U.S. HiLumi Project

MQXFA MAGNETS

FUNCTIONAL REQUIREMENTS SPECIFICATION

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Revision History

Revision	**Date**	**Section No.**	**Revision Description**
1.0	TBD	All	Initial Draft Release
Draft	5/7/15		Incorporated comments from Lucio Rossi
Draft	8/10/15		Incorporated comments from Ezio Todesco
Draft	8/17/15		Added section on definitions
Draft	9/22/15		Incorporated comments from Ezio Todesco and Giorgio Ambrosio
Draft	10/9/15		Incorporated comments from Giorgio Apollinari, Giorgio Ambrosio, Jim Kerby
Draft	10/13/15		Incorporated additional comments by Jim Kerby

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1. Purpose

This document specifies the functional requirement for the High Luminosity LHC (HL-LHC, or HiLumi LHC) MQXFA Magnets. Twenty (20) of these magnets 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 magnets 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 Q1 or Q3. Since these magnets are identical whether installed in Q1 or Q3, the functional requirements are identical for all MQXFA magnets.

If all the threshold functional requirements specified in this document are verified, then the U.S. HiLumi MQXFA magnet 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 MQXFA 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 [1].

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

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. 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). 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.

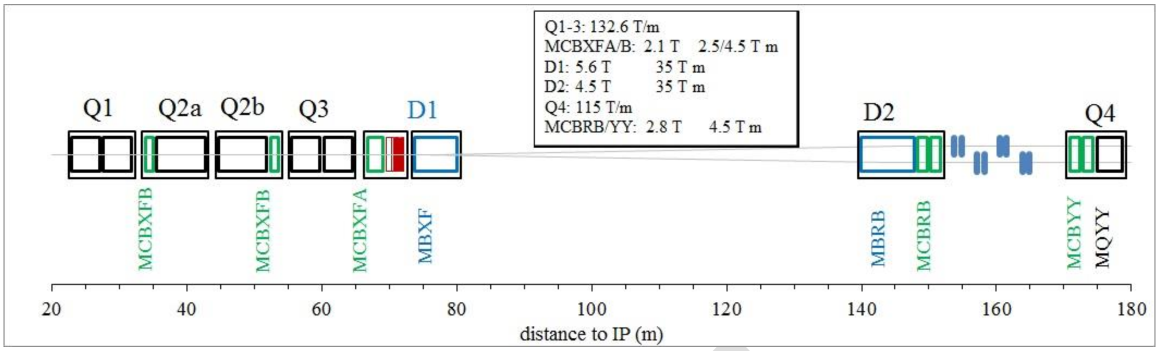

Figure 1**:** Conceptual layout of the IR region of HL-LHC– thick boxes are magnets, thin boxes are cryostats

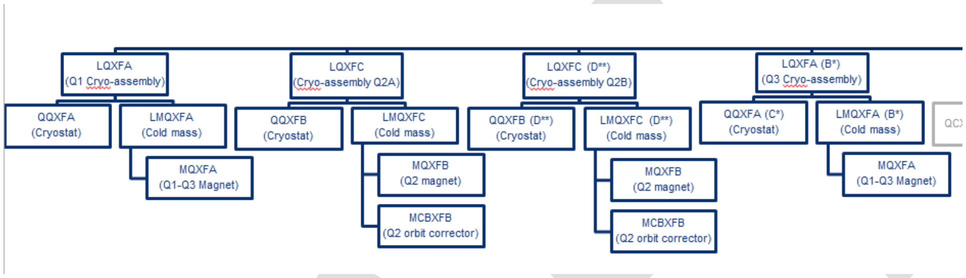

Figure 2: CERN Naming Conventions for HL-LHC Inner Triplets

This functional requirements specification is for MQXFA only, however most of the requirements are the same for MQXFB (the length is the main exception). There will be mutual benefit, for CERN and USHiLumi, in keeping the MQXFA and MQXFB designs as close to each other as possible. A separate functional requirements specification will be written for cold mass assembly, LMQXFA and LMQXFB.

