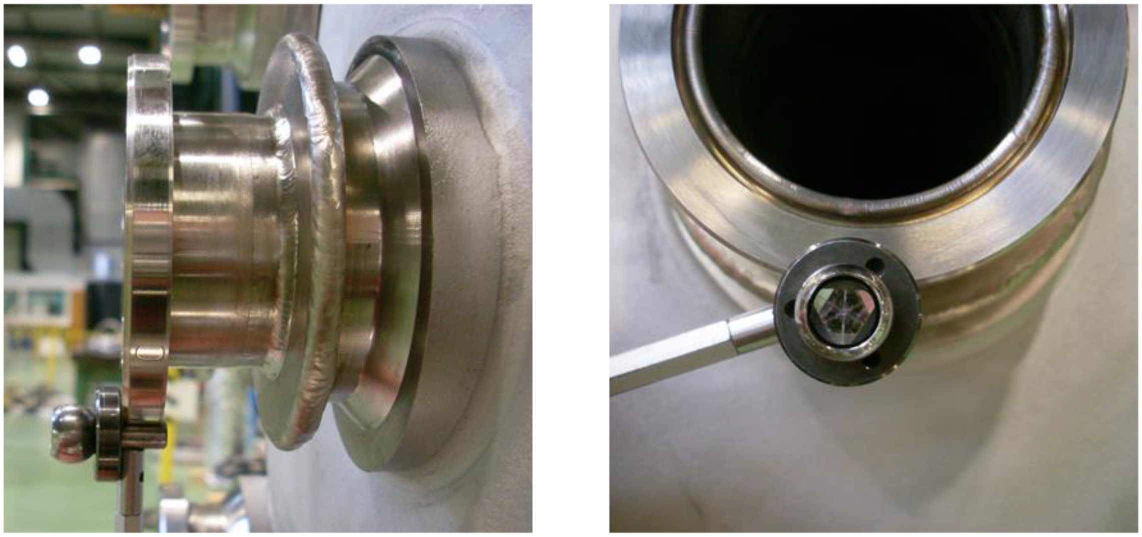


Figure 51: Flange measured with CCR0.5 Reflector [42].

A blanket survey summary excel sheet template can be found in [42] as well and will be used to collect the survey data. In the end, the data will be uploaded to the "HL-LHC AUP Q1 Q3 Cold Mass Assembly Traveler, vector master number 464525" in step 20 Review/Approval by Cold Mass L3".

2.17.5. QC & QA

HL-LHC AUP has a standard Quality Assurance Plan [43] and Configuration Management Plan [44] that the entire project respect and follow.

To maintain a consistent quality throughout the production and prototype units, fabricated parts and assemblies shall be dimensionally inspected and verified for form, fit and function per the requirements of the LMQXFA Cold Mass [3].

To satisfy pressure vessel safety, the Fermilab Environment, Safety and Health Manual chapter 5031 for pressure vessels and ASME B&PV Code Section VIII div.2 rules shall apply to all Cold Mass design and fabrication.

QA/QC is incorporated into the production of the Cold Mass through the released travelers. For the Cold Mass, we have created the following 3 travelers in Vector that will be used during fabrication and testing processes:

- 464574 HL-LHC AUP MQXFA Incoming Inspection and QA Traveler
- 464507 HL-LHC Magnet Bus Traveler
- 464525 HL-LHC AUP Q1 Q3 Cold Mass Assembly Traveler

These travelers include in-process inspections points and management hold points per the FNAL and CERN approved Manufacturing and Inspection Plan (MIP) [45]. Test and Inspection reports for the Cold Mass will be upload to the traveler as identified in the traveler steps and can easily be accessed through the Cold Mass travelers when required.

2.17.6. Interfaces

The responsibility for the cryostat interfaces is described in the "Cold Mass Interface Control" documents [46]. The interface specifications address the following areas:

- Magnet
  - Bus work
  - Instrumentation wiring
  - CLIQ leads
  - Lifting and Handling
- Cryostat
  - Piping dimension – Instrumentation port, helium inlets, beam line
  - Heat exchanger
  - Beam screen
  - Instrumentation – bus wiring, temperature sensor wiring, voltage tap wiring
  - Cold Mass Position Monitoring
  - Cryostat feet
  - Thermal shield
- Interconnect
  - Piping dimensions – helium lines, thermal shield lines
  - Vacuum vessel flange

2.17.7. ES&H

ES&H is integrated into all phases of the Project: Design, Construction, and Installation. ES&H requirements are clearly defined within the Project. The Cold Mass will comply with the Fermilab ES&H manual (FESHM) as well as with additional CERN requirements to be PED compliant. An agreement between CERN and the US AUP has been created which defines these additional requirements [5].

Cold Mass components provided by CERN will be evaluated for compliance to FNAL FESHM requirements.

Design & installation review process includes an ESH component utilizing Fermilab's and CERN's work planning requirements & processes.

All tooling components and assemblies are analyzed for safety and functionality prior to procurement. Peer reviews or Production readiness reviews were conducted for tooling requirements and analysis prior to release for procurement. For these reviews, FRS were created for the Alignment Tooling [37] as well as the welding tooling [33]. Engineering Notes containing analysis for the alignment station tooling [47], End Cover Tooling [38] and welding tooling [34] are also documented and available for review. Tables used for supporting the tooling were analyzed for deflection and are documented in [28].

Hazard Analysis Reports have been drafted for each of the workstations and include the bus soldering procedure as well as the stainless-steel pressure washing.

Communication with the Department Safety Officer (DSO) has begun to identify requirements and plan for Operation Readiness Clearance.

3. Cryostat Assembly

Although CERN is the design authority for the design of the cryostat and the tooling procurement, we summarize them in this section. This helps to better understand the cryostat assembly work execution the US is responsible for in the scope of the AUP project. The Cryo-Assembly will be tested at Fermilab consequently the design needs to comply with US standards and follow Fermilab specific safety codes (FESHM). Due this fact the design went through a rigorous design check (and analysis if required) to ensure that the test facility is capable of testing the Cryo-Assembly and the testing is safe.

3.1. Scope

The scope is to assemble 10 Q1/Q3 Cryo-Assemblies (3 pre-series, 7 series production). The scope also includes 2 Cryo-Assembly re-works. Each Cryo-Assembly has one Cold Mass assembly inside the CERN-supplied cryostat. Activities include receiving a complete kit of cryostat parts from CERN, assembling the CERN cryostat, inserting the Cold Mass assembly into the cryostat, and delivering the Cryo-Assembly to the Horizontal Test Facility for testing. After a successful horizontal test, the Cryo-Assembly is prepared for shipment and shipped to CERN.

The following items are off project scope:

- Q1/Q3 Cryostats design (CERN is the design authority).
- CERN is responsible for the procurement of kits and tooling for the assembly of the Q1/Q3 cryostats, including shipment to AUP at Fermilab.
- CERN is responsible for the development of assembly plans and QA/QC plans for the Q1/Q3 cryostats assembly.

CERN will provide guidance to support the tooling installation and onsite support to train AUP personnel during the assembly of the first pre-series Cryo-Assembly.

The deliverables are designed and will be fabricated to satisfy the Functional Requirement Specification [48] threshold requirements (R-T-XX) and objective requirements (R-O-XX).

All Cryo-Assembly drawings have been cataloged in the drawing tree [4], and pdf copies of all drawings are available [49].

3.2. Cryo-Assembly Design

The Cryo-Assembly design is shown in Figure 52, Figure 53 and Figure 54 [50]. Each Cryo-Assembly includes one LMQXFA Cold Mass (R-T-04). Outside of the Cold Mass are pipes for the thermal shield, beam screen, quench recovery, bus work, and superfluid pumping. The Cold Mass is supported within the Cryo-Assembly on conical glass fiber reinforced epoxy (GFRE) support posts.

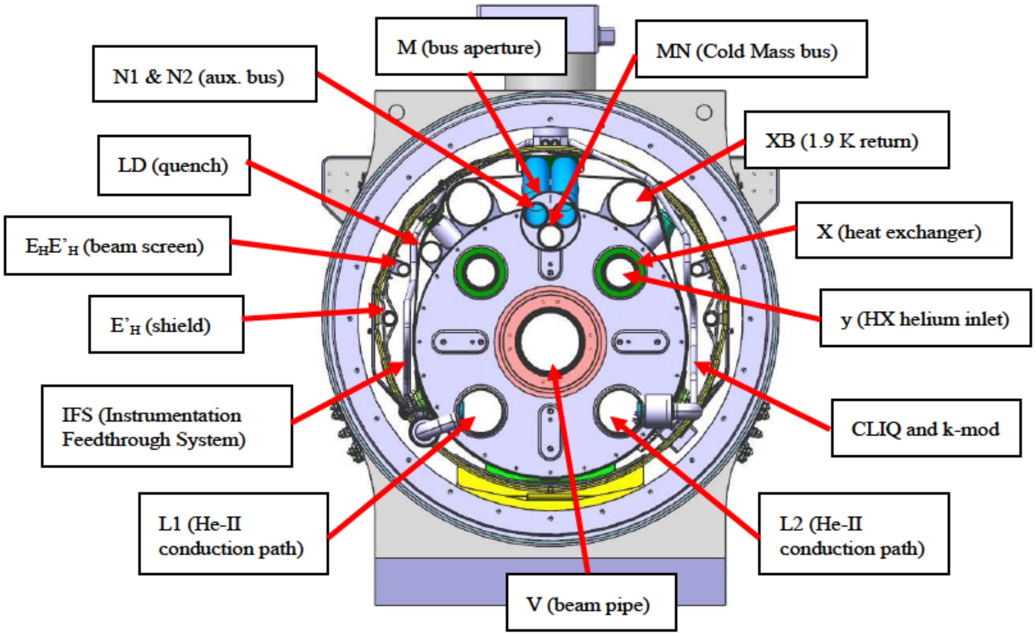


Figure 52: LQXFA/LQXFB end view as seen from the interaction point.

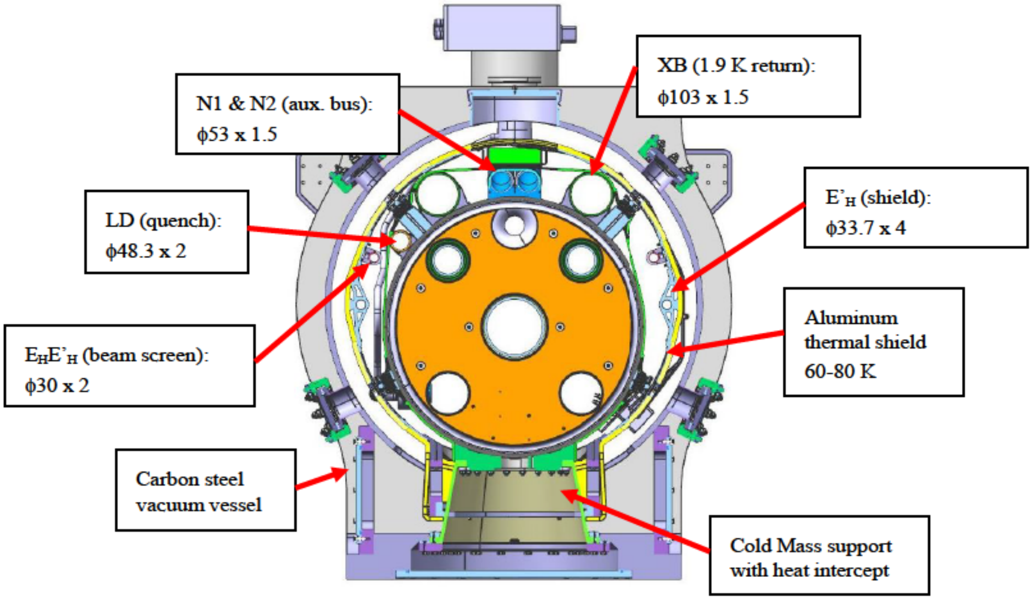


Figure 53: LQXFA/LQXFB cross-section as seen from the interaction point.

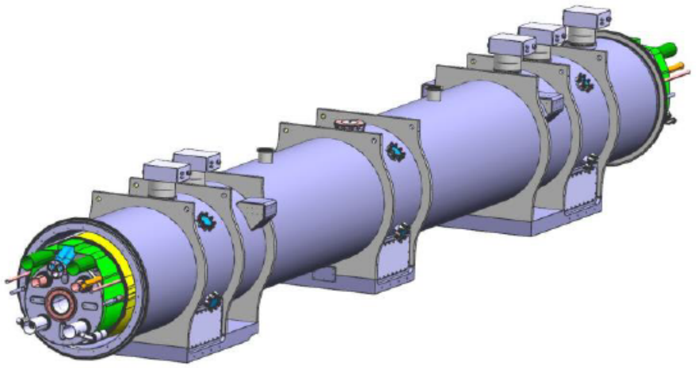


Figure 54: Isometric view of a complete LQXFA/LQXFB Cryo-Assembly.

The cryostat design is the full responsibility of CERN. The cryostat design developed by CERN has a lot of similarity with the design that has been produced for the LHC magnets. The main difference is the Cold Mass size, which has increased from the previous Cold Masses. Calculated heat loads for the Q1 and Q3 Cold Masses are summarized in Table 4. These heat loads were calculated for a 40-60 K thermal shield temperature. The thermal shield temperature has since increased to 60-80 K, meaning the new Cold Mass static heat load will also increase due to conduction and radiation heat loads. The design has also matured to include 6.35 W to 1.9 K for a Q1 or Q3 due to CLIQ leads, k-modulation (trim) leads, and IFS feeders [51].

Table 4: Cold Mass and Thermal Shield calculated heat loads [52].

Component	**Q1**	**Q3**
Length [mm]	10140	10140
Cold Mass		
Temperature [K]	1.9	1.9
Average total heat load [W/m]	13.26(1)	13.63(1)
Average static heat load [W/m]	0.85(1)	0.84(1)
Thermal Shield		
Average total heat load [W/m]	6.26(1)	5.36(1)
Average static heat load [W/m]	6.26(1)	5.36(1)

(1) 40-60 K thermal shield temperature

Designers must continually be cognizant of the heat load to the helium system and of the structural loads imposed on the cryostat systems from static weight, shipping and handling, quench loads, and ambient ground motion. These two considerations are generally at odds with one another. Low heat load implies a minimum of structural material conducting heat from the environment. Sound structural design implies material with sufficient strength to resist both static and dynamic forces. The structural requirements CERN used to develop the design specifications of the Q1 and Q3 are summarized in Table 5. The 21,200 kg Cryo-Assembly is below the 22,500 kg maximum mass (R-T-03).

Table 5: Structural Requirements for the Q1/Q3 Cryo-Assembly.

Component	**Q1/Q3**
Total mass [kg]	21200
Vacuum Vessel	
Temperature [K]	295-1.9
Pressure differential [bar] [48]	1 (external) 0.5 (internal)
Cold Mass	
Temperature [K]	295-1.9
Pressure [bar] [53]	20
Maximum End Loads	
Vacuum force [kN] [54]	86
Pressure force [kN] [53]	83

The vacuum force is calculated with 1 atm differential on the vacuum bellows mean diameter. The pressure force is calculated assuming each line is at its MAWP over the average diameter of its expansion joint. The pressure force is based on an initial possible expansion joint design for the known pipe diameters.

This section summarizes the results of the design effort to date on the HL-LHC interaction region quadrupole cryostats. Thermal and structural aspects of the design will be described in detail. Aspects addressed in turn are: vacuum vessel, thermal radiation shield, multi-layer insulation (MLI), cryogenic piping, support system, and magnet interconnect.

3.2.1. Vacuum Vessel

The vacuum vessel is the outermost cryostat component and, as such, serves to contain the insulating vacuum. In addition, it functions as the major structural element to which all other systems are ultimately attached to the accelerator tunnel floor. Furthermore, it serves as a pressure containment vessel in the event of a failure in an internal cryogen line.

The drawings for the first vacuum vessel produced are LHCQQXFAP0001-0004 [49]. Drawings for the subsequent vacuum vessels, which use more bolts to secure the cover plates, are LHCQQXFA0001-0004 [49]. For reference, drawing LHCQQXFAP0001 is shown in Figure 55 and Figure 56. The vessel has a 914 mm outer diameter with a 12 mm wall thickness. This wall thickness is sufficient for the design differential pressures (R-T-10). The overall length is 9345 mm, less than the 9500 mm maximum vacuum vessel length at room temperature (R-T-01). The overall width and height are 1055 mm and 1388.9 mm, respectively, which fall within the maximum envelope of 1100 mm wide and 1450 mm high (R-T-02). As per LHCQQXFA0002, the weight of the vacuum vessel without cover plates or instrumentation wiring housings is 4,941 kg (10,895 lb).

The material choice for the vacuum vessel is 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 (R-T-09). The end flanges, made from 304L forged rings, must meet the interface specifications with the interconnect sleeve. The reinforcement rings must clear up the space for the interconnect sleeve for interconnect opening and closing activities. 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 feedthrough of instrumentation wiring
- 2 ports for the feedthrough of CLIQ leads
- 1 port for the feedthrough of trim (k-modulation) leads
- 12 ports for Cold Mass positioning/monitoring

There are several attachments to the vacuum vessel:

- Survey monuments
- Support system reinforcement rings
- Lifting lugs

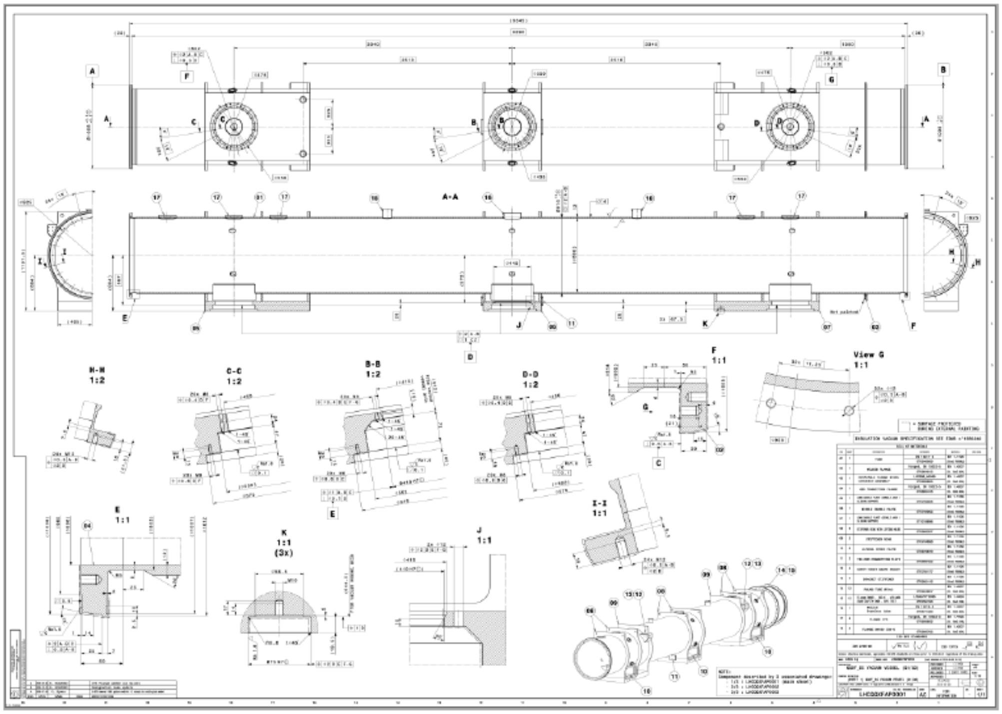


Figure 55: Vacuum Vessel detail drawing.

