U.S. HL-LHC Accelerator Upgrade Project

LMQXFA COLD MASS

FUNCTIONAL REQUIREMENTS SPECIFICATION

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Revision History

Revision	Date	Section No.	Revision Description
Draft	10/13/15	All	Initial Draft
Draft	5/6/2016		a. Incorporated comments from Feb 2016 QXF Workshop and March 2016 HL-LHC Circuits Review b. Changed project name to the official DOE name of "US HL-LHC Accelerator Upgrade Project" (US HL-LHC AUP) throughout the document c. Updated titles on signature page d. Removed section 2.1 "Institutional Responsibilities", this should be specified in a higher level document e. Updated Reference to CERN's HL-LHC PDR and LSA
0.1	5/11/16		First version uploaded in EDMS for review inside the task. EDMS ref document added and list of reviewers and approvers updated
0.2	6/24/16		Updated requirements on alignment. Removed requirement on beam loss monitor.
0.3	3/20/17	All	All the section were worked on

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1. Purpose

This document specifies the functional requirement for the High Luminosity LHC (HL-LHC, or HiLumi LHC) LMQXFA Cold Masses. Ten (10) of these cold masses are expected to be fabricated and delivered to CERN by the U.S. HL-LHC Accelerator Upgrade Project (US HL-LHC AUP) as part to the U.S. contributions to the LHC High Luminosity Upgrade. These cold masses are the quadrupole magnetic components of the HL-LHC Q1 and Q3 inner triplet optical elements in front of the interactions points 1(ATLAS) and 5 (CMS). Two MQXFA magnets are installed in each LMQXFA Cold Mass. MQXFA requirements are specified in [1].

If all the threshold functional requirements specified in this document are verified, then US HL-LHC AUP LMQXFA cold mass deliverables should be fit for the intended use and satisfy CERN's needs for the HL-LHC upgrade. The quality of the US HL-LHC AUP LMQXFA deliverables will be measured by the degree to which its characteristics fulfill the requirements specified in this document [2]

2. Introduction

The Inner Triplet (IT) quadrupoles are the magnetic system used that allow reaching low beta functions around the Interaction Point (IP). 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). For more details see [3].

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

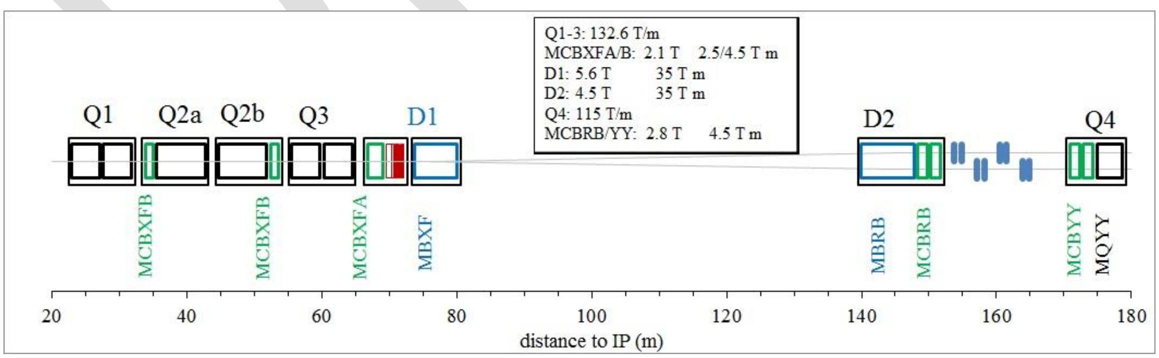


Figure 1**:** Conceptual layout of the IR region of HL-LHC– thick boxes are magnets, thin boxes are cryostats

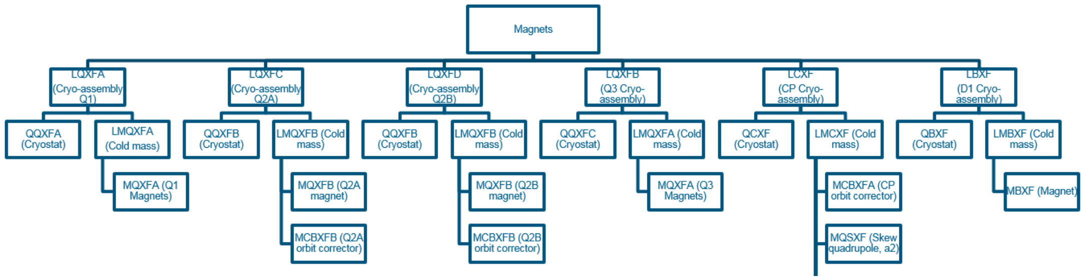


Figure 2: CERN Naming Conventions for HL-LHC Inner Triplets

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 2 shows the LMQXFA cold mass cross section (without the LHe SS vessel one obtains the MQXFA magnet cross section). A pair of ~ 5m MQXFA magnet structures is installed in a stainless steel helium vessel, including the end domes, to make the Q1 and Q3 Cold Mass (LMQXFA), see Figure 3. Q2a and Q2b each consist of a single unit MQXFB ~ 7m 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.

