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FUNCTIONAL SPECIFICATION

MQXFA MAGNETS

Abstract

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

Another separate document will be issued by the American contribution for the MQXFA cold mass functional requirements.

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 V1.4

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1.4	2020-04-16	See Revision History in page 3



U.S. HL-LHC Accelerator Upgrade Project

MQXFA MAGNETS

FUNCTIONAL REQUIREMENTS SPECIFICATION

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MQXFA Magnets

Functional Requirements Specification

Revision History

Revision	Date	Section No.	Revision Description
v.0.5	7/8/2016	All	Release for Work Package Review
	5/2/2017	All	Accepted all changes requested by WP2, and Coil-Ground HVW values requested by F. Rodriguez-Mateos at CM28
V.0.9	27/06/2017	All	Document sent for final approval
V1.1	4/30/2019	All	Various revisions for consistency with the latest approved Acceptance Criteria Part A: MQXFA Magnet (EDMS 2031083)
V1.3	2/05/2020	6.3.2, 7.6	6.3.2: fixed typo in R-T-08 (G-10 changed to G-11) 7.6: In R-T-16, added two rows in Table 2 for the additional hi-pot test at 100K specified in the revised Electrical Design Criteria (EDMS 1963398) and removed "before cold test" from the text.
V1.4	4/16/2020	5, 6, 7, 8, 9, 10, 14	R-O-02, updated the table of the multipoles (removed the line of order 2 in normal and skew). R-T-03 integrated gradient of 596.7 T instead of gradient of 143.2 T/m. R-T-10, changed 100 K to 50 K R-O-07 changed from "The MQXFA magnet must provide an integrated gradient between 554 T and 560 T when powered with current of 16.470 kA ..." to "The difference between the integrated gradient of any pair of series magnets powered with the nominal current shall be smaller than 6 T for all magnets, and smaller than 3 T for magnets with the same cross-section. At the same reference current, the MQXFA magnetic length difference of any pair of magnets should not exceed 10 mm. The precision of the measurement of the integrated gradient shall be within $\pm 0.02\%$." Added R-O-09 After a thermal cycle to room temperature, MQXFA magnets shall attain the nominal operating current with no more than one quench. R-T-16: correction of expected Coil to Ground voltage from 670 V to 353 V in Table 3. Fixed typos and made minor corrections. R-T-05 Replaced wording current by gradient Point 6.3.1 Rewording from "The heat exchanger tubes are required to carry a total heat load on Q1 and Q3 of 360 W at a luminosity of $5 \times 10^{34} \text{ cm}^2 \text{ s}^{-1}$ " with The heat exchanger tubes are required to carry a total (static + dynamic) heat load on Q1 and Q3 of 290 W and 305 W respectively, at ultimate luminosity, without margin.

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1. Purpose

This document specifies the functional requirements for the High Luminosity LHC (HL-LHC, or HiLumi LHC) MQXFA Magnets. Twenty (20) of these magnets shall 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 interaction 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 requirements specified in this document are verified, then the U.S. HL-LHC Accelerator Upgrade Project (US HL-LHC AUP) MQXFA magnet deliverables shall be fit for the intended use and satisfy CERN's needs for HL-LHC. The quality of the US HL-LHC AUP MQXFA deliverables will be measured by the degree to which its characteristics fulfill the requirements specified in this document.

2. Introduction

The triplet quadrupoles are the magnetic system that allows 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 Nb₃Sn technology that provides access to magnetic fields well beyond 9 T, allowing the maximization of the aperture of the triplet 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 Nb₃Sn accelerator magnets. The HL-LHC is expected to be the first application of accelerator-quality Nb₃Sn magnet technology in an operating particle accelerator.

For HL-LHC, 20 triplet Nb₃Sn 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. Figure 1 shows a conceptual layout of the HL-LHC interaction region, and Figure 2 shows the CERN nomenclature of the triplet 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 aluminum outer shell, the connection box on the lead end, and the end plate (including its tie-rods) on the return end of each magnet. A pair of ~4.5-m-long MQXFA magnets is installed in a stainless steel helium vessel, including the end domes, to make the Q1 Cold Mass or the Q3 Cold Mass (both called LMQXFA). Q2a and Q2b each consist of a single unit MQXFB ~7.5-m-long magnet.