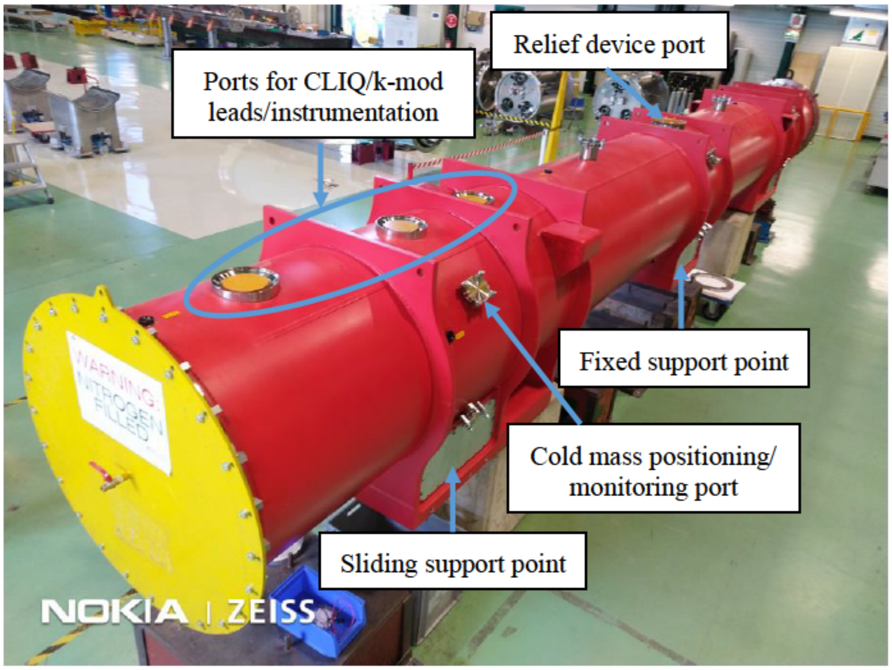


Figure 56: The first received Q1/Q3 Vacuum Vessel.

3.2.2. Thermal Shield

The QQXFA and QQXFC cryostats each have a single shield cooled by helium gas between 60 K and 80 K. The shields intercept heat radiated from the 300 K surface of the vacuum vessel and conducted through the support system. The thermal shield is comprised of two aluminum extrusions welded and riveted to cooling pipe extrusions. The shield itself is a formed shell attached to the cryostat at the support structure. The nature of the shield function requires that the shell have high thermal conductivity to minimize thermal gradients around its circumference. Aluminum 1050, 4 mm thick was chosen for this application.

The lower half of the thermal shield is comprised of nine subshells welded together as shown in assembly drawing LHCQQXFA0038 [49]. This drawing is shown in Figure 57 for reference. The upper half of the thermal shield is comprised of seven subshells as shown in drawings LHCQQXFA0039, 0040, 0043, 0047, 0051 [49], welded together.

The shells are longitudinally welded to an extrusion carrying 60-80 K helium. Figure 58 shows a model of this extrusion and its end fitting [55]. Figure 59 shows extrusion assembly detail drawing LHCQQXFA0024 [49].

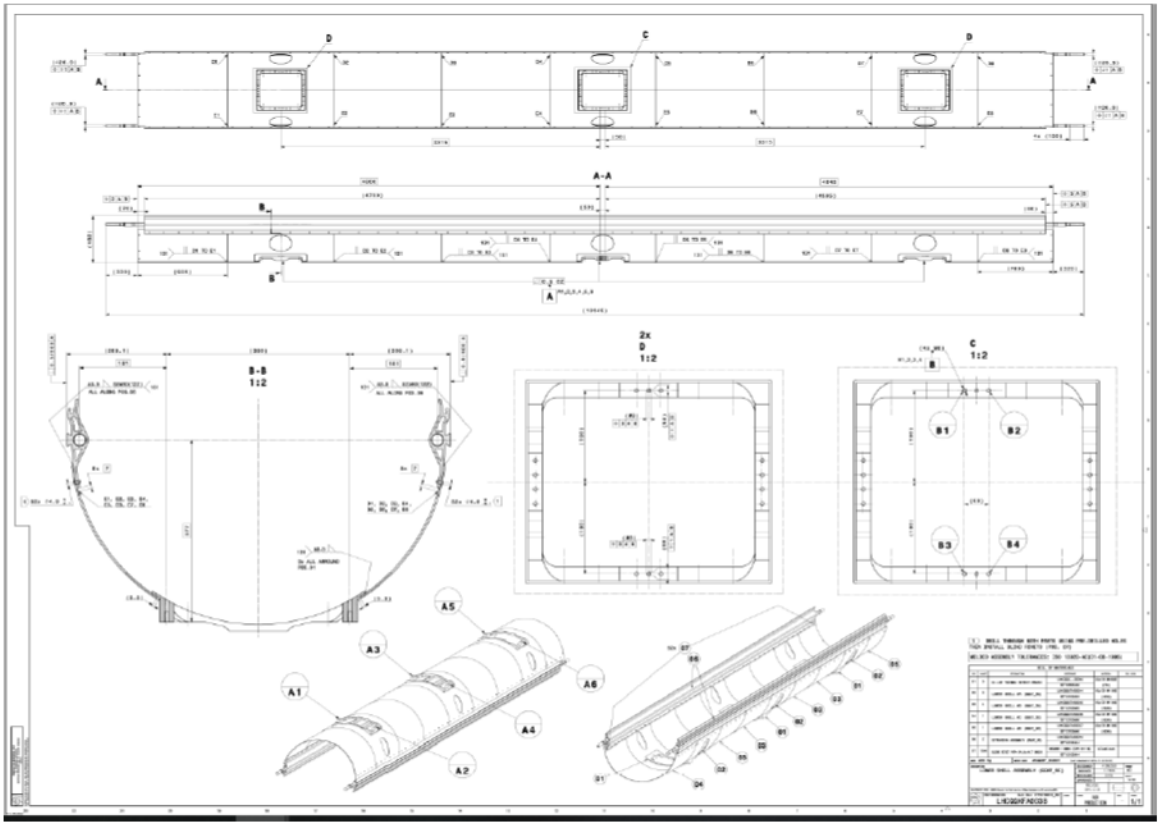


Figure 57: Lower half of the thermal shield.

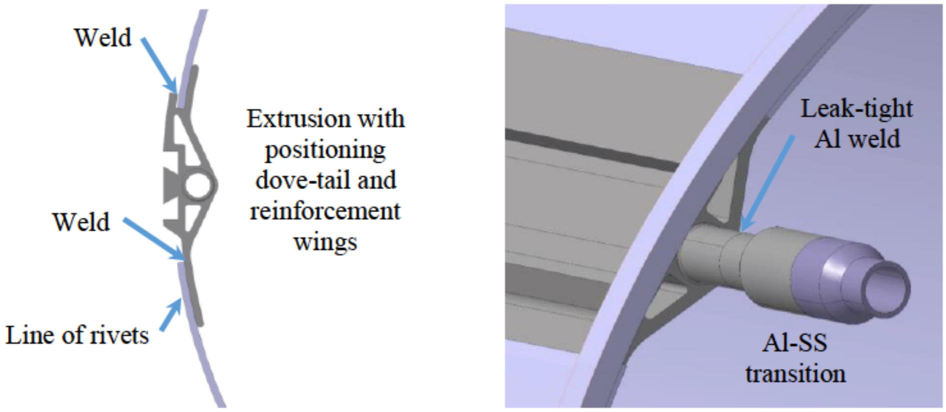


Figure 58: Details of the thermal shield cooling line extrusion and end fitting.

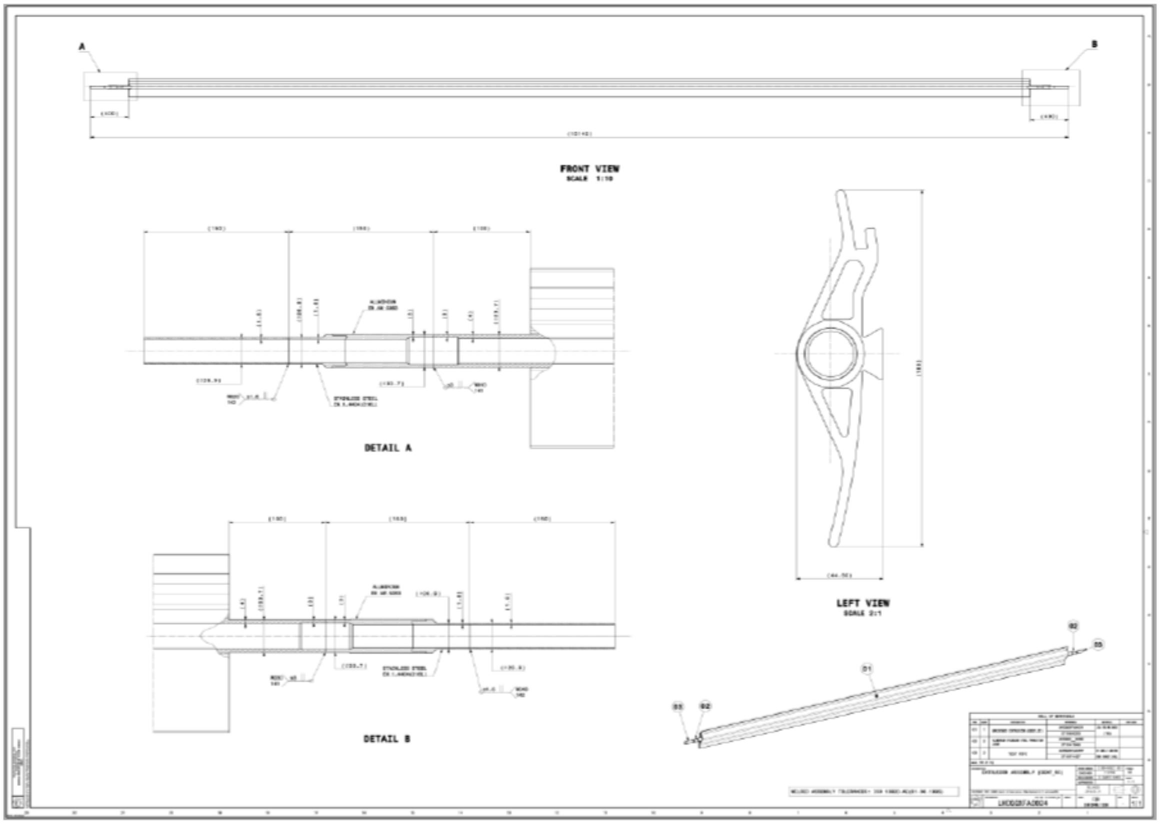


Figure 59: Extrusion assembly detail drawing.

3.2.3. Multilayer Insulation

The multi-layer insulation system is modeled after the insulation system of LHC magnets. The blanket design consists of reflective layers of polyethylene terephthalate (PET) film aluminized on both sides to a nominal thickness not less than 350 angstroms (35 nm) and spacer layers of randomly oriented spunbonded polyester fiber mats. The mean apparent thermal conductivity of an MLI blanket comprised of these materials has been measured to be 0.52 x10^{-6} W/cm-K. The measured mean layer density is 3.61 layers per mm.

The thermal shield will be wrapped in two 15-layer MLI blankets, and the Cold Mass will be wrapped in one 10-layer MLI blanket [56].

3.2.4. Cryogenic Piping

In addition to providing the necessary structural support and thermal insulation for the Cold Mass assembly, the cryostat serves to contain the piping for all of the cryogenic services required for magnet and magnet system operation. The shield extrusions are anchored at one of the magnet supports and are free to slide axially at the others to allow for thermal contraction. All of the 1.9 K pipes are attached to supports that are in turn attached to the Cold Mass. This scheme minimizes the heat load from the structural supports. These pipes are also axially anchored at only one point in the final installation. Table 6 summarizes the size of all the cryostat pipes. All pipe wall thicknesses are sufficient for the design differential pressure and satisfy R-T-10. Table 7 lists the design pressures, normal operating pressures, temperatures, and flows.

Table 6: Cryostat pipe sizes.

Description	**OD (mm)**	**Thickness (mm)**	**Notes**
Quench line (LD)	48.3	2	Stainless steel
Auxiliary busbar line (N1 & N2)	53	1.5	Stainless steel
1.9 K supply line (y, CY)	14	1	Stainless steel
1.9 K return line (XB)	103	1.5	Stainless steel
60-80K shield shell	785	5	Aluminum shell
50 K shield and beam screen supply ($E_H E'_H$)	30	2	Aluminum extrusion
50 K shield flow (E'_H)	33.7	4	Aluminum extrusion
	26.9	1.6	Stainless steel extension

Table 7: Cryostat piping flow parameters under normal operating conditions.

Description	**Fluid**	**P_{max} (bar)** [53]	**P_{oper} (bar)** [57]	**T (K)** [57]	**Flow (g/s)** [57]
Quench line (LD)	LHe	20	1.3	1.9	--
Auxiliary busbar line (N1 & N2)	LHe	20	1.3	1.9	--
1.9 K supply line (y,CY)	LHe	4	0.016	1.8	21.4
1.9 K return line (X,XB)	LHe	4	0.016	1.8	21.4
60 K shield supply ($E_H E'_H$)	GHe	25	24	60	7.5
80 K shield flow (E'_H)	GHe	25	24	80	7.5

3.2.5. Cold Mass and Cryostat Support System

The support system in any superconducting magnet serves as the structural attachment for all cryostat systems to the vacuum vessel that in turn anchors them to the accelerator tunnel floor. The emphasis is on meeting the allowed suspension system conduction heat load, satisfying the structural requirements, and maximizing the suspension stiffness. This last constraint is not explicitly defined in the design criteria but comes from experience testing similar magnets. Assemblies that are more rigid tend to be more structurally stable during shipping and handling.

Table 8 presents the design loads that must be supported by the HL-LHC support posts [53]. Vertical loads are due to weight and acceleration during transport. Longitudinal loads are due to pressure and bellows compression forces. The loads of Table 8 include a 1.35 safety factor for static actions (weight, loads from expansion joints), a 1.50 safety factor for variable actions (pressure end effects in case of quench, transport/handling accelerations), and a 1.10 safety factor for actions during test conditions (pressure end effects during pressure test conditions).

These support posts will be used in the Q1, Q2, Q3, D1, and D2 Cryo-Assemblies, so the load case 1 and 2 values shown in Table 8 are worst-case. Load cases 3 and 4 are meant to specify simple tests to reflect the stresses of load cases 1 and 2.

Table 8: HL LHC support post load cases.

	Load case 1: Cryostat handling and testing conditions	**Load case 2: Operational conditions**	**Load case 3: Compression load test**	**Load case 4: Transverse shear load test**
Vertical compression load (kN)	205	142	250	-
Transverse shear load (kN)	135	125	-	165
Temperature	290 K uniform	1.9 K at top flange 70 K at heat intercept 290 K at bottom flange	290 K uniform	290 K uniform

The vendor drawing for the HL-LHC support posts is LHCQQHXF0001 [49]. It is shown in Figure 60 for reference. The conical support post column is 200 mm high and made of GFRE. The 232 mm inner diameter top flange bolts to the 1.9 K magnet. The 410 mm outer diameter bottom flange is in contact with the room-temperature vacuum vessel. The aluminum heat intercepting ring on the outer conical surface is bonded at an intermediate position to intercept heat at the 60-80 K temperature level. A stainless-steel backing ring is bonded to the inner conical surface, opposite to the aluminum heat intercepting ring, to reduce stresses due to differential thermal contraction. The vendor test reports are provided to verify the design meets the requirements [58].

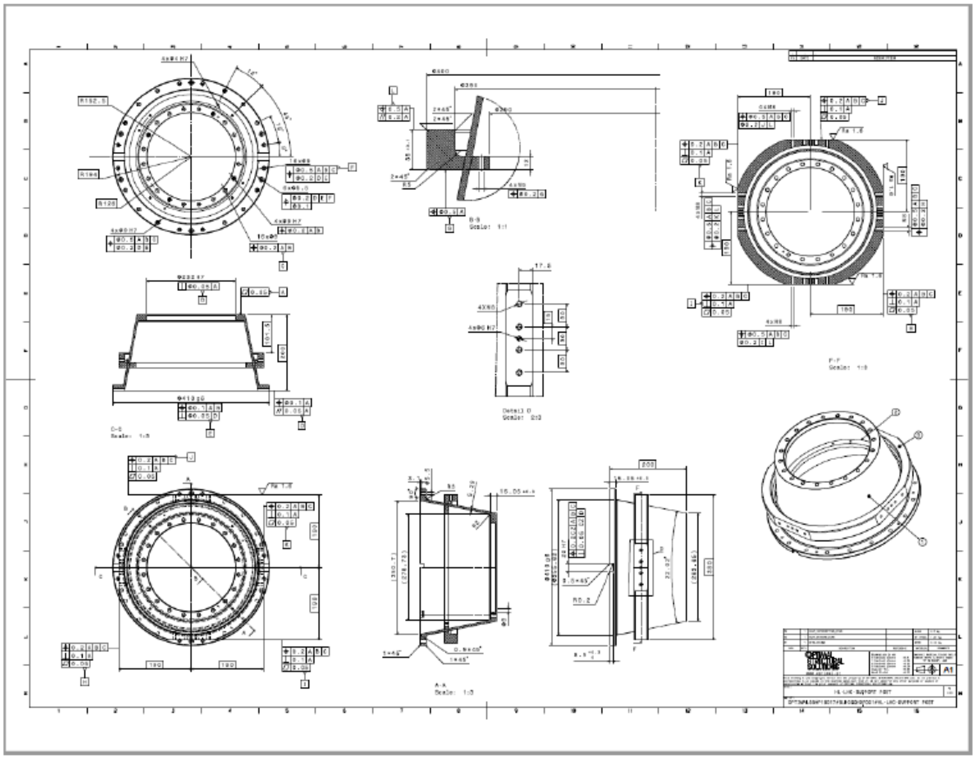


Figure 60: HL-LHC Support Posts.

3.2.6. Interconnect

Interconnect design specifications are not part of the scope of this L3 document. However, they are an essential part of the interface specifications, and expected bellows thrust forces were included in the functional specifications of the Cold Mass GFRE [53] support posts.

3.2.7. Tooling

CERN provides the technical description [59] for two tooling sets for assembly of HL-LHC quadrupole Cryo-Assemblies (R-T-18). Also included are the requirements for safety coordination, personnel, and training for on-site installation and testing of tooling sets. One tooling set will be installed at CERN. The second tooling set will be assembled, installed, and aligned at Fermilab by the tooling vendor and its subcontractors.