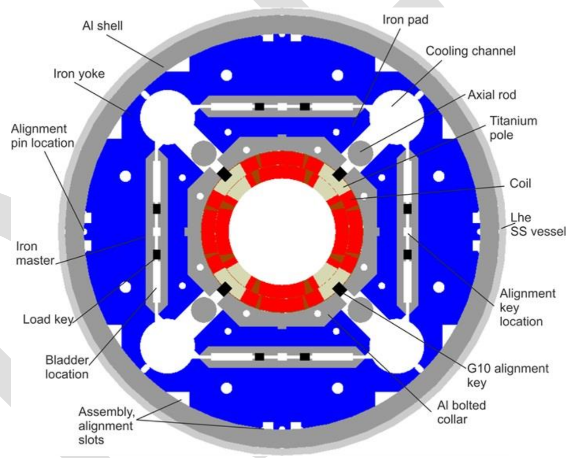


Figure 3: LMQXFA Cross Section. The difference between the cold mass LMQXFA and magnet MQXFA is the LHe SS vessel.

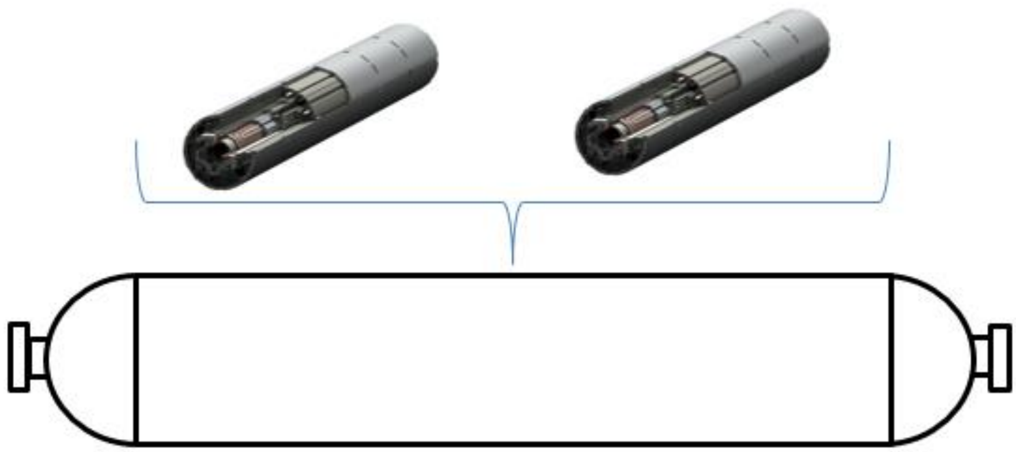


Figure 4: LMQXFA conceptual Cold Mass Assembly comprising of two MQXFA magnet elements

3. Functional Requirements Overview

The LMQXFA functional requirements are the high-level technical requirements for the LMQXFA magnet structure. These requirements are driven by the optics functions that the Q1 and Q3 elements need to satisfy plus physical, operational, environmental, and risk tolerance constraints. In addition to functional requirements, this document also includes some non-functional requirements such as reliability, interface, and safety requirements for completeness.

To clarify the intent, in this document requirements are classified into two groups: “Threshold” requirements and “Objective” requirements. Threshold requirements are requirements that contain at least one parameter that the project must achieve, and objective requirements are requirements that the project should achieve and will strive to achieve.

Each requirement should be verifiable by a Quality Control (QC) process. If all the requirements (specified in this document) are verified at a threshold level, then the U.S. HiLumi LMQXFA cold mass deliverables will be fit for the intended use and satisfy CERN’s needs for the HL-LHC upgrade.

Detailed verification procedures and acceptance criteria are defined in a separate document [2]. At CERN’s discretion, deliverables that fall short of the threshold requirements may still be acceptable.

This document provides some background information for each requirement, and throughout this document requirements are identified by a requirement ID of the format “**R-T-XX**”, and “**R-O-XX**” where “T” is for “Threshold”, “O” is for “Objective” and XX is the corresponding requirement number.

At the end of the document Tables 4 and 5 summarize all LMQXFA threshold and objective requirements.

4. Physical Requirements

4.1. Physical Envelope Requirements

In Figure 5 the layout drawing (LHCLSXH_0010 version AF) of the LHC IR magntes are shown. The dimensions that are listed in the layout drawing are subject to change however any changes needs to be confirmed by equipment owners.