The MQXFA preliminary design (Figures 3 and 4) consists of four 2-layer Nb_3Sn coils. The quadrupole makes use of an aluminum-shell based structure developed within the LARP collaboration. Coils are mainly prestressed by the Al shell during the cool-down, acting as the structure to contain the Lorentz forces during powering. The level of stress is fine-tuned during the loading of the coil, which is done at room temperature using water-pressurized bladders and interference key [1].

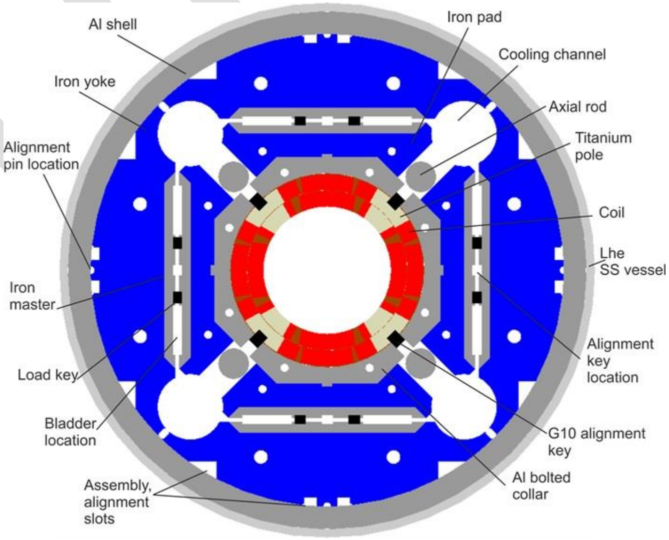

Figure 3: MQXFA cross-section

Figure 4: MQXFA 3-D conceptual cutaway view

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 MQXFA functional requirements are the main technical requirements for the MQXFA 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.

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 4 and 5 summarize all MQXFA threshold and objective functional requirements.

4. Physical Requirements

4.1. Coil Aperture Requirement

R-T-01: The MQXFA coil aperture requirement is 150 mm. This aperture is the coil inner diameter at room temperature, excluding ground insulation, cold bore and beam screens.

This aperture represents an increase of 80 mm over the present LHC inner triplet coil aperture of 70 mm. The larger aperture is a key MQXFA requirement for HL-LHC, because it allows a smaller β^* and higher luminosity. Advances in Nb_3Sn technology for superconducting magnets allow this increase in aperture while keeping the magnet length at acceptable values.

4.2. Physical Envelope Requirements

R-T-02: The MQXFA physical outer diameter must not exceed 614 mm.

The MQXFA physical outer diameter is defined by the outer diameter of the MQXFA structure Aluminum shell (see Figures 3 and 4). The stainless steel shell installed around the Aluminum shell is part of the cold mass assembly scope (LMQXFA/B) and not part of the MQXFA scope.

The diameter limitation is driven by the available physical space envelope in the tunnel provided by CERN, which is 630 mm for the maximum outer diameter of the LMQXFA/B stainless steel vessel shell. A maximum outer diameter of 614 mm for the MQXFA Aluminum shell leaves sufficient space for an 8 mm thick wall stainless steel shell capable of sustaining the peak pressure requirement of 20 bar.

4.3. Twist and Straightness Requirements

[RC Note: after discussion with Ezio and Giorgio: specify that these are mechanical measurements, define terms, provide background as to how to measure, call them targets, etc. This requirement needs more clarification and understanding. It was taken from the present inner triplet MQXB magnet requirements]

R-O-01: MQXFA magnet mechanical twist target is < 1 mrad / 5m, and mechanical straightness target is < 100 μm / 5 m

5. Magnetic Field Requirements

5.1. Operating Gradient

R-T-03: The MQXFA magnet must be capable of reaching a nominal operating gradient of 132.6 T/m and an ultimate gradient of 143 T/m. These values are in superfluid helium at 1.9 K and for the magnetic length specified in R-T-04.

