U.S. DEPARTMENT OF ENERGY | Office of Science

U.S. HiLumi Project

LMQXFA/B COLD MASS

FUNCTIONAL REQUIREMENTS SPECIFICATION

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Revision History

Revision	Date	Section No.	Revision Description
1.0	10/13/15	All	Initial Draft

TABLE OF CONTENTS

1. Purpose

This document specifies the functional requirement for the High Luminosity LHC (HL-LHC, or HiLumi LHC) LMQXFA/B Cold Masses. Ten (10) of these cold masses are expected to be fabricated and delivered to CERN by the U.S. HiLumi project 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 (Cold Mass LMQXFA) and Q3 (Cold Mass LMQXFB) inner triplet optical elements in front of the interactions points 1(ATLAS) and 5 (CMS). Two MQXFA magnets are installed in each LMQXFA/B Cold Mass. MQXFA functional requirements are specified in [1]. Requirements for LMQXFA and LMQXFB are very similar, with differences noted in this document.

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

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 [2].

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

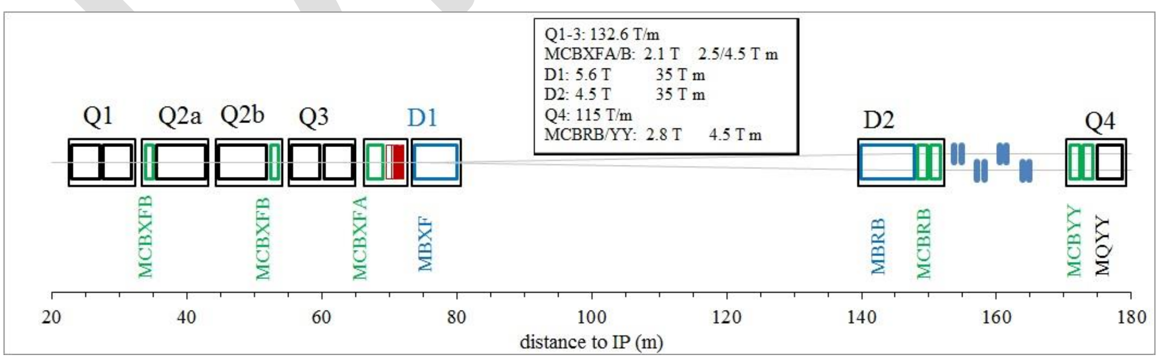

Figure 1: Conceptual layout of the IR region of HL-LHC– thick boxes are magnets, thin boxes are cryostats

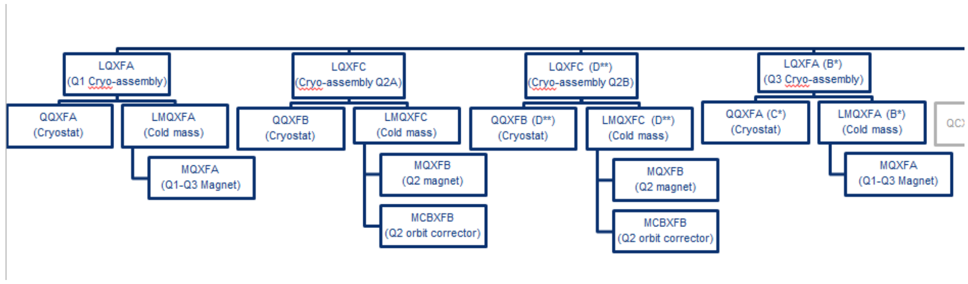

Figure 2: CERN Naming Conventions for HL-LHC Inner Triplets

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 MQXFA 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 Cold Mass (LMQXFA) or the Q3 Cold Mass (LMQXFB), see Figure 3. Q2a and Q2b each consist of a single unit MQXFB ~ 7m long. The LMQXFA or LMQXFB, 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.