After the initial contracted tooling vendor became insolvent, a new CERN contract was placed with Applus+ Laboratories (Barcelona, Spain). A contract kick-off meeting was conducted with CERN personnel in early August 2019, and a Preliminary Design Review was conducted with CERN and Fermilab personnel in late October 2019. Design work has been completed by the vendor, and manufacturing is in progress. The Fermilab tooling set is specifically configured for Q1/Q3 cryostat assembly and includes a work platform specific to the ICBA installation location (R-T-18).

Each tooling set consists of an assembly table, an alignment table, extension rails, sliding elements, two electric cable winches, a controls system, and a series of manually operated synchronized mechanical jacks. Tooling set models and snapshots are available [60]. Snapshots of the Fermilab tooling set and the Fermilab assembly table work platform are provided for reference in Figure 61 and Figure 62, respectively. The tooling has an overall length of 2782 mm (91 ft, 5 in) and a platform width of 3086 mm (10 ft, 1 in).

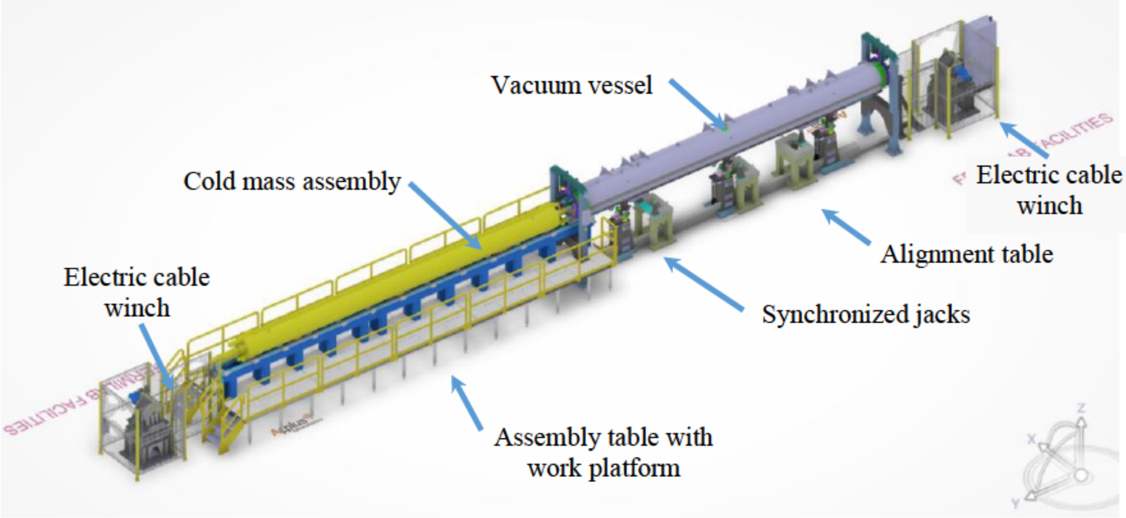


Figure 61: A model of the Fermilab Cryostat Tooling.

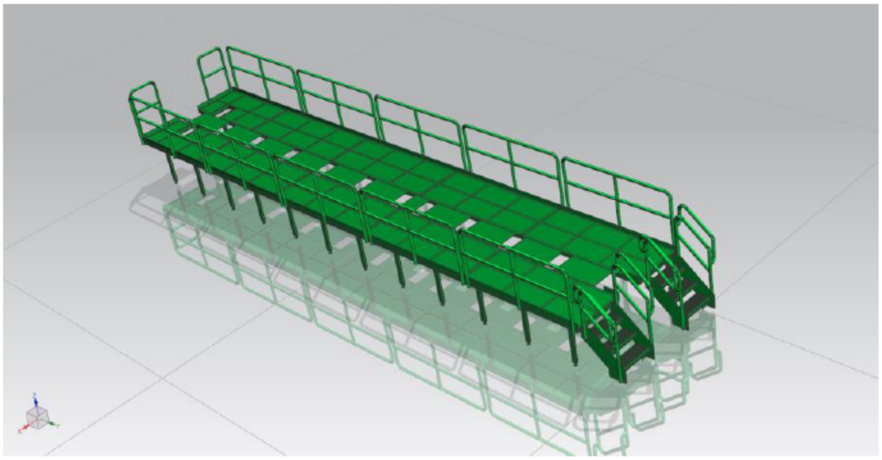


Figure 62: A model of the Fermilab Assembly Table work platform.

An assembly traveler [61] provided by CERN, will detail the cryostat assembly steps using this tooling (R-T-05). A high-level sequence of steps is as follows:

1. The Cold Mass and thermal shield are wrapped with superinsulation and nested together on the assembly table.
2. The vacuum vessel is supported on the alignment table.
3. The cable winch pulls the Cold Mass assembly along sliding elements and the extension rails and into the vacuum vessel.
4. The Cold Mass assembly is raised from below using synchronized jacks integrated with the alignment table.
5. The sliding elements and extension rails are removed and returned to the assembly table.
6. The alignment table allows repositioning of the vacuum vessel relative to the Cold Mass in all three dimensions to a precision within ± 0.5 mm.
7. The Cold Mass is lowered and attached to the vacuum vessel by the support posts.

The two electric cable winches will allow the tooling to be used for both inserting and removing Cold Masses from vacuum vessels. The manually operated synchronized jacks, shown in Figure 63 [62], will raise and lower the Cold Mass as necessary for vacuum vessel insertion/removal and for shipping post-installation in preparation for Cryo-Assembly shipment to CERN.

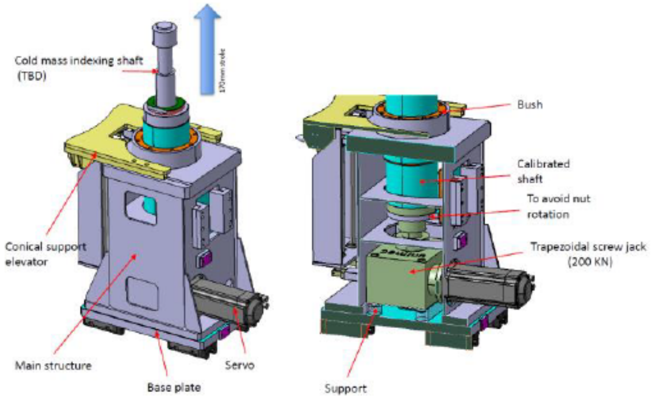


Figure 63: Model of a synchronized jack.

This method of inserting and securing the Cold Mass into the cryostat has been used successfully during the production of the LHC magnets. Photographs of existing dipole magnet assembly tooling are presented in Figure 64.

Figure 64: Existing LHC dipole magnet installation tooling.

A unique feature of this new tooling is the capability to install and remove shipping posts at each of the three Cold Mass support locations. The GFRE support posts described in Section 3.2.5 are delicate and would not survive the overseas shipment of a Cryo-Assembly from Fermilab to CERN. A shipping post, accompanying hardware, and an installation method have been designed to unload the support posts per RT-20 so that all of the transportation forces are carried by the shipping post. The shipping post must fit inside the support post and handle 3g accelerations in any direction. It must interface with the Cold Mass support plate, and the accompanying support post cover plate must interface with the vacuum vessel. Figure 65 shows a model of a shipping post being installed using a cryostat tooling jack. Additional information and snapshots of shipping post hardware can be found in [57].

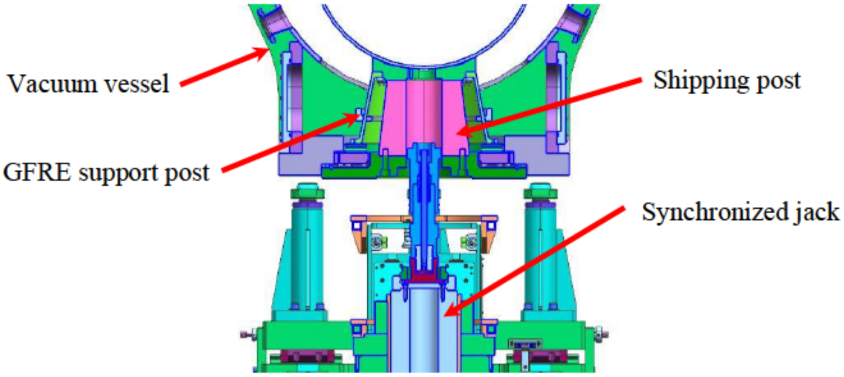


Figure 65: Existing LHC dipole magnet installation tooling.

A detailed finite element analysis of the Cold Mass/shipping post system was conducted [63] for a range of potential accelerations due various modes of transportation. Based on published studies, the maximum acceleration considered was 3g due to loading/offloading operations with a crane. First applying these loads to the combined Cold Mass and shipping post showed that all stresses and strains of the Cold Mass are acceptable. The maximum deformation of the shipping posts was calculated to be 0.155 mm. The results of this first simulation served as inputs to a detailed analysis of the shipping post itself. Shipping post stresses were found to be acceptable for 3g loading conditions, and shipping post deformations calculated by the two analyses were in good agreement. The 3g load limit of the shipping post is an important input for the design of the shipping crate and shipping frame.

3.3. Fabrication

3.3.1. Component Procurement

All the cryostat components including the tooling is the responsibility of CERN (R-T-17). The components to be shipped to FNAL consist of:

- Prototype Cryostat Assembly parts and tooling
- Production Cryostat Assembly parts

3.3.2. Assembly Procedures

CERN provides assembly procedures, QC steps, and QA steps (R-T-19). The Cryostat assembly work will be done in the new ICBA building ICBA. The floorplan for the fabrication facility is shown in Figure 49.

3.3.2.1. First Pre-series

The first cryostat assembly work will be done for a pre-series Cryo-Assembly and will be directed by CERN personnel on-site at Fermilab, working with the Fermilab responsible engineer (R-T-19). The layout for the Cold Mass and Cryostat work is shown in Figure 49.

Assembly of the first Q1/Q3 pre-series Cryo-Assembly will be performed by Fermilab personnel with oversight from CERN personnel. The cryo-mechanical assembly steps are summarized below. Survey and alignment requirements are addressed in the following section.

1. External piping
    a. Cryogenic process lines external to the Cold Mass
        i. Quench line LD
        ii. Pumping lines XB (qty. 2)
        iii. 50 K supply lines $E_H E'_H$ (qty. 2)
        iv. Thermal shield lines E'_H (qty. 2)
    b. Weld tube/pipe/flanges/fittings on each end of each line.
    c. Pressure test and leak check (R-T-05) each line.
    d. Mechanically attach each line to the Cold Mass or the thermal shield.
    e. Perform 4-wire measurements for temperature sensor checkout.
    f. Handling with care (R-T-12), perform continuity checks for CLIQ leads, trim leads, heaters, and voltage taps checkout.
2. Cryogenic assembly
    a. Place a sled on the alignment table.
    b. Put the thermal shield lower half on the sled.
    c. Place Cold Mass on the sled and fasten at each Cold Mass support location.
    d. Wrap and secure 10-layer MLI blanket around the Cold Mass.
    e. Install the thermal shield top half. Fasten it to lower half.
    f. Install and secure two 15-layer MLI blankets around the thermal shield.
3. Vacuum vessel preparation
    a. Place Cold Mass support posts and support components over the alignment table jacks.
    b. Place the vacuum vessel on the alignment table.
    c. Adjust/align the vacuum vessel to the required position in all three dimensions.

4. Cryostating
    a. Connect cryostating fixture to the end of the cryogenic assembly.
    b. Connect the cable winch to the cryostating fixture.
    c. With the cable winch, pull the cryogenic assembly along the sliding elements and extension rails into the vacuum vessel.
    d. Raise the cryogenic assembly using the synchronized jacks integrated with the alignment table.
    e. Remove the sliding elements and extension rails and return them to the assembly table.
    f. Fasten the support posts to the Cold Mass.
    g. Lower the Cold Mass so that all of its weight is supported by the support posts and support components.
    h. Fasten the support posts and support components to the vacuum vessel.
5. Final checkouts
    a. Perform a Hipot of the Cold Mass.
    b. Perform 4-wire measurements for temperature sensor checkout.
    c. Perform continuity checks for CLIQ leads, trim leads, heaters, and voltage taps checkout.
6. Final alignment
7. Prepare for shipment
    a. Place the Cryo-Assembly on the alignment table.
    b. Unbolt the Cold Mass support posts from the vacuum vessel.
    c. Raise the Cold Mass to the necessary height. The support posts are fully unloaded with all of the Cold Mass weight supported by the jacks.
    d. Install shipping post hardware and fasten to the Cold Mass saddle.
    e. Lower the Cold Mass so that all of the Cold Mass weight is supported by the shipping posts. The support posts and jacks are fully unloaded.
    f. Fasten the shipping posts to the vacuum vessel.

3.3.2.2. Production

Assembly of the Q1/Q3 production Cryo-Assemblies will follow the same steps as the first pre-series Cryo-Assembly. Production unit assembly and oversight will be performed by Fermilab personnel.

3.3.3. Tests

The tests of Section 2.17.3 verify the quality of the magnets as they are assembled into a Cold Mass. Additional tests described here are required to verify the Cold Mass meets the electrical and mechanical specifications at each step of the assembly process as the Cold Mass is integrated into a Cryo-Assembly. The tests will include:

- Mechanical tests
    - Dimensions and location of cryostat components
    - Leak check for the Cold Mass and vacuum vessel
    - Pressure tests of the Cold Mass and vacuum vessel
- Electrical tests
    - Dielectric voltage standoff test of the Cold Mass (R-T-13)
    - Temperature sensor four wire measurements
    - V-tap continuity measurements
- Warm magnetic measurements for alignment purposes
    - Stretched wire axis measurements for each element upon insertion
    - Subsequent measurements as necessary during fine adjustment of magnet position
    - Survey transfer of measurements to cryostat fiducials in final position

3.3.4. Alignment

The LMQXFA Cold Mass inside the LQXFA cryostat has undergone alignment as described in Section 2.17.4. During the LQXFA assembly described in Section 3.3.2 several optical surveys using a LEICA AT9xx series laser tracker will be performed to tie the fiducials of the LMQXFA Cold Mass (and its previous magnetic measurements) to the LQXFA cryostat Taylor Hobson fiducials [39]. A Cold Mass Position Monitoring System will be welded to the shell of the LMQXFA. It is based on the frequency scanning interferometry (FSI) technique and will allow to monitor the Cold Mass movement w.r.t. the cryostat under cool-down and powering and is described in [64]. The installation and measurement procedure for the FSI system is detailed in [65]. Four FSI location around the Cold Mass in three locations along the magnet axis are installed shortly after the Cold Mass assembly and surveyed, as they become unavailable to direct survey upon installation of the MLI blankets and thermal shield. The survey and image requirements are detailed in [65]. After assembly, the survey described in [58] will provide the final coordinate frame of the FSI targets. See Figure 66 for the position of the FSI targets around the Cold Mass, Figure 68 for the location of the three stations along the magnet axis and Figure 67 for a detailed view of the system.

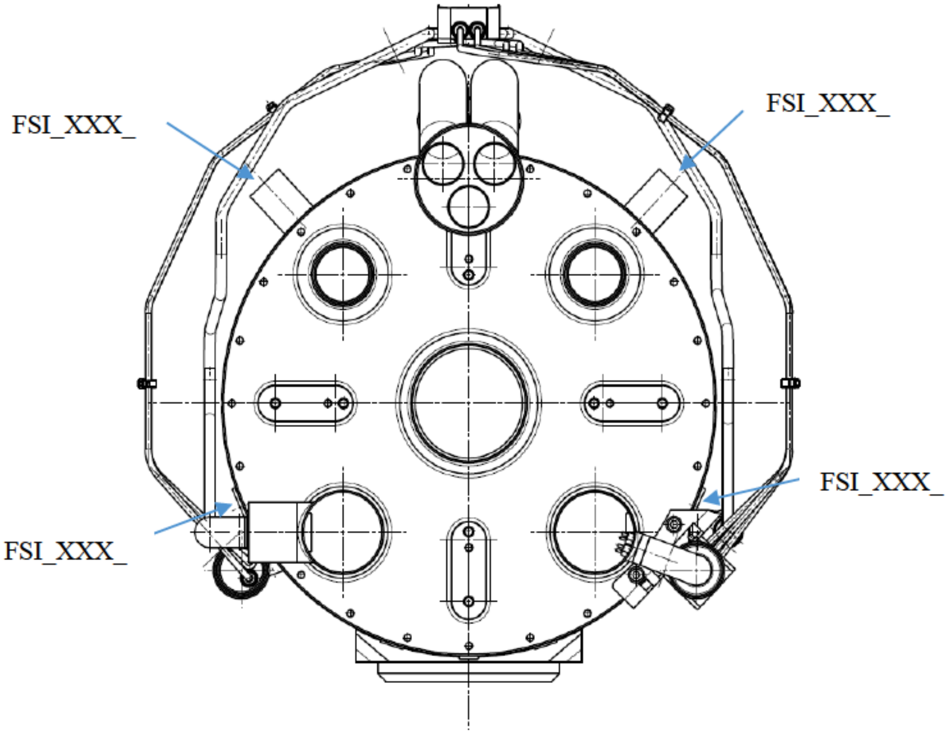


Figure 66: FSI naming convention [42].

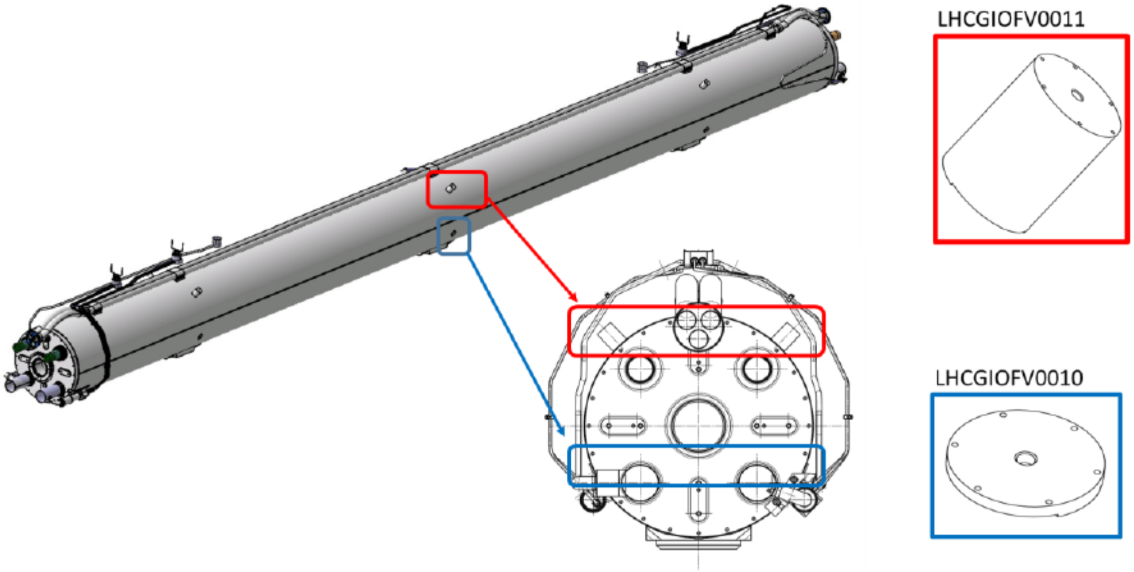


Figure 67: Placement of the long (LHCGIGV0011) and short (LHCGIGV0010) FSI reflector supports [65].

