FUNCTIONAL SPECIFICATION

LMQXFA COLD MASS

Abstract

This document specifies the functional requirements for the LMQXFA cold mass readapted for the American contribution. If all the requirements specified in this document are met, then the U.S. HL-LHC AUP LMQXFA deliverables will be accepted by CERN for the HL-LHC project.

Please note that the definition of threshold as it is being used by the American contribution is not the same as objective, according to the HL-LHC quality policy.

TRACEABILITY V2.0

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1.0	2017-08-02	Valid version of the document with comments to be addressed before issuing the next version
1.4	2020-03-17	Adding missing references, typos and language clarification
1.5	2020-05-11	Section 12: Added R-O-05. Section 14: Added R-T-28
1.6	2022-02-04	Section 8: Requirement R-T-10b added
2.0	2022-02-27	2nd Release version of the document

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
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0.3	3/20/17	All	All the section were worked on
0.4	30/6/17		Ezio version including new information on the cold mass from Herve Prin and Delio Duarte Ramos
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0.6	10/7/17		Comments from Ferracin, Rossi, Feher, Ambrosio, Claudet. Revision of alignment section
0.7	11/7/17		Additional comments
0.8	30/01/18		Feher version includes the material change for the shell material from 316L to 316LN and modifying the appendix to get clear definition of the field angle that is not defined in refence [5].
0.9	28/05/18		Few minor changes; number of instrumentation wires
1.2	31/10/2018		The above changes were highlighted in red
1.4	3/17/2020		CERN approval
1.5	4/16/2020	12, 14	Section 12: Added R-O-05. Section 14: Added R-T-28
1.6	4/5/2022	8	Section 8: Requirement R-T-10b added

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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 met, 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 [2]. 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. Detailed verification procedures and acceptance criteria are defined in a separate document [3]. At CERN's discretion, deliverables that fall short of the threshold requirements may still be acceptable.

2. Introduction

The Inner Triplet (IT) quadrupoles are the magnetic system 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 11.4 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 [2].

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

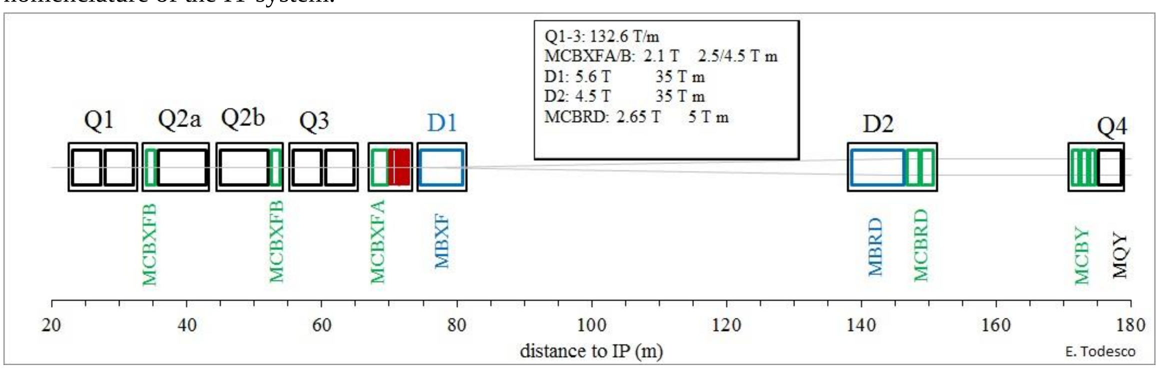

Figure 1**:** Conceptual layout of the IR region of HL-LHC (thick boxes are magnets, thin boxes are cryostats).

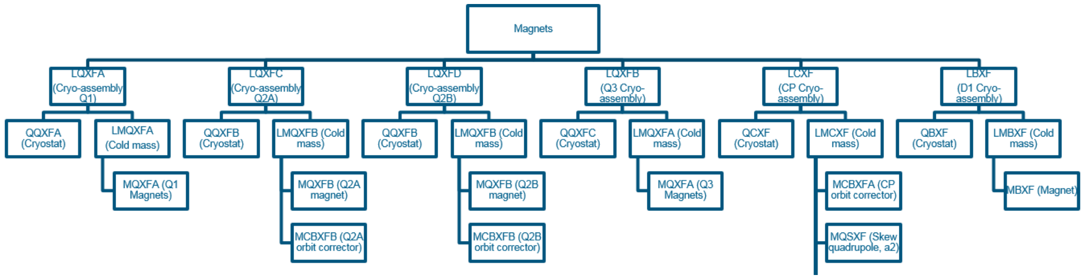

Figure 2: CERN Naming Conventions for HL-LHC Inner Triplets.

