

**US HL-LHC Accelerator Upgrade Project**

**ACCEPTANCE PLAN FOR LQXFA/B**

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1. ACCEPTANCE PROCESS

Section 2 of this document specifies the agreed-upon acceptance criteria for the LQXFA/B cryo-assembly deliverable by the US HL-LHC Accelerator Upgrade Project (HL-LHC AUP) to CERN. If the acceptance criteria are met according to the methods and procedures specified or referenced in this document, then the HL-LHC AUP LQXFA/B cryo-assembly deliverable will be accepted by CERN.

There are several stages to the process of accepting an LQXFA/B cryo-assembly deliverable from HL-LHC AUP, listed below.

1. There is a "pre-acceptance" process in which the cryo-assembly is evaluated during the manufacturing process according to approved Manufacturing and Inspection Plans [MIPs] and HL-LHC AUP Travelers. Here problems are identified while there is still an opportunity to correct them.
2. After a cryo-assembly fabrication and test is completed, an HL-LHC AUP magnet review board is convened to review the manufacturing and test data and verify whether the cryo-assembly meets the acceptance requirements specified in this document. After this review, the board issues a formal recommendation for acceptance to the HL-LHC AUP Project Office. The board recommendation will include any exceptions, any restrictions on use, and the basis of the evaluation. In all cases the board will recommend to the US HL-LHC-AUP Project Office the disposition of the cryo-assembly.
3. The HL-LHC-AUP Project Office reviews and sends the recommendation report with any additional comments it may add to the official CERN contact person for the interaction regions (the WP3 Work Package Leader).
4. CERN management evaluates this information and, if satisfied, will issue a notification to the HL-LHC AUP Project Office that the cryo-assembly may be shipped. For this evaluation, CERN will also have access to all the manufacturing data specified in the agreed upon Manufacturing and Inspection Plans (MIPs) residing in the CERN’s EDMS and MTF electronic systems. Additional manufacturing information details may be provided to CERN upon request if available.
5. On delivery to CERN, a limited incoming inspection at room temperature will be promptly conducted by CERN to verify that the cryo-assembly was not damaged during shipment. After the cryo-assembly successfully passes the CERN incoming inspection, CERN issues the formal acceptance of the HL-LHC AUP deliverable to the HL-LHC AUP Project Office. Once CERN has accepted the cryo-assembly, ownership of all risks related to the deliverable transfers to CERN according to the terms of Addendum II to the Accelerator Protocol III between DOE and CERN [TBD].

Figure 1 shows the acceptance process in graphical form.



Figure 1: Acceptance process diagram (need to redo for better format and clarity)

* 1. MAGNET REVIEW BOARD

The purpose of the HL-LHC AUP magnet review board is to review data from the production process, compare with the acceptance criteria specified in this document, and make recommendations as to the worthiness of this magnet for LHC operation to the HL-LHC AUP Project Office.

This board will be convened as necessary, either in person or electronically. Members of the review board will include the US HL-LHC-AUP Magnets L2, Cryo-Assembly Test L3, Cryostat L3, and Cold Mass L3 or their designees. Other subject matter expert (SME) personnel may be added on an ad hoc basis as needed. Responsibilities among each person are as follows:

Magnets L2—generation of recommendation report, summarize conclusions of the board, forwarding recommendation to US HL-LHC-AUP Project Office

Cryo-Assembly Test L3—reports test results, i.e. warm and cold harmonics, quench results, alignment data, other test results

Cold Mass L3—reports cold mass fabrication results, e.g. pressure test, HiPot and electrical results, mechanical measurements, instrumentation checks, successful bus & instrumentation routing.

Cryostat L3—reports cryostat assembly results, i.e. room temperature leak checks, safety documentation, dimensional checks, preparation for shipping.

* 1. PRE-ACCEPTANCE

There are three components to this process. First is the adherence to the LQXFA/B cryo-assembly Travelers which provide a detailed step by step instruction of the magnet construction. At the completion of each step, the Traveler is signed by the proper L3 manager or his designee. If the step is not completed as planned, e.g. measurement-validated step is out of tolerance, then a non-conformity report is written and signed by the L3 manager or his designee. The purpose of these reports is to acknowledge a deviation from the process that will not affect the final magnet acceptance. The L3 manager may convene the Magnet Review Board to discuss the impact of a non-conformity.

The second component is an evaluation of the harmonics measured during the vertical cold test of each MQXFA magnet. Field quality data, measured at 1.9 K, are evaluated after cold test. Possible use or change of magnetic shims is recommended at this stage by the Test Analysis team. The US HL-LHC-AUP Magnets L2 determines, based on measured values for this magnet, recommendations from the Test and Analysis team, and trends from this and all previous magnets, if this magnet is accepted for use in the LQXFA/B cryo-assembly or if the US HL-LHC-AUP Magnet Review Board shall be convened to evaluate the data. This determination is transmitted to the US HL-LHC-AUP project manager.

