U.S. HL-LHC Accelerator Upgrade Project

REQUIREMENTS SPECIFICATION FOR THE ASSEMBLY OF LMQXFA Cold Mass into QQXF_SC Cryostat

Prepared by: Date: 05/06/2016 Ruben Carcagno, US HL-LHC AUP L1 Deputy Manager Sandor Feher, US HL-LHC AUP L2 manager	**Organization** FNAL	**Contact** ruben@fnal.gov (630) 840-3915
Reviewed by: Date:08/11/2018 Roger Rabehl, US HL-LHC AUP L3 Deputy Manager Thomas Page, US HL-LHC AUP Giorgio Ambrosio, US HL-LHC AUP L2 Manager	**Organization** FNAL	**Contact** giorgioa@fnal.gov (630) 840-2297
Reviewed by: Date: 08/11/2018 Paolo Ferracin, HL-LHC MQXFB Workpackage Engineer Vittorio Parma, TE-MSC-CMI Section Leader Delio Duarte Ramos, TE-MSC-CMI	**Organization** CERN	**Contact** Paolo.Ferracin@cern.ch
Approved by: Date: 11/12/2018 Giorgio Apollinari, US HL-LHC AUP L1 Manager	**Organization** FNAL	**Contact** apollina@fnal.gov (630) 840-4641
Approved by: Date: 11/12/2018 Ezio Todesco, HL-LHC WP3 Work Package Leader Luca Bottura, TE-MSC Group Leader Lucio Rossi, CERN HL-LHC Project Leader	**Organization** CERN	**Contact** Ezio.Todesco@cern.ch

Revision History

Revision	Date	Section No.	Revision Description
Draft	4/01/17	All	Initial Draft
Draft	5/30/2018	All	Entire document has changed
V0.6	6/14/2018	10	Section 10 was removed
V.09	10/08/2018	10	Change on R-T-20
V.096	11/19/2018	All	Merging of Specification for QQXF_SC and LQXFA Cryoassembly

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1. Purpose

This document specifies the functional requirements for the High Luminosity LHC (HL-LHC, or HiLumi LHC) LQXFA/B/E/F cryostat assemblies work that is performed at the US. Ten units of these cryostat assemblies are expected to be fabricated and delivered to CERN by the U.S. HL-LHC Accelerator Upgrade Project (US HL-LHC AUP) as part to the U.S. contributions to the LHC High Luminosity Upgrade. These cryostat assemblies are the quadrupole magnetic components of the HL-LHC Q1 and Q3 inner triplet optical elements in front of the interactions points 1(ATLAS) and 5 (CMS). One LMQXFA cold mass is installed in each QQXF_SC cryostat to create a cryostat assembly. LQXFA/B/E/F requirements are specified in [1]. LMQXFA cold masses will be fabricated by US HL-LHC AUP, cryostats and cryostat-assembly tooling will be fabricated by CERN. US HL-LHC AUP will perform assembly of the cold masses in the cryostats and cold test.

If all the threshold functional requirements specified in this document are verified, then US HL-LHC AUP cryostat assembly 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 cryostat assembly deliverables will be measured by the degree to which its characteristics fulfill the requirements specified in this document [2]

2. Introduction

The Inner Triplet (IT) quadrupoles are the magnetic system used that allow reaching low beta functions around the Interaction Point (IP). The triplet is made of three optical elements: Q1, Q2, and Q3. The upgrade of the Inner Triplets in the high luminosity insertions is the cornerstone of the LHC upgrade. The decision for HL-LHC heavily relies on the success of the advanced Nb_3Sn technology that provides access to magnetic fields well beyond 9 T, allowing the maximization of the aperture of the IT quadrupoles. A 15-year-long study led by the DOE in the US under the auspices of the U.S. LARP program, and lately by other EU programs, has shown the feasibility of Nb_3Sn accelerator magnets. The HL-LHC is expected to be the first application of accelerator-quality Nb_3Sn magnet technology in an operating particle accelerator.