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 Al shell of the magnets and the end plates of each magnet. Figure 3 shows the LMQXFA cold mass cross section. A pair of 4.2-m-long (magnetic) MQXFA magnet structures is 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 7.15-m-long (magnetic) single unit MQXFB. 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.

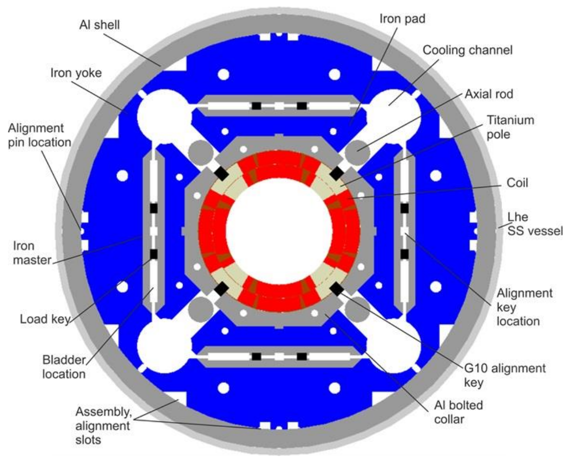

Figure 3: LMQXFA Cross Section. The magnet MQXFA does not include the LHe SS vessel.

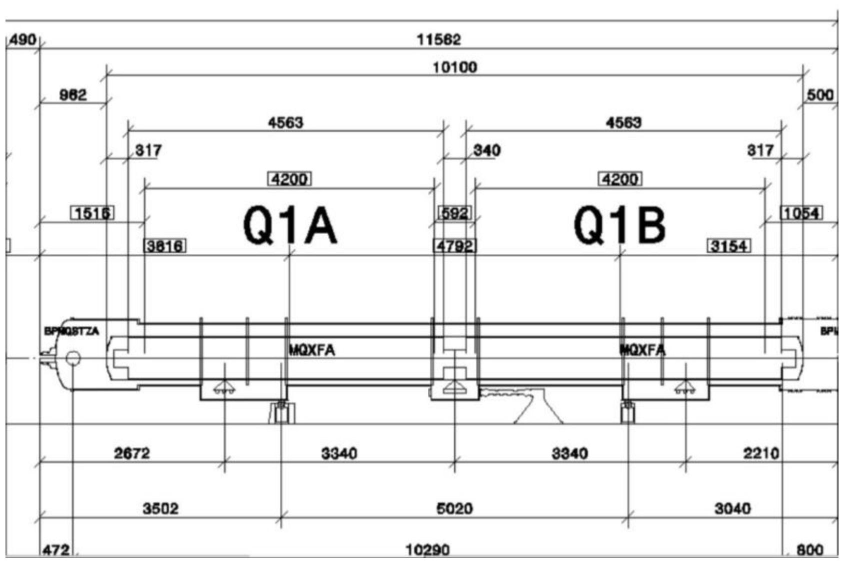

Figure 4: LMQXFA Cold Mass Assembly comprising of two MQXFA magnet elements. Quotes in square boxes are at 1.9 K, otherwise at room temperature.

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 [3]. 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 3 and 4 summarize all LMQXFA threshold and objective requirements.

4. Physical Requirements

4.1. Physical Envelope Requirements

In Figure 4 the layout drawing (LHCLSXH_0010 version AH) of the LHC IR magnets are shown.

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 (296 K).

R-T-02: The LHe stainless steel vessel outer diameter, including tolerances, must not exceed 630 mm. This dimension is at room temperature (296 K).

Note:

- Components attached to the vessel required for cryostat installation may exceed the 630 mm diameter envelope. This dimensional envelope is intended for the vessel shell only.
- Figure 4 is a section from the layout drawing: LHCLSXH_0010 version AF. If at any time the drawing is revised this document 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-03: The LMQXFA end cover must include piping listed in Table 1 for cryogenic and electrical connectivity purposes.