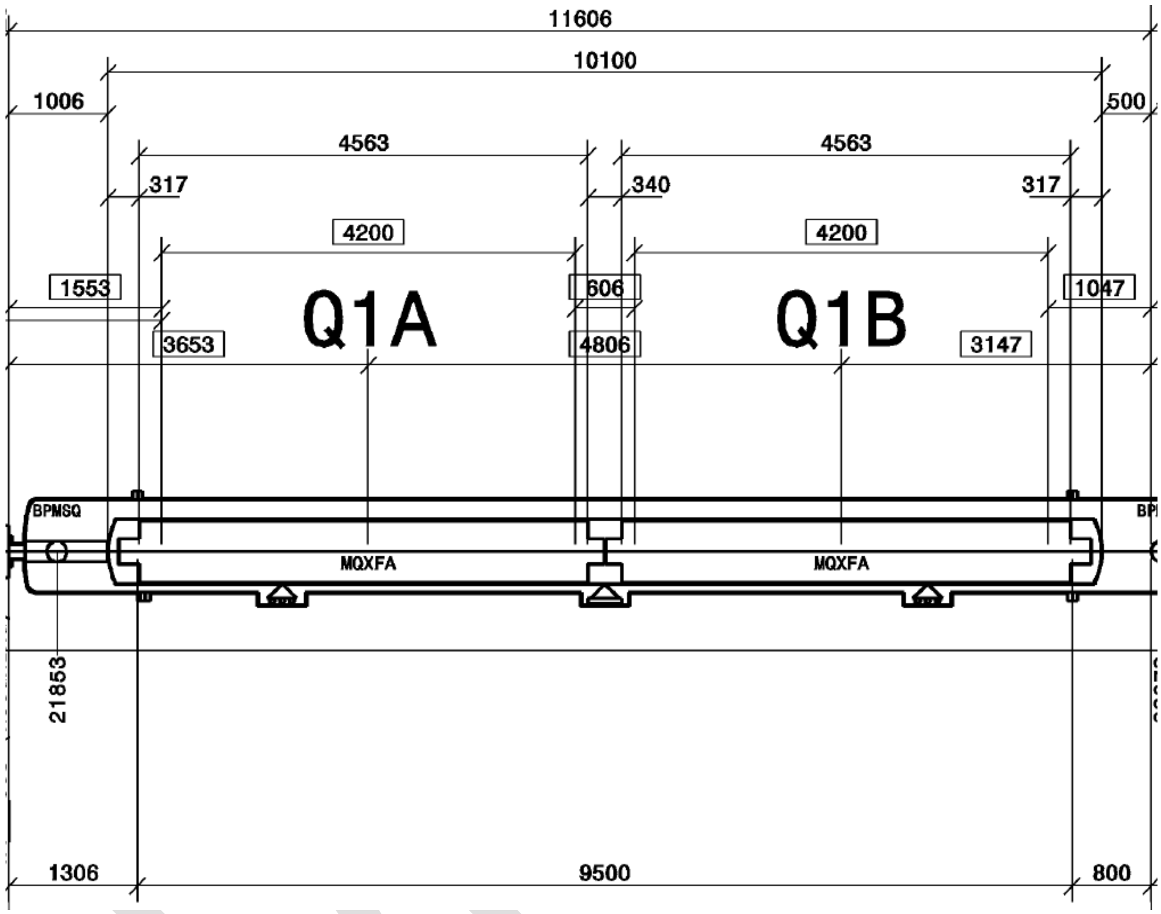


Figure 5 A portion from the LHCLSXH_0010 version AF drwaing is shown for illustration puposes.

R-T-01 Those dimensional values (listed in drawing LHCLSXH_0010) that have direct impact on two different equipment owners must be respected as envelope dimensions that could not be violated even if the fabrication tolerances or other constraints are taking into consideration. Any changes of LHCLSXH_0010 drawing must be approved by the Q1/Q3 equipment owners as well.

From the layout constraints R-T-02 mechanical dimensional requirments are derived:

R-T-02: The LMQXFA assembly physical length (end cover to end cover) must be ≤ 10,100 mm (the actual length shell be specified to make sure that the length plus the tolerance value is less than 10,100 mm). This dimension is at room temperature (296 K).

R-T-03 The physical shell outer diameter must not exceed 630 mm. This dimension is at room temperature (296 K).

Note:

- Components attached to the shell required for cryostat installation may exceed the 630 mm diameter envelope. This dimensional envelope is intended for the vessel shell only.
- Figure 5 is a section from the layout drawing: LHCLSXH_0010 version AF. If at any time the drawing is revised this docment may also be re-vised to indicate changes affected by the Q1/Q3 Cold Mass design.

4.2. End Cover and Piping Requirements

R-T-04: The LMQXFA end cover must include several penetrations, pipings and other features (listed in Table 1) for cryogenic and electrical connectivity purposes.

Table 1: LMQXFA interface piping, penetrations and other functions

Function
Cold Bore Tube
Helium Vessel Connection (18 kA busbar routing)
Heat Exchanger External Shell(s)
Link to external line for busbars <= 2 kA plus possibly the CLIQ leads
Instrumentation (possibly capillary) connection
Pads welded in the horizontal plan and on top in the vertical plane to define reference plane

Heat Exchanger opening(s) and Pipe(s) must be aligned with the MQXFA magnet yoke cooling channel(s).

Note: With the exception of the instrumentation line, the end cover is symmetrical with respect to the vertical plane. This allows use of the end covers on either end of the cold mass. The end cover profile can be 2:1 elliptical or ASME Flashed & Dished without any major changes.

The cold mass assembly must leave a clear and free space to insert the heat exchanger tubes:

R-T-05: The LMQXFA cold mass assembly must not have any obstructions or interferences that will prevent insertion of CERN-supplied 74 mm OD (plus 2 mm for tolerance value) heat exchanger tubes and their supports through the MQXFA cooling channels along the entire LMQXFA length.