For HL-LHC, 20 IT Nb_3Sn quadrupoles (16 plus spares) are needed: they all feature 150 mm aperture and operating gradient of 132.6 T/m, which entails 11.5 T peak field on the coils. In addition, HL-LHC will use the same Nb_3Sn technology to provide collimation in the Dispersion Suppression (DS) region, which will be achieved by replacing a number of selected main dipoles with two shorter 11 T Nb_3Sn dipoles (MBH). For more details, see [3].

Figure 1 shows a conceptual layout of the HL-LHC interaction region. The CERN nomenclature of the IT system is available in [4].

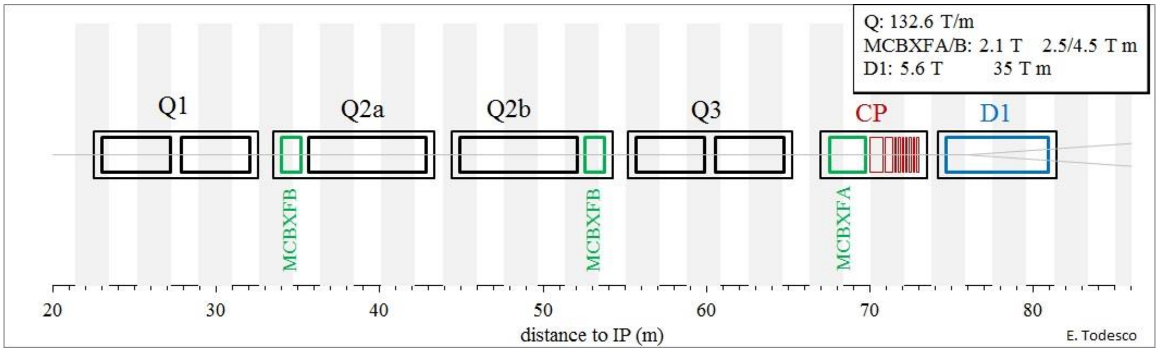

Figure 1: Conceptual layout of the IR region of HL-LHC– thick boxes are magnets, thin boxes are cryostats

The MQXFA magnet is the quadrupole magnetic element of Q1 and Q3, including the coils and mechanical support pieces to a perimeter defined by the outer shell of the magnets and the end plates of each magnet. A pair of ~ 5m MQXFA magnet structures is installed in a stainless steel helium vessel, including the end domes, to make the Q1 and Q3 Cold Mass (LMQXFA). The LMQXFA, when surrounded by the QQXF_SC cryostat shields, piping, and vacuum vessel, and equipped with cryogenic service modules and beam vacuum equipment is then the LQXFA/E cryo-assembly for Q1 and the LQXFB/F cryo-assembly for Q3 (see Figure 2), as installed in the tunnel of LHC [4].