The LMQXFA, when surrounded by the QXQFA or QXQFC 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.

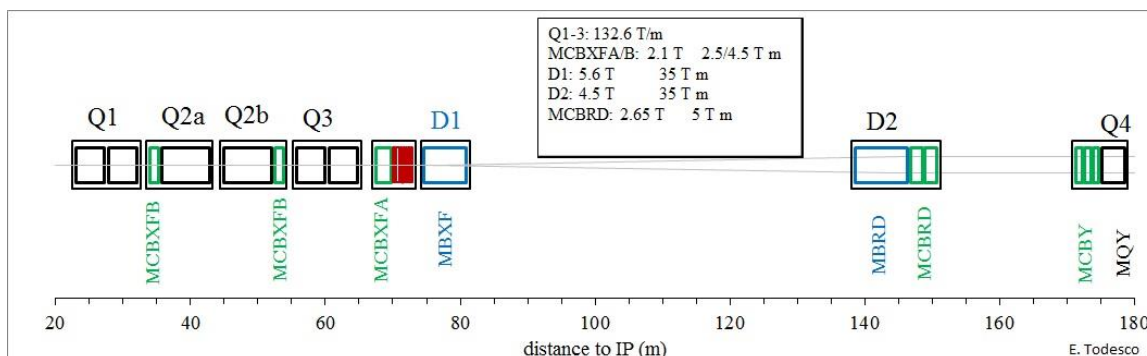


Figure 1: Conceptual layout of the IR region of HL-LHC— thick boxes are magnets, thin boxes are cryostats

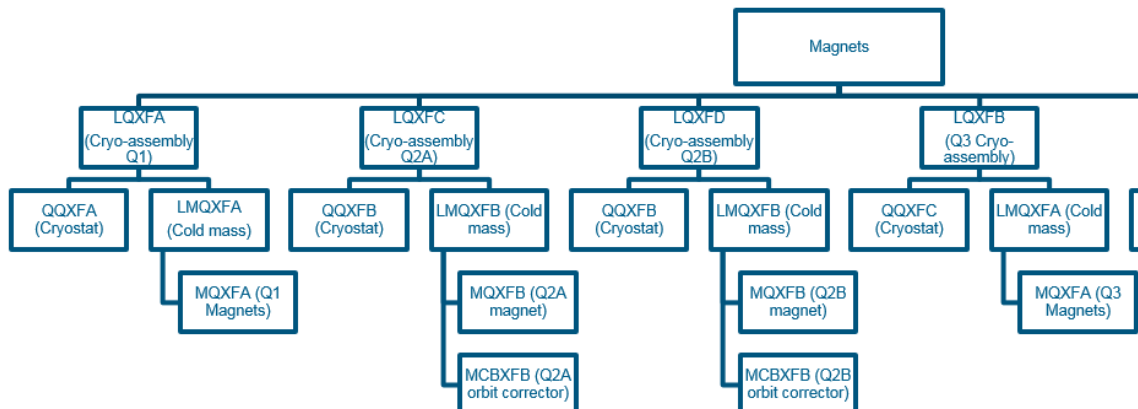


Figure 2: CERN Naming Conventions for HL-LHC Inner Triplets

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 US HL-LHC AUP, 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 MQXF design (Figures 3 and 4) consists of four 2-layer Nb₃Sn coils. The quadrupole makes use of an aluminum-shell based structure developed within the LARP collaboration and optimized by AUP and CERN. Coils are mainly pre-stressed by the Al shells 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 keys [1].