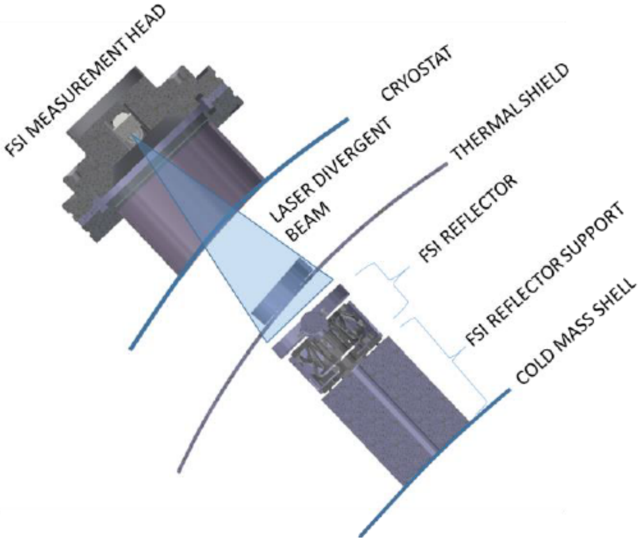


Figure 68: Cross section of single measurement channel of FSI position monitoring system [65].

As described in [48], the LQXFA cryostat has to fulfill all alignment requirements from [3] (R-T-06 in [48]), be positioned as described in [66] (R-T-05 in [48]) and follow the reference frame described in [39] (R-T-07 in [48]). After cryostat assembly, the Cold Mass survey from Section 2.17.4 will be repeated to tie the cryostat fiducials to the Cold Mass fiducials, using the procedures [42].

Survey will be done several times during the assembly process to assure proper alignment of the Cold Mass relative to the vacuum vessel and external (relative to the Cold Mass) piping:

- Cold Mass support components (that will be attached to the support system) will be surveyed before and after installation of the cryostat feet.
- Cryostat piping installation onto the Cold Mass including the heat and radiation shield will be surveyed before and after installation.

- Cold Mass survey before and after insertion of the Cold Mass into the vacuum vessel (mechanical centering determination before and after removal from insertion sled).
- FSI target location after tack welding of the FSI reflector support and upon completed cryostat assembly.
- A measurement of the magnet axis at cold will be performed vis SSW technique during the horizontal testing and is described in Section 4.6.
- A measurement of the cold bore tube deflection at cold will be performed using a mole device (see Figure 69) as prescribed in [42].

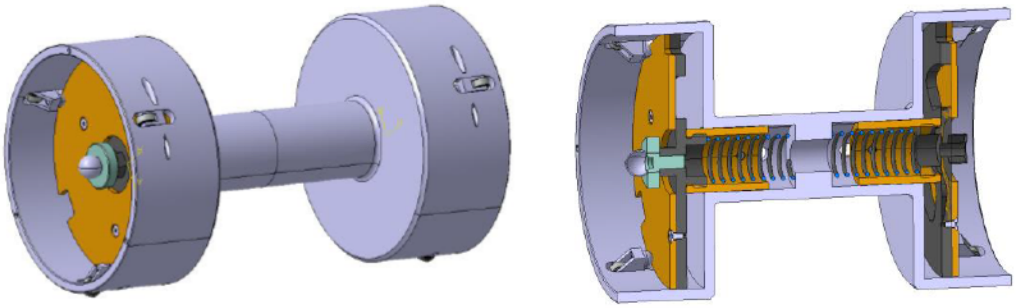


Figure 69: (Left) Self centering mole device with CCR 0.5 reflector in the center, (Right) cross-section of the cold bore mole device.

3.3.5. QC & QA

The cryostat assembly work QA plan follows from the US HiLumi Project Quality Assurance Program [43]. Consistent with the project QA plan, the Cryostat Assembly QA process uses a graded approach to the implementation of the plan. The scope of the QA program includes 1.) Design of systems and components 2.) Procurement of commercial items 3.) Fabrication of components 4.) Calibration of instruments and 5.) Design Documentation. The goal of is to have the Cryo-Assembly reliability equal to that of the Cold Mass (R-O-01).

The cryostat team includes staff from FNAL as well as the collaborating institutions and CERN. The internal QA plans and procedures of the partnering institutions are used when applicable such as when items are procured through the partnering institution.

3.4. Interfaces

Cryo-Assembly interfaces have been identified and documented in internal interface control documents (ICDs) [66] (R-T-15). These interfaces address the following areas:

- Cold Mass
    - Piping – instrumentation port, helium inlets, beam line
    - Heat exchanger
    - Beam screen
    - Instrumentation – temperature sensor wiring, voltage tap wiring
    - Bus, CLIQ leads, trim leads
    - Cold Mass supports
    - Cold Mass position monitoring
- Interconnect
    - Piping – helium lines, thermal shield lines

- Thermal shield
- Vacuum vessel
- Bus and CLIQ leads
- Cryo-Assembly supports
- Lifting, loading/unloading, transport

Cryo-mechanical interface details are provided by the CERN Q1/Q3 model [50] as shown in Figure 70. Electrical interface details are provided by the triplet electrical scheme [67] as shown in Figure 71.

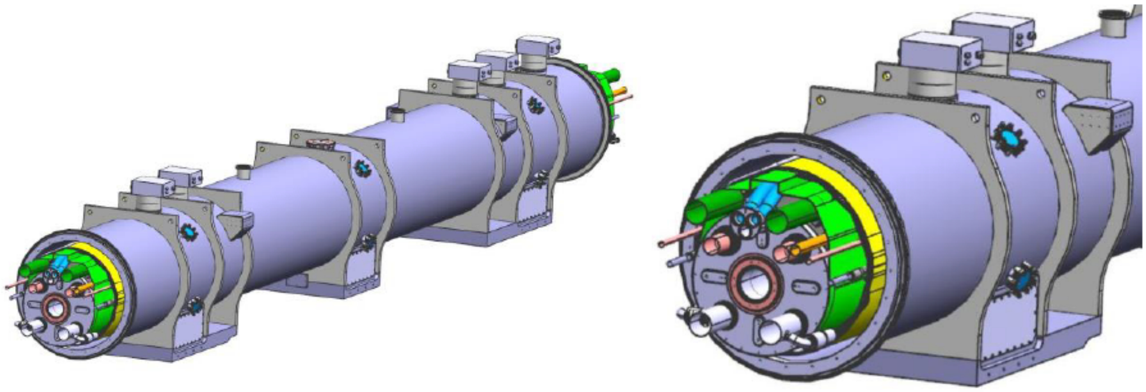


Figure 70: Model view of the complete Cryo-Assembly and the non-IP end.

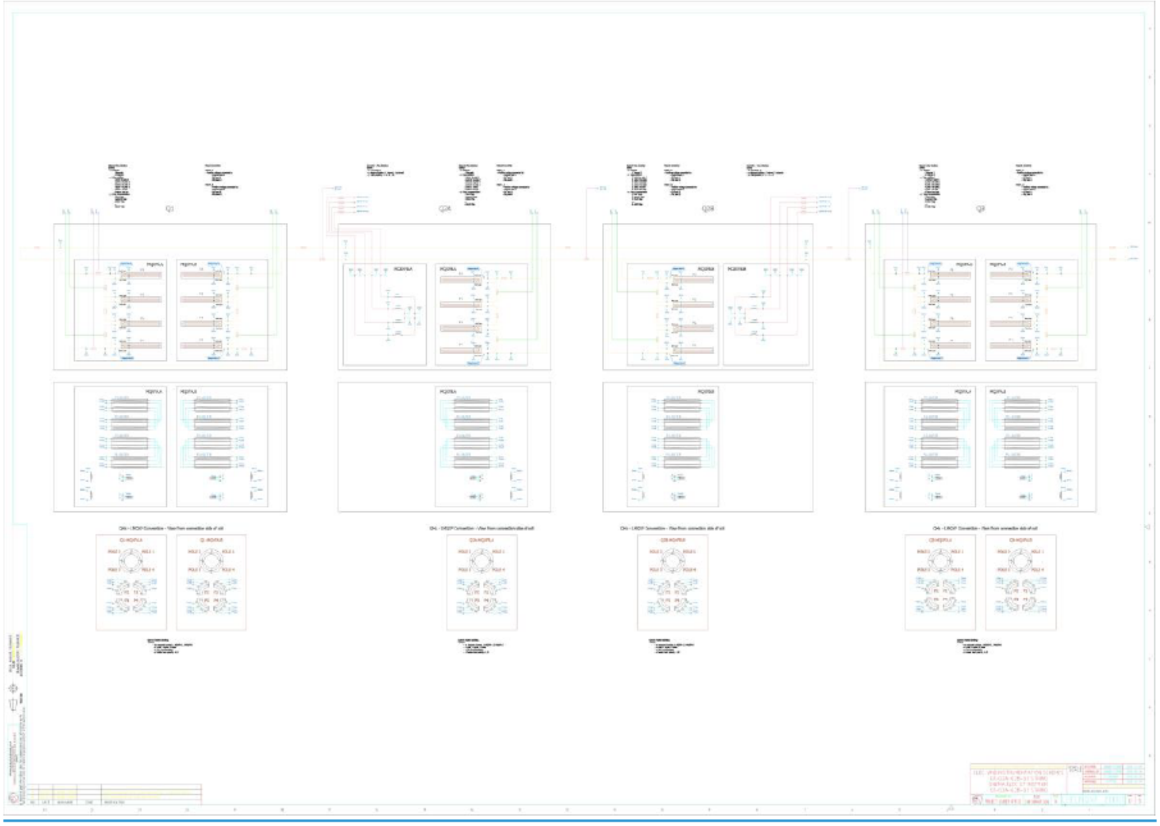


Figure 71: Triplet electrical scheme.

3.5. ES&H

ES&H is integrated into all phases of the Project: Design, Construction, and Installation. ES&H requirements are clearly defined within the Project. The cryostat design, assembly, and accompanying documentation complies with the project safety agreements (R-T-08, R-T-16) as well as the Fermilab ES&H Manual (FESHM).

- Cryostat components provided by CERN will be evaluated for compliance with FNAL FESHM requirements.
    - Fermilab FESHM 5033 Vacuum Vessel Engineering Note based on the CERN vacuum vessel analysis report [68]
    - Fermilab FESHM 5031.1 Piping Engineering Notes for all piping to be put in service
- The cryostat tooling will meet the FESHM requirements for receiving operational readiness clearance (ORC).
    - Fermilab FESHM 5100 Structural Engineering Note based on the Applus+ stress analysis report [69]
    - UL certification
    - LOTO procedures
    - Hazard analyses
    - Operating procedures
    - Wiring diagram
- Design and installation review processes include an ES&H component utilizing Fermilab's and CERN's work planning requirements and processes.

4. LQXFA Horizontal Test

Cryo-Assemblies with the Q1 and Q3 quadrupole elements of the HL-LHC inner triplet will be tested at Fermilab's horizontal test stand. Currently we do not differentiate between Q1 and Q3 elements for test purposes, therefore in the discussion below both Cryo-Assemblies will be referred to as LQXFA.

Two pre-series and 8 series production Cryo-Assemblies will be tested at Fermilab. Two Cryo-Assemblies could be re-worked in case of failure during the initial testing. Therefore, a total of 12 Cryo-Assembly tests are foreseen within the HL-LHC AUP project.

MQXFA magnets for the pre-series Cryo-Assembly and for the first 8 HL-LHC tunnel-bound production Cryo-Assemblies are assumed to be previously tested and trained at the BNL Vertical Test Stand. The magnets for the last two series Cryo-Assemblies (CERN spares) are assumed not to be previously tested and trained.

The horizontal test stand at Fermilab was previously used for testing the existing LHC inner triplet quadrupoles (LQXB) [70]. Cryogenic and mechanical subsystems of the stand are under refurbishment to meet the Q1/Q3 cryostat assembly design and test requirements. All cryo-mechanical upgrades specifically required for the Q1/Q3 Cryo-Assembly testing are budgeted in the Hl-LHC AUP, while reliable cryogenic and electrical test stand operation is supported off-project.

Engineering drawings of the upgraded Horizontal Test Stand and the corresponding cryogenic components are described in [4]. The short description, drawing number and location is shown for each component drawing in this document. Brief guidance how to use the drawing list and links to the associated files are also provided.

All the Horizontal Test Stand related drawings in PDF format are collected in two documents [71] and [72].

4.1. Test Stand Overview

The horizontal test stand, also known as Stand 4, is in Industrial Building 1 (IB1) of the APS-TD Complex [73]. Test Stand layout is shown in Figure 72. All cryogenic test stands in IB1 share the same LHe storage dewar. Two 25-ton and two 10-ton overhead cranes are currently operational in IB1. One of the two 25-ton cranes was fabricated and installed by Superior Crane Inc. in 2019. Two 25-ton cranes will provide up to 50-ton lifting capacity when working in tandem.

The 30 kA Power supply system (CPS3) [74] can power magnets at the horizontal test stand, as well as at the Vertical Magnet Test Facility (VMTF). A 1" x 4" water-cooled solid bus bar (in the trench) and 1500 mcm water-cooled flexible buses connect the CPS3 power system to the Cryo-Assembly at the horizontal test stand.

The AC power for CPS3 is from the 480 V, 3P, 2000 A switchboard by VMTF, which is powered by the 480 V substation YIB1-2-1 to the west side of IB1 building.

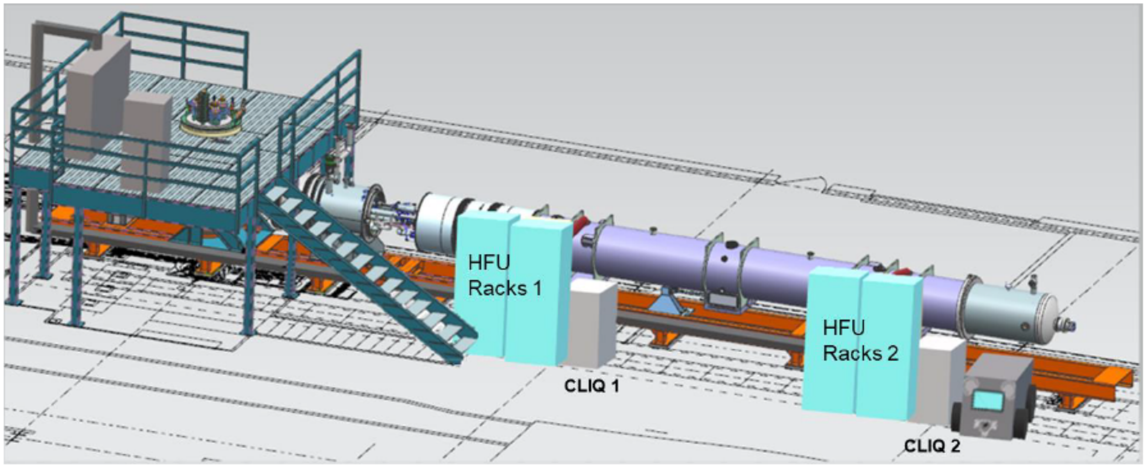


Figure 72: Horizontal test stand layout with Quench Protection racks.

4.1.1. Cryogenic Plant

The Fermilab Industrial Building 1 cryo-plant is a CTI 1500 helium refrigerator [75]. The 1500 W helium refrigerator is a three-stream system (20 atm (maximum) high-pressure supply, 2.5 atm medium-pressure return, and 1.2 atm low-pressure return) using two oil-injected screw compressors, an external liquid nitrogen pre-cooler, and two turboexpanders. Liquid helium is stored in a 10,000-liter dewar. Horizontal test stands, including Test Stand 4, are supplied from this dewar through a distribution box that includes an internal sub-cooler.

Ancillary equipment includes four Kinney pump skids for sub-atmospheric operation, a purifier compressor and two liquid nitrogen-cooled charcoal bed purifiers, six 30,000-gallon helium gas storage tanks, and a 10,000-gallon liquid nitrogen dewar.

Various improvements have been made to improve overall reliability of the cryo-plant. Four 30,000-gallon tanks were added to the existing six buffer tanks for storage of helium gas. Early 2020 Fermilab was planning to procure new liquefier, increasing total LHe make rate to 600 liter/hour and total liquid storage volume to 14,000 liter. Combination of higher liquefaction and He storage capacities will significantly increase throughput in magnet and SRF cavity testing in IB1.

Operational documentation for the cryogenic systems is available at https://tiweb.fnal.gov/website/controller/235. The site is a repository for specifications, procedures, checklists, notes and reports associated with the cryo-plant operations.

4.1.2. Feed Box

The feed box (Figure 73) contains a liquid helium vessel within the vacuum vessel and the liquid nitrogen-cooled thermal shield. A removable insert (Figure 74) includes the helium vessel top plate with three 15 kA vapor-cooled current leads and an instrumentation tree, displacers, a liquid nitrogen-cooled baffle shield, a support plate (formerly the lambda plate) with instrumentation and power feedthroughs, and the power bus. The feed box and adapter box drawings used during the installation in January 2020 is shown in Figure 75.

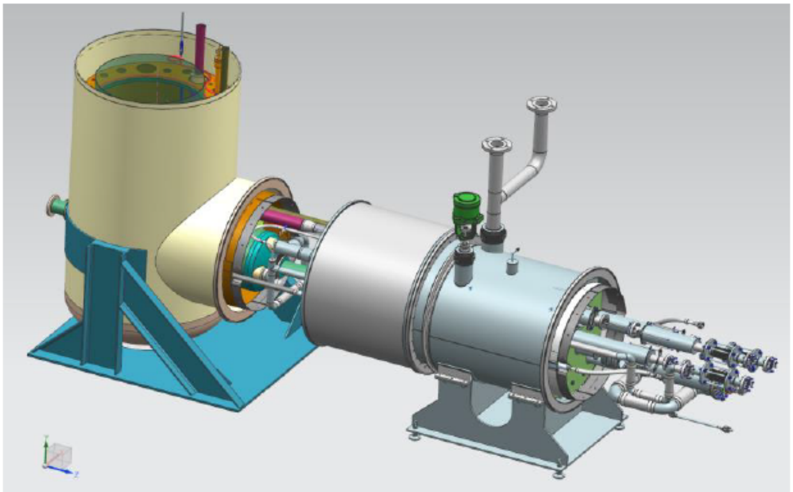


Figure 73: Model of the Horizontal test stand Feed Box and the new Adapter Box.