Table 1: LMQXFA interface piping, penetrations and other functions (dimensions are at room temperature)

Function	**Number**	**Inner diameter (mm)**
Cold Bore Connection	1	150
Helium Vessel Connection	2	100
Busbar Connection	1	50
Heat Exchanger Connection	2	100

Heat exchanger and helium vessel connection openings must be aligned with the MQXFA magnet yoke cooling channel(s), see Figures 3 and 5.

Note: 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 covers will be provided by CERN.

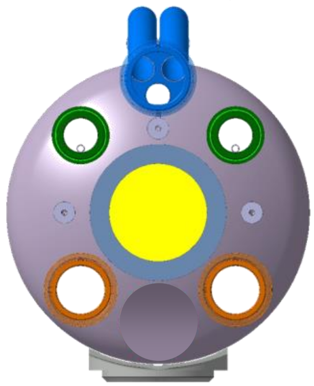

Figure 5: LMQXFA Cold Mass Assembly seen from the end covers.

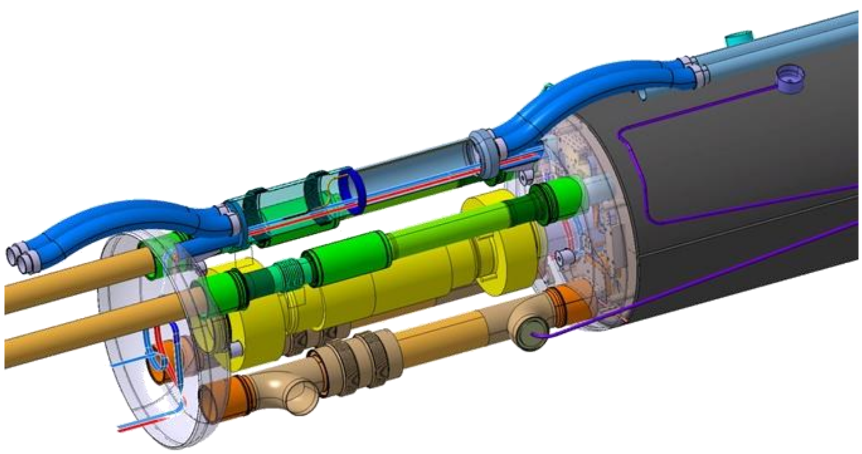

Figure 6: Detail of the interconnection between two LMQXFA Cold Mass Assembly: heat exchangers (green), helium vessel connection (brown), beam tube (yellow), and busbar parallel line (blue).

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

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 (i) the CERN-supplied 74 mm OD (plus 2 mm for tolerance value) heat exchanger tubes and their supports through the MQXFA cooling channels, of (ii) the busbar cartridge used to connect in series the two magnets making the cold mass, and of (iii) the cold bore.

5. Magnetic Elements Requirements

R-T-05: The LMQXFA magnetic elements are two identical MQXFA magnets connected in series and with the same polarity. 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 4200 mm at 1.9 K [1,2]. Figure 4 shows dimensions and distances for the two magnets inside the cold mass in the present lattice layout. We first give the tolerances on the relative longitudinal position of the active part of the magnets (magnetic length). The reference system is described in [5], with the additional definition of the local field direction as provided in the Appendix. The magnetic axis of each magnet is localized with a stretched wire measurements with respect to the cold mass fiducials. The nodal point of a magnet is the midpoint of the magnetic axis. The magnetic axis of the cold mass goes through the two nodal points of each magnet (see Fig. 7).

R-T-06: The distance between the two nodal points of the MQXFA magnetic lengths is 4806 mm ± 5 mm at nominal operating temperature (1.9 K).

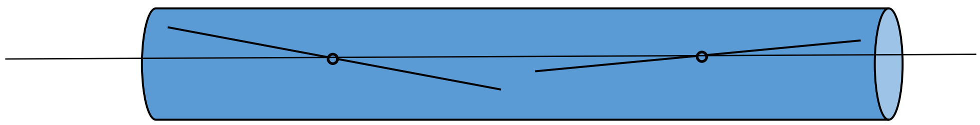

Figure 7. MQXFA magnetic axis, nodal points, and the cold mass magnetic axis.

R-O-01: The maximum deviation of each MQXFA magnet axis along the common magnetic axis must be within ±0.5 mm both in horizontal and in vertical direction. The deviation of each MQXFA field angle from the common magnetic field angle must be within ±2 mrad.

A threshold requirement for the above quantities will be set in the acceptance plan.