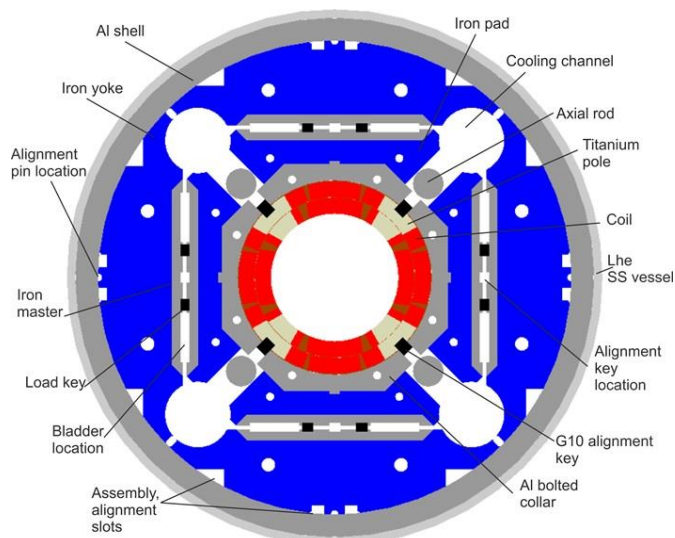


Figure 3: MQXFA cross-section



Figure 4: MQXFA 3-D conceptual cutaway view

3. Functional Requirements Overview

The MQXFA functional requirements are the high-level 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. In addition to functional requirements, this document also includes some non-functional requirements such as reliability, interface, and safety requirements for completeness.

Some requirements in this document may be 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. The CERN/AUP Acceptance Document will describe the acceptance criteria for the magnets, including the case of magnets not fulfilling the objective requirements.

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

Detailed verification procedures and acceptance criteria will be defined in a separate document [7]. 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 MQXFA threshold and objective requirements.

4. Physical Requirements

4.1. Coil Aperture Requirement

R-T-01: The MQXFA coil aperture at room temperature without preload is 149.5 mm. Coil bumpers (pions) of 1.2 mm thickness shall be installed on the four coil poles. The minimum free coil aperture at

room temperature after coil bumpers installation, magnet assembly and preload shall be 146.7 mm. This guarantees an annulus free for HeII of minimum thickness 1.2 mm, average thickness larger or equal to 1.5 mm.

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 Nb₃Sn 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 nominal outer diameter without preload is 614 mm. The MQXFA outer diameter best-fit after assembly and preload shall not exceed 615 mm.

The MQXFA physical outer diameter is defined by the outer diameter of the MQXFA structure aluminum shells (see Figures 3 and 4). The stainless steel shell installed around the aluminum shells 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 cryostat 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. Alignment Requirements

R-O-01: The positions of the local magnetic center and magnetic field angle are measured along the magnet axis with values obtained by averaging sections ≤ 500 mm. In each section, the local magnetic center is to be within ± 0.5 mm from the magnet magnetic axis both in horizontal and in vertical direction. The local magnetic field angle in each section is to be ± 2 mrad from the average magnetic field angle of the whole magnet, with the exception of the first measurement in the connection side where field angle is affected by magnet leads.

5. Magnetic Field Requirements

5.1. Nominal and Ultimate integrated Gradient

R-T-03: The MQXFA magnet must be capable of operating at steady state providing an integrated gradient of 596.7 T in superfluid helium at 1.9 K

This gradient corresponds to the HL-LHC ultimate integrated gradient (operation at 7.5 TeV). We define the nominal integrated gradient as 556.9 T (operation at 7 TeV). Nominal/ultimate current is the average of the currents required to reach nominal/ultimate integrated gradient for all magnets. Their values are given in EDMS 2114564 and shall be updated after successful test of the first three units.

5.2. Magnetic Length and Integrated Gradient spread

R-O-07: The difference between the integrated gradient of any pair of series magnets powered with the nominal current shall be smaller than 6 T for all magnets, and smaller than 3 T for magnets with the same cross-section. At the same reference current, the MQXFA magnetic length difference of any pair of magnets should not exceed 10 mm. The precision of the measurement of the integrated gradient shall be within $\pm 0.02\%$.

During MQXFA coil fabrication the HL-LHC WP3 Leader requested a cross-section change (achieved by swapping midplane and pole shims) in order to adjust b6. The “3-T range” requirement is applicable to magnets with the same cross-section (i.e. either before or after the b6 change).

5.3. Field Quality

R-O-02: The MQXFA field harmonics shall be optimized at nominal current. Table 1 provides expected values for integral field harmonics at a reference radius of 50 mm [5].