Verification of this requirement is expected to involve testing the magnet in a vertical test stand to a maximum test current corresponding to the ultimate gradient of 143 T/m (17.8 kA). This is consistent with quench training requirement R-T-18.

The inner triplets Q1 and Q3 ramp with the energy of the LHC, with a nominal gradient of 8.5 T/m at 450 GeV, and of 132.6 T/m at 7 TeV. During squeeze, its gradient is constant or decreases by no more than 10% [1].

5.2. Magnetic Length

R-T-04: The MQXFA magnetic length requirement is 4.2 meters at 1.9 K.

[RC Note: definition of magnetic length?]

The required magnetic length of Q1 or Q3 is 8.4 meters. Q1 or Q3 are made up of two MQXFA magnets, therefore the MQXFA magnetic length is 4.2 meters.

5.3. Field Quality

R-O-02: The MQXFA field harmonics must be optimized at high field. Table 2 provides specific target values for field harmonics at a reference radius of 50 mm.

Table 2: Expected systematic harmonics in the triplet, with separation of head contributions

	Triplet field quality version 4 - May 20 2015 - R_{ref}=50 mm															
	Straight part										Ends		Integral			
	Systematic						Uncertainty		Random				Q1/Q3		Q2a/b	
Normal	Geometric	Ass. & cool	Saturation	Persistent	Injection	High Field	Injection	High Field	Injection	High Field	Conn. Side	Non conn. Side	Injection	High Field	Injection	High Field
2									10	10						
3	0.000	0.000	0.000	0.000	0.000	0.000	0.820	0.820	0.820	0.820			0.000	0.000	0.000	0.000
4	0.000	0.000	0.000	0.000	0.000	0.000	0.570	0.570	0.570	0.570			0.000	0.000	0.000	0.000
5	0.000	0.000	0.000	0.000	0.000	0.000	0.420	0.420	0.420	0.420			0.000	0.000	0.000	0.000
6	-2.200	0.900	0.660	-20.000	-21.300	-0.640	1.100	1.100	1.100	1.100	8.943	-0.025	-16.692	0.323	-18.593	-0.075
7	0.000	0.000	0.000	0.000	0.000	0.000	0.190	0.190	0.190	0.190			0.000	0.000	0.000	0.000
8	0.000	0.000	0.000	0.000	0.000	0.000	0.130	0.130	0.130	0.130			0.000	0.000	0.000	0.000
9	0.000	0.000	0.000	0.000	0.000	0.000	0.070	0.070	0.070	0.070			0.000	0.000	0.000	0.000
10	-0.110	0.000	0.000	4.000	3.890	-0.110	0.200	0.200	0.200	0.200	-0.189	-0.821	3.119	-0.175	3.437	-0.148
11	0.000	0.000	0.000	0.000	0.000	0.000	0.026	0.026	0.026	0.026			0.000	0.000	0.000	0.000
Skew																
2									10.000	10.000	-31.342		-2.985	-2.985	-1.753	-1.753
3	0.000	0.000	0.000	0.000	0.000	0.000	0.650	0.650	0.650	0.650			0.000	0.000	0.000	0.000
4	0.000	0.000	0.000	0.000	0.000	0.000	0.650	0.650	0.650	0.650			0.000	0.000	0.000	0.000
5	0.000	0.000	0.000	0.000	0.000	0.000	0.430	0.430	0.430	0.430			0.000	0.000	0.000	0.000
6	0.000	0.000	0.000	0.000	0.000	0.000	0.310	0.310	0.310	0.310	2.209		0.210	0.210	0.124	0.124
7	0.000	0.000	0.000	0.000	0.000	0.000	0.190	0.190	0.190	0.190			0.000	0.000	0.000	0.000
8	0.000	0.000	0.000	0.000	0.000	0.000	0.110	0.110	0.110	0.110			0.000	0.000	0.000	0.000
9	0.000	0.000	0.000	0.000	0.000	0.000	0.080	0.080	0.080	0.080			0.000	0.000	0.000	0.000
10	0.000	0.000	0.000	0.000	0.000	0.000	0.040	0.040	0.040	0.040	0.065		0.006	0.006	0.004	0.004
11	0.000	0.000	0.000	0.000	0.000	0.000	0.026	0.026	0.026	0.026			0.000	0.000	0.000	0.000
	Magnetic length straight part				Q1/Q3	3.459	Q2a/b	6.409	Mag. Len. Ends		0.400	0.341				