The third component is an evaluation of the alignment of the two MQXFA magnets that make up the LMQXFA cold-mass. Room temperature Single Stretch Wire (SSW) measurements are performed on the individual MQXFA magnets to determine their relative magnetic axes. The US HL-LHC-AUP Cryo-Assembly Test L3 determines, based on the alignment requirements [TBD], if the alignment is acceptable or if the US HL-LHC-AUP Magnet Review Board shall be convened to evaluate the data. This determination is transmitted to the US HL-LHC-AUP project manager and Magnets L2.

* 1. ACCEPTANCE BY FERMILAB OF CERN SUPPLIED COMPONENTS

The completion of the LQXFA/B cryo-assembly requires the integration of several CERN supplied components listed in [TBD]. Components include instrumentation wires, insulated bus work, thermometers, heaters, cold mass steel, beam pipe, and the entire LQXFA/B cryostat kit. The specifications of these components are covered through control documents in the CERN Document Control. For instrumentation wires and bus work, continuity and voltage standoff (hipot) will be checked during the LQXFA/B manufacturing. The room temperature resistance of the CERN supplied thermometers will be performed prior to installation and compared to thermometer Traveler. Resistance will be monitored during the construction and test process.

All QC associated with the Cryostat Kit delivered by CERN is assumed to have been done by CERN. (What about spot QC checks of the cryostat kit? This section seems a little thin, we should update and add more details.)

* 1. MAGNET RECEIPT AT CERN

Upon arrival at CERN, a set of measurements and checks will be performed promptly, to verify the integrity of the magnet following shipment. These tests, which are specified in section 3, generally involve measurements which can be compared with specified tolerance bands. If any measurements are out of tolerance, or there are any indications of damage in transit, the disposition of the magnet will be discussed among: the official CERN contacts for the US Project and for the Insertions, the PMO, the US HL-LHC-AUP Magnet L2, and others as appropriate. Disposition may include return of the magnet to FNAL for repair and rework, repair done at CERN by FNAL or CERN personnel, or acceptance by CERN of the magnet with the noted deviations. CERN will document its acceptance of the magnet by memo (paper or e-mail) from the official CERN contact [TBD]. Once CERN has accepted the cryo-assembly, ownership of all risks related to the deliverable transfers to CERN according to the terms of Addendum II to the Accelerator Protocol III between DOE and CERN [TBD].

1. ACCEPTANCE CRITERIA BEFORE SHIPMENT

For the LQXFA/B cryo-assembly to be accepted, each requirement must be verified according to the methods and procedures specified or referenced in this document. Approved requirements (EDMS v1.0 or above) are specified in the following documents:

MQXFA Functional Requirements Specification [TBD]

LMQXFA/B Functional Requirements Specification [TBD]

Requirements Specification for the Assembly of the LQXFA/B cryo-assembly [TBD]

**NOTE: Requirements for the assembly of the LQXFA/B cryo-assembly will be added after the requirements document for this system is at the EDMS release 1.0 level.**

This section specifies, for each requirement, the following items:

1. **Verification Method**: the general method that will be used to verify the requirement. Examples include mechanical measurements, magnetic measurements, visual inspection, engineering check, etc. This section also indicates if the verification is done on a prototype only or on every production item.
2. **Procedure Summary**: a summary of the procedure used to verify the requirement using the verification method. For example, magnetic measurements by Single Stretched Wire System. Any tolerances agreed upon are also included here.
3. **Reference**: a reference with the detailed procedure and equipment to be used to verify the requirement. Usually this is captured in the corresponding MIPs, travelers, or other documents.

In general, acceptance tests are performed the last time they can be done on the magnet, cold mass, or cryo-assembly. Thus, some of the checks occur during magnet or cold mass construction while others occur just before the cryo-assembly is placed in the shipping container. Travelers will include a note cross-referencing the step to the requirement for clear traceability.

**NOTE: The role of Travelers, MIPs and MTF in the acceptance process are under discussion in the Project Office. One possibility is that a subset of travelers’ data directly supporting the requirements verification will be extracted and uploaded to MTF and referenced it the MIPs.**

Following are the acceptance criteria for each requirement. Requirements are identified with the ID number for traceability to the respective requirements specification document.

* + 1. PHYSICAL DIMENSIONS

**Requirement LMQXFA-R-T-01:** The LMQXFA assembly physical length (end cover to end cover, including tolerances) must be ≤ 10,100 mm. This dimension is at room temperature (296 K).

**Verification Method**: Mechanical measurements after fabrication of each cold mass assembly

**Procedure summary:** Laser Tracker survey

**Reference:** Cold Mass Assembly Traveler [TBD]

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

**Verification Method**: Mechanical measurements after fabrication of each cold mass assembly

**Procedure summary:** Laser Tracker survey

**Reference:** Cold Mass Assembly Traveler [TBD]

**Requirement LMQXFA-R-T-03:** The LMQXFA end cover must include pipings listed in Table 1 (in [TBD]) for cryogenic and electrical connectivity purposes.