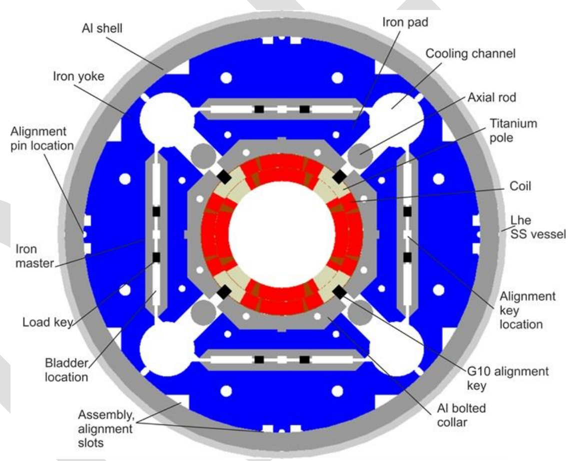

Figure 2: MQXFA Cross Section

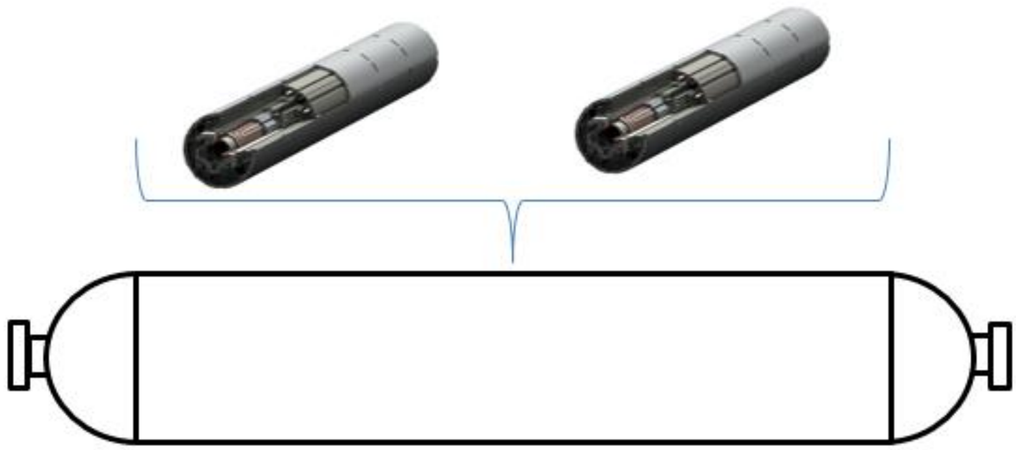

Figure 3: LMQXFA/B conceptual Cold Mass Assembly comprising of two MQXFA magnet elements

2.1. Institutional responsibilities

[RC Note: This section may be moved to a higher-level document when available, it is included here for reference]

The MQXFA magnet production is expected to be the responsibility of the U.S. HiLumi Project. The LMQXFA and LMQXFB Cold Mass assembly production responsibility is TBD [RC Note: the cold mass assembly is part of the US-HiLumi tentative baseline, pending CERN/DOE approved collaboration agreement]. CERN is responsible for the design and assembly of the QQXFA and QQXFC cryostat assemblies and for the production of Q2a, Q2b. Table 1 shows a list of anticipated institutional responsibilities and quantities (including spares) for HL-LHC Inner Triplet Nb_3Sn magnets.

Table 1: Anticipated institutional responsibilities for HL-LHC Inner Triplet Nb_3Sn Magnets

		Qty	U.S.	CERN
LQXFA	**Q1 Cryo-assembly**	5		X
QQXFA	Cryostat	5		X
LMQXFA	Cold Mass	5	TBD	TBD
	Beam Screen			X
MQXFA	Magnets	10	X	
LQXFA (B*)	**Q3 Cryo-assembly**	5		X
QQXFA (C*)	Cryostat	5		X
LMQXFA (B*)	Cold Mass	5	TBD	TBD
	Beam Screen			X
MQXFA	Magnets	10	X	
Q2A				
QQXFB	Cryostat	5		X
LMQXFC	Cold Mass	5		X

MQXFB	Magnet	5		X
MCBXFB	Corrector	5		X
Q2B				
QQXFB (D*)	Cryostat	5		X
LMQXFC (D*)	Cold Mass	5		X
MQXFB	Magnet	5		X
MCBXFB	Corrector	5		X

3. Functional Requirements Overview

The LMQXFA/B functional requirements are the main technical requirements for the LMQXFA/B Cold Mass Assembly 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.

Some requirements in this document are expressed using CERN terms such as “nominal”, “target”, and “ultimate”. 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 functional requirements specified in this document are verified at threshold level, then the U.S. HiLumi MQXFA magnet deliverables will be fit for the intended use and satisfy CERN’s needs for the HL-LHC upgrade.