Contributions of the coil ends have to be taken into account and optimized and/or compensated through the straight part [1].

Random components are estimated for a 25 µm random error in the block positioning for non-allowed, and 100 µm for the allowed (see Table 2); most critical components are low order harmonics (b3, a3, b4, a4). Magnetic shimming is allowed for correcting these components [1**]**.

5.4. Fringe Field

R-O-03: The fringe field target at a TBD cm distance from the MQXFA magnetic field axis is 50 mT or less.

6. Cryogenic Requirements

6.1. Operating Temperature

R-T-05: MQXFA magnets must be capable of operation in pressurized static superfluid helium (HeII) bath at 1.3 bar and at a temperature of 1.9 K

6.2. Heat Loads

The primary heat load in MQXFA magnets is collision debris from the interaction point. Although the HL-LHC has a nominal luminosity 5 times larger than the nominal design goal of the LHC, CERN is planning to install a newly designed absorber, using thick tungsten (W) shielding attached to the outer surface of the beam screen to reduce the effect of collision debris on both MQXFA radiation damage and heat load (Figure 7). This new absorber is assumed to be installed and working as expected for the following requirements.

6.2.1. Coil Peak Power

MQXFA magnets are expected to operate under a coil peak power of 4 mW/cm^3 (at ultimate peak luminosity). For reference, the present Nb-Ti LHC inner triplet has a target of 4 mW/cm^3 coil peak power; however, as a result of the tungsten screen previously mentioned, the coil peak power expected for MQXFA coils are always below the present target of 4 mW/cm^3.

6.2.2. Total Heat Load

The static heat load on the MQXFA magnets is mainly due to collision debris. In Q1 the collision debris is expected to generate a heat load of 110 W [1].

6.3. Cooling Requirements

Cooling is ensured via two 68-mm-inner-diameter heat exchangers in which saturated HeII circulates. In these heat exchangers the heat is extracted by vaporization of the superfluid helium which travels as a low pressure two-phase flow through them. The bayonet heat exchangers are installed in-line through all the Inner Triplet magnets (Q1, Q2a, Q2b, Q3) and interconnects, with a possible phase separator at the Q2a-Q2b interconnect.

6.3.1. Provisions for installation of Heat Exchangers Tubes

The heat exchanger tubes are required to carry a total inner triple heat load of 800 W at a luminosity of 7.5×10^{34} cm^2 s^{-1}. This requirement resulted in the following CERN choices and parameters relevant to MQXFA [2]:

R-T-06: The MQXFA cooling channels must be capable of accommodating two (2) heat exchanger tubes running along the length of the magnet in the yoke cooling channels. The minimum diameter of the MQXFA yoke cooling channels that will provide an adequate gap around the heat exchanger tubes is 77 mm

6.3.2. Provisions for heat extraction

R-T-07: At least 40% of the coil inner surface must be free of polyamide.

This is a measureable requirement to keep the peak operating coil within its temperature margin.