NOTE: End covers are supplied by CERN

**Verification Method**: Mechanical measurements after fabrication of each cold mass assembly

**Procedure summary:** Laser Tracker survey and comparison with piping locations specified in the Interface Specification [TBD]

**Reference:** Cold Mass Assembly Traveler [TBD], Interface Specification [TBD]

**Requirement LMQXFA-R-T-04:** The LMQXFA cold mass assembly must not have any obstructions or interferences that will prevent insertion along the entire LMQXFA length of the CERN-supplied 74 mm OD (plus 2 mm for tolerance value) heat exchanger tubes and their supports through the MQXFA cooling channels. The LMQXFA cold mass assembly must not have any obstructions or interferences that will prevent insertion along the entire LMQXFA length of the busbar cartridge used to connect in series the two magnets making the cold mass.

**Verification Method**: Visual Inspection on each cold mass assembly

**Procedure summary:** Visual Inspection, pictures?

**Reference:** Cold Mass Assembly Traveler [TBD]

* + 1. MAGNETIC ELEMENTS

**Requirement LMQXFA-R-T-05:** The LMQXFA magnetic elements are two identical MQXFA magnets connected in series. The MQXFA magnets must satisfy the MQXFA requirements specification [TBD] and the LMQXFA interface specification [TBD]

**Verification Method**: Refer to requirements and verification method for MQXFA magnets below

Following are the requirements and verification procedure for MQXFA magnets.

**Requirement MQXFA-R-T-01:** The MQXFA coil aperture requirement is 150 mm. This aperture is the nominal coil inner diameter at room temperature, excluding ground insulation, inner layer quench heaters, cold bore, and beam screens. The electrical insulation and heater thicknesses have to be compatible with an outer diameter of the cold bore of 145.75 mm at room temperature, ensuring a gap of 1.5 mm for the cooling between the coils and the cold bore. The cold bore has to be supported inside the magnet aperture by slides attached to the coil poles.

**Verification Method:** Mechanicalmeasurements after fabrication of each magnet

**Procedure summary:** Use an ID bore gauge, or equivalent, that will pass through the bore.

Dan Cheng Comment: by the mention of “1.5 mm gap” does it mean it is also required? Or, is this more a go-no go measurement that only needs to pass a 145.75 mm diameter object with some clearance? Or, is there a minimum of 1.5 mm annular space required for cooling purposes, etc…? Perhaps some clarification on this would be helpful.

**Reference:** Magnet Assembly Traveler [TBD]

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

**Verification Method:** Mechanicalmeasurements after fabrication of each magnet

**Procedure summary:** Laser Tracker survey

**Reference:** Magnet Assembly Traveler [TBD]

**Requirement MQXFA-R-O-01:** Variation of local position of magnetic center must be within ±0.5 mm; variation of local position of magnetic axis within ±2 mrad. Local positions are measured with a 500 mm long probe every 500 mm.

**Verification Method:** Magneticmeasurements of magnetic axis to external fiducials at room temperature

**Procedure summary:** Use laser tracker to monitor the probe’s position and orientation during magnetic measurements.

**Reference:** Magnet Assembly Traveler [TBD]

**Requirement MQXFA-R-T-03:** The MQXFA magnet must be capable of operate at steady state providing a gradient of 143.2 T/m in superfluid helium at 1.9 K and for the magnetic length specified in R-T-04, when powered with current of 17.89 kA.

**Verification Method:** Magnetic measurements during cold testing (note that we do not specify vertical testing or horizontal testing)

**Procedure summary:** Measure the field strength using a rotating probe system

**Reference:** Magnet Assembly Traveler [TBD]

**Requirement MQXFA-R-T-04:** The MQXFA magnetic length requirement is 4.2 m with a tolerance of ± 5 mm at 1.9 K.

**Verification Method:** Magnetic measurements duringcold testing

Guram Note: Cold magnetic measurements are possible only at horizontal test stand. If cold magnetic length is within +/- 5 mm tolerance: accepted without discussion. If outside of tolerance: full report and review acceptance determination with CERN.

**Procedure summary:** Rotating coil measurements along the z axis

**Reference:** Cryo-assembly test plan [TBD]

**Requirement MQXFA-R-O-02:** The MQXFA field harmonics must be optimized particularly at high field. Table 2 provides expected values for field harmonics at a reference radius of 50 mm [5].

**Verification Method:** Magnetic measurements during cold testing of the cold mass assembly and both magnets powered simultaneously. Results compared with three “acceptance bands” with different actions depending on which band the results fall into. Acceptance bands are determined by the following method (example for normal harmonics (bn), the same algorithm is applied to the skew harmonics (an)):

Band 1: <bn> ±(Δbn + 1σ(bn))

Band 2: <bn> ±(Δbn + 2σ(bn)

Band 3: <bn> ±(Δbn + 3σ(bn))

Where <b> is the expected harmonic, Δb is the uncertainty component, and σ(b) is the random component. These values are integral values for Q1 or Q3 at High Field. For illustration purposes, using the values for b6 from the table of field quality in the MQXFA Functional Requirements Specification [TBD] we would have:

<b6> = 0.323

Δb6 = 1.1

σ(b6) = 1.1

Therefore:

Band 1: -1.88 to 2.52

Band 2: -2.98 to 3.62

Band 3: -4.08 to 4.72

**NOTE: Actual acceptance band values will be specified after MQXFA02 prototype testing following the method described above**