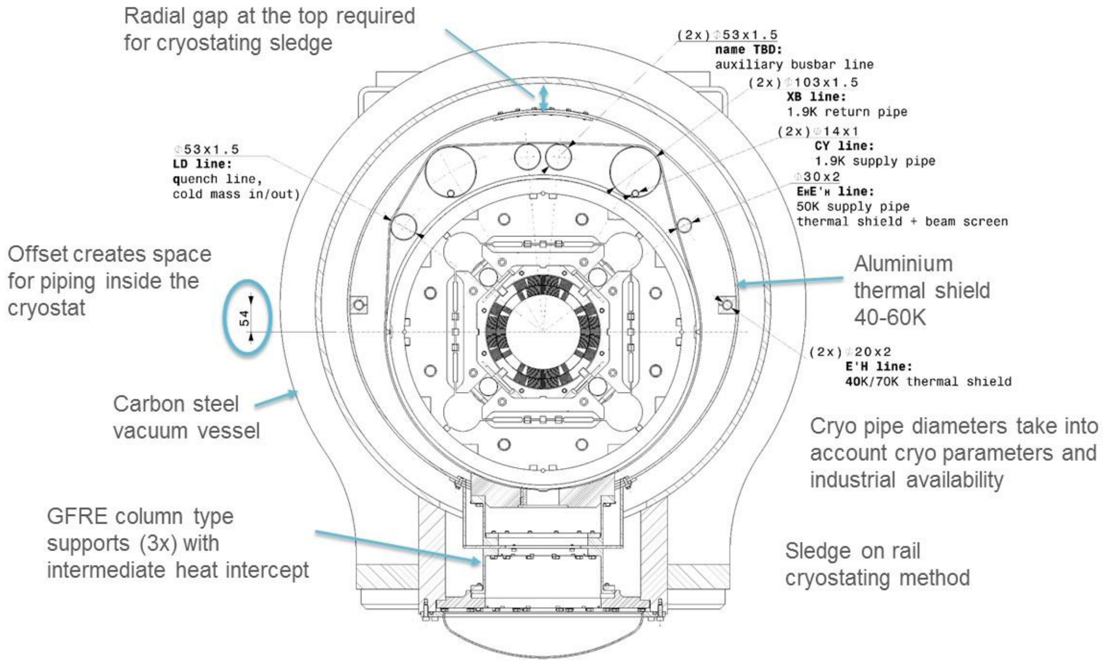

Figure 2: LQXF Preliminary Cross Section (measurements are in mm).

3. Functional Requirements Overview

The LQXFA/B/E/F functional requirements are the high-level technical requirements for the LQXFA/B/E/F cryostat assembly. 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.

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 a threshold level, then the U.S. HiLumi LQXFA/B/E/F Cryostat Assembly deliverables will be fit for the intended use and satisfy CERN's needs for the HL-LHC upgrade.

Detailed verification procedures and acceptance criteria are defined in a separate document [2]. 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.

Table 1and Table 2 summarize all QQXF_SC threshold and objective requirements.

4. Physical Requirements

Physical Envelope Requirements

In Figure 3 the layout drawing [5]of the LHC IR magnets are shown.