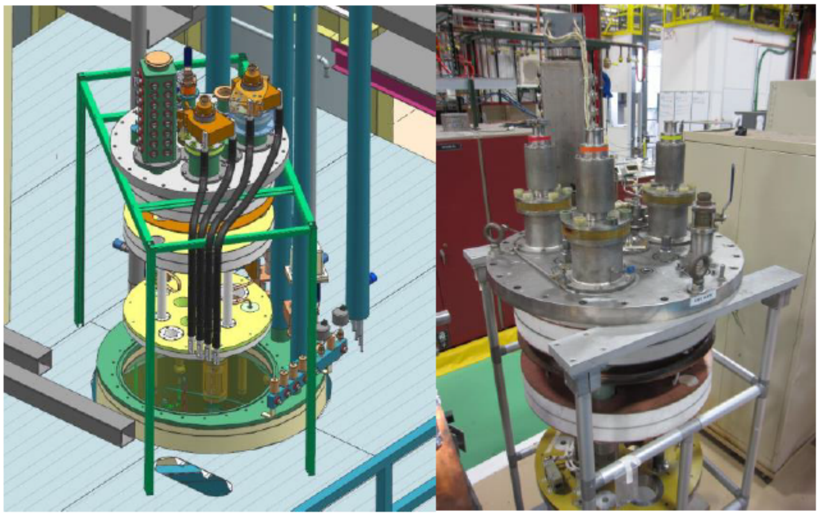


Figure 74: Model of the Feed Box insert (left) and photo of the insert (right).

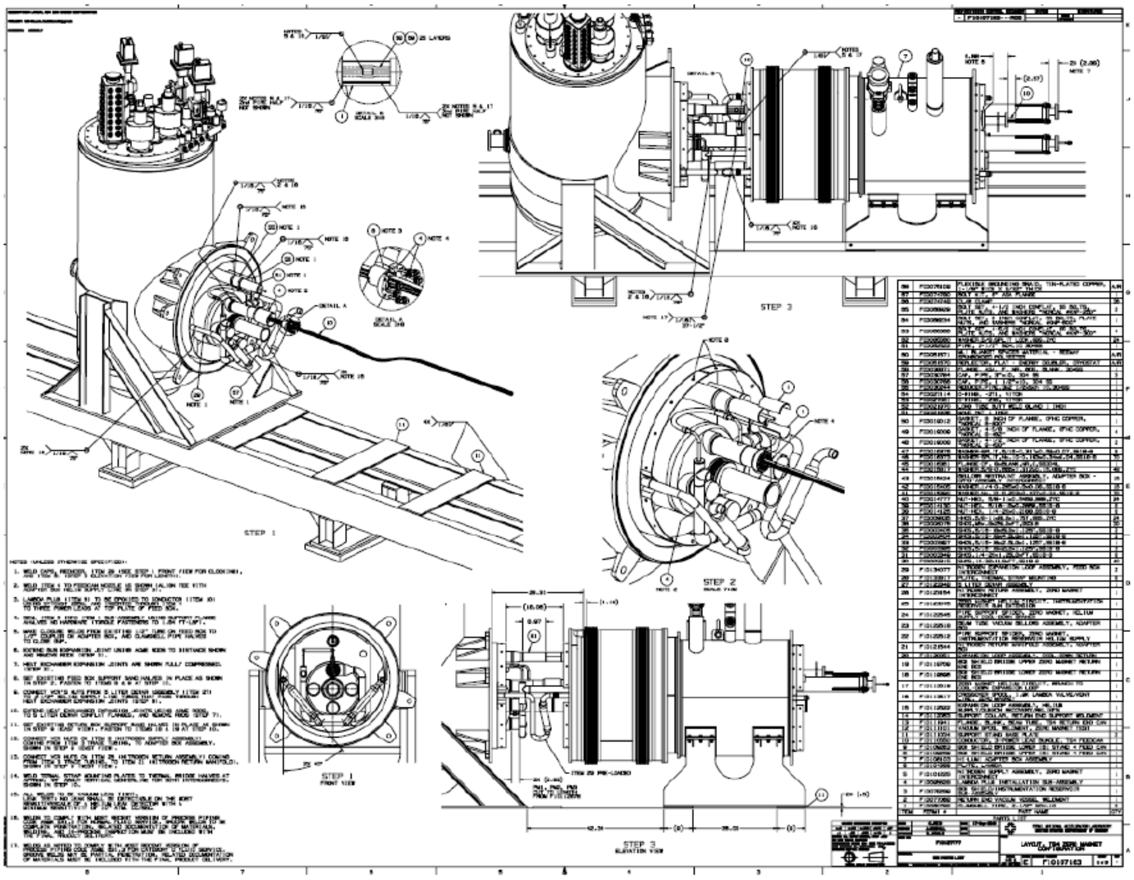


Figure 75: F10107163 Layout of the Feed Box and the Adapter Box.

4.1.3. Adapter Box and Interconnect

The Adapter Box is an extension of the feed box and contains features required to test the HL-LHC Cryo-Assemblies. The Adapter box allows to use the old feed box without modifications for the new design of the Cryo-Assembly. Assembly of the adapter box was completed in December 2019 (Figure 76 and Figure 77).

The separation between the 4.5 K and 1.9 K temperature levels is within the Adapter Box. A lambda plug passes the power bus (Figure 78), and a lambda fill valve allows helium to flow between the two volumes during cool-down and warm-up. Both functions were previously accomplished by the feed box lambda plate. Including these features in the adapter box allows the feed box and Cryo-Assemblies to operate at different pressures following a quench. The adapter box also includes relief devices to protect the Cryo-Assemblies from over-pressurization, and provisions to connect the Cryo-Assembly to the quench recovery system to recover helium gas.

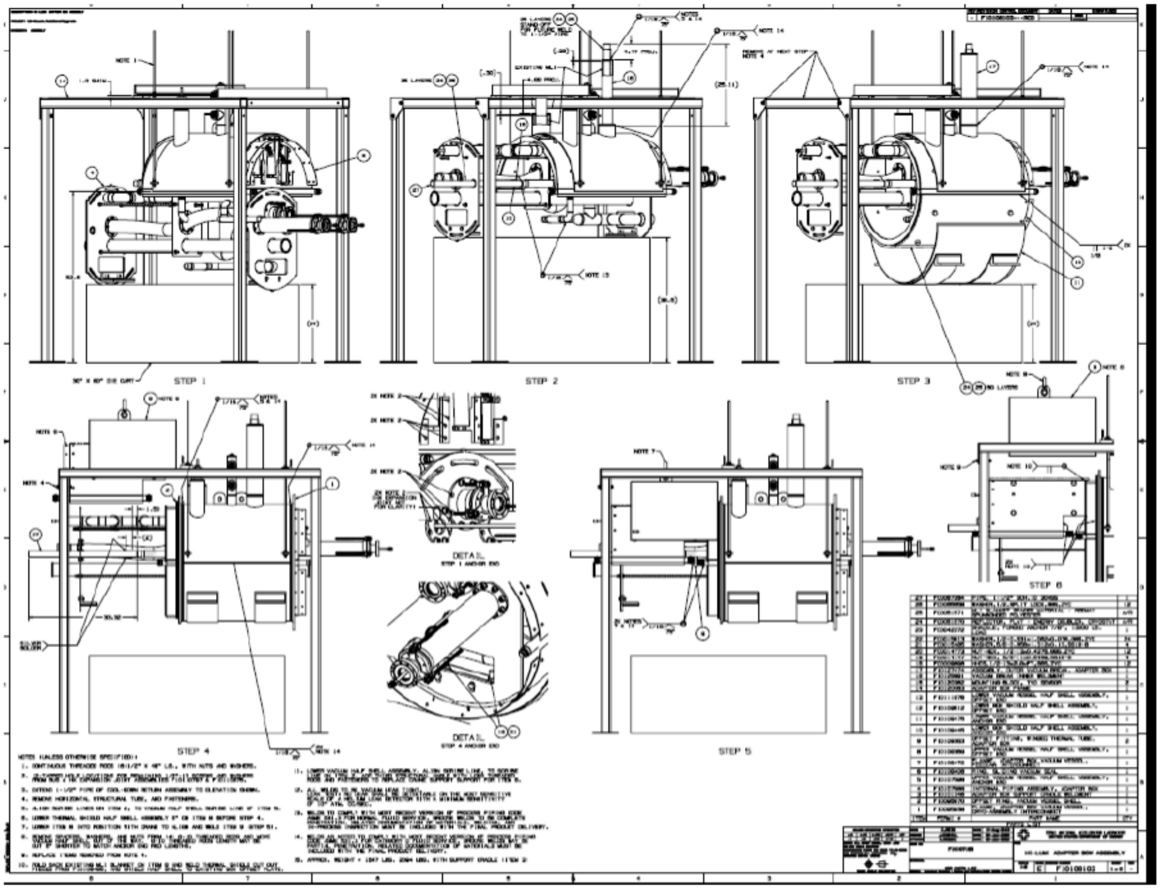


Figure 76: F10106103 New Adapter Box assembly drawings.

Figure 77: New Adapter Box with a thermal shield between the feed can and the Cryo-Assembly.

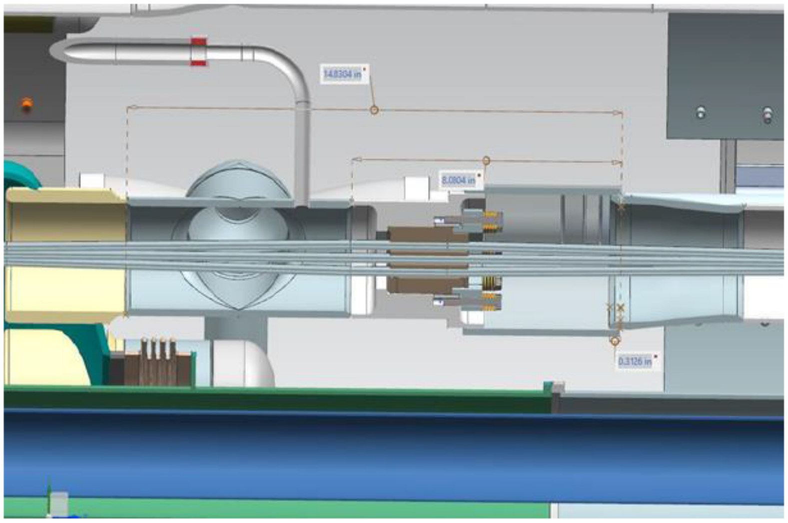


Figure 78: Lambda plug with the power bus between the feed can and the Adapter Box.

The Interconnect makes the final connections between the Cryo-Assembly and the Adapter Box. These are temporary connections installed when the Cryo-Assembly is placed on the test stand. They include process piping for liquid helium and liquid nitrogen, and the warm bore used for magnetic measurements during cold testing of the Cryo-Assembly. The process connections use either metal gasket VCR fittings or CF-flanges and copper gaskets. Bellows assemblies take up the thermal contraction between the feed box and the Cryo-Assembly fixed support. Threaded rod assemblies provide the support for the quench forces that the flexible bellows assemblies are not able to support. Thermal shield bridges connect the feed box thermal shield to the Cryo-Assembly thermal shield, and a sliding sleeve closes the insulating vacuum space between the feed box and the Cryo-Assembly.

4.1.4. Lambda Plug Test

Lambda plug design was adopted from the CERN designed lambda plug, which has been demonstrating reliable operation at the Large Hadron Collider (LHC, CERN) for many years. This design was modified to accommodate 3 power cables for the LQXFA horizontal test at Fermilab (Figure 79). To justify the design, a prototype lambda plug has been manufactured and tested. Short pieces of the NbTi superconductor were used for his test.

The stand designed for this test allows flow of cold GHe through the lambda plug at liquid nitrogen temperatures. Successful justification of the design is achieved by measuring GHe leak rate through the lambda plug and comparing with previously calculated estimates. Several tests with full thermal cycle in between were performed at different pressures up to 20 bar (the maximum expected pressure after the production magnet quench is about 18 bar). Estimated GHe mass flow rate as a function of pressure in one of the test runs is shown in Figure 80.

The effective heat leak after 12 test runs was estimated as 32 +/- 5 mW. Obtained mass flow and estimated heat load values are within the test stand requirements (100 mW). Detailed results of the lambda plug tests are presented in [76].

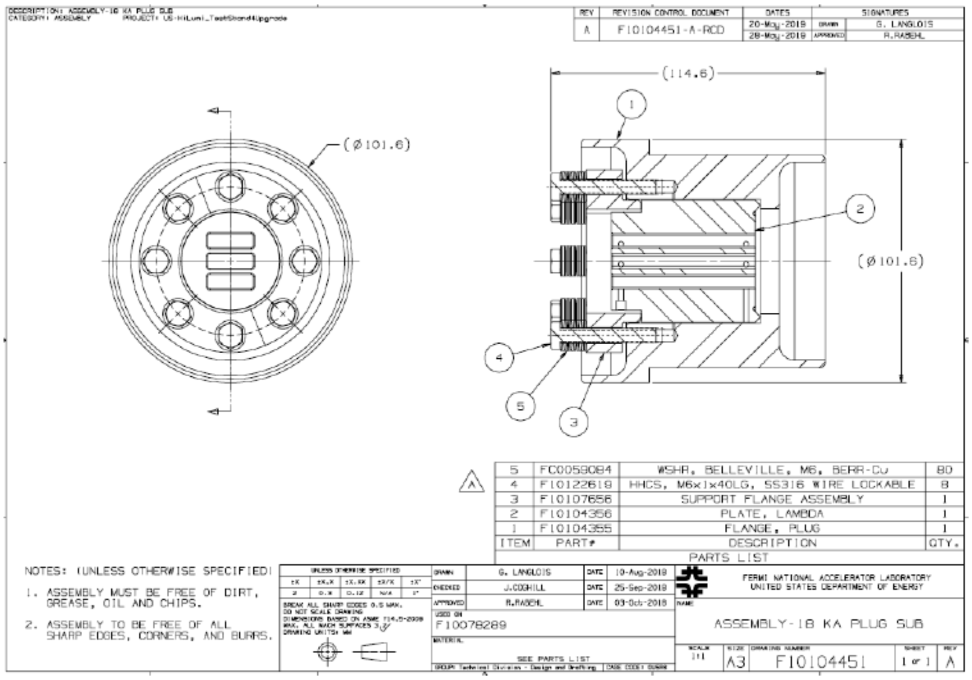


Figure 79: F10104451 Lambda plug for the horizontal test stand.

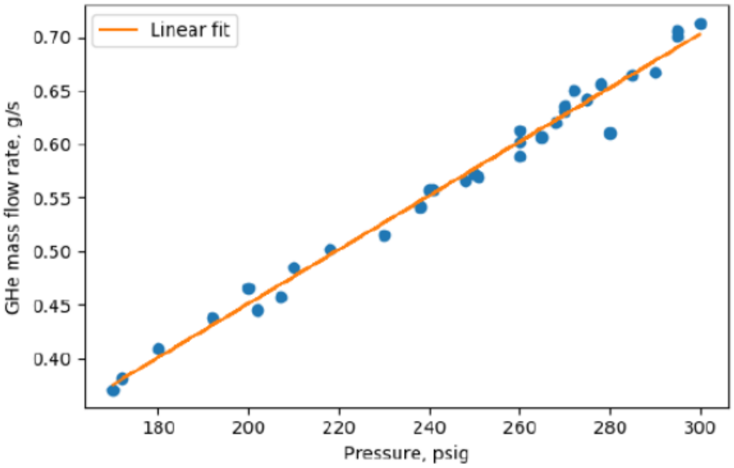


Figure 80: Estimated GHe mass flow at different pressure. Linear fit of the experimental data is show.

4.1.5. Return End

The Return End includes piping to complete the helium circuits: reservoirs for the bayonet heat exchangers, cool-down and warm-up return, and covers for the buswork. Small instrumentation port is used for temperature and liquid level sensors at the return end. A thermal shield mates with the Cryo-Assembly to complete the 80 K enclosure surrounding the 1.9 K volume.

The end-can (Figure 81 and Figure 82) completes the insulating vacuum enclosure.

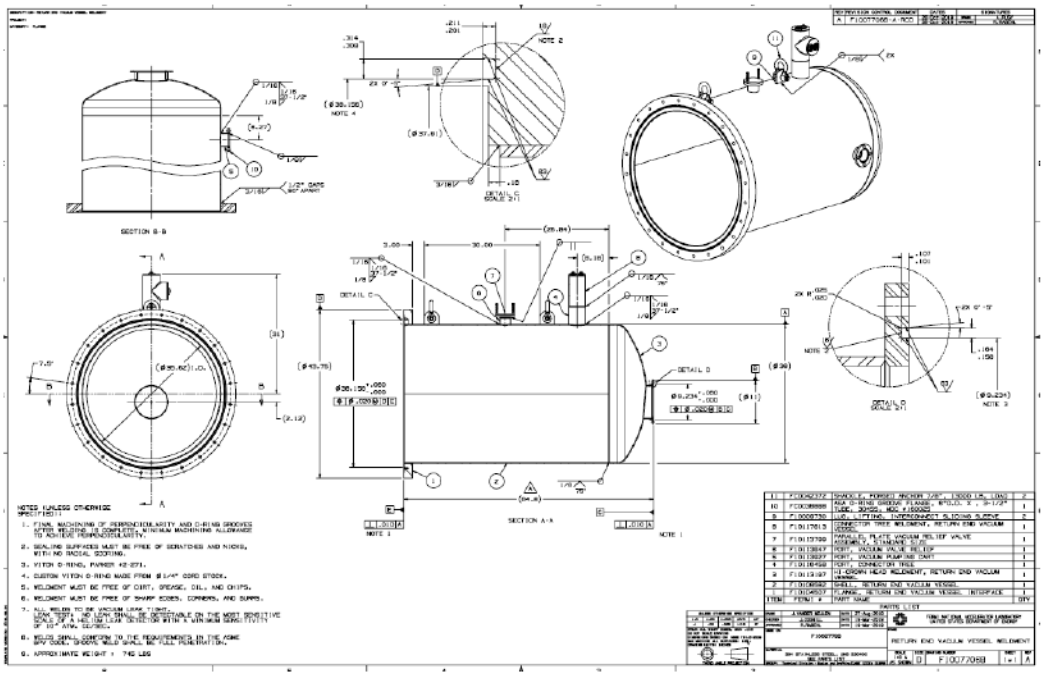


Figure 81: F10077068, Return End Vacuum Vessel.

Figure 82: The Return End Vacuum Vessel at Test Stand 4.

4.2. Test Stand Electrical Systems

4.2.1. Power Supply

The existing 30 kA cryogenic power system (CPS3) [74] will be used for powering Q1/Q3 cryostat assemblies at the horizontal test stand. The system includes six commercial 150 kW Power Energy Industries (PEI) power supply modules, each delivering 5 kA at 30 VDC, and two 15 kA, 1000 VDC solid-state dump switches. These power supplies can also be tapped to 2.5 kA, 60 VDC or 1.25 kA, 120 VDC. A diagram of the systems is presented in Figure 83.