**Procedure summary:** During cold testing, measure harmonics (up to b10, a10) at nominal field (132.6 T/m) and compare results to the three acceptance bands for each harmonic. Actions for each band are as follows:

* If harmonic result is within Band 3: accepted without discussion
* If harmonic result is outside of Band 3: full report and review acceptance determination with CERN

**Reference:** Cold Mass Assembly Traveler [TBD], Cryo-assembly Test Plan [TBD],Test Report [TBD]

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

**Verification Method:** Prototype cryo-assembly measurements at horizontal test stand

**Procedure summary:** fringemagnetic field measurements with a Hall Probe

**Reference:** Prototype Run Plan [TBD], Cryo-assembly test plan [TBD], Prototype Test Report [TBD]

**Requirement MQXFA-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.

**Verification Method:** cold testing on prototype and every production magnet

**Procedure summary:** operation at ultimate current at a bath temperature of 1.9K for 120 minutes for prototype and 60 minutes for production magnets

**Reference:** Prototype Run Plan [TBD], , Cryo-assembly Test Plan [TBD], Prototype Test Report [TBD]

**Requirement MQXFA-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.

**Verification Method:** considered verified after heat exchanger tubes are successfully inserted during the cold mass assembly

**Procedure summary:** n/a

**Reference:** n/a

**Requirement MQXFA-R-T-07:** At least 40% of the coil inner surface must be free of polyimide.

**Verification Method:** Engineering check and visual inspection of each coil

**Procedure summary**: lead engineer verifies trace design and approves trace drawing, QC checks are performed after delivery of each trace to verify compliance, and lead technician verifies that the trace is correctly installed after each coil fabrication by visual inspection

**Reference:** Design Report [TBD]**,** Approved trace drawing [TBD]**,** TraceQC Report [TBD],

Coil Fabrication Traveler [TBD]

**Requirement MQXFA-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 four yoke cooling channels holes; and (3) a free cross sectional area of at least 150 cm2.

**Verification Method:** Engineering check and visual inspection of each coil/magnet

**Procedure summary** lead engineer verifies parts design and approves drawing, QC checks are performed after delivery of each part to verify compliance, and lead technician verifies that parts are correctly installed after each coil/magnet fabrication by visual inspection

**Reference:** Design Report [TBD]**,** Approved parts drawings [TBD]**,** QC Reports [TBD],

Coil Fabrication Traveler [TBD]

**Requirement MQXFA-R-T-09:** The MQXFA magnet structure must be capable of sustaining a sudden rise of pressure from atmospheric up to 26 bar without damage and without degradation of subsequent performance.

**Verification Method:** prototype testing

**Procedure summary:** inducequench at ultimate current, verify pressure peak exceeds 26 bar, ramp to quench again and verify that magnet can reach ultimate current (has this already been demonstrated with MQXFAP1?. If so, it should be written in the Test Report)

**Reference:** Prototype Test Run Plan [TBD], Prototype Test Report [TBD]

**Requirement MQXFA-R-T-10:** The MQXFA magnet structure must be capable of surviving a maximum temperature gradient of 100 K, during a controlled warm-up or cool-down, and to experience the thermal dynamics following a quench without degradation in its performance.

**Verification Method:** prototype testing

**Procedure summary:** control maximum temperature magnet difference during cool-down and warm-up to less than 100K and verify operability at ultimate current following an induced quench at ultimate current and a thermal cycle

**Reference:** Prototype Run Plan [TBD], Prototype Test Report [TBD]

**Requirement MQXFA-R-T-11:** The MQXFA magnets must be capable of operating at a ramp rate smaller than ±30 A/s.

**Verification Method:** cold testing of each production magnet

**Procedure summary:** verify that the magnet does not quench while ramping to/from ultimate current at ramp rates up to ±30 A/s.

**Reference:** Production Run Plan [TBD], Production Test Reports [TBD]

**Requirement MQXFA-R-T-12:** The MQXFA magnet must withstand a maximum operating voltage of 670 V to ground during quench.

**Verification Method:** calculations and cold testing

**Procedure summary:** document calculations in design report and conduct a hipot to at least 670 Volts in cold conditions.

**Reference:** Design Report [TBD]**,** Production Run Plan [TBD]

**Requirement MQXFA-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 electrical bus.

**Verification Method:** engineering checkfor each magnet and cold test

**Procedure summary:** for each magnet,lead engineer verifies that approved lead materials and procedures have been used. After verification, lead engineer signs compliance in magnet Traveler. Successful cold test.

**Reference:** Magnet Assembly Traveler [TBD]

**Requirement MQXFA-R-T-14:** Splices are to be soldered with CERN approved materials.

**Verification Method:** Technician verification

**Procedure summary:** Leadtechnician verification that the approved flux and solder for the tinning and soldering operations was used as specified within the traveler.