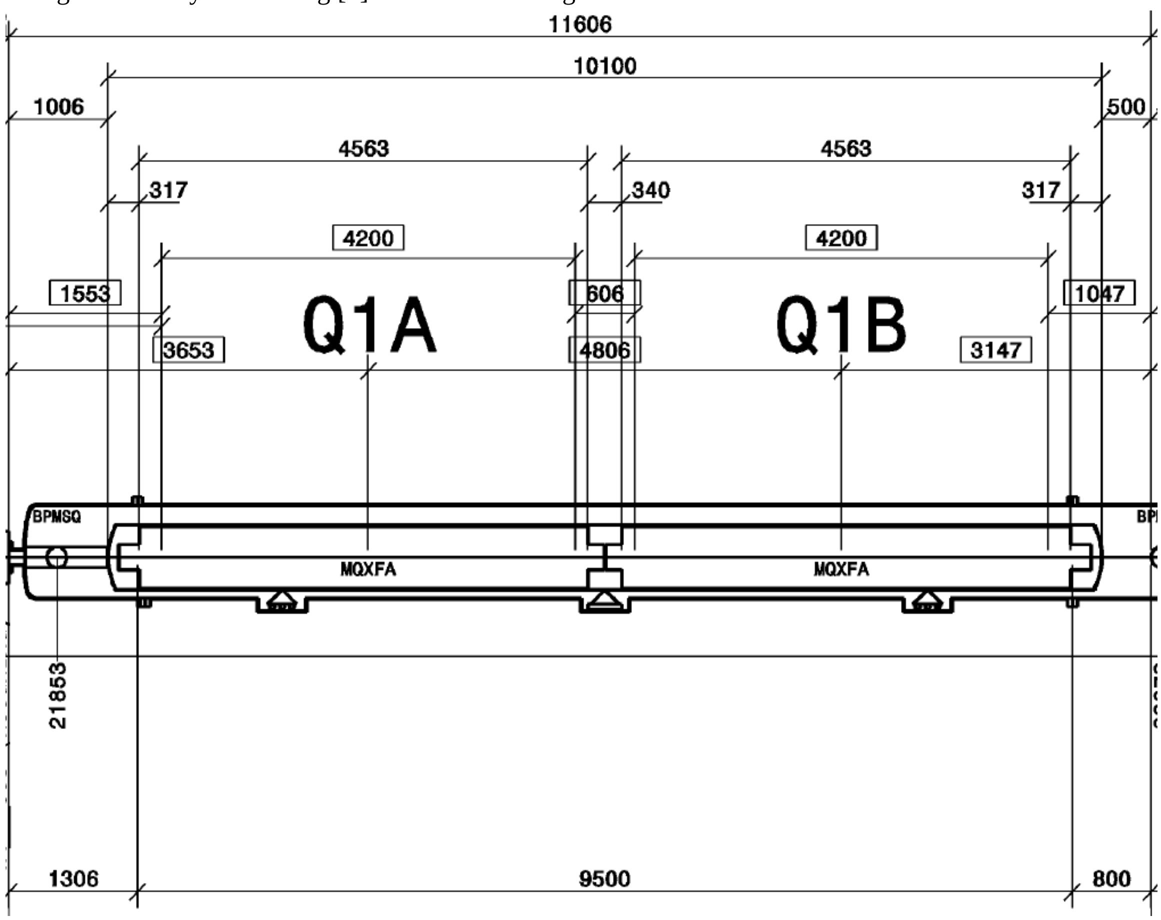

Figure 3: LMQXFA Cold Mass comprising of two MQXFA magnet elements. Quotes in square boxes are at 1.9 K, otherwise at room temperature.

R-T-01: The QQXF_SC vacuum vessel physical length (end flange to end flange) must be ≤ 9,500 mm (the actual length shell be specified to make sure that the length plus the tolerance value is less than 9,500 mm). This dimension is at room temperature (296 K).

R-T-02: Any support structure attached to the vacuum vessel must be within the "stay clear" envelope sown in Figure 4. The dimensions are taken at room temperature (296 K).