The procedure of alignment of the magnets in the cold mass, the fiducial systems in the magnets and in the cold mass, and the tolerances of the alignment with respect to the cold mass fiducials will be given in a separate document [6].

Finally, we give a requirement on the precision of the measurements.

- The measurements in the transverse plane are required to allow reaching the final tolerances on the alignment through a motor system acting on the cryostat.
- The measurements on the longitudinal direction are necessary for the setting of the quadrupole power trims to reach the nominal optics.

R-O-02: The common magnetic axis of the two-magnet system should be determined with respect to cold mass fiducials with accuracy of ±0.2 mm to both nodal points. The common average MQXFA field angle with respect to cold mass fiducials should be measured with accuracy better than 0.5 mrad. The magnetic length and the nodal points of each of the two MQXFA magnets in the cold mass need to be known within ±1 mm accuracy relative to external fiducials.

A threshold requirement for these quantities will be set in the acceptance plan

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. This is guaranteed by the 35 A trim (see R-T-13). 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.

7. Pressure Vessel Requirements

R-T-07: 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 [7][8][9].

R-T-08: The LMQXFA pressure vessel material for the cylindrical shell and end covers must be Austenitic Stainless Steel Grade 316LN with Co content lower than 0.1%.

R-T-09: The LMQXFA provides a 1.9 K helium vessel that must be designed for a Maximum Allowable Working Pressure (MAWP) of 20 bar differential with an applied test pressure of 25 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 cryogenic operation and to quench of other magnets.

R-T-10a: The LMQXFA cold mass assembly, as installed and operated in the LHC machine, must be capable of sustaining loads resulting from up to 20 bar of pressure differential without physical damage or performance degradation. The load conditions on the cold mass support posts are specified in [10].

R-T-10b: The fixed points of the MQXFA magnet shall not move inside the LMQXFA cold mass when subject to 2.5 bar differential pressure between the ends of each MQXFA magnet in accordance with a global pressure gradient of 5 bar linearly distributed over the cold mass length (induced by cryogenic operation or by quench of other magnets [11] version 1.0) and this load shall not introduce any physical damage or performance degradation during the cryomagnet lifetime.

9. Cold Bore Tube Requirements

The cold bore tube is inserted in the completed LMQXFA assembly, centered in the MQXFA magnets by contact between the insulation on the outside of the cold bore tube and the insulating slides set on the coil poles in the magnet assembly. The cold bore tube is terminated with a flange at either end of the end domes of the LMQXFA and includes supports and insulation as specified in [4]. Cold bore tube will be provided by CERN. Its material shall be seamless austenitic stainless steel grade 316LN with Co content lower than 0.1%.

10. Busbars Scheme and Requirements

The purpose of the main bus for LMQXFA is to connect in series the two magnets, and to bring the connection side of one the two magnets to the connection of the other magnet; these two busbars will be coupled together and will travel inside the cold mass, in one of the holes not used by the heat exchangers. A resistive lead trim is also needed in each cold mass (see Fig. 8). There will be no busbars relative to other circuits travelling through the cold mass. The cable for the busbars will be provided by CERN.

R-T-11: The LMQXFA cold mass will have two main superconducting leads on each side going through the busbar line connection. An additional pair of resistive leads (trim) are required to have current unbalance up to 35 A between the two magnets during operation. The additional leads exit the cold mass through the helium vessel connection. Four additional resistive leads (CLIQ, two per magnet) are required for protection system. These four additional leads exits the cold mass through the helium vessel connection.

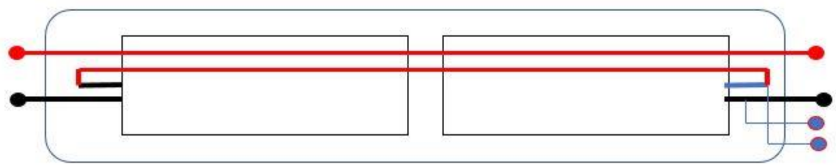

Figure 8: Electrical scheme of the cold mass, with the two magnets (rectangles), busbars cartridge (red lines), trim leads (light blue), and cold mass envelope (rounded rectangle). CLIQ leads are not shown.

R-T-12: The 18 kA busbars will be made with the same Nb-Ti cable used for the connections of the magnet.

The two busbars are coupled in a busbar cartridge fitting the yoke hole. The cartridge is inserted in the cold mass after the SS shell welding and before the electrical connections to the magnets and the end dome welding.