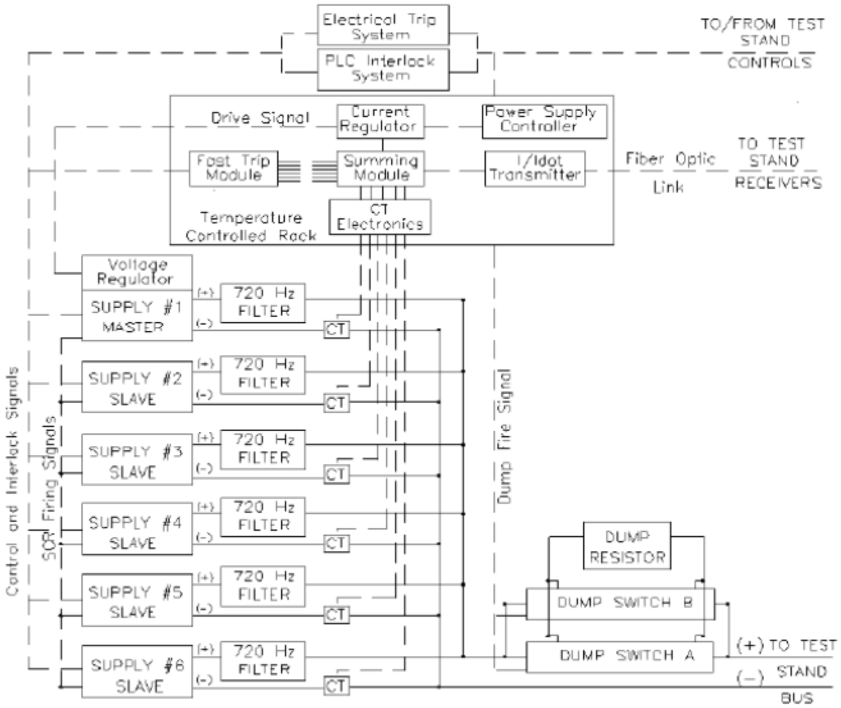


Figure 83: 30 kA power system block diagram.

The master power supply provides the Silicon Controlled Rectifiers (SCR) firing signals for all modules. Current regulation is accomplished by an external precise current regulator cascaded to the master power supply internal regulator set to “voltage” mode.

Operational documentation for the power systems, in particular for the 30 kA power supply, is available at https://tiweb.fnal.gov/website/controller/236
The site is a repository for specifications, procedures, checklists, notes and reports associated with the power systems operations

4.2.2. Power Bus to the Test Stand

Power to the horizontal test stand will be supplied from the CPS3 power system through water-cooled high current solid bus (Figure 84) currently sitting in an existing trench through the IB1 floor. It is supported off the concrete floor with Unistrut and insulating saddle clamp assemblies up to the Test Stand area in IB1.

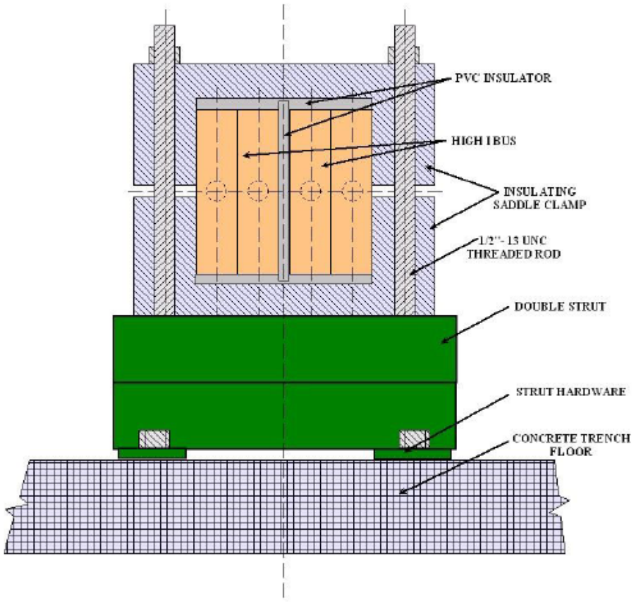


Figure 84: Model of the solid power bus bar located in IB1.

Connections from the power supply cabinets to the DC bus bar near the VMTF pit, and from the DC bus bar to the Horizontal Test Stand Feedbox top plate are made with flexible water-cooled power cables (Figure 85). These flexible power cables are upgraded to accommodate the increased power supply requirement to test stand (from 15 kA to 18 kA) with the use of 1500 MCM cable.

The entire bus circuit is water cooled with Low Conductivity Water (LCW) as supplied from the existing IB1 LCW System. The previously used configuration of the LCW supply will be used, but with the replacement and refurbishment of miscellaneous components (water hoses, fittings, flow switches, and temperature sensors), and acceptance testing of the circuit prior to use.

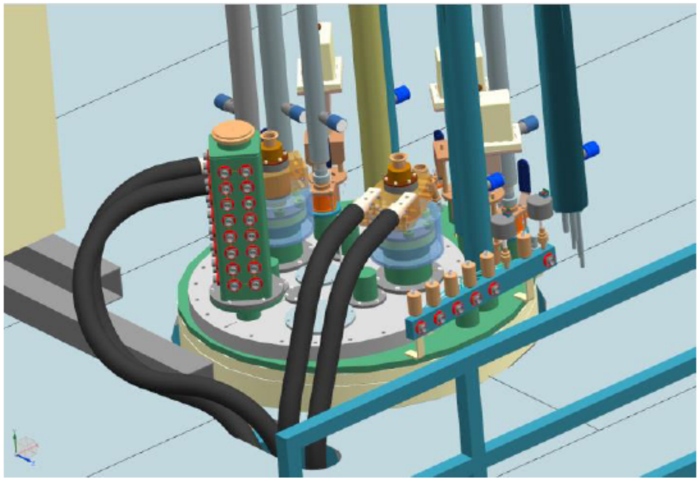


Figure 85: Model of the top plate power leads to flexible cable connections.

4.2.3. Shorted bus test at the Horizontal Test Stand

The entire power bus circuit from the CPS3 power supply system down to the horizontal test stand, including pair of the flexible power cables were tested in July 2018. In a shorted bus configuration, the current was ramped up to 20 kA, maximum voltage in the circuit reached about 16 V (Figure 86). With a 30 V limit in the power supply circuit and expected magnet inductance of 68 mH, we can ramp up and down the magnet current at rates above 200 A/s.

The shorted-bus test results demonstrated that the Test Stand Functional Requirements are satisfied [77] and that we can verify one of the MQXFA threshold requirements (R-T-18 in [40]) about stable magnet operation at ramp rates below 150 A/s.

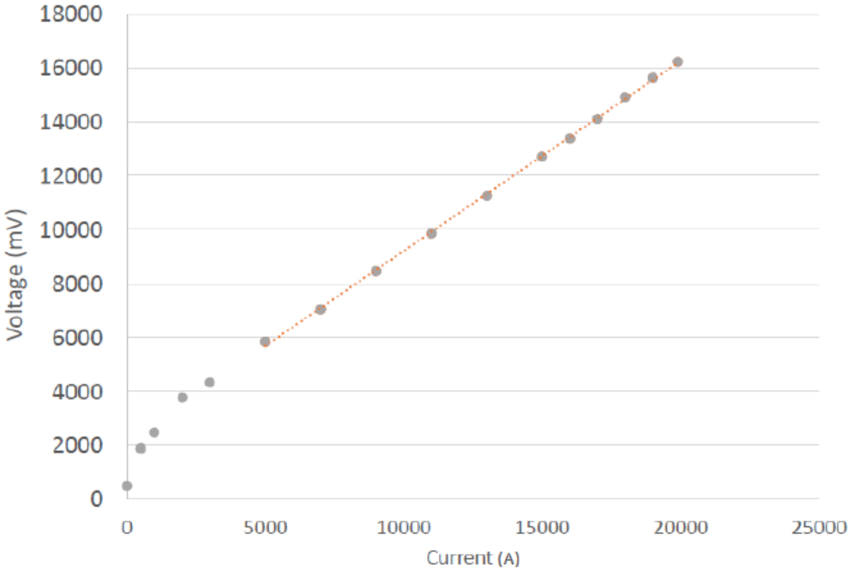


Figure 86: Voltage drop in the power bus bar and flexible leads at different currents.

4.2.4. Interlock System

A Programmable Logic Controller (PLC) provides the CPS3 safety interlock and system status monitoring. It includes the Series 505 Siemens module for PLC and Input-Output modules, Ethernet communication to the control room and iFix32 Human Machine Interface.

The PLC monitors the status of various temperature, flow and other switches. Also, there is a “Fast Trip Module” which monitors the signals from each zero-flux current transformer to detect a positive or negative current imbalance caused by failures such as a shorted Silicon Controlled Rectifier (SCR). If an imbalance is detected, this module initiates a phase-back (ramp down) to avoid damaging the SCR.

The new Siemens S7 PLC at Stand 4 manages the interlocks from the cryogenic conditions and other miscellaneous conditions on the Stand 4 side. The cryogenic system will have interlocks based on test stand insulating vacuum, operation of the cryo-plant, and failure of critical instrumentation.

The cryogenic process control system will supply a single digital signal to the power supply control system to indicate that the process systems are ready for magnet powering. Parameters required to energize this signal are liquid level, lead flow, flow and temperature of LCW in the hard bus and flexible current leads, availability of the quench recovery system, and the absence of cryogenic system interlocks.

Magnet Test Safety interlocks are described in [78]. Test Stand 4 interlock block diagram is shown in Figure 87.

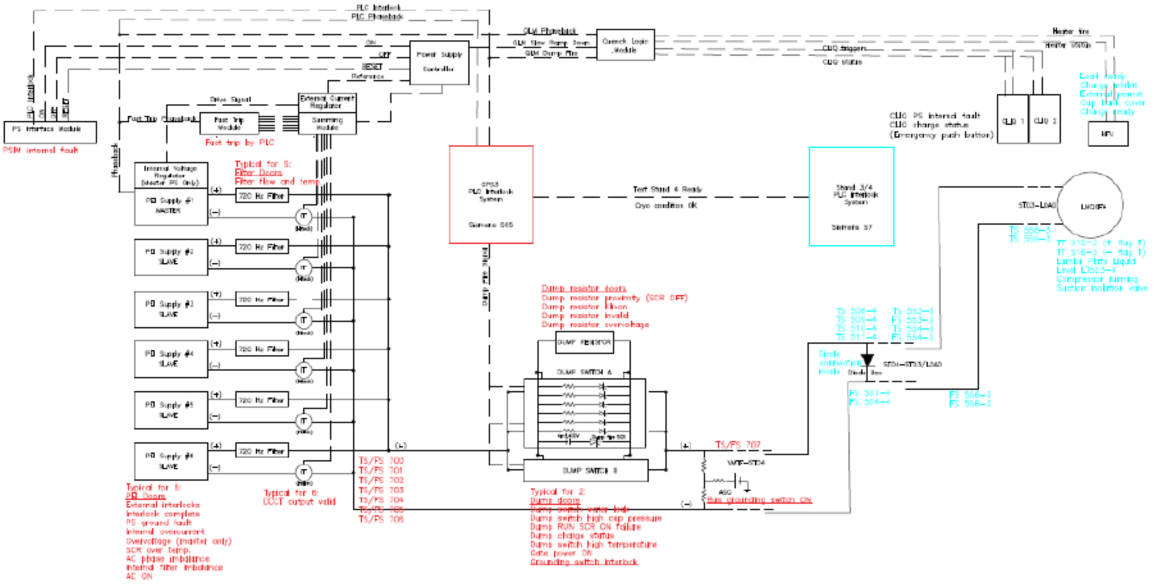


Figure 87: Test Stand 4 Interlock block diagram.

4.3. Quench Protection and Monitoring

The MQXFA magnets in the Cryo-Assembly require an active Quench Protection system. Quench Detection is accomplished by the standard measurement of voltages from whole coil and center coil voltage taps and comparison with pre-established thresholds. Once any threshold is exceeded, after validation, the Quench Protection system turns off the power supply, triggers protection “strip” heaters embedded in the coils to spread the normal zone and switches a room temperature “dump” resistor to extract part of the coil stored energy.

A novel protection system based on Coupling Loss Induced Quench (CLIQ) will be used for additional protection of Nb_3Sn magnets [25].

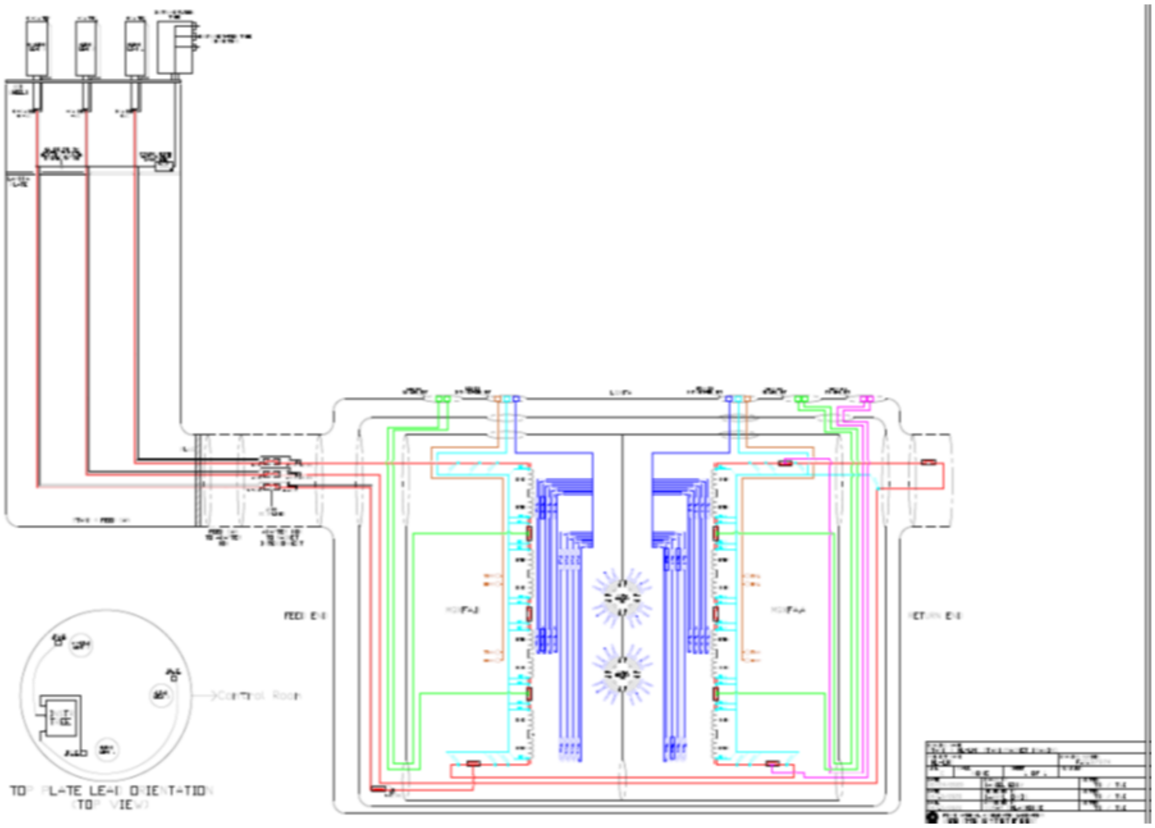


Figure 88: Test Stand 4 Power bus and Voltage Tap connections.

The Quench Protection and monitoring system architecture is based on a recent development for the Mu2e experiment. Quench logic and protection parameters follow the Q1/Q3 Cryo-Assemblies horizontal test stand requirements [77].

Power bus and voltage tap connections for Q1/Q3 Cryo-Assemblies are described in [79]. Voltage tap locations in Figure 88 follows the CERN electrical drawing LHCLMQXF_E0001 [67].

4.3.1. Quench Protection

The following Quench Detection (QD) channels are required to protect the magnet during testing:

- Whole Coil – Reference
- Whole Coil – Idot
- Half Coil – Half Coil
- Copper Leads
- SC Leads
- Active Ground Fault

Thresholds should be current-dependent because of the possibility of voltage spikes at lower currents. The delay between voltages crossing the threshold and the Quench Detection system trigger is adjustable for validation time (if needed), which varies from 0 ms (less than 0.1 ms) to 10 ms.

There are two completely independent Quench Detection paths from the quench sensor through to the power and energy extraction systems. The Quench Detection system is a three-tier design: Tier 1 – Primary QD, Tier 2 – Redundant QD; Tier 3 – System Monitoring and Data Management.

The primary quench detector is digital (FPGA) and the redundant quench detector is analog. Both the analog and digital Quench Detection systems (AQD and DQD respectively) should have the validation time and current dependent thresholds.

New Quench Logic Module (QLM) was designed and assembled to interface the TS4 Quench Detection system to the 30 kA power system and energy extraction, power supply control and Quench Protection elements.

A diagram of the Quench Detection system is shown in Figure 89. Assembly of the full chasses of Analog and Digital Quench Detection modules was completed in November 2019 (Figure 90).

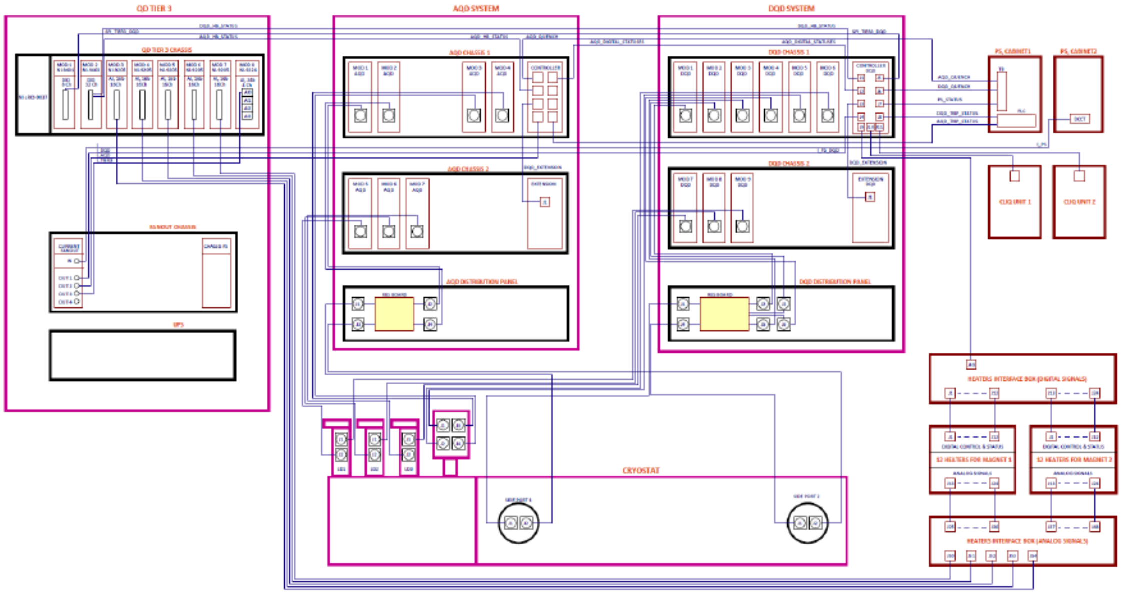


Figure 89: Quench Detection system block diagram.