The heat loads from the coils and the beam-pipe area can only evacuate to the two heat exchangers mentioned above by means of the static pressurized HeII. To this end the MQXFA cold mass design shall incorporate the necessary helium passages specified in [1] and [2], resulting in:

R-T-08: The MQXFA must have provisions for the following cooling passages: (1) Free passage through the coil pole and subsequent G-10 alignment key equivalent of 8 mm diameter holes repeated every 50 mm; and (2) free helium paths interconnecting the yoke cooling channels holes

[RC Note: more details about this requirement, in particular (2)?]

6.4. Peak Pressure

The maximum internal pressure in the MQXFA magnet structure is 20 bar, set by the cold mass helium vessel Maximum Allowable Working Pressure (MAWP). Peak pressures might be experienced by the MQXFA magnet after a full energy magnet system quench, and will be kept below the MAWP by the CERN supplied relief system. Therefore:

R-T-09: The MQXFA magnet structure must be capable of sustaining a sudden rise of pressure from atmospheric up to 20 bar without damage and without degradation of subsequent performance.

6.5. Cooldown and Warmup

The maximum temperature gradient imposed on the MQXFA magnet during cooldown and warmup is expected to be during testing. The temperature gradient during cooldwon and warmup in the tunnel is expected to be less than this upper limit. Therefore:

R-T-10: The MQXFA magnet structure must be capable of surviving a maximum temperature gradient of TBD K during testing without degradation in its performance.

[RC Note: Need to find out what is this temperature gradient at the BNL, FNAL, and CERN test facilities]

7. Electrical Requirements

The HL-LHC quadrupole Triplets (Q1, Q2 and Q3) are powered via two main circuits, each equipped with one trim power converter. The two Q2 units are powered in series with a 100 A trim converter on Q2b. Q1 and Q3 are powered in series with a 2 kA trim converter on Q3 (Figure 6). The trim is needed for special beam measurements requiring a different powering between Q1 and Q3.

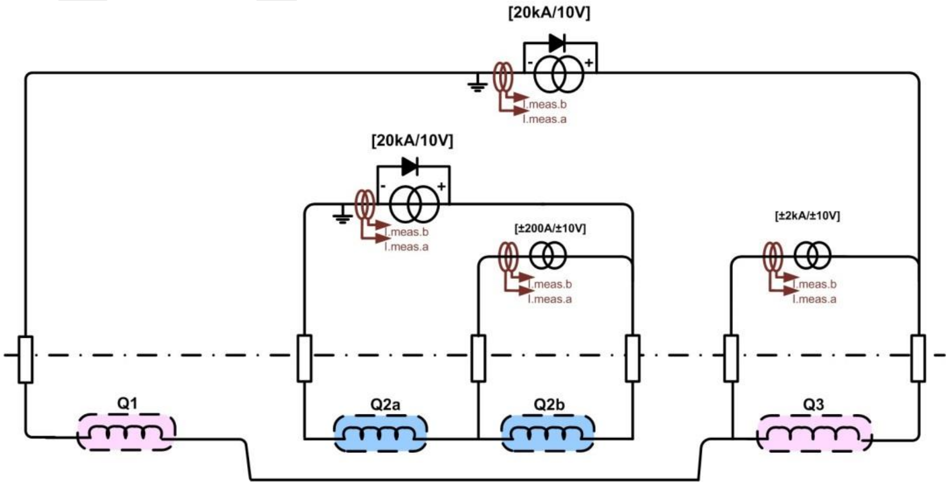

Figure 6: Powering layout of the High-Luminosity Inner Triplets

7.1. Operating Current

The planned capacity of HL-LHC electrical circuits is 18 kA. The nominal MQXFA operating current is expected to be 16.45 kA, and the ultimate operating current is expected to be 17.8 kA [1]

7.2. Maximum Operating Current Ramp Rate

R-T-11: The MQXFA magnets must be capable of operating at the ramp rate of 14 A/s

7.3. Maximum Operating Voltage

The differential inductance of the MQXFA cold mass (two 4.2 m long magnets in series) is expected to be 68±1 mH at nominal current. During operation, the 14 A/s ramp rate creates a voltage of ~1 V at the end of the cold mass. The maximum operating voltage is during a quench, therefore the requirement is:

R-T-12: The MQXFA magnet must withstand a maximum operating voltage of 800 V to ground during quench.

