



U.S. HL-LHC Accelerator Upgrade Project

MQXFA MAGNETS

FUNCTIONAL REQUIREMENTS SPECIFICATION

Prepared by: Date: Ruben Carcagno, US HL-LHC AUP Deputy Project Manager	Organization FNAL	Contact ruben@fnal.gov (630) 840-3915
Reviewed by: Date: Giorgio Ambrosio, US HL-LHC AUP MQXFA L2 Manager	Organization FNAL	Contact giorgioa@fnal.gov (630) 840-2297
Reviewed by: Date: Ezio Todesco, HL-LHC (IR Magnets) Manager	Organization CERN	Contact Ezio.Todesco@cern.ch
Approved by: Date: Giorgio Apollinari, US HL-LHC AUP Project Manager	Organization FNAL	Contact apollina@fnal.gov (630) 840-4641
Approved by: Date: Lucio Rossi, CERN HL-LHC Project Coordinator	Organization CERN	Contact Lucio.Rossi@cern.ch

MQXFA Magnets

Functional Requirements Specification

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
Draft	2/15/16		<p>Incorporated comments from Feb 2016 QXF Workshop. Summary of changes:</p> <ul style="list-style-type: none"> a. Added paragraph in Functional Requirements Overview to clarify that document also includes some non-functional requirements such as reliability, interface, and safety requirements. b. Consolidated gradient and training current requirements into a single requirement for gradient c. Changed alignment targets based on workshop discussions and further discussions with Herve Prin. These new targets need to be confirmed by CERN. d. Changed "TBD" to 0.5m for the fringe field target distance e. Added a free cross sectional area of 150 cm² to the cooling passages requirements f. Changed "TBD" to 100K as the maximum temperature gradient and eliminated "during testing" g. Removed the powering layout figure and introduction since this is still under discussion at CERN h. Changed splice resistance target from 2 nΩ to 1.5 nΩ i. Eliminated the requirement on routing of electrical buses, this is still under discussion at CERN j. Eliminated the requirement on number of thermal cycles because it is difficult to verify k. Added a note on safety requirements expectations for MQXFA
Draft	5/6/2016		<ul style="list-style-type: none"> a. Changed project name to the official DOE name of "US HL-LHC Accelerator Upgrade Project" (US HL-LHC AUP) throughout the document b. Updated titles on signature page c. Removed section 2.1 "Institutional Responsibilities", this should be specified in a higher level document d. Updated worst case peak voltage to ground to 520 V (E. Ravaoli analysis presented at CERN's HL LHC Circuits Review) e. Updated Reference to CERN's HL-LHC PDR and LSA

TABLE OF CONTENTS

1. PURPOSE	5
2. INTRODUCTION	5
3. FUNCTIONAL REQUIREMENTS OVERVIEW	7
4. PHYSICAL REQUIREMENTS.....	8
4.1. COIL APERTURE REQUIREMENT	8
4.2. PHYSICAL ENVELOPE REQUIREMENTS	8
4.3. TWIST AND STRAIGHTNESS REQUIREMENTS.....	8
5. MAGNETIC FIELD REQUIREMENTS.....	8
5.1. OPERATING GRADIENT.....	8
5.2. MAGNETIC LENGTH.....	9
5.3. FIELD QUALITY	9
5.4. FRINGE FIELD.....	9
6. CRYOGENIC REQUIREMENTS.....	9
6.1. OPERATING TEMPERATURE	10
6.2. HEAT LOADS	10
6.2.1. <i>Coil Peak Power</i>	10
6.2.2. <i>Total Heat Load</i>	10
6.3. COOLING REQUIREMENTS	10
6.3.1. <i>Provisions for installation of Heat Exchangers Tubes</i>	10
6.3.2. <i>Provisions for heat extraction</i>	10
6.4. PEAK PRESSURE	11
6.5. COOLDOWN AND WARMUP	11
7. ELECTRICAL REQUIREMENTS.....	11
7.1. OPERATING CURRENT	11
7.2. MAXIMUM OPERATING CURRENT RAMP RATE	11
7.3. MAXIMUM OPERATING VOLTAGE	11
7.4. ELECTRICAL BUSES	11
7.5. INSTRUMENTATION	12
7.6. VOLTAGE LIMITS.....	12
8. QUENCH REQUIREMENTS.....	12
8.1. QUENCH TRAINING REQUIREMENTS.....	12
8.2. QUENCH WHILE RAMPING DOWN	12
8.3. QUENCH PROTECTION	13
9. RADIATION HARDNESS REQUIREMENTS	13
10. RELIABILITY REQUIREMENTS.....	14
10.1. NUMBER OF POWERING CYCLES	14

10.2. NUMBER OF QUENCHES.....14

11. INTERFACE REQUIREMENTS.....14

12. SAFETY REQUIREMENTS.....14

13. CERN PROVIDED PARTS15

14. REQUIREMENTS SUMMARY TABLES16

15. REFERENCES18

DRAFT

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 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 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 should be fit for the intended use and satisfy CERN's needs for the HL-LHC upgrade. The quality of the US HL-LHC AUP 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 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 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 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 IT Nb₃Sn 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 Nb₃Sn 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 Nb₃Sn 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 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 ~ 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 if different than LMQXFA). Q2a and Q2b each consist of a single unit MQXFB ~ 7m long.