Figure 90: First article of AQD (left) and DQD (right) systems.

4.3.2. Quench Monitoring

Slow scan systems monitor all magnet specific instrumentation, as well as the power leads and SC bus. An example of the slow monitoring requirements for some magnet instrumentation is shown in Table 9.

Table 9: Requirements for the temperature and resistance measurements.

Sensor	Accuracy	Resolution	Range	Measurement Rate
Splice Resistance (2-wire Channels)	+/-1% Range	0.01 nOhm	0.1-10 nOhm	N/A
RRR Resistance of Al and Cu	+/-1%	0.1	10-1000	N/A
Warm-up & Cool Down Temperature (Cernox)	+/-0.5%	0.02K	4-300 K	1/min
Supply & Return Manifolds Temperature (Cernox)	+/- 0.2%	0.01K	4-300 K	3/min
80K Temperature (Platinum) (Shields & Cu. Leads)	+/-0.5%	0.1K	70-300K	1/min

Low voltage signals for splice measurements will be read by a Keithley nanovoltmeter based system and controlled by a Beckhoff subordinate PLC via RS232/GPIB.

4.3.3. Protection Heaters and Energy Extraction

There are 16 strip heaters in each MQXFA magnet (4 per coil, installed only on the outer coil surface) wired in 8 independent groups (Figure 91). The protection strip heaters resistance is 1.9 Ω at room temperature and 1.1 Ω at 1.9 K.

Heater power supplies, so called “Heater Firing Units” (HFUs) are provided by CERN. HFUs are capacitive-based supplies with a maximum discharge voltage of 900 Volts and maximum capacitance of 7 mF. A total of 8 HFUs will be required per magnet, i.e. 16 HFUs for a cryostat assembly.

Connection of CLIQ units in all Q1/Q2/Q3 quadrupoles are shown in Figure 92. One CLIQ unit is used per MQXFA magnet. CLIQ operating voltage is up to 1000 V, capacity 50 mF. Three CLIQ units were assembled at *Jager Elektrotechnic GmbH* (Germany) and delivered to Fermilab in February 2020.

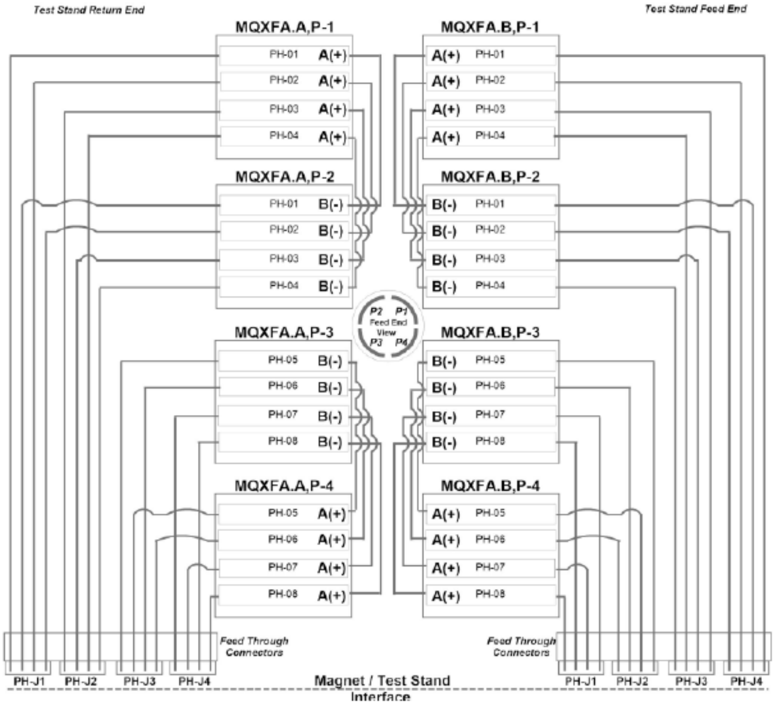


Figure 91: LQXFA protection heater wiring diagram.

A slow ramp down, i.e., a safe ramp down of the magnet current at rates 50-100 A/s, is initiated in case of a ground fault, protection heater or CLIQ charge status interlock lost. Quench Detection system and data loggers will stay armed if a quench occurs during the slow ramp down.

The Quench Detection system is interlocked to prevent magnet powering if more than two HFUs are not charged.

The dump resistor for energy extraction shall have a resistance range of 2.5 mΩ to 120 mΩ; and shall be rated for the maximum required current. For Quench Protection studies, after a quench is detected, the dump resistor shall be capable of switching with a user-specified delay in the range 0-1000 ms.

After a Quench Detection trigger and the quench validation time, the power supply will phase back with no delay (less than 0.1 ms).

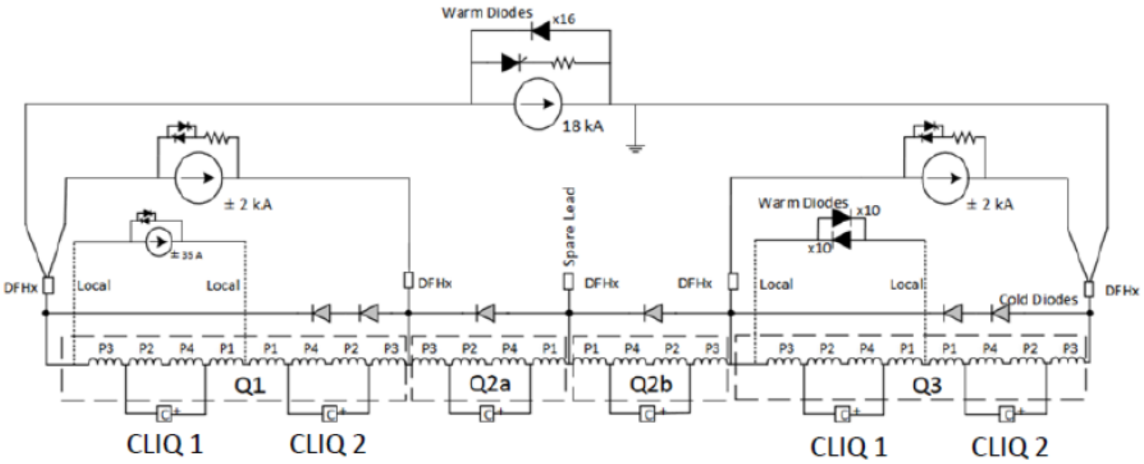


Figure 92: CLIQ units in Q1/Q3 Cryo-Assemblies.

4.3.4. Quench Protection Failure Mode

CLIQ and heaters are required for magnet protection. Both systems together with the external energy extraction will be used during horizontal test of magnets.

DQD & AQD triggers are OR'd so either will trigger the protection system, and both trigger all three protection systems. If either the DQD or AQD fails, all three protection systems are still triggered.

4.4. Horizontal Test Scope and Objective

The primary objective of the horizontal test is final qualification and acceptance of the project deliverable – LQXFA Cryo-Assembly before shipping to CERN.

The scope of horizontal test includes confirmation of magnet quench performance in the Cryo-Assembly, room temperature (warm) and 1.9 K (cold) alignment measurements, translation of the common Cold Mass magnetic axis to the external fiducials, and selected field quality measurements.

The two MQXFA magnets in an LQXFA Cryo-Assembly will be powered up to the nominal (16.5 kA) and ultimate (17.9 kA) currents to verify stable operation and quench training memory of the magnets. Magnet protection with protection heaters and CLIQ units but without external energy extraction will be demonstrated for the prototype and the first production Cryo-Assemblies only. Further cold testing will be performed with the external energy extraction to save liquid helium inventory and reduce the quench recovery time in case of induced or spontaneous quenches.

NbTi-NbTi splices between the magnet leads and the power busbars will be inspected at room temperature and monitored after the magnet cooldown.

Major checkouts and measurements to be conducted at the horizontal test stand include:

At room temperature, before cooldown

- Mechanical checkouts and connections to the lead end (Feed) and the return end boxes.
- Electrical checkouts and tests ensuring the integrity of the insulation
- RRR measurements
- Magnetic measurements

After cooldown at 1.9 K

- Electrical checkouts
- Ramp up to the nominal and ultimate currents
- Alignment and field quality measurements: integral field strength and harmonics
- Magnet endurance tests for the prototype and first production magnets
- Thermal cycle (memory test) for the prototype and first production magnets
- Protection tests for the prototype and first production magnets
- NbTi-NbTi splice measurements
- RRR measurements (during warm up)

At room temperature after warm-up

- Magnetic measurements

Final electrical checkouts.

Full thermal cycle is foreseen only with the pre-series Cryo-Assembly

4.5. Horizontal Test Stand Operation

Cryostat assemblies on a shipping fixture will be delivered from the Cold Mass and cryostat assembly area in Building ICBA using a flatbed truck.

4.5.1. Cryo-Assembly Mechanical Mounting

An upgraded overhead crane will be used to move the Cryo-Assembly shipping fixtures as received in the IB1 high bay area to the designated staging area on the IB1 floor. Here, the magnet will be prepared with the attachment of vacuum vessel adapter box sleeves prior to lifting and placement of the Cryo-Assembly to the test bench in the horizontal test stand area.

The Cryo-Assembly will then be mounted to the Test Stand on the test bench with a similar 3-point mounting support system that was used for the LHC IR Quadrupoles. The support legs will mount to the designated vacuum vessel interfaces and connect to the test bench. Due to the larger size of the new Cryo-Assembly, the support legs will be lower than the previously mounted supports, so some additional support beams will be attached to the test stand bench to accommodate the static load due to the weight of the assembly. An additional fixed support bracket will be required to restrain the Cryo-Assembly to the test bench when longitudinal loads are applied due to vacuum and quench pressure loads in the axial direction. The interfaces for these brackets will accommodate the interfaces as detailed in the vacuum vessel design.

Figure 93 and Figure 94 show the main components of the system.

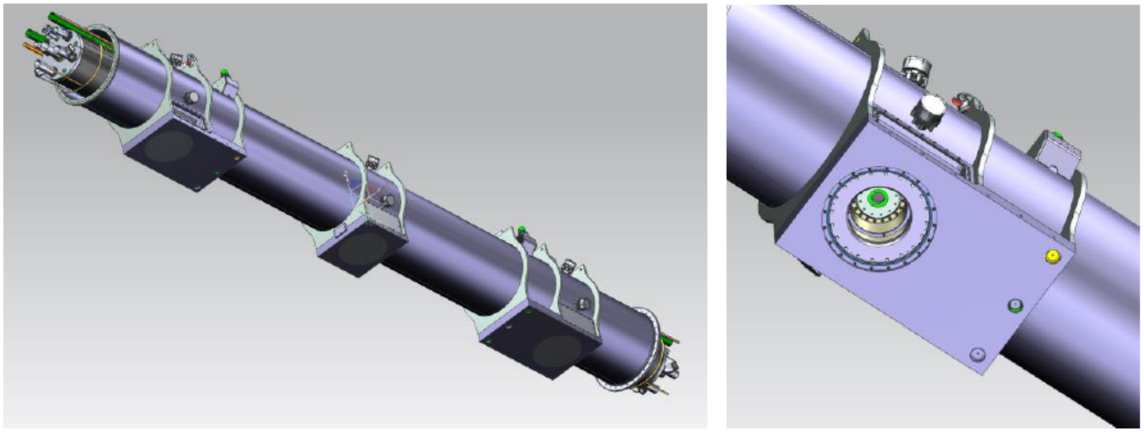


Figure 93: Interfaces of the support brackets to the Vacuum Vessel.

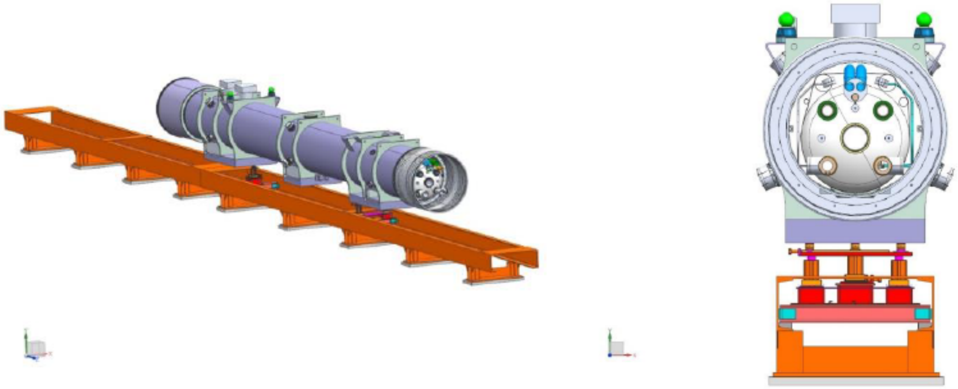


Figure 94: Conceptual design of the 3-point static load support brackets of the Cryo-Assembly.

Once the assembly is positioned in place, the power leads splice connection required between the Cryo-Assembly and the test stand power leads coming from the feedbox will be made. This splice connection and any temporary piping interconnect connections between the Cryo-Assembly to the Stand 4 adapter box will be made prior to final leak checks on the piping and power testing of the leads.

The final step of closing the interconnect piping with the vacuum vessel adapter box sleeves will then be made to close the vacuum vessel of the Cryo-Assembly with that of the feedbox and return can ends on the test stand. A final leak check of the vacuum vessel system will be required prior to further checkouts.

4.5.2. Cool Down

The Cryo-Assemblies will be cooled down in a controlled manner with a maximum ΔT of 50 K across a magnet. Helium supply temperatures between 80 K and 300 K will be accomplished by mixing 80 K helium gas and 300 K helium gas. Helium supply temperatures below 80 K will be accomplished by mixing 80 K helium gas and 4.5 K helium liquid. 80 K helium gas will be supplied by a repurposed Tevatron sub-cooler (Figure 95) operating with a liquid nitrogen bath.

The Cryo-Assemblies will be similarly warmed up in a controlled manner with a maximum ΔT of 100 K across a magnet.

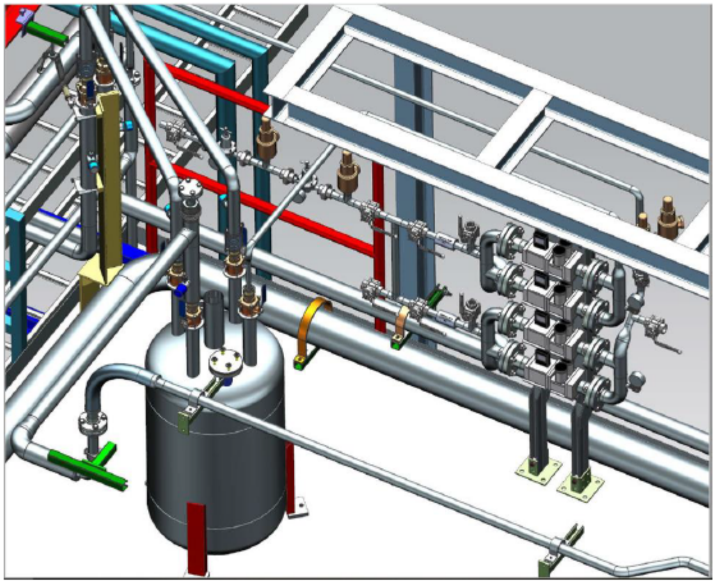


Figure 95: Model of the Tevatron sub-cooler used for controlled cool-down and warm-up.

4.5.3. Cryo-plant/gas Handling and Maintenance

The quench recovery system used by the Vertical Magnet Test Facility (VMTF) is extended to include Test Stand 4. The system consists of a reconfigured 30,000 gallon helium gas storage tank connected to the test stand by a 6-inch pipe. When a quench occurs, a valve is opened at the test stand to begin recovering helium gas in the storage tank. Recovering the entire helium inventory of a Cryo-Assembly will raise the tank pressure by only 35 psi. Use of the Adapter Box allows the Cryo-Assembly to reach higher pressures and provide sufficient pressure differential to maximize helium recovery.

4.6. Alignment and Field Quality Measurements

Alignment and field quality measurements are performed at room temperature before and after the cooldown, and at 1.9 K. Alignment and integral strength measurements are performed with a Single Stretched Wire (SSW) system [80]. The field harmonics are measured with a rotating probe based on the multi-layer printed circuit board (PCB) [81]. Magnetic measurement system requirements and specifications are summarized in [82].

The horizontal test facility shall be equipped with a vacuum jacketed “warm finger” or anti-cryostat to allow insertion of a stretched wire, or a rotating room temperature magnetic measurement probe into the cold-mass aperture. Reference current levels for the magnetic measurements are shown in the Table 10 below. A laser tracker is used to transfer fiducial positions of the measurement probe to the external fiducials of the Cryo-Assembly.

Alignment measurements are critical for positioning the quadrupoles in the LHC beamlines. Relative positioning of the Cold Mass within the cryostat and the actual Cold Mass positions must be measured and transferred to the external fiducials which are used for magnet installation in the LHC tunnel. There will be extensive alignment measurements to determine waviness of the magnetic axis in the Cryo-Assembly. The magnetic axis in each individual Q1/Q3 element will be compared to the average (common) magnetic axis in the Cryo-Assembly.

Table 10: Reference current levels for the Q1/Q3 Cryo-Assembly magnetic measurements.

Current [kA]	Gradient [T/m]	Remarks
0.1	0.9	Reset level for pre-cycle
0.96	8.5	Injection level
16.48	132.6	Nominal level
17.89	143.2	Ultimate level

At room temperature, we will measure integral field strength and field harmonics at low currents. These measurements will be repeated after cooldown at 1.9 K. Integral field strength and field harmonics will be measured at the injection (960 A) and collision (16480 A) currents.

Alignment stability should be verified over thermal cycles, as well as after transportation from the assembly building to the test facility for the prototype and first production cryo-assembles only

4.6.1. Magnetic Measurements Systems

Rotating coil (RC) and Single Stretched Wire (SSW) measurement systems will be used for field quality and alignment measurements of Q1/Q3 cryostat assembly at the horizontal test stand.

The printed circuit board (PCB) based rotating probes of various dimensions were developed at Fermilab. PCB with a reference radius of 50 mm will be used for MQXFA magnetic measurements. A pair of 110 mm and 220 mm long PCB probes will be included in the Ferret (Fermilab Rotating Coil Encapsulated Tesla-Probe) – portable mole-type (self-contained) probe system. The Ferret features a non-magnetic phosphor-bronze flexible shaft driven by a motor which resides external to the magnet. The flex shaft spins a PCB probe (housed in an FDM support structure) within an outer tube. An internal encoder and slip-ring relate the angular position and probe signals to data acquisition electronics. A MEMS 2-axis gravity sensor chip is used to track the overall orientation with respect to gravity. All internal parts can be adapted for use in larger or smaller Ferret probes by means of spacers. DAQ is based on a commercial Dynamic-Signal-Acquisition (DSA) modules NI-4464 (24-bit differential, 200 kHz sampling rate). Figure 96 and Figure 97 shows the main mechanical components of the probe system.

Assembled Data Acquisition System for the Fermilab developed SSW measurement system is shown in Figure 98.

Figure 96: 220 mm and 110 mm long multi-layer PCB probes.