Detailed acceptance criteria and procedures will be defined in a separate document. 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 5 and 6 summarize all MQXFA threshold and objective functional requirements.

4. Physical Requirements

4.1. Physical Envelope Requirements

R-T-01: The LMQXFA/B assembly physical length (cold bore flange to cold bore flange) must be TBD mm, and the physical shell outer diameter must not exceed 630 mm. These dimensions are at room temperature (296 K).

These LMQXFA/B dimension constraints are dictated by the available LHC tunnel space for installation of Q1 and Q3. With a maximum MQXFA outer diameter of 614 mm [1], the maximum MQXFA shell thickness is 8 mm. Note that 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 4: LMQXFA/B Physical Envelope Dimensions

[RC Note: please verify the length, I could not find a good source for this number]

4.2. Piping Requirements

Figure 5 shows a conceptual drawing of the LMQXFA/B piping at the IP end, and table 2 shows the functional description for each pipe. The same pipe arrangement is at the non-IP end.

Figure 5: conceptual layout of LMQXFA/B piping at the IP end and non-IP end (not to scale)

[RC Note: This piping layout is a guess. Note that in the present cold mass, one pipe (M4) was left completely open for heat transport and quench venting. This layout no longer provides this function (the cross section of M1 and M2 is occupied with either instrumentation wires and connectors or busses, and the previously open pipe is now occupied with a heat exchanger tube and renamed “L2”). Is this a problem for quench venting? Please verify and correct as necessary.]

Table 2: LMQXFA/B piping functions

Pipe	Function
V	Cold Bore Tube
M1	Helium Vessel Connection (Bus Routing)
M2	Helium Vessel Connection (Instrumentation Routing)
L1	Heat Exchanger External Shell 1
L2	Heat Exchanger External Shell 2

Pipes L1 and L2 must be aligned with the two upper MQXFA magnet yoke cooling channels. The exact dimensions and positions for each pipe are specified in [3].

R-T-02: LMQXFA/B must include piping of minimum inner diameter TBD mm allowing for two heat exchangers passing straight through the upper half of the MQXFA, and in addition two identically sized pipes in the lower half symmetric with the upper passages (see Figure 5 and Table 2 for a concept layout).

The LMQXFA/B heat exchanger is a Helium II bayonet heat exchanger type similar in concept to the present inner triplet heat exchanger [8]. However, the main differences are that there are two instead of one heat exchanger tube, and these tubes are installed in the two MQXFA magnet yoke upper cooling channels (see Figure 2) instead of inside a dedicate pipe in the pressure vessel [2].

The heat exchanger tubes are outside the scope of the LMQXFA/B cold mass assembly deliverable, and it is part of CERN's scope for the complete Q1 and Q3 assemblies. However, the cold mass assembly must leave a clear and free space for CERN to insert the heat exchanger tubes:

R-T-10: The LMQXFA/B cold mass assembly must not have any obstructions or interferences to allow insertion of two 74 mm OD heat exchanger tubes and their supports through the top two MQXFA cooling channels and along the entire LMQXFA/B length.

[RC Note: since the heat exchangers tubes can be inserted/removed from the cold mass assembly, I am proposing to make these part of CERN's scope. We would have to have re-usable heat exchanger tubes for the cold mass testing. Does this make sense? Are the heat exchanger tubes part of the cold mass assembly or part of the cryostat? If they are part of the cold mass assembly, then another option would be for CERN to supply the HT tubes and for Fermilab to install them, just like the cold bore tube. Need to discuss and agree]

5. Magnetic Elements Requirements

R-T-04: The LMQXFA/B magnetic elements are two identical MQXFA magnets connected in series. The MQXFA magnets must satisfy the MQXFA functional requirements specification [1] and the LMQXFA/B interface specification [3].

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

6. Alignment Requirements

The distance between the two MQXFA magnets inside the cold mass is critical for the accelerator layout and performance, and also for the magnet to magnet splices design. The magnetic length of each MQXFA is 4.2 m at 1.9K [1]. Figure 6 shows dimensions and distances for Q1A and Q1B (Q2A and Q3B are the same) assumed in the present lattice layout [Reference?]. Therefore, the requirement for minimal distance between magnetic lengths inside LMQXFA/B is:

R-T-05: The distance between MQXFA magnetic lengths is 646 mm ± TBD mm at nominal operating temperature (1.9K) [reference to lattice layout?]