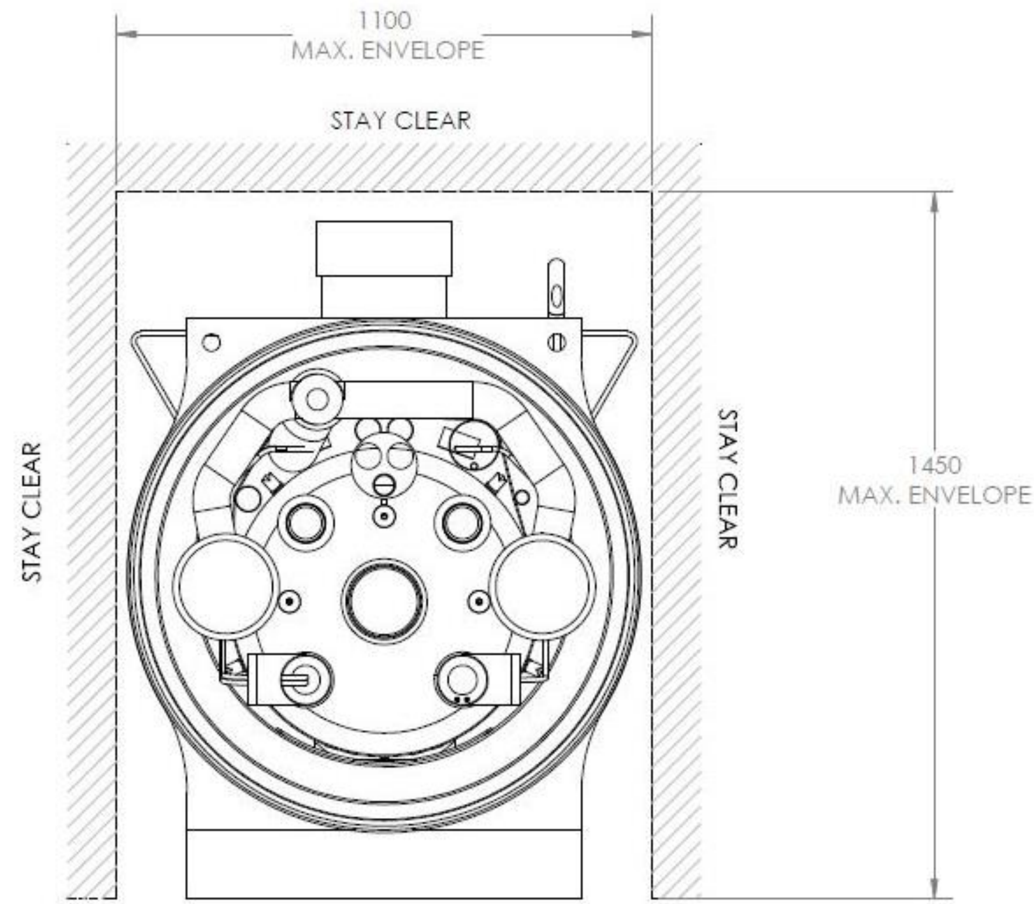

Figure 4: The “stay clear” is shown that has to be respected by the cryostat design.

Weight Requirements

R-T-03: The total weight of the whole cryostat assembly including the cold mass must be ≤ 22 500 kg.

Note: The total weight should include any accessories to the cryostat assembly that are permanently attached to it and could not be removed during lifting operation.

5. Cold Mass Requirements

R-T-04: The LQXFA/B/E/F cryostat assembly contains one LMQXFA cold mass. The LMQXFA cold mass must satisfy the LMQXFA requirements specifications [1] and the QQXF_SC cryostat interface specifications [6].

The **QQXF_SC cryostat** Interface Specification provides details for the attachment of the LMQXFA cold mass to the cryostat feet and the alignment interface of LMQXFA to the Cryostat.

6. Alignment Requirements

R-T-05: LMQXFA positioning inside the QQXF_SC cryostat is described in the LMQXFA and QQXF_SC interface document [7].

R-T-06: LMQXFA alignment requirement [1] must be met after the LQXFA/B/E/F cryostat assembly is completed.

R-T-07: Reference frame for Survey data and magnetic measurements data described in [8] must be used.

7. Vacuum Vessel Requirements

R-T-08: The QQXF_SC cryostat must be designed and documented in accordance with CERN and U.S. HL-LHC Accelerator Upgrade Project safety agreements [9].

R-T-09: The QQXF_SC vacuum vessel must be designed for a Maximum Allowable Working Pressure (MAWP) of 1 bar outside pressure and 0.5 bar inside pressure differential (1.5 bar absolute pressure inside the vacuum vessel) [10].

8. Forces Requirements

Once installed as part of the LHC Inner Triplet System, the LQXFA/B/E/F cryostat assemblies can experience asymmetric axial forces due to quench on other magnets and other events.

R-T-10: The LQXFA/B/E/F cryostat assembly must be capable of sustaining loads resulting from pressure differential values (described in [10]) in the LHe containment vessel (cold mass and associated pipes) and pressure differential values (described in [10]) in the vacuum vessel without physical damage or performance degradation.

Note: CERN is responsible to provide design, fabrication procedures and components that meet the R-T-10 requirements. Fermilab is responsible that the execution of the assembly meets the assembly specifications.

9. Leak Rate

R-T-11: The LHe containment vessel (Cold Mass and associated pipes) and all other pressurized pipes need to be leak tight under their operating pressure. The leak check must measure that the leak rate is lower than 10^{-9} torr-liter/sec.

10. Electrical/Instrumentation Requirements

Instrumentation Wiring and Electrical Busses

R-T-12: Instrumentation wiring and electrical busses during the assembly process must be handled carefully not to introduce any performance degradation.

Note:

- Wiring introduced performance degradation is any wiring issues that cause magnet operational deficiency like QPS is not fully functional due to a lost V-tap etc.
- CERN will provide all wires and busses routing and installation procedures used in LQXFA/B/E/F cryostat assemblies.

Voltage Limits

R-T-13: The LQXFA/B/E/F cryostat assembly voltage limits must meet or exceed the LMQXFA voltage limit requirements specified in [1].