The LMQXFA or LMQXFB, when surrounded by the QXXFA or QXXFC 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.

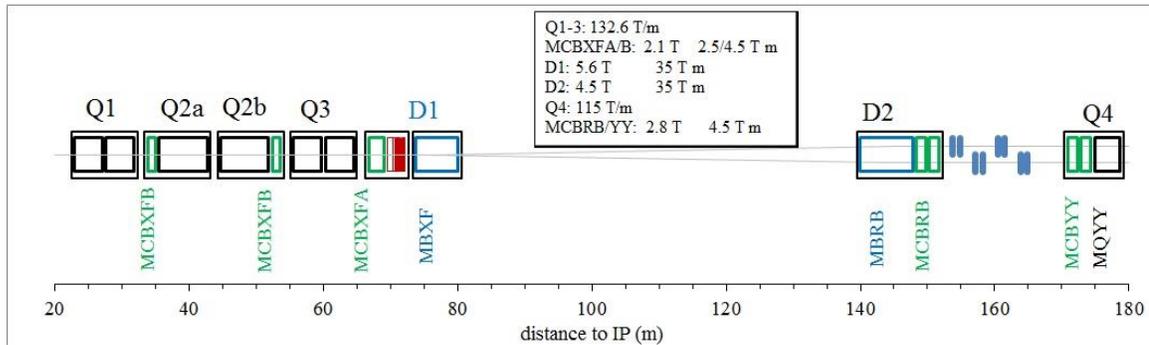


Figure 1: Conceptual layout of the IR region of HL-LHC— thick boxes are magnets, thin boxes are cryostats

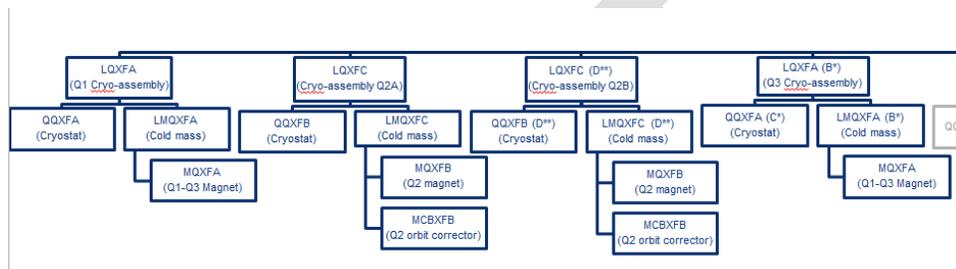


Figure 2: CERN Naming Conventions for HL-LHC Inner Triplets

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 MQXFA preliminary 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. 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].

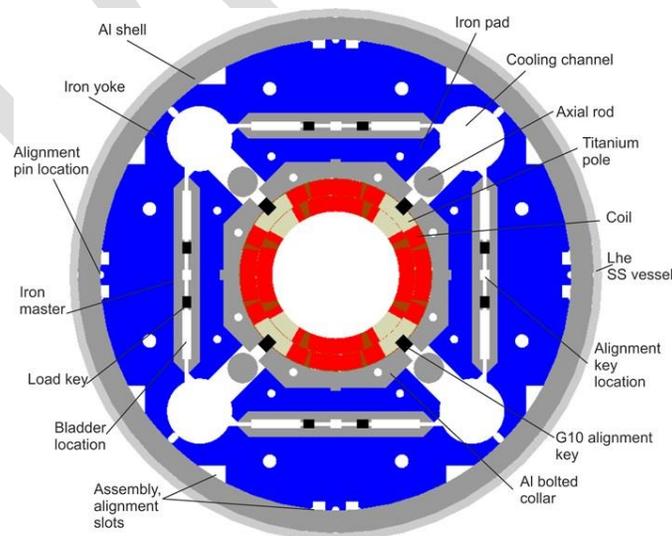


Figure 3: MQXFA cross-section



Figure 4: MQXFA 3-D conceptual cutaway view

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.

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. 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 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 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 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

R-O-01: MQXFA magnet twist target is < 2.0 mrad, and mechanical straightness target is < 0.5 mm

[These parameters are under discussion with CERN]

5. Magnetic Field Requirements

5.1. Operating Gradient

R-T-03: The MQXFA magnet must be capable of reaching a gradient of 143.0 T/m in superfluid helium at 1.9 K and for the magnetic length specified in R-T-04.

This gradient corresponds to the HL-LHC ultimate gradient, which is 108% above the nominal operating gradient of 132.6 T/m. 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].