**Reference:** Coil Fabrication Traveler [TBD], Magnet Fabrication Traveler [TBD]

**Requirement MQXFA-R-O-04:** Splice resistance target is less than 1.0 nΩ at 1.9 K**.**

**Verification Method:** measurements during cold testing of each magnet

**Procedure summary:** measure splice resistance at 1.9K and verify values under 1.0 nΩ

**Reference:** Production Test Run Plan [TBD], Production Test Report [TBD]

**Requirement MQXFA-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; two (2) voltage taps for each quench strip heater; and two (2) voltage taps for each internal MQXFA Nb3Sn-NbTi splice. Each voltage tap used for critical quench detection must have a redundant voltage tap.

**Verification Method**: engineering check and inspection during assembly of each magnet

**Procedure summary:** lead engineer checks that design meets this requirement and approves electrical drawing. For each magnet, lead engineer inspects and signs compliance in Traveler.

**Reference:** Design Report [TBD] and Magnet Assembly Traveler [TBD]

**Requirement MQXFA-R-T-16:** The MQXFA magnet coils and quench protection heaters must pass a hi-pot test specified in Table 3.

Table 3: Required hi-pot test voltages and leakage current

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Circuit Element** | **Expected Vmax [V]** | **V hi-pot** | **I hi-pot**  **[µA]** | **Minimum time duration [s]** |
| Coil to Ground at RT \* | n.a. | 3.7 kV | 10 | 30 |
| Coil to Quench Heater at RT \* | n.a. | 3 kV | 10 | 30 |
| Coil to Ground at cold \*\* | 670 | 1.8 kV | 10 | 30 |
| Coil to Quench Heater at cold \*\* | 900 | 2.3 kV | 10 | 30 |

\* Room Temperature conditions refer to air at 20±3 °C and relative humidity lower than 60% (values t.b.c.)

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

**Verification Method**: hi-pot measurements for each magnet

**Procedure summary:** conduct hi-pot measurements for the conditions specified in Table 3 and verify that leakage current is below the specified limit. Room temperature conditions are in air (relative humidity lower than 60%) or bagged in dry N2.

**Reference:** Production Run Plan [TBD], Production Test Report [TBD]

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

**Verification Method**: testing for each magnet

**Procedure summary**: for each magnet and after training is completed, perform a thermal cycle and verify that the magnet is capable of reaching nominal operating current with no more than 3 quenches. Beyond 3 quenches, a discussion with CERN is required for magnet acceptance.

**Reference:** Production Run Plan [TBD], Production Test Report [TBD]

**Requirement MQXFA-R-T-18**: MQXFA magnets must not quench while ramping down at 300 A/s from the nominal operating current

**Verification Method**: testing for each magnet

**Procedure summary**: for each magnet and during cold testing, verify that the magnet does not quench while ramping down at 300 A/s from the nominal operating current.

**Reference:** Production Run Plan [TBD], Production Test Report [TBD]

**Requirement MQXFA-R-T-19**: 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].

**Verification Method**: engineering check

**Procedure summary**: lead engineer verifies design compliance with the approved interface documentation and approves detailed fabrication travelers

**Reference:** Design Report [TBD], Interface Document [TBD]

**Requirement MQXFA-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 [TBD]

**Verification Method**: Material properties and CERN approval of MQXFA materials list

**Procedure summary**: Design uses materials capable of surviving a radiation dose of 35 MGy, or CERN formally approves materials to be used in specific magnet locations.

**Reference:** Design Report [TBD], Approved List of Materials [TBD]

**Requirement MQXFA-R-T-21**: MQXFA magnets will operate in the HL LHC era for an order of magnitude of 5000 cycles. The long term reliability of the design will be proven with a magnet submitted to 2,000 powering cycles in individual test.

**Verification Method**: testing on a short model magnet by CERN

**Procedure summary**: Subject a short model magnet to at least 2,000 powering cycles and verify operability. This test will be conducted by CERN, and the results used to verify compliance with this requirement.

**Reference:** Design Report [TBD], CERN Test Report [TBD]

**Requirement MQXFA-R-O-06**: MQXFA magnets shall survive at least 50 quenches after the acceptance test.

**Verification Method**: prototype testing

**Procedure summary**: after reaching ultimate current, a short model/prototype magnet are subjected to a minimum of 50/30 quenches after which the magnet is still capable of attaining nominal current.

**Reference:** Prototype Run Plan [TBD], Prototype Test Report [TBD]

**Requirement MQXFA-R-T-22**: The MQXFA magnets must meet the detailed interface specifications with the following systems: (1) other LMQXFA 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].

**Verification Method**: engineering check, test of magnet/cold mass assembly interface

**Procedure summary**: L2 checks compliance of fabrication drawings with approved interface specifications and approves drawings for fabrication. Cold mass test verifies the magnet/cold mass assembly interface.

**Reference:** Design Report [TBD], Interface Documents [TBD]

**Requirement MQXFA-R-T-23**: The MQXFA magnets must comply with CERN’s Launch Safety Agreement (LSA) for IR Magnets (WP3) [4].

**Verification Method**: CERN approval of safety documentation

**Procedure summary**: Safety documentation is submitted to CERN for approval, and CERN verifies compliance with the LSA and any other safety agreements.

**Reference:** Launch Safety Agreement [TBD], other agreements [TBD]

* + 1. ALIGNMENT

**Requirement LMQXFA-R-T-06:** The distance between the two ends of the MQXFA magnetic lengths is 606 mm ± 5 mm at nominal operating temperature (1.9 K).