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-13: The busbars must include expansion loops, to be contained within the end cover section and able to accommodate up to 30 mm of axial movement due to differential thermal expansion/contraction. The maximum force allowed for a 30 mm displacement is 500 N, to be confirmed after manufacturing of the first cold mass.

R-O-03: The busbars will include maximum four internal splices. Each splice resistance target value must be less than 1.0 nΩ at 1.9 K. A target value at room temperature will also be specified after the completion of the prototype program. An acceptance threshold will be defined after the completion of the short model program.

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

R-T-14: Splices are to be soldered with CERN approved materials [12]

Note:

- The joint resistance is measured with voltage taps.

R-T-15: The 35 A leads and the CLIQ leads are copper resistive leads. The cross-section of the 35 A leads and the CLIQ lead has a 10 mm^2 cross-section.

11. Electrical/Instrumentation Requirements

11.1. Instrumentation

R-T-16: In each cold mass, two temperature sensors will be installed. These sensors are the short type thermometer assembly (36 mm x 12 mm x 10 mm) typically used by CERN and specified in [13]

The location is chosen to minimize the radiation dose and to give the most reliable information for both magnets. Two sensors in the same positions are used for redundancy. The thermometer assemblies will be calibrated and supplied by CERN.

R-T-17: The LMQXFA cold mass assembly includes a minimum of 16 voltage taps. The Quench Detection voltage taps should follow MQXFA redundancy requirement (see [1] R-T-15).

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:

11.2. Instrumentation Wiring

R-T-18: Instrumentation wires type, preliminary quantity and function are given in Table 2.

R-T-19: The LMQXFA instrumentation wiring must exit the cold mass assembly through the helium vessel connection. Instrumentation of each magnet will exit the cold mass on opposite sides.

Note:

- The routing and termination of the wiring will be specified in the interface document [4][15].

A preliminary list of the LMQXFA instrumentation wires is shown in Table 2.

Table 2: LMQXFA Instrumentation wiring

LMQXFA Wiring	Qty	Type
Voltage Taps	40	26 AWG polyamide coated wire
Temperature Sensor Leads for Tunnel operation	16	30 AWG polyamide coated wire
Temperature Sensor leads for Test stand operation	4	4x36 AWG polyamide + tefcell quad twist single strand wire
Warm Up Heater Leads	8	18 AWG polyamide coated wire
Quench Heater Leads	32	18 AWG polyamide coated wire

11.3. Voltage Limits

R-T-20: The LMQXFA cold mass assembly voltage limits must meet or exceed the MQXFA voltage limit requirements specified in [1].

11.4. Survey

R-T-21: The LMQXFA cold mass assembly will have 12 mirrors positioned in groups of 4, in the mid-point and towards the cold mass ends, at 45°, 135°, 225° and 315°, to be used for the monitoring of the position of the cold mass inside the cryostat.

These mirrors have to be fixed to the SS shell in the positions and with tolerances that will be specified by CERN. The mirrors will be provided by CERN. The mirrors will reflect the laser beam sent through a hole in the cryostat vessel and thermal shields.

12. Quench Requirements

R-T-22: The LMQXFA quench performance requirements must meet or exceed the MQXFA magnet quench performance requirements specified in [1].

R-O-05: After a thermal cycle to room temperature, LMQXFA cold mass should attain the nominal operating current with no more than 2 quenches.
(NOTE: This objective requirement might be reconsidered and changed to threshold after additional testing experience is obtained on the first two pre-series cold masses).

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.

12.1. Free Cross Section

R-T-23: After installation and routing of heat exchanger tubes, instrumentation wiring, and superconducting busbars 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.

13. 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 expected radiation damage over the HL-LHC lifetime to a maximum of 35 MGy. This value is similar to the expected radiation doses for the nominal LHC [2], and is reached only in some locations of the cold mass, namely around the magnet aperture. Therefore, lower radiation hardness requirements can be accepted depending on the location in the cold mass.

R-T-24: All LMQXFA components should withstand a maximum radiation dose of 35 MGy or shall be approved by CERN for use in a specific location

14. Reliability Requirements

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

R-T-28: LMQXFA cold mass shall be capable of continuous steady-state operation at nominal current in pressurized static superfluid helium (HeII) bat at 1.3 bar and at a temperature of 1.9K.

15. 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-25: 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 Documents [4].