5. Magnetic Elements Requirements

R-T-06: The LMQXFA magnetic elements are two identical MQXFA magnets connected in series. The MQXFA magnets must satisfy the MQXFA requirements specification [1] and the LMQXFA interface specification [4].

The LMQXFA Interface Specification provides details for the MQXFA welding and alignment interface to the LMQXFA stainless steel pressure vessel.

6. Alignment Requirements

The magnetic length of each MQXFA is 4.2 m at 1.9 K [1]. Figure 5 shows dimensions and distances for Q1A and Q1B (Q3A and Q3B are the same) assumed in the present lattice layout. Therefore, the requirement for minimal distance between magnetic lengths inside LMQXFA is:

R-T-07: The distance between the two ends of the MQXFA magnetic lengths is 606 mm ± 5 mm at nominal operating temperature (1.9K). The two MQXFA magnets are centered in Z within ± 5 mm with respect to the two ends of LMQXFA using the Z-center of the magnetic lengths. The magnetic length and the Z-center of the magnetic length need to be known within ±1 mm accuracy relative to external fiducials.

Note;

- Reference [5] shows that in the current MQXFA design the minimum distance between magnetic lengths is ?618? mm at warm, in the hypothesis of contact between the magnets. Therefore, the 606 mm of distance between magnetic lengths at cold temperature is feasible.
- The Z-center of the magnetic length for the combined two MQXFA system is the mid-point between the two individual MQXFA magnetic Z-centers.
- Measurement accuracy of the magnetic length needs to be better than ± 1 mm (at 1.9 K).

R-O-01: The common magnetic axis of the two-magnet system should be determined with respect to fiducials with accuracy of ? +/-0.2 mm ? to both nodal points. The maximum deviation of the MQXFA true axis (of both magnets) along the common magnetic axis must be less than +/-0.5 mm. The common average MQXFA field angle with respect to gravity should be measured with accuracy better than ? 0.5mrad ?. The deviation of both MQXFA average field angles from the common magnetic field angle must be less than ±2 mrad.

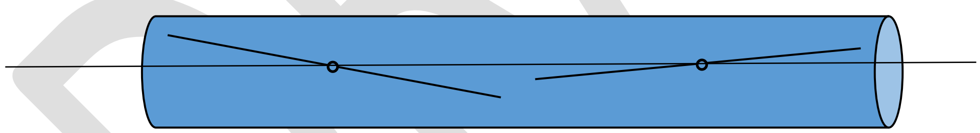


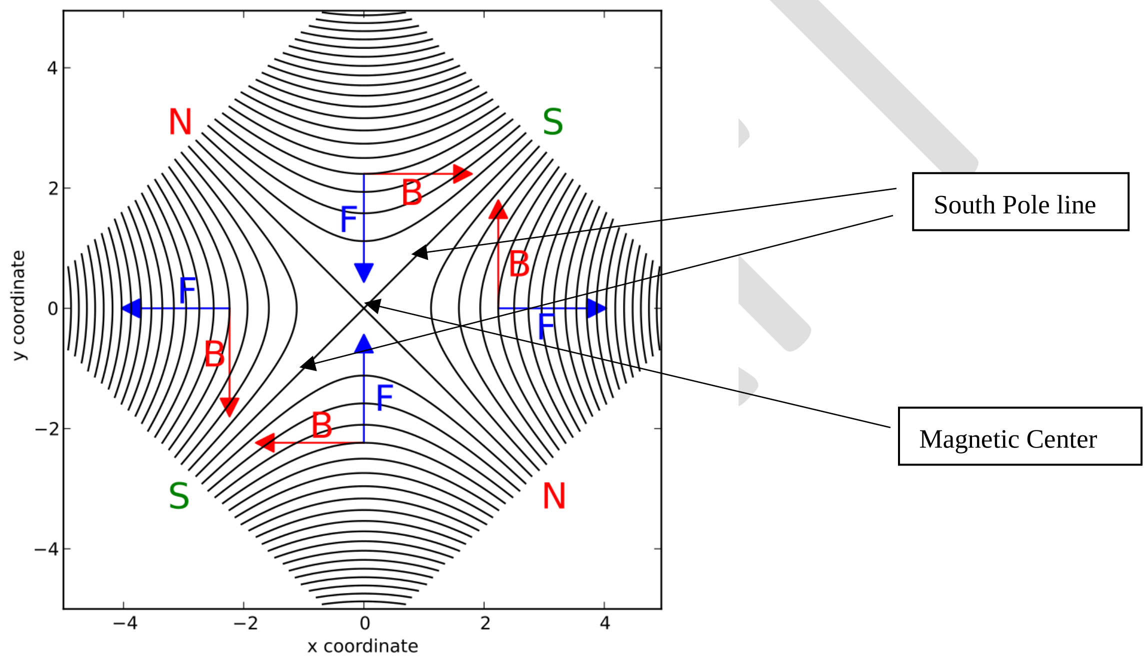
Figure 6. Shows three lines that represent the two MQXFA and the common magnetic axis.