7.4. Electrical Busses

R-T-13: MQXFA magnets must be delivered with a (+) Nb-Ti superconducting lead and a (-) Nb-Ti superconducting lead, both rated for 18 kA and adequately stabilized for connection to the Cold Mass LMQXFA or LMQXFAB electrical bus.

These leads must be adequately spliced to the Nb_3Sn coil cable. Both leads must come out at the same end of MQXFA magnet. The requirement for splices are:

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

R-O-04: Splice resistance target is less than 2 nΩ at 1.9K.

The joint resistance is measured with voltage taps.

R-O-5: The MQXFA cross section must have provisions for routing the LMQXFA or LMQXFB superconducting busses. This is anticipated to be done by using available yoke cooling channels without heat exchanger tubes.

[RC Note: this is still under discussion, pending CERN analysis of free cross section area for adequate helium venting during quench]

7.5. Instrumentation

R-T-14: Voltage Taps: the MQXFA magnet shall be delivered with three (3) quench detection voltage taps located on each magnet lead and at the electrical midpoint of the magnet circuit; two (2) voltage

taps for each quench strip heater; and two (2) voltage taps for each internal MQXFA Nb_3Sn-NbTi splice.

7.6. Voltage Limits

R-T-15: The MQXFA magnet coils and quench protection heaters must pass a hi-pot test in liquid helium at 1 atm pressure as specified in Table 3.

Table 3: Required hi-pot test voltages and leakage current in liquid helium at 1 atm pressure

Circuit Element	**Vmax**	**V hi-pot**	**I hi-pot**
Quench Protection Heaters - Coil	500 V	TBD	< TBD µA
Magnet Coil - Ground	1,000 V	TBD (2,500 V?)	< TBD µA

[RC Note: Values for this table are still under discussion with CERN]

8. Quench Requirements

8.1. Quench Training Requirements

R-T-18: MQXFA magnets must be delivered trained to a current of 108% (17.8 kA) of the nominal operating current.

The training current corresponds to the ultimate gradient specified in R-T-01. This requirement sets an upper limit to the MQXFA magnet test current.

R-O-06: After training and after following a thermal cycle to room temperature, MQXFA magnets can attain the nominal operating current with a target of no more than 1 quench.

8.2. Quench while ramping down

R-T-19: MQXFA magnets must not quench while ramping down at 300 A/s from the nominal operating current

8.3. Quench Protection

MQXFA quench protection will be accomplished with CERN supplied power supplies, CERN supplied quench detection system, and CERN supplied strip heater power supplies, through the use of MQXFA voltage taps and quench protection strip heaters. A CERN supplied CLIQ (Coupling Loss Induced Quench) system is also under consideration.

The MQXFA magnet must have voltage taps located on each magnet lead and at the electrical midpoint of the magnet circuit as specified in **R-20**. This configuration allows quenches to be detected via a voltage imbalance between half magnet coil circuits. Once a quench is detected in any element in the inner triplet, the power supply system will be turned off and all quench protection strip circuits in all magnets in the triplet will be energized.

R-T-20: The MQXFA quench protection components must be compatible with the CERN-supplied quench protection system and comply with the corresponding interface document specified by CERN [3]

This is an important interface between MQXFA and CERN supplied equipment. The quench protection system is a highly integrated system with a complex interface between CERN supplied equipment and MQXFA components.

9. Radiation Hardness Requirements

The MQXFA magnet structure 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 7) 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]. Note that this value is for the coil components, other MQXFA structure components will be subject to a lower expected dose.

R-O-07: All MQXFA components can withstand a maximum radiation dose of 30 MGy.