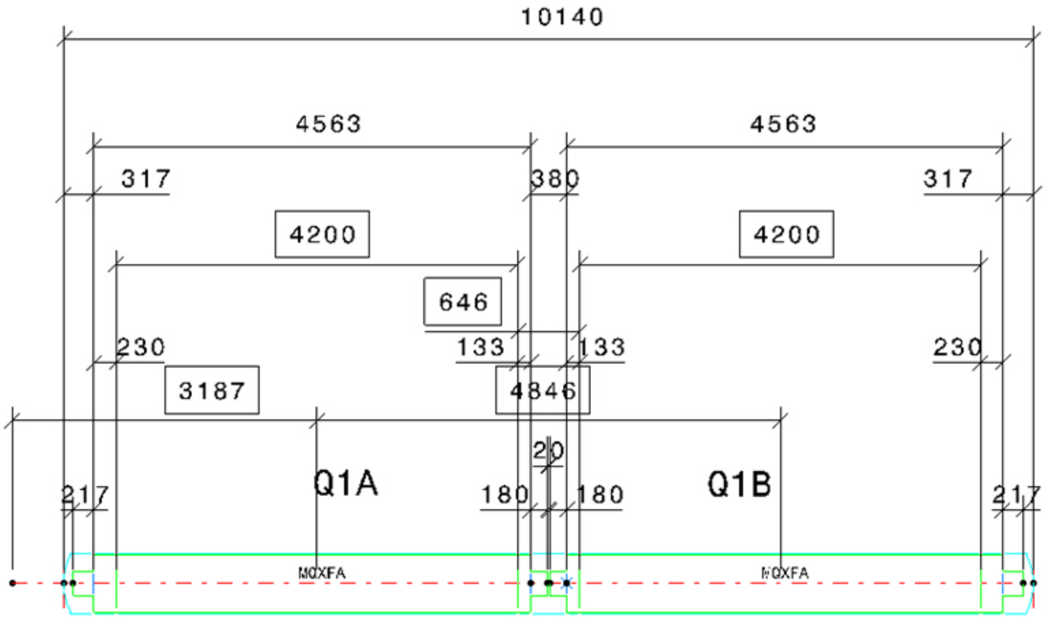

Figure 6: Dimensions and distances for Q1A and Q1B. Number within squares are at cold temperature

Reference [5] shows that in the current MQXFA design the minimum distance between magnetic lengths is 618 m at warm, in the hypothesis of contact between the magnets. Therefore, the 646 mm of distance between magnetic lengths at cold temperature seems feasible.

R-O-01: The relative alignment target requirements of two MQXFA magnetic axis within the LMQXFA/B Cold Mass Assembly are: transverse offset within 500 microns, relative roll within 1 mrad, and relative pitch and yaw within 0.1 mrad.

The relative alignment target requirement comes from [4], and it is the same specification for the present Q2a and Q2b in LMQXB (see LHC-LQX-ES-0006 rev 1.2). All values shown are for the average magnetic axes of each individual MQXFA magnetic element.

[RC Note: the analysis in the reference was for the present Q2 magnetic elements MQXB (Q2a and Q2b). Please verify and confirm that the same values can be used for the MQXFA Q1 and Q3 magnetic elements]

Note that the cryostat must include an adjustment system to modify the relative position of the MQXFA magnets over a range of a few mm transversely and few mrad in roll during cold testing. This functionality is indispensable for obtaining good final alignment, as the experience with the present Q2 demonstrated. This is not a requirement for LMQXFA/B, but it is a requirement for the cryostats QQXFA/C which are part of CERN's scope.

[RC Note: this was a difficult requirement to satisfy for the present Q2s. Note that the cold mass shell had a cylindrical sleeve in the middle with circumferential welds. This allowed to use additional weld passes on some sections as a "weld straightening" technique as described in "Alignment of Production Quadrupole Magnets for the LHC Interaction Regions", IEEE Transactions on Applied Superconductivity, Vol. 14, No. 2, June 2004 and "LHC Interaction Region Quadrupole Cryostat Production, Alignment, and Performance Summary", IEEE Transactions on Applied Superconductivity, Vol. 13. No. 2, June 2003. The alignment of the ends of the magnets was observed to depend to a large extent on the way it is supported, which ultimately relies on the cryostat. In the case of Q2, fasteners are inserted from outside the vessel to anchor the cold mass assembly into final alignment]

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 1.9K testing. The assumption is that low current alignment measurements are representative of alignment at any other currents. Therefore:

R-T-06: The LMQXFA/B 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.