Table 1: Expected systematic harmonics in the triplet, with separation of head contributions

<i>Triplet field quality version 4 - May 20 2015 - R_{ref}=50 mm</i>																
Normal	Straight part								Ends		Integral					
	Systematic				Uncertainty		Random		Conn. Side	Non conn. Side	Q1/Q3		Q2a/b			
Geometric	Ass. & cool	Saturation	Persistent	Injection High Field	Injection High Field	Injection High Field	Injection High Field	Injection High Field			Injection High Field	Injection High Field	Injection High Field	Injection High Field	Injection High Field	
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
12	0.000	0.000	0.000	0.000	0.000	0.000	0.018	0.018	0.018	0.018			0.000	0.000	0.000	0.000
13	0.000	0.000	0.000	0.000	0.000	0.000	0.009	0.009	0.009	0.009			0.000	0.000	0.000	0.000
14	-0.790	0.000	-0.080	1.000	0.210	-0.870	0.023	0.023	0.023	0.023	-0.545	-1.083	0.033	-0.856	0.106	-0.862
Skew																
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
12	0.000	0.000	0.000	0.000	0.000	0.000	0.014	0.014	0.014	0.014			0.000	0.000	0.000	0.000
13	0.000	0.000	0.000	0.000	0.000	0.000	0.010	0.010	0.010	0.010			0.000	0.000	0.000	0.000
14	0.000	0.000	0.000	0.000	0.000	0.000	0.005	0.005	0.005	0.005	-0.222		-0.021	-0.021	-0.012	-0.012
Magnetic length straight part					Q1/Q3	3.459	Q2a/b	6.409	Mag. Len. Ends	0.400	0.341					

In the table, we use the following definitions: (i) The standard deviation of the integrated values of the 10 magnets should be smaller or equal to the random; (ii) the average of the integrated values of the 10 magnets will be within the range integral \pm uncertainty. As shown in Table 1, 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 μ m random error in the block positioning for non-allowed, and 100 μ m for the allowed (see Table 1); most critical components are low order harmonics (b3, a3, b4, a4). Magnetic shimming is allowed for correcting these harmonics [1]. Threshold values for harmonics are given in the Acceptance Document [7].

5.4. Fringe Field

R-O-03: The fringe field target, for the magnet installed in the cryostat, is lower than 50 mT at 10 mm from the outer surface of the cryostat.

6. Cryogenic Requirements

6.1. Operating Temperature

R-T-05: MQXFA magnets must be capable of steady-state operation at ultimate gradient 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 an 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 absorber shall be installed in the LQXFA and LQXFB cryoassemblies at CERN.

6.2.1. Coil Peak Power

MQXFA magnets are expected to operate under a maximum coil peak power of 3 mW/cm^3 (at nominal peak luminosity), as in the present Nb-Ti LHC inner triplet. They shall operate at 4.5 mW/cm^3 at ultimate peak luminosity, without margin.

6.2.2. Total Heat Load

The total 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 114 W, and in Q3 of 134 W; both loads are at nominal luminosity of $5 \times 10^{34} \text{ cm}^2 \text{ s}^{-1}$ [1]. They shall operate with a total (static + dynamic) heat load of 290 W and 305 W heat load at ultimate luminosity, without margin.

6.3. Cooling Requirements

Cooling to remove the heat loads mentioned in the previous section 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 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 (static + dynamic) heat load on Q1 and Q3 of 290 W and 305 W respectively, at ultimate luminosity, without margin. This requirement resulted in the following CERN choices and parameters relevant to MQXFA [2]:

R-T-06: The MQXFA cooling channels shall 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 polyimide.

This is a measurable 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-11 alignment key equivalent of 8 mm diameter holes repeated every 50 mm; (2) free helium paths interconnecting the four yoke cooling channels holes; and (3) a free cross sectional area of at least 150 cm^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.

6.5. Cooldown and Warmup

R-T-10: The MQXFA magnet shall be able to survive a maximum temperature gradient of 50 K during a controlled warm-up or cool-down, and to experience the thermal dynamics following a quench without degradation in its performance.

The maximum temperature gradient imposed on the MQXFA magnet during cooldown and warmup is expected to be 50 K during testing. The temperature gradient during cooldown and warmup in the tunnel is expected to be less than this upper limit.

7. Electrical Requirements

7.1. Operating Current

The planned capacity of HL-LHC electrical circuits, including electrical connections inside the magnets, is 18 kA. The nominal MQXFA operating current is expected to be ≤ 16.47 kA, and the ultimate operating current is expected to be ≤ 17.89 kA [1].