16. Safety Requirements

Each HL-LHC work package will be subject to safety requirements specified in a CERN "Launch Safety Agreement (LSA)" document [7]. 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-26: The LMQXFA cold mass assembly must comply with CERN's Launch Safety Agreement (LSA) for IR Magnets (WP3) [7]

17. CERN Provided Parts

R-T-27: CERN provided parts for LMQXFA assemblies are specified in [14]. These parts for the prototype and series (including spares) will be supplied by CERN.

18. Functional Requirements Summary Tables

Table 3: LMQXFA Threshold Functional Requirements Specification Summary Table

ID	Description
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 (296 K).**
R-T-02	**The LHe stainless steel vessel outer diameter, including tolerances, must not exceed 630 mm. This dimension is at room temperature (296 K).**
R-T-03	**The LMQXFA end cover must include piping listed in Table 1 for cryogenic and electrical connectivity purposes.**
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 (i) the CERN-supplied 74 mm OD (plus 2 mm for tolerance value) heat exchanger tubes and their supports through the MQXFA cooling channels, of (ii) the busbar cartridge used to connect in series the two magnets making the cold mass, and of (iii) the cold bore.**
R-T-05	**The LMQXFA magnetic elements are two identical MQXFA magnets connected in series and with the same polarity. The MQXFA magnets must satisfy the MQXFA requirements specification [1] and the LMQXFA interface specification [4].**

R-T-06	**The distance between the two nodal points of the MQXFA magnetic lengths is 4806 mm ± 5 mm at nominal operating temperature (1.9 K).**
R-T-07	**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 [7][8][9].**
R-T-08	**The LMQXFA pressure vessel material for the cylindrical shell and end covers must be Austenitic Stainless Steel Grade 316LN with Co content lower than 0.1%.**
R-T-09	**The LMQXFA provides a 1.9 K helium vessel that must be designed for a Maximum Allowable Working Pressure (MAWP) of 20 bar differential with an applied test pressure of 25 bar differential.**
R-T-10a	**R-T-10a: The LMQXFA cold mass assembly, as installed and operated in the LHC machine, must be capable of sustaining loads resulting from up to 20 bar of pressure differential without physical damage or performance degradation. The load conditions on the cold mass support posts are specified in [10].**
R-T-10b	**R-T-10b: The fixed points of the MQXFA magnet shall not move inside the LMQXFA cold mass when subject to 2.5 bar differential pressure between the ends of each MQXFA magnet in accordance with a global pressure gradient of 5 bar linearly distributed over the cold mass length (induced by cryogenic operation or by quench of other magnets [11] version 1.0) and this load shall not introduce any physical damage or performance degradation during the cryomagnet lifetime.**
R-T-11	**The LMQXFA cold mass will have two main superconducting leads on each side going through the busbar line connection. An additional pair of resistive leads (trim) are required to have current unbalance up to 35 A between the two magnets during operation. The additional leads exit the cold mass through the helium vessel connection. Four additional resistive leads (CLIQ, two per magnet) are required for protection system. These four additional leads exit the cold mass through the helium vessel connection.**
R-T-12	**The 18 kA busbars will be made with the same Nb-Ti cable used for the connections of the magnet.**
R-T-13	**The busbars must include expansion loops, to be contained within the end cover section and able to accommodate up to 30 mm of axial movement due to differential thermal expansion/contraction. The maximum force allowed for a 30 mm displacement is 500 N, to be confirmed after manufacturing of the first cold mass.**
R-T-14	**Splices are to be soldered with CERN approved materials [12].**
R-T-15	**The 35 A leads and the CLIQ leads are copper resistive leads. The cross-section of the 35 A leads and the CLIQ lead has a 10 mm^2 cross-section.**
R-T-16	**In each cold mass, two temperature sensors will be installed. These sensors are the short type thermometer assembly (36 mm x 12 mm x 10 mm) typically used by CERN and specified in [13]**
R-T-17	**The LMQXFA cold mass assembly includes a minimum of 16 voltage taps. The Quench Detection voltage taps should follow MQXFA redundancy requirement (see [1] R-T-15).**
R-T-18	**Instrumentation wires type, preliminary quantity and function are given in Table 2.**
R-T-19	**The LMQXFA instrumentation wiring must exit the cold mass assembly through the helium vessel connection. Instrumentation of each magnet will exit the cold mass on opposite sides.**
R-T-20	**The LMQXFA cold mass assembly voltage limits must meet or exceed the MQXFA voltage limit requirements specified in [1]**
R-T-21	**The LMQXFA cold mass assembly will have 12 mirrors positioned in groups of 4, in the mid-point and towards the cold mass ends, at 45°, 135°, 225° and 315°, to be used for the monitoring of the position of the cold mass inside the cryostat.**
R-T-22	**The LMQXFA quench performance requirements must meet or exceed the MQXFA magnet quench performance requirements specified in [1].**
R-T-23	**After installation and routing of heat exchanger tubes, instrumentation wiring, and superconducting busbars there must be a free LMQXFA cross section area of 150 cm^2 in the helium volume.**