[RC Note: maybe voltage taps or CLIQ leads can be used for this purpose, but need to make sure. If that does not work, dedicated leads may be needed. The present Q2s had a separate main bus to allow powering each Q2a/Q2b magnet independently at full current. We are not planning to have this capability for Q1/Q3 because each magnet will be individually trained at the BNL vertical test stand. This was not the case for Q2, where each magnet was trained in the horizontal test stand after they were installed in the cold mass assembly and cryostated]

7. Pressure Vessel Requirements

R-T-07: The LMQXFA/B is a pressure vessel that must be designed and documented in accordance with CERN and US-HiLumi safety agreements [6].

[RC Note: This is a potential cost and schedule driver for the U.S. project, and we need to agree on the exact terms of this requirement such as welding, radiography, and other inspection and certification requirements soon! This agreement is not expected to include a CE mark or ASME stamped vessel, but the vessel is expected to be designed in accordance to ASME.]

R-T-08: The LMQXFA/B pressure vessel material for the cylindrical shell and end domes must be Austenitic Stainless Steel Grade 304L. The material for the cold bore is specified in R-12.

[RC Note: this is the material that was used for the present Q2 cold mass assembly. Please verify this requirement. Are other grades acceptable? Nearest European steel designation is X2CrNi 19-11 I believe]

R-T-09: The LMQXFA/B 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/B cold mass assemblies can experience asymmetric axial forces due to quench on other magnets and other events.

R-T-10: The LMQXFA/B cold mass assembly must be capable of sustaining axial loads resulting from up to 20 bar of pressure differential without physical damage or performance degradation.

[RC Note: is this the correct way to specify axial loads? Other sources of these or other external loads? How to verify this requirement?]

9. Cold Bore Requirements

The cold bore is inserted in the completed LMQXFA/B assembly, centered 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/B and includes supports and insulation as specified in [3]

R-T-11: The LMQXFA/B beam tube material must be seamless Austenitic Stainless Steel Grade 316LN and must comply with CERN technical specification LHC-VCC-CI-0001 and interface requirements specified in [3].

The cold bore material (316LN stainless steel) is difficult to find in the U.S. Therefore, as it was done for the present MQXB bore tubes, CERN will provide the cold bores for installation in the LMQXFA/B cold mass assembly at no cost to US-HiLumi.

10. Electrical/Instrumentation Requirements

10.1. Instrumentation

R-T-12: 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]

The thermometer assemblies will be calibrated and supplied by CERN.

R-T-13: A 50 W warm up heater attached to each of the four MQXFA end plates.

These heaters are independently powered.

[RC Note: will CERN supply these heaters?]

Beam loss monitors will be located inside the triplet cold mass to have the possibility of monitoring beam losses closer to the beam pipe and to the coil. Installation of special beam loss monitors in one of the iron holes not used by the heat exchangers or by the busbars is foreseen:

R-T-14: A beam loss monitor located in one of the iron yoke cooling channels not used by the heat exchanger tubes or by the busbars.

This beam loss monitor will be supplied by CERN.

R-T-15: The LMQXFA/B 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.

[RC Note: voltage taps are the only way to very verify splice resistance at 1.9K. Internal MQXFA splice resistance between Nb_3Sn and Nb-Ti is verified during MQXFA vertical test, so no voltage taps are needed in the cold mass assembly for those splices]

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

10.1. Instrumentation Wiring

R-T-16: 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, and beam loss monitor are TBD wires.

[RC Note: I took these wiring sizes from the present LMQXB functional requirements. Please verify that this is still the case for Q1 and Q3]

CERN will provide all wires used within the LMQXFA/B cold mass assemblies.