**Verification Method**: magnetic measurements during cold testing

**Procedure summary**: (how do we get the distance between magnetic lengths from magnetic measurements?)

**Reference:** Production Run Plan [TBD], Production Test Report [TBD]

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

NOTE: A threshold requirement for the above quantities needs to be set in this acceptance plan.

**Verification Method**: warm and cold magnetic measurements for all cold masses

**Procedure summary**: single stretched wire magnetic measurements during cold testing (how are these deviations computed? What is the threshold value?)

**Reference:** Cold Mass Assembly Traveler [TBD], Production Run Plan [TBD], Production Test Report

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

NOTE: A threshold requirement for the above quantities needs to be set in this acceptance plan.

**Verification Method**: warm and cold magnetic measurements for all cold masses

**Procedure summary**: single stretched wire magnetic measurements during cold testing (how are these distances computed? What are the threshold values?)

**Reference:** Cold Mass Assembly Traveler [TBD], Production Run Plan [TBD], Production Test Report

* + 1. PRESSURE VESSEL

**Requirement LMQXFA-R-T-07:** The LMQXFA is a pressure vessel that must be designed and documented in accordance with CERN and U.S. HL-LHC Accelerator Upgrade Project safety agreements [TBD].

**Verification Method**: CERN approval of agreed upon pressure vessel safety documentation for each cold mass assembly

**Procedure summary**: submit safety documentation demonstrating compliance with CERN safety requirements, including pressure testing at 25 bar. CERN verifies that submitted documentation complies with the US-CERN pressure vessel safety agreement.

**Reference:** Launch Safety Agreement [TBD], Other US-CERN safety agreements [TBD]

**Requirement LMQXFA-R-T-08:** The LMQXFA pressure vessel material for the cylindrical shell and end covers must be Low cobalt content Austenitic Stainless Steel Grade 316L.

**Verification Method**: This material will be supplied by CERN according to the agreed list of materials in [TBD], therefor as long as CERN is the supplier this requirement is considered to be met.

**Procedure summary**: n/a.

**Reference:** List of Materials [TBD]

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

**Verification Method**: CERN approval of pressure vessel design safety documentation

**Procedure summary**: design is first reviewed and approved by the standard FNAL safety process. Safety documentation is then submitted to CERN demonstrating compliance with CERN safety requirements. CERN verifies that submitted documentation complies with the US-CERN pressure vessel safety agreements.

**Reference:** Launch Safety Agreement [TBD], Other US-CERN safety agreements [TBD]

* + 1. FORCES

**Requirement LMQXFA-R-T-10:** The LMQXFA cold mass assembly must be capable of sustaining loads resulting from up to 25 bar of pressure differential without physical damage or performance degradation.

**Verification Method**: prototype test

**Procedure summary**: induce a 25-bar pressure differential load during the cold mass assembly prototype test and verify that there is no performance degradation (how is this done?)

**Reference:** Cold Mass Assembly Traveler [TBD], Prototype Run Plan [TBD], Prototype Test Report [TBD]

* + 1. BUSBARS

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

**Verification Method**: engineering check

**Procedure summary**: lead engineer verifies compliance with approved interface documentation and approves drawings for fabrication. For each cold mass assembly and prior to assembling end domes, visually inspect bus for proper installation including solder joints and insulation.

**Reference:** Design Report [TBD]**,** Cold Mass Assembly Traveler [TBD], Interface Documentation [TBD]

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

**Verification Method**: engineering check

**Procedure summary**: lead engineer verifies that approved materials are used on each cold mass assembly

**Reference:** Cold Mass Assembly Traveler [TBD]

**Requirement LMQXFA-R-T-13:** The busbars must include expansion loops, to be contained within the end cover section and able to accommodate up to 30 mm of axial movement due to differential thermal expansion/contraction.

**Verification Method**: engineering check and visual inspection

**Procedure summary**: lead engineer verifies that design satisfies requirement and approves drawings for fabrication. Visually inspects each cold mass assembly for compliance.

**Reference:** Design Report [TBD],Cold Mass Assembly Traveler [TBD], Interface Documentation [TBD]

**Requirement LMQXFA-R-O-03:** The busbars will include two internal splices. Splice resistance target value must be less than 1.0 nΩ at 1.9 K. A target value at room temperature will also be specified after the completion of the prototype program.

**Verification Method:** measurements during cold testing of each cold mass assembly

**Procedure summary:** measure splice resistance at 1.9K and verify values under 1.0 nΩ

**Reference:** Production Test Run Plan [TBD], Production Test Report [TBD]

**Requirement LMQXFA-R-T-14: Splices are to be soldered with CERN approved materials [7]**

**Verification Method:** engineering checkfor each splice in cold mass assembly

**Procedure summary:** for each cold mass assembly, lead engineer verifies that approved materials and procedures have been used in all splices. After verification, lead engineer signs compliance in Traveler.