Note:

- The pole line is a line (see Figure 7) perpendicular to the magnet z-axis connecting the two similar poles (N-N or S-S, 180 degree apart) (at the center of the pole) .
- Field angle is defined as the angle of the pole line connecting the South poles. The angle is measured counter clockwise, looking from the interaction point toward the IR magnets and the zero angle is defined as the gravity line pointing upward. Field angle is equivalently defined as the angle with respect to gravity that gives a zero average skew quadupole component (with an additional 45 degree offset compared to pole line definition).
- The average field angle is the field angle averaged over the length of a single magnet.
- The common average field angle is the angle that bisects the average field angle of the two magnets.
- Magnetic transverse center (or simply magnetic center) is the point at the intersection of the two crossing pole lines.
- The average magnetic axis is one of the idealized lines through the bore of the magnet which has zero integrated field value when performing the field integration along this line. The point at the

Z-center of the magnet which is common to any of the family of average magnetic axes is referred to as the nodal point.

- The magnetic axis (or true magnetic axis – see Figure 6) is the idealized line which is both an average magnetic axis and which minimizes the second moment of field integration along the line.
- The common axis of the two magnets is the average magnetic axis for the two magnets. This is the line that intersects the individual magnetic axes of both MQXA magnets at their Z-centers (i.e. contains the nodal points of both magnets).
- In determining deviation from the common axis, the distance between the common magnetic axis and the point on the magnetic axes of MQXFA is measured on the line perpendicular to the common magnetic axes (though for the small angles required here, the cosine error using a line perpendicular to the individual axes would be negligible anyway).
- Angles between any pole lines are compared relative to the projected (perpendicular projection) lines onto the plane that is perpendicular to the common magnetic axes (again the small angles and cosine effects generally make the "would-be errors" from these effects negligible).



- Figure 7. Definition of the pole line and magnetic center point are shown. The pole line is an idealized line connecting the two similar poles (N-N or S-S, 180 degree apart) at their centers. The magnetic center point is the point where the idealized pole lines cross each other.

R-T-08: Beam tube must be positioned relative to the geometrical center line of the two MQXFA or relative to common magnetic axes.

Note:

- Geometrical center line of the two MQXFA is the line that gives the most clearance between the beam tube and the magnet bore.

R-T-09: The integrated field angle with respect to the gravity line (vertical line) must be 785 mrad ± 5 mrad (45 degree) with pipes in nominal orientation with respect to gravity line.

Note:

- The integrated field angle is measured along the common magnetic axis.
- The orientation of the pole lines must be the same for the two MQXFA magnets.

The relative alignment values are verified by a single stretched wire (SSW) measurement system. This measurement requires each magnet to be powered independently at a minimum of 10 A AC current during 1.9 K testing. The common axis and angle measured at low current alignment measurements will be verified at high current values at least once so to verify that the low current alignment measurements are representative of alignment at higher currents. Therefore:

R-T-10: The LMQXFA cold mass assembly must include provisions for powering each MQXFA magnet independently at a minimum of 10 A AC current during 1.9 K testing to measure and verify relative alignment with a Single Stretched Wire (SSW) measurement system.

Note:

- It is important to have a lead (that is connected to the bus that connects the two MQXFA electrically) accessible at the end of the cold mass to perfrom the 10 A AC SSW measurements. The lead must be sized to be able to handle 15 A DC current.

7. Pressure Vessel Requirements

R-T-11: The LMQXFA is a pressure vessel that must be designed and documented in accordance with CERN and U.S. HL-LHC Accelerator Upgrade Project safety agreements [6].

R-T-12: The LMQXFA pressure vessel material for the cylindrical shell and end coveres must be Low cobalt content Austenitic Stainless Steel Grade 316L. The material for the cold bore is specified in R-11.

R-T-13: The LMQXFA provides a 1.9K helium vessel that must be designed for a Maximum Allowable Working Pressure (MAWP) of 20 bar differential.

8. Forces Requirements

Once installed as part of the LHC Inner Triplet System, the LMQXFA cold mass assemblies can experience asymmetric axial forces due to quench on other magnets and other events.

R-T-14: 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.

9. Cold Bore Requirements

The cold bore is inserted in the completed LMQXFA assembly, centered (see **R-T-08)** in the MQXFA magnets by contact between the insulation on the outside of the cold bore tube and the ground insulation that covers the pole of the collars in the magnet assembly. The cold bore is terminated with a flange at either end of the end domes of the LMQXFA and includes supports and insulation as specified in [4]

R-T-15: The LMQXFA beam tube material must be seamless Low cobalt content Austenitic Stainless Steel Grade 316LN and must comply with CERN technical specification LHC-VCC-CI-0001 and interface requirements specified in [4].

10. Electrical/Instrumentation Requirements

10.1. Instrumentation

R-T-16: Two (2) temperature sensors attached to the return end plate of each MQXFA magnet assembly. These sensors are the short type thermometer assembly (36 mm x 12 mm x 4.2 mm) typically used by CERN and specified in [7]

The thermometer assemblies will be calibrated and supplied by CERN at no cost to US HL-LHC AUP.