All instrumentation and control wiring inside the end volume is routed through the inner triplet quadrupoles back to the DFBX, where the wiring for the inner triplet is routed to room temperature en masse. Therefore, the LMQXFB (Q3) cold mass assembly routes more instrumentation wiring than LMQXFA (Q1):

R-T-17: The LMQXFB (Q3) cold mass assembly must have provisions to route all instrumentation wiring from LMQXFA (Q1), LMQXFC (Q2a), and LMQXFD (Q2b).

[RC Note: This is the case for the present inner triplet. Please verify this is this still the case]

A complete tabulation of the instrumentation wires passing through the LMQXFA/B cold mass assembly is shown in Table 3.

Table 3: Instrumentation wiring passing through LMQXFA/B

LMQXFA Wiring	**Qty**	**Description**
Voltage Taps	TBD	26 AWG polyamide coated wire
Temperature Sensor Leads	TBD	30 AWG polyamide coated wire
Warm Up Heater Leads	TBD	20 AWG polyamide coated wire
Quench Heater Leads	TBD	20 AWG polyamide coated wire
Beam Loss Monitor	TBD	TBD
LMQXFB Wiring	**Qty**	**Description**
Voltage Taps	TBD	26 AWG polyamide coated wire
Temperature Sensor Leads	TBD	30 AWG polyamide coated wire
Warm Up Heater Leads	TBD	20 AWG polyamide coated wire
Quench Heater Leads	TBD	20 AWG polyamide coated wire
Beam Loss Monitor	TBD	TBD

10.1. Instrumentation Connectors

R-T-18: LMQXFA/B instrumentation wiring must be terminated in Hypertronic-style connectors similar to the ones used in the present inner triplets. The exact connector pin layout is specified in [3]

[RC-Note: are these hypertronic connectors CERN preferred way to connect the instrumentation wiring for Q1, Q2, and Q? Maybe the preference is to terminate as loose wires with labels? Need to agree on a termination method].

10.2. Electrical Busses

The main bus is made by soldering Nb-Ti Cable (specs for this cable?) rated for 20 kA to a copper only cable fabricated to the same dimensions. Two of these buses are assembled together to provide all the high current bus required in the LMQXFA/B, as shown in Figure 4. A G11 housing is placed around the bus assembly before insertion in the cold mass assembly. Expansion loops are needed in the end domes of the assembly to accommodate thermal contraction/expansion of the bus work both internal to the cold mass assembly and external, resulting in the following requirement:

R-T-19: The bus work must include expansion loops at both LMQXFA/B end domes sufficient to accommodate up to TBD mm of axial movement of the bus work due to differential expansion and contraction.

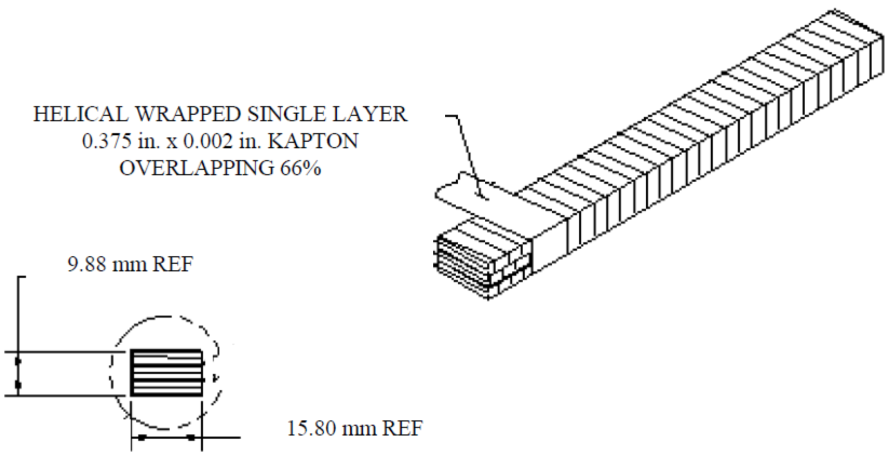

Figure 7: Main buswork in LMQXFA/B, before packaging in housing

[RC Note: This figure needs to be updated for the LMQXFA/B bus work]

Each MQXFA magnet has a (+) Nb-Ti lead and a (-) Nb-Ti lead. These leads are spliced to the LMQXFA/B main bus cables, and there are CERN requirements for the splice resistance and flux used for these splices:

R-T-20: Splices are to be soldered with CERN approved materials [TBD]

R-O-02: Splice resistance target is less than 2 nΩ at 1.9K.