**Reference:** Cold Mass Assembly Traveler [TBD]

**Requirement LMQXFA-R-T-15: The 35A lead and the CLIQ leads are copper resistive leads. The cross-section of the 35A lead is to be specified. The CLIQ lead has a 10 mm2 cross-section.**

**Verification Method**: engineering check and visual inspection

**Procedure summary**: lead engineer verifies that design satisfies requirement and approves drawings for fabrication. Visually inspects each cold mass assembly and signs cold mass assembly Traveler for compliance.

**Reference:** Design Report [TBD], Cold Mass Assembly Traveler [TBD]

* + 1. INSTRUMENTATION

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

Note: Thermometer assemblies will be calibrated and supplied by CERN

**Verification Method**: measurements, visual inspection

**Procedure summary**: for each cold mass assembly and after installation of these CERN-provided sensors, a 4-wire resistance measurement of each sensor is conducted and recorded to verify the identity and operability of the device. The lead engineer inspects the measurements and visually inspects each device for appropriate placement and strain relief and verifies that these sensors are installed according to instructions. After verification, the lead engineer signs cold mass assembly Traveler for compliance.

**Reference:** Cold Mass Assembly Traveler [TBD]

**Requirement LMQXFA-R-T-17:** The LMQXFA cold mass assembly includes a minimum of 16 voltage taps.

**Verification Method**: engineering check, measurements

**Procedure summary**: the lead engineer verifies that the design satisfies this requirement and approves drawings for fabrication. For each cold mass assembly, measurements of continuity and resistance are recorded. The lead engineer inspects these measurements and visually inspects the voltage taps to verify compliance. After verification, the lead engineer signs the cold mass assembly Traveler.

**Reference:** Design Report [TBD], Cold Mass Assembly Traveler [TBD]

**Requirement LMQXFA-R-T-18:** Instrumentation wires type, preliminary quantity and function are given in Table 2 of [TBD].

Note: Instrumentation wiring specification supplied by CERN

**Verification Method**: QC testing

**Procedure summary**: use vendors qualified by CERN, QC to verify compliance with specifications

**Reference:** List of Materials [TBD]

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

**Verification Method**: engineering check, visual inspection

**Procedure summary**: the lead engineer verifies that the design satisfies this requirement and approves drawings for fabrication. For each cold mass assembly, the lead engineer visually inspects that instrumentation wiring has been installed according to approved procedures. After verification, the lead engineer signs the cold mass assembly Traveler.

**Reference:** Design Report [TBD],Cold Mass Assembly Traveler [TBD], Interface Specification [TBD]

* + 1. VOLTAGE LIMITS

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

Table 3: Required hi-pot test voltages and leakage current

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Circuit Element** | **Expected Vmax [V]** | **V hi-pot** | **I hi-pot**  **[µA]** | **Minimum time duration [s]** |
| Coil to Ground at RT \* | n.a. | 3.7 kV | 10 | 30 |
| Coil to Quench Heater at RT \* | n.a. | 3 kV | 10 | 30 |
| Coil to Ground at cold \*\* | 670 | 1.8 kV | 10 | 30 |
| Coil to Quench Heater at cold \*\* | 900 | 2.3 kV | 10 | 30 |

\* Room Temperature conditions refer to air at 20±3 °C and relative humidity lower than 60% (values t.b.c.)

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

**Verification Method**: hi-pot measurements for each magnet

**Procedure summary:** conduct hi-pot measurements for the conditions specified in Table 3 and verify that leakage current is below the specified limit. Room temperature conditions are in air (relative humidity lower than 60%) or bagged in dry N2.

**Reference:** Cold Mass Assembly Traveler [TBD], Cryo-assembly Test Plan [TBD]

* + 1. SURVEY

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

**Verification Method**: Mechanical measurements after fabrication of each cold mass assembly

**Procedure summary:** Laser Tracker survey and comparison with piping locations specified in the Interface Specification [TBD]

**Reference:** Cold Mass Assembly Traveler [TBD]

* + 1. QUENCH

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

1. After a thermal cycle to room temperature, the cold mass should attain the nominal operating current with no more than 3 quenches per magnet (**MQXFA-R-T-17)**
2. The cold mass must not quench while ramping down at 300 A/s from the nominal operating current (**MQXFA-R-T-18)**
3. The cold mass quench protection components must be compatible with the CERN-supplied quench protection system and comply with the corresponding interface document specified by CERN [3] (**MQXFA-R-T-19)**

**Verification Method**: testing for each magnet

**Procedure summary**: for each cold mass assembly and after training is completed, perform a thermal cycle and verify that the cold mass assebmly is capable of reaching nominal operating current with no more than 3 quenches per maget. Beyond 3 quenches per magnet, a discussion with CERN is required for cold mass assembly acceptance. Verify that the cold mass assembly does not quench while ramping down at 300 A/s from the nominal operating current.

Guram Note: GC: For each cold mass assembly verify that the nominal current will be reached with no more than 3 quenches per magnet (after training at BNL, it will a second cool down for every magnet in the cold mass assembly)

Comment: We do not need to check 300 A/s ramp down, since it was already demonstrated at BNL

**Reference:** Cold Mass Assembly Traveler [TBD], Production Test Run Plan [TBD], Production Test Report [TBD]

**Requirement LMQXFA-R-T-23:** After installation and routing of heat exchanger tubes, instrumentation wiring, and superconducting busbars there must be a free LMQXFA cross section area of 150 cm2 in the helium volume.