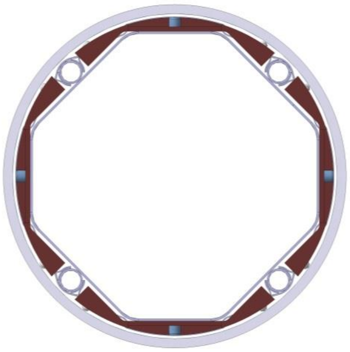

Figure 7: Beam screen (grey) with tungsten shielding (dark brown) and cooling tubes in Q1 (left) and in Q2-D1 (right)

10. Reliability Requirements

The MQXFA magnets are expected to sustain 10 years of HL-LHC operation under nominal luminosity conditions, limited primarily by the integrated dose to the materials in the coils. In the course of these 10 operational years, the magnets are expected to survive the following conditions:

10.1. Number of Thermal Cycles

R-O-08: MQXFA magnets can survive 25 thermal cycles during HL-LHC tunnel operations.

10.2. Number of Powering Cycles

R-O-09: MQXFA magnets can survive 3,000 powering cycles during HL-LHC tunnel operations.

10.3. Number of Quenches

R-O-10: MQXFA magnets can survive 50 quenches during HL-LHC tunnel operations.

[RC Note: how do we verify the number of thermal cycles and number of powering cycles?. For the number of quenches, is it sufficient to provide data from prototypes?]

11. Interface Requirements

The MQXFA magnet structure interfaces with the following systems:

1. The LMQXFA or LMQXFB System, including:
    a. The 1.9 K stainless steel helium vessel, including the beam pipe and end domes
    b. Two heat exchanger pipes installed in the MQXFA yoke cooling channels
    c. The LMQXFA or LMQXFB electrical busbars and instrumentation wiring system
2. The CERN supplied Cryogenic System, consisting of:
    a. The CERN supplied cooling system
    b. The CERN supplied pressure relief system
3. The CERN supplied power system
4. 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
5. The CERN supplied instrumentation system

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

R-T-21: The MQXFA magnets must meet the detailed interface specifications with the following systems: (1) other LMQXFA(B) Cold Mass components; (2) 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] (to be defined)

12. Safety Requirements

Each HL-LHC work package will be subject to safety requirements specified in a CERN "Launch Safety Agreement (LSA)" document [1]. 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-22: The MQXFA magnets must meet the corresponding Work Package (WP) Launch Safety Agreement (LSA) specification [4] (to be defined).

No pressure vessel or welding components are expected to be present in MQXFA.

[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!]

13. CERN Provided Parts

MQXFA CERN provided parts are under discussion, and are not expected to be part of the functional requirements.