R-T-17: ?A 50 W warm up heater attached to each of the four MQXFA end plates. ?

These heaters are independently powered. CERN will supply the warmup heaters at no cost to US HL-LHC AUP.

R-T-18: The LMQXFA cold mass assembly must include a total of 14 voltage taps to verify the splice resistance requirement between each MQXFA magnet and the main current bus and to protect the magnet with the bus.

The instrumentation requirement for each MQXFA magnet inside the cold mass assembly is specified in [1]. The LMQXFA assembly includes the wiring for MQXFA instrumentation:

10.1. Instrumentation Wiring

R-T-19: Quench protection heater leads and warmup heaters leads are 18 Gauge polyimide coated wire, voltage taps are 22 Gauge polyimide wires, thermometer leads are 30 Gauge polyimide coated wire.

CERN will provide all wires used within the LMQXFA cold mass assemblies at no cost to US HL-LHC AUP.

R-T-20: The LMQXFA Instrumentation Wiring must exit the cold mass assembly through the instrumentation port.

Note:

- The routing and termination of the wiring will be specified in the interface document [4].

A complete tabulation of the LMQXFA instrumentation wires is shown in Table 3.

Table 3: LMQXFA Instrumentation wiring

LMQXFA Wiring	Qty	Description
Voltage Taps	TBD	22 AWG polyamide coated wire
Temperature Sensor Leads	TBD	30 AWG polyamide coated wire
Warm Up Heater Leads	TBD	18 AWG polyamide coated wire
Quench Heater Leads	TBD	18 AWG polyamide coated wire
Beam Loss Monitor	TBD	TBD

10.2. Electrical Busses

The purpose of the main bus for LMQXFA is to carry the current to the two MQXFA magnets from the interconnect region where the busses are spliced together. In principle there will be four major sections, two long sections and two short sections.

R-T-21: The main bus shell carry up to 20 kA DC electrical current continuously.

R-T-22: The bus design must take into consideration that if the bus quenches at any operating current value, the bus can be protected by measuring the resistive voltage rise of the bus. The detection voltage threshold value must be ≥ 50 mV. The bus hot spot temperature must be below 150 K.

Expansion loops are needed in the end domes of the assembly to accommodate thermal contraction/expansion of the magnets and bus work both internal to the cold mass assembly and external, resulting in the following requirement:

R-T-23: The bus work must include expansion loops for the two long bus sections that connect the lead ends of the two MQXFA magnets. The expansion loops must be contained within the end cover section and should each be able to accommodate up to 50 mm of axial movement due to differential expansion and contraction of the bus or magnet.

R-O-02: The bus work include four internal splices. Splice resistance target value must be less than 1.0 nΩ at 1.9K.

There are CERN requirements for the splice resistance as well as the solder and flux used for these splices:

R-T-24: Splices are to be soldered with CERN approved materials [8]

Note:

- The joint resistance is measured with voltage taps.

In additional to the main bus work, the LMQXFA cold mass assembly must include TBD leads for CLIQ:

R-T-25: The LMQXFA assembly must include TBD leads for CLIQ. These leads are specified in [9].

10.3. Voltage Limits

R-T-26: The LMQXFA cold mass assembly voltage limits must meet or exceed the MQXFA voltage limit requirements specified in [1].

11. Quench Requirements

R-T-27: The LMQXFA quench performance requirements must meet or exceed the MQXFA magnet quench performance requirements specified in [1].

This requirement means that the cold mass assembly quench performance is limited by the MQXFA magnets, and not by cold mass assembly superconducting components such as busbars and splices. Therefore, superconducting busbars must be designed and fabricated with adequate margin, support, expansion loops, and cooling provisions.

11.1. Free Cross Section

R-T-28: After installation and routing of heat exchanger tubes, instrumentation wiring, and superconducting busses there must be a free LMQXFA cross section area of 150 cm^2 in the helium volume.

This requirement is to allow adequate 1.9 K helium communication for heat transport and quench venting path. Note that this requirement also sets a minimum diameter for end cover pipes.

12. Radiation Hardness Requirements

The LMQXFA cold mass assembly will be located near the IP where radiation is expected. With a nominal luminosity 5 times larger than the nominal design goal of the LHC, CERN is planning to fabricate and install a newly designed absorber, using thick tungsten (W) shielding attached to the beam screen to reduce the effect of collision debris. The W shielding will limit the radiation damage over the HL-LHC accumulated luminosity of 3000 fb^{-1} to a maximum of 30 MGy. This value is similar to the expected radiation doses for the nominal LHC [3]. Table 4 shows a map of maximum radiation dose

R-O-03: All MQXFA components can withstand a maximum radiation dose of 30 MGy.

13. Reliability Requirements

R-O-04: LMQXFA reliability requirements are the same as the MQXFA reliability requirements specified in [1].