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 143.0 T/m (17.8 kA).

5.2. Magnetic Length

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

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				
Normal 2	Systematic				Uncertainty		Random		Conn. Side	Non conn. Side	Q1/Q3		Q2a/b			
	Geometric	Ass. & cool	Saturation	Persistent	Injection	High Field	Injection	High Field			10	10	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	
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 μ m random error in the block positioning for non-allowed, and 100 μ m 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 0.5 m 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 during MQXFA operation.

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 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 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 $7.5 \times 10^{34} \text{ cm}^2 \text{ s}^{-1}$. 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; (2) free helium paths interconnecting the yoke cooling channels holes; and (3) a free cross sectional area of at least 150 cm²

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

R-T-10: The MQXFA magnet structure must be capable of surviving a maximum temperature gradient of 100 K without degradation in its performance.

The maximum temperature gradient imposed on the MQXFA magnet during cooldown and warmup is expected to be 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 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 520 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 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 [TBD]

R-O-04: Splice resistance target is less than 1.5 nΩ at 1.9K.

[RC Note: The value of 1.5 nΩ may be reduced to 1.0 nΩ pending the outcome of MQXFA prototype measurements]

The joint resistance is measured with voltage taps.

7.5. Instrumentation

R-T-15: 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 Nb₃Sn-NbTi splice.

7.6. Voltage Limits

R-T-16: The MQXFA magnet coils and quench protection heaters must pass a hi-pot test specified in Table 3 (to be defined).

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

Circuit Element	V _{max}	V hi-pot	I hi-pot
Coil to Ground	520 V	TBD	< TBD μA
Coil to Quench Heater	520 V	TBD	< TBD μA

[RC Note: Hipot values and Table 3 are under discussion with CERN. V_{max} is from E. Ravaioli's presentation at the HL-LHC Circuits Review at CERN in March 2016]

8. Quench Requirements

8.1. Quench Training Requirements

R-O-05: After training and after following a thermal cycle to room temperature, MQXFA magnets should 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 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 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 or some 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-06: All MQXFA components can withstand a maximum radiation dose of 30 MGy.

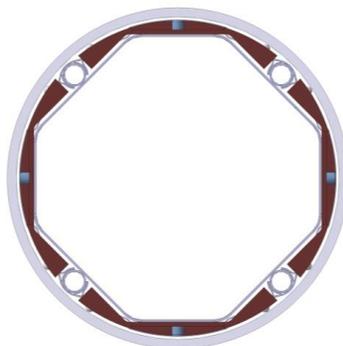


Figure 7: Beam screen (grey) with tungsten shielding (dark brown) and cooling tubes in Q1 (left) and in Q2-D1 (right)

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 Powering Cycles

R-O-07: MQXFA magnets can survive 3,000 powering cycles during HL-LHC tunnel operations.

10.2. Number of Quenches

R-O-08: MQXFA magnets can survive 50 quenches during HL-LHC tunnel operations.

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 cold bore tube 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 (is this still in the baseline?)**
 - d. 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 Interface Control Document [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 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-22: 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 Co traces under 0.1% in weight for massive iron and steel components.

13. CERN Provided Parts

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

DRAFT

14. Requirements Summary Tables

Table 4: MQXFA Threshold 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 gradient of 143.0 T/m 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 ; (2) free helium paths interconnecting the yoke cooling channels holes; and (3) a free cross sectional area of at least 150 cm²
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 100 K 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 520 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	Splices are to be soldered with CERN approved materials
R-T-15	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 ₃ Sn-NbTi splice.
R-T-16	The MQXFA magnet coils and quench protection heaters must pass a hi-pot test specified in Table 3 (to be defined)
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 Interface Control Document [3] (all to be defined)
R-T-22	The MQXFA magnets must comply with CERN's Launch Safety Agreement (LSA) for IR Magnets (WP3) [4]

Table 5: LMQXFA/B Objective Requirements Specification Summary Table

MQXFA Magnets

Functional Requirements Specification

ID	Description
R-O-01	MQXFA magnet twist target is < 2.0 mrad, and mechanical straightness target is < 0.5 mm
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 0.5 m distance from the MQXFA magnetic field axis is 50 mT or less.
R-O-04	Splice resistance target is less than 1.5 n Ω at 1.9K
R-O-05	After training and after following a thermal cycle to room temperature, MQXFA magnets should attain the nominal operating current with a target of no more than 1 quench.
R-O-06	All MQXFA components can withstand a maximum radiation dose of 30 MGy.
R-O-07	MQXFA magnets can survive 3,000 powering cycles during HL-LHC tunnel operations.
R-O-08	MQXFA magnets can survive 50 quenches during HL-LHC tunnel operations.

DRAFT

15. References

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

[2] R. van Weelderren, 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 Control Document (**to be defined**)

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

DRAFT