R-T-24	**All LMQXFA components should withstand a maximum radiation dose of 35 MGy, or shall be approved by CERN for use in a specific location.**
R-T-25	**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].**
R-T-26	**The LMQXFA cold mass assembly must comply with CERN's Launch Safety Agreement (LSA) for IR Magnets (WP3) [7].**
R-T-27	**CERN provided parts for LMQXFA assemblies are specified in [14]. These parts for the prototype and series (including spares) will be supplied by CERN.**
R-T-28	**LMQXFA cold mass shall be capable of continuous steady-state operation at nominal current in pressurized static superfluid helium (HeII) bat at 1.3 bar and at a temperature of 1.9K.**

Table 4: LMQXFA Objective Functional Requirements Specification Summary Table

ID	**Description**
R-O-01	**R-O-01: The maximum deviation of each MQXFA magnet axis along the common magnetic axis must be within ±0.5 mm both in horizontal and in vertical direction. The deviation of each MQXFA field angle from the common magnetic field angle must be within ±2 mrad.**
R-O-02	**The common magnetic axis of the two-magnet system should be determined with respect to cold mass fiducials with accuracy of ±0.2 mm to both nodal points. The common average MQXFA field angle with respect to cold mass fiducials should be measured with accuracy better than 0.5 mrad. The magnetic length and the nodal points of each of the two MQXFA magnets in the cold mass need to be known within ±1 mm accuracy relative to external fiducials.**
R-O-03	**R-O-03: The busbars will include maximum four internal splices. Each splice resistance target value must be less than 1.0 nΩ at 1.9 K. A target value at room temperature will also be specified after the completion of the prototype program. An acceptance threshold will be defined after the completion of the short model program.**
R-O-04	**LMQXFA reliability requirements are the same as the MQXFA reliability requirements specified in [1].**
R-O-05	**After a thermal cycle to room temperature, LMQXFA cold mass should attain the nominal operating current with no more than 2 quenches.**

19. References

[1] MQXFA Functional Requirements, US-HiLumi-doc-36, EDMS 1535430
[2] High-Luminosity Large Hadron Collider (HL-LHC). Technical Design Report, edited by G. Apollinari, I. Béjar Alonso, O. Brüning, M. Lamont, L. Rossi, CERN-2017-007-M
[3] Acceptance Criteria Document, EDMS 2323981.
[4] LMQXFA Interface Control Documents: US-HiLumi-doc-210 and US-HiLumi-doc-372 EDMS 1868475
[5] L. Bottura, D. Missiaen, "Definitions of Survey and Magnetic Data for the Inner Triplet Systems at IR1, 2, 5 and 8", CERN EDMS 367802 .
[6] Alignment procedure for the triplet magnets in the cold mass, in preparation. EDMS 2324506
[7] CERN Launch Safety Agreement for IR Magnets (WP3), CERN EDMS 1550065.
[8] Conformity approach for Pressure Equipment for the High Luminosity LHC Project, CERN EDMS 1698982.
[9] Exceptional Approach to Conformity Assessment of Pressure Vessels in WP3, CERN EDMS 1753780

[10] Design load cases for the support posts of the HL-LHC cryo-magnetsEDMS NO. 1868420.
[11] Requirements on pressure waves in the MQXF magnets EDMS NO. 2675955 v.1.0
[12] Soldering material and procedure defined by CERN EDMS 2324588.
[13] LHC-QIT-ES-0001 rev 1.1, "LHC Cryogenic Thermometers" EDMS 107381
[14] "Exchange of components between HL LHC AUP and CERN for the triplet", CERN EDMS 1825173.
[15] "Triplet electrical Wiring Scheme", US-HiLumi-doc-968 EDMS 2002347