14. Interface Requirements

The LMQXFA cold mass assembly interfaces with the following systems:

1. The MQXFA magnets
2. The CERN supplied QXFA/B Cryostats
3. The CERN supplied piping
4. The CERN supplied Cryogenic System, consisting of:
    a. The CERN supplied cooling system
    b. The CERN supplied pressure relief system
5. The CERN supplied power system
6. The CERN supplied quench protection system, consisting of:
    a. Quench Detection System
    b. Strip Heaters Power Supplies
    c. Possibly a CLIQ system
7. The CERN supplied instrumentation system

Detailed interface documentation must be provided for each of these interfaces.

R-T-29: The LMQXFA cold mass assembly must meet the detailed interface specifications with the following systems: (1) MQXFA magnets; (2) The CERN supplied QQXFA/B Cryostats; (3) the CERN supplied piping; (4) CERN supplied Cryogenic System; (5) the CERN supplied power system; (6) the CERN supplied quench protection system, and (7) the CERN supplied instrumentation system. These interfaces are specified in Interface Control Document [4].

15. Safety Requirements

Each HL-LHC work package will be subject to safety requirements specified in a CERN “Launch Safety Agreement (LSA)” document [6]. This LSA will specify the CERN safety rules and host state regulations applicable to the systems/processes and the minimal contents of the Work Package safety file needed to meet the Safety Requirements.

R-T-30: The LMQXFA cold mass assembly must comply with CERN’s Launch Safety Agreement (LSA) for IR Magnets (WP3) [6]

16. CERN Provided Parts

R-T-31: CERN provided parts for LMQXFA assemblies are specified in Table 5. These parts for the prototype and 10 production units will be supplied by CERN at no cost to US HL-LHC AUP.

Table 5: LMQXFA CERN provided parts

Item	Quantity/unit
Cylindrical shell material must be Low cobalt content Austenitic Stainless Steel Grade 316L	1
End coveres must be Low cobalt content Austenitic Stainless Steel Grade 316L	2
Beam tubes must be Low cobalt content Austenitic Stainless Steel Grade 316LN	1
Heat exchanger tubes	2
Instrumentation wire AWG 22	TBD km
Instrumentation wire AWG 18	TBD km

Thermometer cable, 4 x AWG 30 (twisted)	TBD km
Temperature Sensors	4
Warm up heaters	2
Bus bars	TBD
Beam Loss Monitor	?
Instrumentation Connectors and Feedthroughs (if applicable)	?

17. Functional Requirements Summary Tables

ID	Description
R-T-01	**Those dimensional values (listed in drawing LHCLSXH_0010) that have direct impact on two different equipment owners must be respected as envelope dimensions that could not be violated even if the fabrication tolerances or other constraints are taking into consideration. Any changes of LHCLSXH_0010 drawing must be approved by the Q1/Q3 equipment owners as well.**
R-T-02	**The LMQXFA assembly physical length (end cover to end cover) must be ≤ 10,100 mm (the actual length shell be specified to make sure that the length plus the tolerance value is less than 10,100 mm). This dimension is at room temperature (296 K).**
R-T-03	**The physical shell outer diameter must not exceed 630 mm. This dimension is at room temperature (296 K).**
R-T-04	**The LMQXFA end cover must include several penetrations, pipings and other features (listed in Table 1) for cryogenic and electrical connectivity purposes.**
R-T-05	**The LMQXFA cold mass assembly must not have any obstructions or interferences that will prevent insertion of CERN-supplied 74 mm OD (plus 2 mm for tolerance value) heat exchanger tubes and their supports through the MQXFA cooling channels along the entire LMQXFA length.**
R-T-06	**The LMQXFA magnetic elements are two identical MQXFA magnets connected in series. The MQXFA magnets must satisfy the MQXFA requirements specification [1] and the LMQXFA interface specification [3].**
R-T-07	**R-T-07: The distance between the two ends of the MQXFA magnetic lengths is 606 mm ± 5 mm at nominal operating temperature (1.9K). The two MQXFA magnets are centered in Z within ± 5 mm with respect to the two ends of LMQXFA using the Z-center of the magnetic lengths. The magnetic length and the Z-center of the magnetic length need to be known within ±1 mm accuracy relative to external fiducials.**
R-T-08	**R-T-08 Beam tube must be positioned relative to the geometrical center line of the two MQXFA or relative to common magnetic axes.**
R-T-09	**R The integrated field angle with respect to the gravity line (vertical line) must be 785 mrad ± 5 mrad (45 degree) with pipes in nominal orientation with respect to gravity line.**
R-T-10	**The LMQXFA cold mass assembly must include provisions for powering each MQXFA magnet independently at a minimum of 10 A AC current during 1.9 K testing to measure and verify relative alignment with a Single Stretched Wire (SSW) measurement system.**
R-T-11	**The LMQXFA is a pressure vessel that must be designed and documented in accordance with CERN and U.S. HL-LHC Accelerator Upgrade Project safety agreements [6].**
R-T-12	**The LMQXFA pressure vessel material for the cylindrical shell and end domes must be Low cobalt content Austenitic Stainless Steel Grade 316L. The material for the cold bore is specified in R-11.**
R-T-13	**The LMQXFA provides a 1.9K helium vessel that must be designed for a Maximum Allowable Working Pressure (MAWP) of 20 bar differential.**
R-T-14	**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.**
R-T-15	**The LMQXFA beam tube material must be seamless Low cobalt content Austenitic Stainless Steel Grade 316LN and must comply with CERN technical specification LHC-VCC-CI-0001 and interface requirements specified in [3].**
R-T-16	**Two (2) temperature sensors attached to the return end plate of each MQXFA magnet assembly. These sensors are the short type thermometer assembly (36 mm x 12 mm x 4.2 mm) typically used by CERN and specified in [9]**
R-T-17	**A 50 W warm up heater attached to each of the four MQXFA end plates.**
R-T-18	**The LMQXFA cold mass assembly must include a total of 8 voltage tap pairs to verify the splice resistance requirement R-21 between each MQXFA magnet and the main current bus.**