7.2. Maximum Operating Current Ramp Rate

R-T-11: The MQXFA magnets shall be capable of operating at any ramp rate within ± 30 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. During a quench, the maximum operating voltage to ground is expected to be 353 V [8].

7.4. Electrical Buses

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 stabilized for connection to the LMQXFA cold mass electrical bus.

These leads must be adequately spliced to the Nb₃Sn 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.

R-T-29: Splice resistance must be less than 1.0 n Ω at 1.9 K.

The joint resistance is measured with voltage taps.

7.5. Instrumentation

R-T-15: Voltage Taps: the MQXFA magnet shall be delivered with three redundant (3x2) quench detection voltage taps located on each magnet lead and at the electrical midpoint of the magnet circuit; and two (2) voltage taps for each internal MQXFA Nb₃Sn-NbTi splice. Each voltage tap used for critical quench detection shall have a redundant voltage tap.

The exact location of each voltage tap will be specified in the interface document [3]

7.6. Voltage Withstand Levels

R-T-16: The MQXFA magnet coils and quench protection heaters shall pass the hi-pot tests specified in Table 2.

Table 2: Required hi-pot test voltages and leakage current

Based on Electrical Design Criteria for HL-LHC Inner Triplet Magnets [8]

Circuit Element	Expected Vmax [V]	V hi-pot	I hi-pot [μ A]***	Minimum time duration [s]
Coil to Ground at RT before helium exposure *	n.a.	3.68 kV	10	30
Coil to Quench Heater at RT before helium exposure *	n.a.	3.68 kV	10	30
Coil to Ground at cold **	353	1.84 kV	10	30
Coil to Quench Heater at cold **	900	2.3 kV	10	30
Coil to Ground at RT after helium exposure *	n.a.	368 V	10	30
Coil to Quench Heater at RT after helium exposure *	n.a.	460 V	10	30
Coil to Ground at 100 \pm 20K and 1.2 \pm 0.2 bar	n.a.	425 V	10	30
Coil to Quench Heater at 100 \pm 20K and 1.2 \pm 0.2 bar	n.a.	425 V	10	30

* Room Temperature conditions refer to air at 20 \pm 3 °C and relative humidity lower than 60%

** Cold conditions refer to nominal cryogenic conditions (superfluid helium)

*** Maximum leakage current does not include leakage of the test station.

For details about the values in Table 2, please refer to CERN's Electrical Design Criteria for the HL-LHC Inner Triplet Magnets [8]

8. Quench Requirements

8.1. Quench Training Requirements

R-T-17: After a thermal cycle to room temperature, MQXFA magnets shall attain the nominal operating current with no more than 3 quenches.

R-O-09: After a thermal cycle to room temperature, MQXFA magnets shall attain the nominal operating current with no more than 1 quench.

8.2. Quench while ramping down

R-T-18: MQXFA magnets shall not quench while ramping down at 150 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 part of the protection scheme.

The MQXFA magnet must have voltage taps located on each magnet lead and at the electrical midpoint of the magnet circuit. 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 or some quench protection strip circuits in all magnets in the triplet will be energized.

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 dose over the HL-LHC accumulated luminosity of 3000 fb^{-1} to a maximum of 35 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-T-20: All MQXFA components must withstand a radiation dose of 35 MGy, or shall be approved by CERN for use in a specific location as shown in MQXFA Materials List [6].

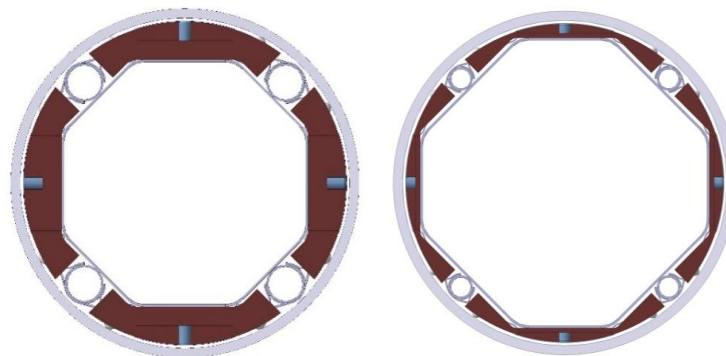


Figure 7: Beam screen (grey) with tungsten shielding (dark brown) and cooling tubes in Q1 (left) and in Q2-D1 (right)

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 radiation 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 Powering Cycles

R-T-30: MQXFA magnets will operate in the HL LHC era for an order of magnitude of 10000 cycles. The long-term reliability of the design will be proven by having a short model magnet submitted to 1000 powering cycles during individual test.