Figure 97: Ferret system with a flexible shaft.

Figure 98: Fermilab SSW DAQ system.

4.7. High Voltage Withstand Levels

Requirements for testing electrical integrity of the magnets were developed together with a working group at CERN. The electrical design criteria for the magnet design, manufacturing and test were recently discussed at Structural and Electrical Design Criteria Review of the MQXF Magnets at Fermilab (Apr. 23-24, 2018). Peak voltage estimates, the electrical test requirements and QC plans are summarized in [83]. MQXFA electrical test values are presented in Table 11.

Table 11: Values of withstand voltages for the acceptance of LMQXFA Cold Mass.

Test name		Test voltage	Value
Test voltage at Normal Operating Condition (1.9 K) at *'Manufacturing Facilities and Test Stations'* stage (V)	To ground	$V_{test1\ (ground)}$	1840
	To quench heater	$V_{test1\ (heater)}$	2300
Test voltage at gaseous helium conditions* (V)	To ground	V_{test5}	500
	To quench heater		
Test voltage at warm** before first helium bath (V)	To ground	$V_{test2\ (ground)}$	3680
	To quench heater	$V_{test2\ (heater)}$	3680
Test voltage at warm after helium bath (V)	To ground	$V_{test3\ (ground)}$	368
	To quench heater	$V_{test3\ (heater)}$	460
Maximum leakage current (µA) – not including leakage of the test station			10
Test voltage duration (s)			30

* 100 ± 20 K and 1.2 ± 0.2 bar

** 20±3 °C and relative humidity lower than 60%

4.8. Helium and Nitrogen Consumption

Helium and Nitrogen consumption at the horizontal test stand were estimated from the previous experience of testing the old LHC IR quadrupoles and based on the proposed test plan of LQXFA Cryo-Assemblies. A dedicated model was developed for cryogen cost estimate utilizing experience of running cold magnet and cavity tests at Fermilab's magnet test facility over the last 6-8 years [84] [85].

Based on short term contracts with the helium and nitrogen suppliers about 3.5% increase of helium price and 3-6% increase of nitrogen price is expected every year. The two largest helium delivery companies have merged recently into one company and this may create a less competitive environment when it comes to pricing.

4.9. Interfaces

Internal interfaces are identified and mapped between the Cryo-Assembly fabrication and Cryo-Assemblies horizontal test. Details of these interfaces are summarized in [66].

According to this document, the LQXFA Cryo-Assembly will be received from the cryostat assembly area in ICBA building. After cold test is complete, Cryo-Assemblies will be delivered back to assembly area for shipping preparation.

For every Cryo-Assembly test appropriate travelers, inspection and survey documentation, as well as test reports will be provided.

A discrepancy report will be generated if any of the Cryo-Assembly parameters is out of tolerance as described in the acceptance documents approved by CERN and HL-LHC AUP.

4.10. Safety

The design, fabrication, and operation of Test Stand 4 shall comply with all applicable FESHM chapters [86]. This may include engineering notes required for: the mechanical, cryogenic, and structural safety requirements FESHM 5000 chapters (i.e. pressure/vacuum vessel notes, piping notes, etc.), electrical safety FESHM 9000 chapters (i.e. Electrical Safety Program requirements and review), and Material Handling and Transportation FESHM 10000 chapters (i.e. Below the Hook notes and review).

A commissioning process will be established as required by FESHM 2000 chapters for the planning of safe operations. This shall include mechanical safety and electrical safety sub-committee reviews, with a final Operational Readiness Clearance (ORC) approval given by the division head prior to the start of any testing on the Cryo-Assembly.

The preliminary ORC for a zero-magnet (shorted bus) test was initiated in March 2020. The engineering notes and other documents prepared for the cryo-mechanical and electrical safety reviews are listed in Table 12 and Table 13.

Table 12: Engineering notes prepared for the cryo-safety review.

	Engineering Notes	TC number		Engineering Notes	TC number
1	P&ID	F10121488	15	Cold GHe jumper	EN03323
2	Valve, Instrument, and Equipment (VIE) list	ED0009958	16	Cold GHe to Feed Box	EN03391
3	Failure Mode Effects Analysis (FMEA)	ED0010083	17	Feed Box relief piping	EN03531
4	Process controls description	ED0011588	18	LN2 bath vent	EN03530
5	System description	ED0010620	19	Vacuum vessel	EN02044
6	What If Analysis	ED0011786	20	Zero magnet turnaround piping	EN03897
7	LN2 supply to thermal shield	EN03232	21	Feed Box-Adapter Box interconnect He piping	EN03454
8	LN2 supply to baffle shield	EN03216	22	Pumping line	EN03851
9	LHe supply	EN03233	23	Cryo-Assembly relief spool	EN03755
#	Feed Box/Interconnect/Adapter Box therm	EN03449	24	Cryo-Assembly relief vent line	EN03757
#	TeV subcooler pressure vessel	EN01498	25	High-pressure GHe supply	EN03800
#	Feed Box LHe vessel	EN02043	26	Return end thermal shield piping	EN03801
#	LN2 jumper	EN03323	27	Cool-down return	EN03838
#	LN2 supply to bath	EN03324	28	Leads bypass/suction return	EN03835
			29	Quench line	EN03898

Table 13: Documents prepared for the electrical safety review.

#	Category	Name	Document Link
1	Design	TID-N-1285: QPM Grounding & Shielding Specification	https://tiweb.fnal.gov/website/controller/3912
2	Design	TID-N-1278: Stand 4 Floor Layout and AC Power Distribution SLED	https://tiweb.fnal.gov/website/controller/3902
3	Design	TID-N-1301: F10135145: Stand4 HL-LHC VoltageTaps (ZMT) Drawing	https://tiweb.fnal.gov/website/controller/3935
4	Design	TID-N-1279: Hi-Lumi Magnet Test Trip Matrix	https://tiweb.fnal.gov/website/controller/3903
5	Operations	TID-N-1300: Zero-Magnet_Hipot_Procedure	https://tiweb.fnal.gov/website/controller/3934
6	Operations	TID-N-1306: Zero Magnet Test DUT Description Document	https://tiweb.fnal.gov/website/controller/3940
7	Operations	TID-N-1308: Stand4_Zero_Magnet_Shorted Bus_Test_Plan-V1	https://tiweb.fnal.gov/website/controller/3942
8	Operations	TID-N-1292: Zero Magnet Test QP Readiness Verification Procedure	https://tiweb.fnal.gov/website/controller/3926
9	Safety	TID-N-82: CPS-3 LOTO Procedure	https://tiweb.fnal.gov/website/controller/254
10	Safety	TID-N-1307: Zero Magnet Test DUT Safety Data Sheet	https://tiweb.fnal.gov/website/controller/3941
11	Safety	TID-N-1280: Hi-Lumi Magnet Test Safety Interlocks	https://tiweb.fnal.gov/website/controller/3904
12	Safety	TID-N-1294: CPS-3 Interlock Checkout Procedure	https://tiweb.fnal.gov/website/controller/3928
13	Safety	TID-N-1293: TS-4 Interlock Checkout Procedure	https://tiweb.fnal.gov/website/controller/3927
14	Safety	TID-N-1259: CPS-3 LCW Interlock PLC Selection	https://tiweb.fnal.gov/website/controller/3858

References

[1] G. Apollinari, A. I. Bejar, O. Bruning, M. Lamont and L. Rossi, "High-Luminosity Large Hadron Collider (HL-LHC). Technical Design Report," 2016. [Online]. Available: https://edms.cern.ch/ui/file/1723851/0.71/HL_TDR_V07.0.2016.10.05.Version15.2h.pdf.

[2] E. Todesco et al, "Exchange of components between HL LHC AUP and CERN for the triplet," CERN EDMS 1825173.

[3] "LMQXFA Functional Requirements," US-HiLumi-doc-64.

[4] "US-HiLumi Engineering Drawings BOM," Spreadsheet for FDR, US-HiLumi-doc-3010.

[5] "Compliance with Pressure Equipment Directive (PED 2014/68/EU) Essential Safety Requirements," Technical Note EDMS No. 1891856, US-HiLumi-doc-850.

[6] "Fermilab Environment, Safety and Health Manual (FESHM)," [Online]. Available: http://eshq.fnal.gov/manuals/feshm/.

[7] "ASME Boiler & Pressure Vessel Code Section VIII division 2," [Online].

[8] LBNL Technical Note # SU-1007-5656.

[9] C. Narug, "ED0011351, US HL-LHC AUP Engineering Note for Cold Mass Shell," US-HiLumi-doc-2934, 2020.

[10] "US HL-LHC AUP Engineering Note for Tack Block," US-HiLumi-doc-3100.

[11] "Q1/Q3 Tack Block Test Fixture," US-HiLumi-doc-3205.

[12] "LMQXFA ASME Welding Qualification," US-HiLumi-doc-3058.

[13] "MQXFS1d Shell preparation," US-HiLumi-doc-977.

[14] "Test of stainless steel shell welding on MQXFS1d," US-HiLumi-doc-927.

[15] "Characterization of NbTi busbar for LMQFXA cold masses," US-HiLumi-doc-2314.

[16] P. Ferracin, et al, "The HL-LHC Low-ßQuadrupole Magnet MQXF:From Short Models to Long Prototypes," *IEEE Transactions on Applied Superconductivity,* vol. 29 , no. 5, Aug 2019.

[17] "Empty Shell Displacement Analysis Welding Note," US-HiLumi-doc-2937.

[18] "End Cover Circumferential Welding Note," US-HiLumi-doc-3055.

[19] "Q1/Q3 Magnet Helium Flow Area," US-HiLumi-doc-3214.

[20] E. Barzi, R. Bossert, S. Feher, J. Kerby, V. V. Kashikhin, M. J. Lamm, D. Orris, M. Tartaglia, G. Ray and A. V. Zlobin, "Splice testing for LHC quadrupole magnets," *IEEE Transactions on Applied Superconductivity,* vol. 13, no. 2, pp. 1301-1304, June 2003.

[21] "Strand critical current vs heat treatment test results," To be published.

[22] "Q1/Q3 Bus Thermal Expansion Analysis," US-HiLumi-doc-3208.

[23] "Q1/Q3 and Q2 Mockup Report," US-HiLumi-doc-3289.

[24] "Q1/Q3 Bus Housing Structural Analysis," US-HiLumi-doc-3211.

[25] E. Ravaioli. et al, "Quench Protection System Optimization for the High Luminosity LHC Nb3Sn Quadrupoles," *IEEE Transactions on Applied Superconductivity,* vol. 27, no. 4, Jun 2017.

[26] "CLIQ LEADS," US-HiLumi-doc-998.

[27] "LMQXFB Q2 Bus Bar Functional Requirements Specifications," US-HiLumi-doc-3295.

[28] "US HL-LHC AUP Analysis for Station table deflections, US-HiLumi-doc-3157," US-HiLumi-doc-3157.

[29] "MQXFA1 Lifting & Handling," US-HiLumi-doc-3259.

[30] "AUP Lifting Fixtures Procedure," US-HiLumi-doc-3067.

[31] "CERN lifting fixture," CERN EDMS 1716217.

[32] "ICBA Lifting Fixture," US-HiLumi-doc-1142.

[33] "US HL-LHC AUP FRS for Cold Mass Weld Tooling," US-HiLumi-doc-3145.

[34] "US HL-LHC AUP Analysis for Cold Mass Weld Tooling," US-HiLumi-doc-3148.

[35] "AUP Bus Bar Soldering," HiLumi-doc-3256.

[36] "Q1/Q3 and Q2 Bus Solder Fill Tests," US-HiLumi-doc-3286.

[37] "US HL-LHC AUP FRS for Cold Mass Alignment and End Cover Tooling," US-HiLumi-doc-3142.

[38] "US HL-LHC AUP Analysis for Cold Mass End Cover Alignment Tooling," US-HiLumi-doc-3154.

[39] E. Todesco, "Definitions of Survey and Magnetic Data for the inner triplet system at IR1 and 5," EDMS 2227462 and US-HiLumi-doc-3281.

[40] "MQXFA Functional Requirements," US-HiLumi-doc-36.

[41] J. DiMarco, et al, "Field alignment of quadrupole magnets for the LHC interaction regions," *IEEE Transactions on Applied Superconductivity,* vol. 10, no. 1, pp. 127-130, March 2000.

[42] "METROLOGICAL CONTROLS & MEASUREMENTS FOR THE COLDMASS," EDMS 2168888 and US-HiLumi-doc-3278.

[43] "Quality Assurance Plan," US-HiLumi-doc-80.

[44] "AUP Configuration Management Plan," US-HiLumi-doc-1067.

[45] "LMQXFA Manufacturing and Inspection Plan," EDMS 1866244.

[46] "Cold Mass related ICDs," US-HiLumi-doc-216, US-HiLumi-doc-207, US-HiLumi-doc-210, US-HiLumi-doc-375.

[47] "US HL-LHC AUP Analysis for Cold Mass Alignment Tooling," US-HiLumi-doc-3151.

[48] "LQXFA/LQXFB Functional Requirements," US-HiLumi-doc-246.

[49] "US-HiLumi Cryo-Assembly Drawings – From CERN For Final Design Review," US-Hi-Lumi-3001.

[50] "LQXFA/LQXFB 3-D model," US-HiLumi-doc-1085.

[51] F. Pasdeloup and L. Williams, "Design for the Protection and Diagnostic Feeders of the HL-LHC Triplets," International Review of the HL-LHC Magnet Circuits 2019, September 9, 2019. US-HiLumi-doc-3112.

[52] "Preliminary summary of the heat loads on the LSS.R5 of HL-LHC," , CERN EDMS 1610730. US-HiLumi-doc-3127.

[53] "Functional Specification: Design Load Cases for the Support Posts of the HL-LHC Cryo-Magnets,," CERN EDMS 1868420. US-HiLumi-doc-3130.

[54] "Longitudinal Anchoring of the HL-LHC Triplet Cryo-Magnets," CERN EDMS 1856323. US-HiLumi-doc-3265..

[55] D. D. Ramos et al,, "Status and plan of MQXFB cold mass and cryostat," HL-LHC Collaboration Meeting, October 16, 2018. US-HiLumi-doc-3115.

[56] "Cryogenic Static Heat Loads in the HL-LHC Continuous Cryostat Q1-Q2A-Q2B-Q3-CP-D1-DFX," CERN EDMS 1690235. US-HiLumi-doc-3124.

[57] "Estimation of the Hydraulic Parameters for the Inner Triplets for HL-LHC," CERN EDMS 1710017. US-HiLumi-doc-3136.

[58] "Cold Mass support post manufacturing documentation," US-HiLumi-doc-3169.

[59] "Technical Specification: Supply, Installation, and Commissioning of Two Versatile Tooling Sets for the Assembly of High Luminosity LHC Cryomgnets," CERN EDMS 1855811. US-HiLumi-doc-3133.

[60] "Cryostat tooling models and snapshots, Applus+ Laboratories (Barcelona, Spain)," US-HiLumi-doc-3163.

[61] "Cryostat assembly traveler," CERN EDMS LHC-QQXFA-PRD-0001.

[62] "Applus+ Laboratories, Alignment Table, August 9, 2019 Preliminary Design Review," US-HiLumi-doc-3175.

[63] "US-HiLumi Engineering Note for Q1-Q3 Shipping Support Post Analysis, Fermilab Teamcenter," ED0010721, US-HiLumi-doc-3172.

[64] H. M. Durand et al,, "Frequency Scanning Interferometry as a new solution for online monitoring inside a cryostat for the HL-LHC project," in *IPAC2018, https://doi.org/10.18429/JACoW-IPAC2018-WEPAF068.*

[65] "POSITION AND INSTALLATION OF FSI REFLECTORS SUPPORTS ON THE COLD MASS," EDMS 2371420 and US-HiLumi-doc-3284.

[66] "LQXFA/B Interface Control Documents," US-HiLumi-doc-210, US-HiLumi-doc-213, US-HiLumi-doc-375.

[67] "Elec. And Instrumentation Schemes Q1-Q2A-Q2B-Q3 String," CERN drawing LHCLMQXF_E0001.

[68] "Evaluation of the Equivalent Stresses of HL-LHC Q1/Q3, Q2A/Q2B, D1, D2, and CP Vacuum Vessels for Different Load Scenarios," CERN EDMS 2349761. US-HiLumi-doc-3118.

[69] "Cryostat tooling analysis report and validation plan/template," CERN EDMS CERN-0000198880. US-HiLumi-doc-3262..

[70] M. J. Lamm et al, "Test results of Fermilab-built quadrupoles for the LHC interaction regions," in *10th EPAC*, Edinburgh, 2006.

[71] "US-HiLumi TS4 Magnet Drawings," US-HiLumi-doc-3037.

[72] "US-HiLumi TS4 External Piping Drawings," US-HiLumi-doc-3049.

[73] R. H. Carcagno et al,, "A Cryogenic Test Stand for LHC Quadrupole Magnets," AIP Conference Proceedings 710, 225 (2004); https://doi.org/10.1063/1.1774686.

[74] R. H. Carcagno, et al, "New 30 kA Power System at Fermilab and Its Use for Measuring the Effects of Ripple Current on the Performance of Superconducting High Field Magnets," *IEEE Transactions on Applied Superconductivity,* vol. 15, no. 2, pp. 1520 - 1523, June 2005.

[75] "Operator's Manual: 1500 Watt Helium Refrigerator for Fermi/LBL," Helix Process Systems, March 1978.

[76] "Lambda plug leak flow test report," US-HiLumi-doc-2852.

[77] "Test Stand Functional Requirements for Testing MQXFA Magnets and Q1/Q3 Cryostat Assemblies," US-HiLumi-doc-1109.

[78] "Magnet Safety Interlocks," TID-N-1280, https://tiweb.fnal.gov/website/controller/3904.

[79] "Test Stand 4 Power Bus and Voltage Tap Diagrams," US-HiLumi-doc-3073.

[80] J. DiMarco, et al, "Field alignment of quadrupole magnets for the LHC interaction regions," *IEEE Transactions on Applied Superconductivity,* vol. 10, no. 1, pp. 127-130, March 2000.

[81] G. Velev, et al, "Magnetic Field Measurements of LHC Inner Triplet Quadrupoles Fabricated at Fermilab," *IEEE Transactions on Applied Superconductivity,* vol. 17, no. 2, pp. 1109-1112, June 2007.

[82] "Magnetic measurement systems requirements and design specifications for Q1/Q3 cryostat assemblies horizontal test," US-HiLumi-doc-818.

[83] "MQXFA Electrical Design Criteria," US-HiLumi-doc-826.

[84] A. Hemmati, B. Squires and R. Rabehl, "IB1 Cryogen Usage Studies," TID-N-307: Rev. 2.0, (May 19, 2011).

[85] R. Rabehl, "Evaluation of VTS LHe Usage for Interdewar Transfer, Displacers, and Pre-Cooler," TID-N-680, 6/4/2014.

[86] "Fermilab Environment, Safety and Health Manual (FESHM)," [Online]. Available: http://eshq.fnal.gov/manuals/feshm/.