R-T-19	**Quench protection heater leads and warmup heaters leads are 20 Gauge polyimide coated wire, voltage taps are 26 Gauge polyimide wires, thermometer leads are 30 Gauge polyimide coated wire.**
R-T-20	**The LMQXFA Instrumentation Wiring must exit the cold mass assembly through the instrumentation port.**
R-T-21	**The main bus shell carry up to 20 kA DC electrical current continuously.**
R-T-22	**The bus work must include expansion loops for the two long bus sections that connect the lead ends of the two MQXFA magnets. The expansion loops must be contained within the end cover section and should each be able to accommodate up to 50 mm of axial movement due to differential expansion and contraction of the bus or magnet.**
R-T-23	**The bus work must include expansion loops for the two long bus sections that connect the lead ends of the two MQXFA magnets. The expansion loops must be contained within the end cover section and should each be able to accommodate up to 50 mm of axial movement due to differential expansion and contraction of the bus or magnet.**
R-T-24	**Splices are to be soldered with CERN approved materials [8]**
R-T-25	**The LMQXFA assembly must include TBD leads for CLIQ. These leads are specified in [9].**
R-T-26	**The LMQXFA cold mass assembly voltage limits must meet or exceed the MQXFA voltage limit requirements specified in [1].**
R-T-27	**The LMQXFA quench performance requirements must meet or exceed the MQXFA magnet quench performance requirements specified in [1].**
R-T-28	**After installation and routing of heat exchanger tubes, instrumentation wiring, and superconducting busses there must be a free LMQXFA cross section area of 150 cm^2 in the helium volume.**
R-T-29	**The LMQXFA cold mass assembly must meet the detailed interface specifications with the following systems: (1) MQXFA magnets; (2) The CERN supplied QQXFA/B Cryostats; (3) the CERN supplied Cryogenic System; (3) the CERN supplied power system; (4) the CERN supplied quench protection system, and (5) the CERN supplied instrumentation system. These interfaces are specified in Interface Control Document [3].**
R-T-30	**The LMQXFA cold mass assembly must comply with CERN's Launch Safety Agreement (LSA) for IR Magnets (WP3) [6]**
R-T-31	**CERN provided parts for LMQXFA assemblies are specified in Table 5. These parts for the prototype and 10 production units will be supplied by CERN at no cost to US HL-LHC AUP.**

Table 6: LMQXFA Objective Functional Requirements Specification Summary Table

ID	Description
R-O-01	**R-O-01: The common magnetic axis of the two-magnet system should be determined with respect to fiducials with accuracy of ? +/-0.2 mm ? to both nodal points. The maximum deviation of the MQXFA true axes (of both magnets) along the common magnetic axis must be less than +/-0.5 mm. The common average MQXFA field angle with respect to gravity should be measured with accuracy better than ? 0.5mrad ?. The deviation of both MQXFA average field angles from the common magnetic field angle must be less than ±2 mrad.**
R-O-02	**The bus work include four internal splices. Splice resistance target value is less than 1.0 nΩ at 1.9K.**
R-O-03	All MQXFA components can withstand a maximum radiation dose of **30** MGy.
R-O-04	LMQXFA reliability requirements are the same as the MQXFA reliability requirements specified in [1].

18. References

[1] MQXFA Functional Requirements, US-HiLumi-doc-36 (draft)

[2] High-Luminosity Large Hadron Collider (HL-LHC). Preliminary Design Report, edited by G. Apollinari, I. Béjar Alonso, O. Brüning, M. Lamont, L. Rossi, CERN-2015-005 (CERN, Geneva, 2015), DOI: http://dx.doi.org/10.5170/CERN-2015-005

[3] Acceptance Criteria (to be defined)

[4] LMQXFA Interface Control Document (to be defined)

[5] Study of the Minimal Distance between two coils in a cold mass, HILUMILHC-Mil-MS39, December 4 2014.

[6] CERN Launch Safety Agreement for IR Magnets (WP3), CERN EDMS 1550065

[7] Installation Guide for LHC Cryogenic Thermometers, LHC-QIT-ES-0002 (I could not find this reference, found instead: LHC-QIT-ES-0001 rev 1.1, "LHC Cryogenic Thermometers")

[8] Soldering material and procedure defined by CERN (to be defined)

[9] CLIQ leads specifications (to be defined)