10.2. Number of Quenches

R- T-31: MQXFA magnets must survive at least 50 quenches.

11. Interface Requirements

The MQXFA magnet structure interfaces with the following systems:

1. The LMQXFA System, including:
 - a. The 1.9 K stainless steel helium vessel, including the cold bore tube and end domes
 - b. Two heat exchanger pipes installed in the MQXFA yoke cooling channels
 - c. The LMQXFA 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. CLIQ system
5. The CERN supplied instrumentation system

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

R-T-22: The MQXFA magnets shall meet the interface specifications with the following systems: (1) other LMQXFA Cold Mass components; (2) the CERN supplied power system; (3) the CERN supplied quench protection system; and (4) the CERN supplied instrumentation system. These interfaces are specified in Interface Control Document [3].

12. Safety Requirements

Each HL-LHC work package will be subject to safety requirements specified in a CERN “Launch Safety Agreement (LSA)” document [4]. This LSA specifies 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-23: The MQXFA magnets must comply with CERN’s Launch Safety Agreement (LSA) for IR Magnets (WP3) [4].

No pressure vessel or welding components are expected to be present in MQXFA. Safety requirements are expected to include a list of MQXFA materials and their mass for activation studies, and to have Co traces under 0.1% in weight for massive iron and steel components.

Requirement MQXFA-R-T-24: All travelers must be completed and delivered to CERN, and all NCR must be closed.

13. CERN Provided Parts

MQXFA CERN-provided parts are specified in [9] and are not part of these requirements.

14. Requirements Summary Tables

Table 3: MQXFA Threshold Requirements Specification Summary Table

ID	Description
R-T-01	The MQXFA coil aperture at room temperature without preload is 149.5 mm. Coil bumpers (pions) of 1.2 mm thickness shall be installed on the four coil poles. The minimum free coil aperture at room temperature after coil bumpers installation, magnet assembly and preload shall be 146.7 mm. This guarantees an annulus free for HeII of minimum thickness 1.2 mm, average thickness larger or equal to 1.5 mm.

MQXFA Magnets

Functional Requirements Specification

R-T-02	The MQXFA nominal outer diameter without preload is 614 mm. The MQXFA outer diameter best-fit after assembly and preload shall not exceed 615 mm.
R-T-03	The MQXFA magnet must be capable of operating at steady state providing an integrated gradient of 596.7 T in superfluid helium at 1.9 K (This is now replaced by R-O-07)
R-T-05	MQXFA magnets shall be capable of steady-state operation at ultimate gradient 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 shall 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 polyimide.
R-T-08	The MQXFA structure shall have provisions for the following cooling passages: (1) Free passage through the coil pole and subsequent G-11 alignment key equivalent of 8 mm diameter holes repeated every 50 mm ; (2) free helium paths interconnecting the four yoke cooling channels holes; and (3) a free cross sectional area of at least 150 cm²
R-T-10	The MQXFA magnet shall be able to survive a maximum temperature gradient of 50 K, during a controlled warm-up or cool-down, and to experience the thermal dynamics following a quench without degradation in its performance.
R-T-11	The MQXFA magnets shall be capable of operating at any ramp rate within ±30 A/s .
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 stabilized for connection to the LMQXFA cold mass electrical bus.
R-T-14	Splices are to be soldered with CERN approved materials.
R-T-15	Voltage Taps: the MQXFA magnet shall be delivered with three redundant (3x2) quench detection voltage taps located on each magnet lead and at the electrical midpoint of the magnet circuit; and two (2) voltage taps for each internal MQXFA Nb ₃ Sn-NbTi splice. Each voltage tap used for critical quench detection shall have a redundant voltage tap.
R-T-16	The MQXFA magnet coils and quench protection heaters shall pass the hi-pot tests specified in Table 2 .
R-T-17	After a thermal cycle to room temperature, MQXFA magnets shall attain the nominal operating current with no more than 3 quenches.
R-T-18	MQXFA magnets shall not quench while ramping down at 150 A/s from the nominal operating current
R-T-20	All MQXFA components must withstand a radiation dose of 35 MGy, or shall be approved by CERN for use in a specific location as shown in MQXFA Materials List [6]
R-T-30	MQXFA magnets will operate in the HL LHC era for an order of magnitude of 10000 cycles. The long-term reliability of the design will be proven by having a short model magnet submitted to 1,000 powering cycles during individual test.
R-T-22	The MQXFA magnets shall meet the interface specifications with the following systems: (1) other LMQXFA Cold Mass components; (2) the CERN supplied power system; (3) the CERN supplied quench protection system; and (4) the CERN supplied instrumentation system. These interfaces are specified in Interface Control Documents [3].
R-T-23	The MQXFA magnets must comply with CERN's Launch Safety Agreement (LSA) for IR Magnets (WP3) [4].
R-T-24	All travelers must be completed and delivered to CERN, and all NCR must be closed
R-T-29	Splice resistance must be less than 1.0 nΩ at 1.9 K.
R-T-31	MQXFA magnets must survive at least 50 quenches