11. Quench Requirements

R-T-14: The LQXFA/B/E/F quench performance must meet the LMQXFA cold mass quench performance requirements specified in [1].

This requirement means that the cryostat assembly quench performance is limited by the LMQXFA cold mass, ultimately the MQXFA magnet, and not by cryostat assembly superconducting components such as heat loads.

12. Radiation Hardness Requirements

The LQXFA/B/E/F cryostat assembly will be located near the IP where radiation is expected. With a nominal luminosity 5 times larger than the nominal design goal of the LHC, CERN is planning to fabricate and install a newly designed absorber, using thick tungsten (W) shielding attached to the beam screen 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 100 kGy. Based on this low radiation value there are no plans to perform radiation tests on cryostat components.

13. Reliability Requirements

R-O-01: LQXFA/B/E/F reliability requirements are the same as the LMQXFA reliability requirements specified in [1].

14. Interface Requirements

The LQXFA/B/E/F cryostat assembly interfaces with the following systems:

1. The LMQXFA cold mass;
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-15: The LQXFA/B/E/F cryostat assembly must meet the detailed interface specifications with the following systems: (1) LMQXFA cold masses; (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 [6].

15. Safety Requirements

Each HL-LHC work package will be subject to safety requirements specified in a CERN "Launch Safety Agreement (LSA)" document [5]. This LSA will specify the CERN safety rules and host state regulations applicable to the systems/processes and the minimal contents of the Work Package safety file needed to meet the Safety Requirements.

R-T-16: The LQXFA/B/E/F cryostat assembly must comply with CERN's Launch Safety Agreement (LSA) for IR Magnets (WP3) [9].

16. CERN Provided Parts

R-T-17: CERN provides all the parts for QQXF_SC cryostat . The cryostat kit for the prototype and 10 production units will be supplied and shipped to Fermilab by CERN at no cost to US HL-LHC AUP. The list of the components of the kit can be found in [11].

Note: Shipping document will provide the inspection forms for all the different parts.

17. Tooling

R-T-18: Cryostat assembly tooling will be designed, procured and shipped to Fermilab by CERN or a vendor selected by CERN. The tooling that will be used for cryostat assemblies at CERN and Fermilab will be identical with minor differences that are site and cryostat specific (if any).

Note: Fermilab personnel will be responsible to work with CERN or with the vendor selected by CERN during the installation of the tooling at Fermilab site.

18. Cryostat assembly procedures

R-T-19: Cryostat assembly procedures including every QC and QA steps will be developed by CERN. The first prototype cryostat assembly work will be directed by CERN personnel to assure proper transfer of the procedures to Fermilab. At Fermilab an engineer will be assigned to be in charge for the cryostat assembly work.

19. Shipping of the Cryo-assemblies to CERN

R-T-20: AUP is responsible for shipping the Cryo-assemblies to CERN without any performance degradation.

20. Functional Requirements Summary Tables

Table 1: LQXFA/B/E/F Threshold Functional Requirements Specification Summary Table