The joint resistance is measured with voltage taps.

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

R-T-21: The LMQXFA/B assembly must include TBD leads for CLIQ. These leads are specified in [TBD].

10.3. Voltage Limits

R-T-22: The LMQXFA/B cold mass assembly voltage limits must meet or exceed the MQXFA voltage limit requirements specified in [1].

11. Quench Requirements

R-T-23: The LMQXFA/B 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-24: After installation and routing of heat exchanger tubes, instrumentation wiring, and superconducting busses there must be a free LMQXFA/B cross section area of TBD mm^2 in the helium volume to allow for an adequate quench venting path.

[RC Note: I think the present plan is to route the main bus and instrumentation wiring inside the MQXFA lower cooling channels. The upper cooling channels are already used for the heat exchanger tubes. Note that in the present inner triplet, all four cooling channels cross sections are free from obstructions because the wiring, busses, and heat exchanger tubes are routed in dedicated slots or pipes. As a result, there is a low resistance venting path through the cooling channels in case of a quench which will no longer be the case for LMQXFA/B. Please verify that these obstructions are OK from quench venting point of view and calculate how much free cross section area is needed.]

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 (Figure 8) 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 [1]. Table 4 shows a map of maximum radiation dose

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

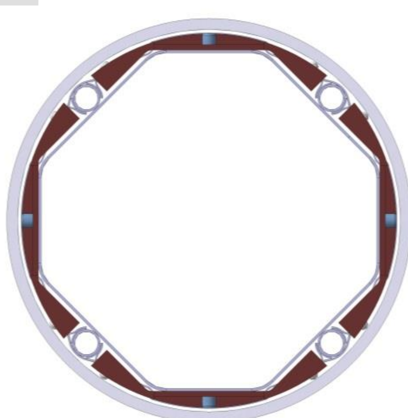

Figure 8: Beam screen (grey) with tungsten shielding (dark brown) and cooling tubes in Q1 (left) and in Q2-D1 (right)

13. Reliability Requirements

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

14. Interface Requirements

The LMQXFA/B 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. Dump Resistor
    d. 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/B 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 [3].

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-26: The LMQXFA/B cold mass assembly must meet the corresponding Work Package (WP) Launch Safety Agreement (LSA) specifications [6].

[RC Note: This is a potential cost and schedule driver for the U.S. project, we need to agree on the exact terms of this requirement soon! No CE marking or ASME stamp is expected as part of the U.S. deliverable]

16. CERN Provided Parts

R-T-27: CERN provided parts for LMQXFA/B assemblies are specified in Table 5.

Table 5: LMQXFA/B CERN provided parts

Item	Quantity
Beam tubes	10
Heat exchanger tubes[1]	20
Instrumentation wire AWG 20	TBD km
Instrumentation wire AWG 26	TBD km
Thermometer cable, 4 x AWG 30 (twisted)	TBD km
Temperature Sensors	40
Warm up heaters	20
Beam Loss Monitor	1
Instrumentation Connectors and Feedthroughs (if applicable)	TBD

[1]If Heat Exchanger Tubes are part of the cold mass assembly scope (to be discussed)