14. Functional Requirements Summary Tables

Table 4: MQXFA Threshold Functional Requirements Specification Summary Table

ID	**Description**
R-T-01	The MQXFA coil aperture requirement **is 150 mm**. This aperture is the coil inner diameter at room temperature, excluding ground insulation, cold bore and beam screens.
R-T-02	The MQXFA physical outer diameter must not exceed **614 mm**.
R-T-03	The MQXFA magnet must be capable of reaching a nominal operating gradient of **132.6 T/m** and an ultimate gradient of **143 T/m**. These values are in superfluid helium at 1.9 K and for the magnetic length specified in R-T-04.
R-T-04	The MQXFA magnetic length requirement **is 4.2 meters** at 1.9 K.
R-T-05	MQXFA magnets must be capable of operation in pressurized static superfluid helium (HeII) bath at **1.3 bar** and at a temperature of **1.9 K**
R-T-06	The MQXFA cooling channels must be capable of accommodating **two (2)** heat exchanger tubes running along the length of the magnet in the yoke cooling channels. The minimum diameter of the MQXFA yoke cooling channels that will provide an adequate gap around the heat exchanger tubes is **77 mm**
R-T-07	At least **40%** of the coil inner surface must be free of polyamide
R-T-08	The MQXFA structure must have provisions for the following cooling passages: (1) Free passage through the coil pole and subsequent G-10 alignment key equivalent of **8 mm** diameter holes repeated every **50 mm**; and (2) free helium paths interconnecting the yoke cooling channels holes
R-T-09	The MQXFA magnet structure must be capable of sustaining a sudden rise of pressure from atmospheric up to **20 bar** without damage and without degradation of subsequent performance.
R-T-10	The MQXFA magnet structure must be capable of surviving a maximum temperature gradient of **TBD K** during testing without degradation in its performance.
R-T-11	The MQXFA magnets must be capable of operating at **14 A/s**
R-T-12	The MQXFA magnet must withstand a maximum operating voltage of **800 V to ground** during quench.
R-T-13	MQXFA magnets must be delivered with a (+) Nb-Ti superconducting lead and a (-) Nb-Ti superconducting lead rated for **18 kA** and adequately stabilized for connection to the Cold Mass LMQXFA or LMQXFAB electrical bus
R-T-14	Voltage Taps: the MQXFA magnet shall be delivered with **three (3)** quench detection voltage taps located on each magnet lead and at the electrical midpoint of the magnet circuit; **two (2)** voltage taps for each quench strip heater; and **two (2)** voltage taps for each internal MQXFA Nb_3Sn-NbTi splice.
R-T-15	The MQXFA magnet coils and quench protection heaters must pass a hi-pot test in liquid helium at 1 atm pressure as specified in **Table 3** (to be defined)
R-T-18	MQXFA magnets must be delivered trained to ultimate current of **108% (17.8 kA)** of the nominal operating current.
R-T-19	MQXFA magnets must not quench while ramping down at **300 A/s** from the nominal operating current
R-T-20	The MQXFA quench protection components must be compatible with the CERN-supplied quench protection system and comply with the corresponding interface document specified by CERN [3] (to be defined)
R-T-21	The MQXFA magnets must meet the detailed interface specifications with the following systems: (1) other LMQXFA(B) Cold Mass components; (2) 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] (all to be defined)
R-T-22	The MQXFA magnets must meet the corresponding Work Package Launch Safety Agreement (LSA) specification [4] (to be defined)

Table 5: LMQXFA/B Objective Functional Requirements Specification Summary Table

ID	**Description**
R-O-01	MQXFA magnet mechanical twist target is < 1 mrad / 5m, and mechanical straightness target is < 100 µm / 5 m
R-O-02	The MQXFA field harmonics must be optimized at high field. Table 2 provides specific target values for field harmonics at a reference radius of **50** mm.
R-O-03	The fringe field target at a **TBD** cm distance from the MQXFA magnetic field axis is **50** mT or less.
R-O-04	Splice resistance target is less than **2** nΩ at 1.9K
R-O-05	The MQXFA cross section must have provisions for routing the LMQXFA or LMQXFB superconducting busses.
R-O-06	After training and after following a thermal cycle to room temperature, MQXFA magnets can attain the nominal operating current with a target of no more than **1** quench.
R-O-07	All MQXFA components can withstand a maximum radiation dose of **30** MGy.
R-O-08	MQXFA magnets can survive **25** thermal cycles during HL-LHC tunnel operations.
R-O-09	MQXFA magnets can survive **3,000** powering cycles during HL-LHC tunnel operations.
R-O-10	MQXFA magnets can survive **50** quenches during HL-LHC tunnel operations.

15. References

[1] HL-LHC Preliminary Design Report, v0.6.55, October 27 2014.

[2] R. van Weelderen, B. Bozza, "Specific QXF cold-mass requirements to ensure a robust cooling by superfluid helium", 4th Joint HiLumi LHC-LARP Annual Meeting, November 17-21 2014, KEK. https://indico.cern.ch/event/326148/timetable/#20141118.detailed

[3] MQXFA Interface Specification (to be defined)

[3] CERN Launch Safety Agreement for MQXFA magnets (to be defined)

[4] CERN Provided Parts for MQXFA magnets (to be defined)