MQXFA Magnets

Functional Requirements Specification

Table 4: MQXFA Objective Requirements Specification Summary Table

ID	Description
R-O-01	The positions of the local magnetic center and magnetic field angle are measured along the magnet axis with values obtained by averaging sections ≤ 500 mm. In each section, the local magnetic center is to be within ± 0.5 mm from the magnet magnetic axis both in horizontal and in vertical direction. The local magnetic field angle in each section is to be ± 2 mrad from the average magnetic field angle of the whole magnet, with the exception of the first measurement in the connection side where field angle is affected by magnet leads.
R-O-02	The MQXFA field harmonics shall be optimized at nominal current. Table 1 provides expected values for integral field harmonics at a reference radius of 50 mm .
R-O-03	The fringe field target, for the magnet installed in the cryostat, is lower than 50 mT at 10 mm from the outer surface of the cryostat.
	(This is now R-T-29)
	(This is now R-T-31)
R-O-07	The difference between the integrated gradient of any pair of series magnets powered with the nominal current shall be smaller than 6 T for all magnets, and smaller than 3 T for magnets with the same cross-section. At the same reference current, the MQXFA magnetic length difference between any pair of magnets should not exceed 10 mm. The precision of the measurement of the integrated gradient shall be within $\pm 0.02\%$.
R-O-09	After a thermal cycle to room temperature, MQXFA magnets shall attain the nominal current with no more than 1 quench

15. References

- [1] High-Luminosity Large Hadron Collider (HL-LHC). Technical Design Report, edited by G. Apollinari, I. Béjar Alonso, O. Brüning, M. Lamont, L. Rossi, <http://dx.doi.org/10.23731/CYRM-2017-004>
- [2] D. Bozza and R. van Weelden, HiLumi LHC, FP7 High Luminosity Large Hadron Collider Design Study, Deliverable Report, Design Study of the Cooling, 12 October 2015, CERN-ACC-2015-012, R. van Weelden, https://indico.cern.ch/event/633630/contributions/2573050/attachments/1464927/2264386/Recap_v1.3.pdf and D. Berkowitz, "Preliminary summary of the heat loads on the LSS.R5 of HL-LHC", CERN EDMS [1610730](#)
- [3] Interface Control Document WBS 302.2.02 and 302.4 – CERN WP3, [US-Hilumi-doc-375](#); and Internal Interface Control Document WBS 302.2.07 - 302.4.02, US-HiLumi-Doc-216
- [4] CERN Launch Safety Agreement for IR Magnets (WP3), CERN EDMS [1550065](#)
- [5] R. Wolf, "FIELD ERROR NAMING CONVENTIONS FOR LHC MAGNETS", CERN EDMS [90250](#).
- [6] "MQXFA Material list" US-HiLumi-doc-96 and CERN EDMS [1786261](#)
- [7] Acceptance Criteria Part A: MQXFA Magnet, US-HiLumi-doc-1103 and CERN EDMS [2031083](#)
- [8] Electrical Design Criteria for the HL-LHC Inner Triplet Magnets, CERN EDMS [1963398](#)
- [9] Parts Exchange Between US HL-LHC AUP & CERN HL-LHC WP3, US-HiLumi-doc-844 and CERN EDMS [1825173](#)