**Verification Method**: engineering check, visual inspection

**Procedure summary**: lead engineer checks compliance of fabrication drawings with approved interface specifications and approves drawings for fabrication. Visual inspection during each cold mass assembly to verify that this requirement is met.

**Reference:** Design Report [TBD], Cold Mass Assembly Traveler [TBD]

* + 1. RADIATION HARDNESS

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

**Verification Method**: Material properties and CERN approval of materials

**Procedure summary**: Design uses materials capable of surviving a radiation dose of 35 MGy, or CERN formally approves materials to be used in LMQXFA fabrication.

**Reference:** Design Report [TBD], Approved List of Materials [TBD]

* + 1. RELIABILITY

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

1. The cold mass will operate in the HL LHC era for an order of magnitude of 5000 cycles. The long term reliability of the design will be proven with a magnet submitted to 2,000 powering cycles in individual test (**MQXFA-R-T-21)**
2. The cold mass shall survive at least 50 quenches after the acceptance test (**MQXFA-R-O-06**)

**Verification Method**: CERN string test

**Procedure summary**: TBD

**Reference:** TBD

* + 1. INTERFACES

**Requirement LMQXFA-R-T-25:** The LMQXFA cold mass assembly must meet the detailed interface specifications with the following systems: (1) MQXFA magnets; (2) The CERN supplied QQXFA/B Cryostats; (3) the CERN supplied piping; (4) CERN supplied Cryogenic System; (5) the CERN supplied power system; (6) the CERN supplied quench protection system, and (7) the CERN supplied instrumentation system. These interfaces are specified in Interface Control Document [4].

**Verification Method**: engineering check, test of LQXFA/B and string tes.

**Procedure summary**: L2 checks compliance of fabrication drawings with approved interface specifications and approved drawings for fabrication; test of LQXFA/B verifies interface between cold mass and cryostat; string test of prototype and pre-series cryo-assemblies verifies all interfaces with CERN systems.

**Reference:** Design Report [TBD]

* + 1. SAFETY

**Requirement LMQXFA-R-T-26**: The LMQXFA cold mass assembly must comply with CERN’s Launch Safety Agreement (LSA) for IR Magnets (WP3) [6]

**Verification Method**: CERN approval of safety documentation

**Procedure summary**: Safety documentation is submitted to CERN for approval, and CERN verifies compliance with the LSA and any other safety agreements.

**Reference:** Launch Safety Agreement [TBD], other agreements [TBD]

* + 1. CERN PARTS

**Requirement LMQXFA-R-T-26**: CERN provided parts for LMQXFA assemblies are specified in [9]. These parts for the prototype and series (including spares) will be supplied by CERN.

**Verification Method**: See section “Acceptance of CERN supplied Parts”

**Procedure summary:**

**Reference:** List of Materials [TBD]

* + 1. CRYO-ASSEMBLY

**NOTE: Acceptance for requirements for the assembly of the LQXFA/B cryo-assembly will be added after the requirements document for this system is at the EDMS release 1.0 level.**

1. ACCEPTANCE CRITERIA AFTER ARRIVAL AT CERN

The following list is a summary of the acceptance tests to be performed at CERN following shipment. These tests are in three categories: physical inspection, mechanical measurements and electrical measurements.

* 1. PHYSICAL INSPECTION

Physical inspection of shipping container for signs of damage during transit. If container is installed with instrumentation, such as an accelerometer, hygrometer or thermometer, instruments should be sent back to Fermilab for evaluation. FNAL will summarize the data in a report to CERN. At the present time, acceptance criteria for these parameters have not been established.

* 1. MECHANICAL MEASUREMENTS

(This section needs to be updated)

Pipe locations should be re-measured to verify compliance with interface document [TBD].

The position of the cold mass within the cryostat should be checked under warm conditions using a single stretched wire (SSW) system.

* 1. ELECTRICAL MEASUREMENTS

(This section needs to be updated)

The following set of measurement are to be performed at room temperature, either in air or in dry N2, and compared to provided acceptance bands.

**a)** **Continuity of all instrumentation wires**. Verify using “2-wire” technique that wires are properly connected; feed through wires show continuity from one connector to another, heater wires attached to heaters etc. Use interconnect wiring diagrams as shown in Interface specification [12].

**b) Hipot requirements**: In room temperature N2 or air

- Coils to ground 1.5 kV, ≤30 µA leakage

- Coils to heaters 1.5 kV, ≤30 µA leakage

**c)** **Resistance to ground**

- Temperature sensors >20MΩ

- Warmup heaters >20 MΩ

**d)** **Resistance/inductance/Q measurements**

- Using coil voltage taps as defined in [12] measure whole coil, Half coil resistances. Values should agree with nominal to +/- 0.05 Ω

- Thermometer resistance +/-5 Ω relative to calibration value

- Magnet inductance +/- 0. 3 mH of nominal

- Q factor +/- 0.3 of nominal

1. REFERENCES

(This section needs to be done)