ID	Description
R-T-01	The QQXF_SC vacuum vessel physical length (end flange to end flange) must be ≤ 9,500 mm (the actual length shell be specified to make sure that the length plus the tolerance value is less than 9,500 mm). This dimension is at room temperature (296 K).
R-T-02	Any support structure attached to the vacuum vessel must be within the “stay clear” envelope sown in Figure 4. The dimensions are taken at room temperature (296 K).
R-T-03	The total weight of the whole cryostat assembly including the cold mass must be ≤ 22 500 kg.
R-T-04	The LQXFA/B/E/F cryostat assembly contains one LMQXFA cold mass. The LMQXFA cold mass must satisfy the LMQXFA requirements specifications [1] and the QQXF_SC cryostat interface specifications **[6].**
R-T-05	LMQXFA positioning inside the QQXF_SC cryostat is described in the LMQXFA and QQXF_SC interface document [7].
R-T-06	LMQXFA alignment requirement [1] must be met after the LQXFA/B/E/F cryostat assembly **is completed.**
R-T-07	Reference frame for Survey data and magnetic measurements data described in [8] must be used.
R-T-08	The QQXF_SC cryostat must be designed and documented in accordance with CERN and U.S. HL-LHC Accelerator Upgrade Project safety agreements [9**].**
R-T-09	The QQXF_SC vacuum vessel must be designed for a Maximum Allowable Working Pressure (MAWP) of 1 bar outside pressure and 0.5 bar inside pressure differential (1.5 bar absolute pressure inside the vacuum vessel) [10]**.**
R-T-10	The LQXFA/B/E/F cryostat assembly must be capable of sustaining loads resulting from pressure differential values (described in [10]) in the LHe containment vessel (cold mass and associated pipes) and pressure differential values (described in [10]) in the vacuum vessel without physical damage or performance degradation.
R-T-11	The LHe containment vessel (Cold Mass and associated pipes) and all other pressurized pipes need to be leak tight under their operating pressure. The leak check must measure that the leak rate is lower than 10-9 torr-liter/sec.
R-T-12	Instrumentation wiring and electrical busses during the assembly process must be handled carefully not to introduce any performance degradation.
R-T-13	The LQXFA/B/E/F cryostat assembly voltage limits must meet or exceed the LMQXFA voltage limit requirements specified in **[1].**
R-T-14	The LQXFA/B/E/F quench performance must meet the LMQXFA cold mass quench performance requirements specified in **[1].**
R-T-15	The LQXFA/B/E/F cryostat assembly must meet the detailed interface specifications with the following systems: (1) LMQXFA cold masses; (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 **[6].**
R-T-16	The LQXFA/B/E/F cryostat assembly must comply with CERN’s Launch Safety Agreement (LSA) for IR Magnets (WP3) **[9].**
R-T-17	CERN provides all the parts for QQXF_SC cryostat . The cryostat kit for the prototype and 10 production units will be supplied and shipped to Fermilab by CERN at no cost to US HL-LHC AUP. The list of the components of the kit can be found in [11].
R-T-18	Cryostat assembly tooling will be designed, procured and shipped to Fermilab by CERN or a vendor selected by CERN. The tooling that will be used for cryostat assemblies at CERN and Fermilab will be identical with minor differences that are site and cryostat specific (if any).
R-T-19	Cryostat assembly procedures including every QC and QA steps will be developed by CERN. The first prototype cryostat assembly work will be directed by CERN personnel to assure proper transfer of the procedures to Fermilab. At Fermilab an engineer will be assigned to be in charge for the cryostat assembly work.

R-T-20	**AUP is responsible for shipping the Cryo-assemblies to CERN without any performance degradation.**

Table 2: LQXFA/B/E/F Objective Functional Requirements Specification Summary Table

ID	**Description**
R-O-01	LQXFA/B/E/F reliability requirements are the same as the LMQXFA reliability requirements specified in **[1].**

21. References

[1] LMQXFA Functional Requirements Specification, US-HiLumi-doc-64; CERN EDMS 1686197

[2] Cryoassembly Acceptance Criteria, US-HiLumi-doc-xx; CERN EDMS 1868479

[3] 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

[4] WP3 System architecture and interfaces identification - IR Magnets CERN EDMS 1405220

[5] LHCLSXH_0010 version AF CERN EDMS 1395366

[6] QQXF_SC Interface Control Documents, US-HiLumi-doc-XX; CERN EDMS 1995150

[7] LMQXFA and QQXF_SC interface specification, in preparation. CERN EDMS 1868475

[8] L. Bottura, D. Missiaen, “Definitions of Survey and Magnetic Data for the Inner Triplet Systems at IR1, 2, 5 and 8”, CERN EDMS 367802. .

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

[10] Load conditions for the triplet cold masses in different operational scenario, CERN EDMS 1868420

[11] Parts exchange between US HL-LHC AUP and CERN HL-LHC WP3, US-HiLumi-doc-844; CERN EDMS 1825173