17. Functional Requirements Summary Tables

ID	Description
R-T-01	The LMQXFA/B assembly physical length (cold bore flange to cold bore flange) must be **TBD** mm, and the physical shell outer diameter must not exceed **630** mm. These dimensions are at room temperature (296 K).
R-T-02	LMQXFA/B must include piping of minimum inner diameter **TBD** mm allowing for two heat exchangers passing straight through the upper half of the MQXFA, and in addition two identically sized pipes in the lower half symmetric with the upper passages (see Figure 5 and Table 2 for a concept layout)
R-T-03	The LMQXFA/B cold mass assembly must not have any obstructions or interferences to allow insertion of two **74** mm OD heat exchanger tubes and their supports through the top two MQXFA cooling channels and along the entire LMQXFA/B length.
R-T-04	The LMQXFA/B magnetic elements are two identical MQXFA magnets connected in series. The MQXFA magnets must satisfy the MQXFA functional requirements specification [1] and the LMQXFA/B interface specification [3]
R-T-05	The distance between MQXFA magnetic lengths is **646** mm ± **TBD** mm at nominal operating temperature (1.9K) [reference to lattice layout?]
R-T-06	The LMQXFA/B 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-07	The LMQXFA/B is a pressure vessel that must be designed and documented in accordance with CERN and US-HiLumi safety agreements [5]
R-T-08	The LMQXFA/B pressure vessel material for the cylindrical shell and end domes must be Austenitic Stainless Steel Grade **304L**. The material for the cold bore is specified in R-12
R-T-09	The LMQXFA/B provides a 1.9K helium vessel that must be designed for a Maximum Allowable Working Pressure (MAWP) of **20** bar differential.
R-T-10	The LMQXFA/B cold mass assembly must be capable of sustaining axial loads resulting from up to **20** bar of pressure differential without physical damage or performance degradation.
R-T-11	The LMQXFA/B beam tube material must be seamless Austenitic Stainless Steel Grade **316LN** and must comply with CERN technical specification LHC-VCC-CI-0001 and interface requirements specified in [3].
R-T-12	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-13	A **50** W warm up heater attached to each of the four MQXFA end plates.
R-T-14	A beam loss monitor located in one of the iron yoke cooling channels not used by the heat exchanger tubes or by the busbars.
R-T-15	The LMQXFA/B 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-16	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, and beam loss monitor are **TBD** wires.
R-T-17	The LMQXFB (Q3) cold mass assembly must have provisions to route all instrumentation wiring from LMQXFA (Q1), LMQXFC (Q2a), and LMQXFD (Q2b).
R-T-18	LMQXFA/B instrumentation wiring must be terminated in Hypertronic-style connectors similar to the ones used in the present inner triplets. The exact connector pin layout is specified in [3]
R-T-19	The bus work must include expansion loops at both LMQXFA/B end domes sufficient to accommodate up to **TBD** mm of axial movement of the bus work due to differential expansion and contraction.
R-T-20	Splices are to be soldered with CERN approved materials [TBD]
R-T-21	The LMQXFA/B assembly must include **TBD** leads for CLIQ. These leads are specified in [**TBD**].

R-T-22	The LMQXFA/B cold mass assembly voltage limits must meet or exceed the MQXFA voltage limit requirements specified in [1].
R-T-23	The LMQXFA/B quench performance requirements must meet or exceed the MQXFA magnet quench performance requirements specified in [1].
R-T-24	After installation and routing of heat exchanger tubes, instrumentation wiring, and superconducting busses there must be a free LMQXFA/B cross section area of **TBD** mm^2 in the helium volume to allow for an adequate quench venting path.
R-T-25	The LMQXFA/B 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 [3].
R-T-26	The LMQXFA/B cold mass assembly must meet the corresponding Work Package (WP) Launch Safety Agreement (LSA) specifications [5].
R-T-27	CERN provided parts for LMQXFA/B assemblies are specified in Table 5.

Table 6: LMQXFA/B Objective Functional Requirements Specification Summary Table

ID	Description
R-O-01	The relative alignment target requirements of two MQXFA magnetic axis within the LMQXFA/B Cold Mass Assembly are: transverse offset within **500** microns, relative roll within **1** mrad, and relative pitch and yaw within **0.1** mrad.
R-O-02	Splice resistance target is less than **2** nΩ at 1.9K.
R-O-03	All MQXFA components can withstand a maximum radiation dose of **30** MGy.
R-O-04	LMQXFA/B 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] HL-LHC Preliminary Design Report, v0.6.55, October 27 2014.

[3] LMQXFA/B Interface Specification (to be defined)

[4] Tanaji Sen, "Alignment Tolerances of IR Quadrupoles in the LHC", FERMILAB-Conf-99/304, LHC IR Alignment Workshop, Fermilab, October 4-5, 1999 (to be updated by CERN)

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

[6] LMQXFA/B Launch Safety Agreement (to be defined)

[7] Soldering flux applied to the main bus-bar cables of the LHC, LHC-DC-ES-0003 rev 1.0

[8] P. Lebrun et al, "Cooling Strings of Superconducting Devices below 2K: The Helium II Bayonet Heat Exchanger", LHC Project Report 144, CEC-ICMC 1997, Portland-OR-USA, July 28-August 1 1997

[9] 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")