

The Cryogenic Distribution System for the High Luminosity LHC upgrade at CERN

M. Sisti^{1*}, S Claudet¹, J. Metselaar¹, A. Lees¹, F. Merli¹, A. Perin¹ and V Gahier¹

¹Cryogenic Group, Technology Department, CERN, Geneva, Switzerland

*E-mail: Michele.Sisti@cern.ch

Abstract. The High Luminosity upgrade of the Large Hadron Collider (HL-LHC) will require the replacement of the final focusing superconducting magnets, the implementation of new superconducting links to power the magnets and the implementation of new Superconducting Radio-Frequency (SRF) crab cavities, totalling a length of about 150 m on both sides of the collision points of the ATLAS (P1) and of the CMS (P5) experiments in the LHC accelerator. To cool the new and reconfigured cryogenic devices, a new Cryogenic Distribution System will replace the existing LHC cryogenic distribution line on each side of the experiments. Two multi-header cryo-distribution lines (QXL) for each of P1 and P5 will transfer helium at different temperature levels, pressures, and mass flows between the HL-LHC machine components and new helium refrigerator located in a cavern next to the LHC tunnel. The QXL system, manufactured and installed by industry on the basis of CERN detailed specification, will have a total length of approximately 1.5 km and will be installed in two phases, first in the underground service galleries and then in the LHC tunnel. This paper first describes the cryogenic configuration of the new equipment of the HL-LHC machine and the main functional requirements of the QXL. The cryogenic parameters for the different circuits and operation modes are presented. The paper emphasizes the architecture of the cryogenic distribution system, the conceptual design of its main components and its integration in the HL-LHC environment.

1. Introduction

The High-Luminosity Large Hadron Collider (HL-LHC) project will upgrade the LHC collider to exploit its full capacity [1]. By increasing its peak luminosity by a factor five over nominal value it will be able to increase the LHC initially planned integrated luminosity by nearly 10 times. To reach this goal, about 150 m of the accelerator will be entirely replaced on each side of the two collision points holding ATLAS (P1) and CMS experiments (P5) with new equipment that will require a new cryogenic distribution system. Due to the much-increased luminosity, the final focusing magnets will face a significant increase of dynamic heat loads that will require new refrigerators and a new cryogenic distribution system.



2. HL-LHC Cryogenic System Architecture

Each new HL-LHC cryogenic system, as presented in Figure 2, will provide cooling in a closed circuit at various temperature levels between 1.9 K and 80 K to different types of superconducting magnets, crab cavities, beam screens, thermal shields and current leads.

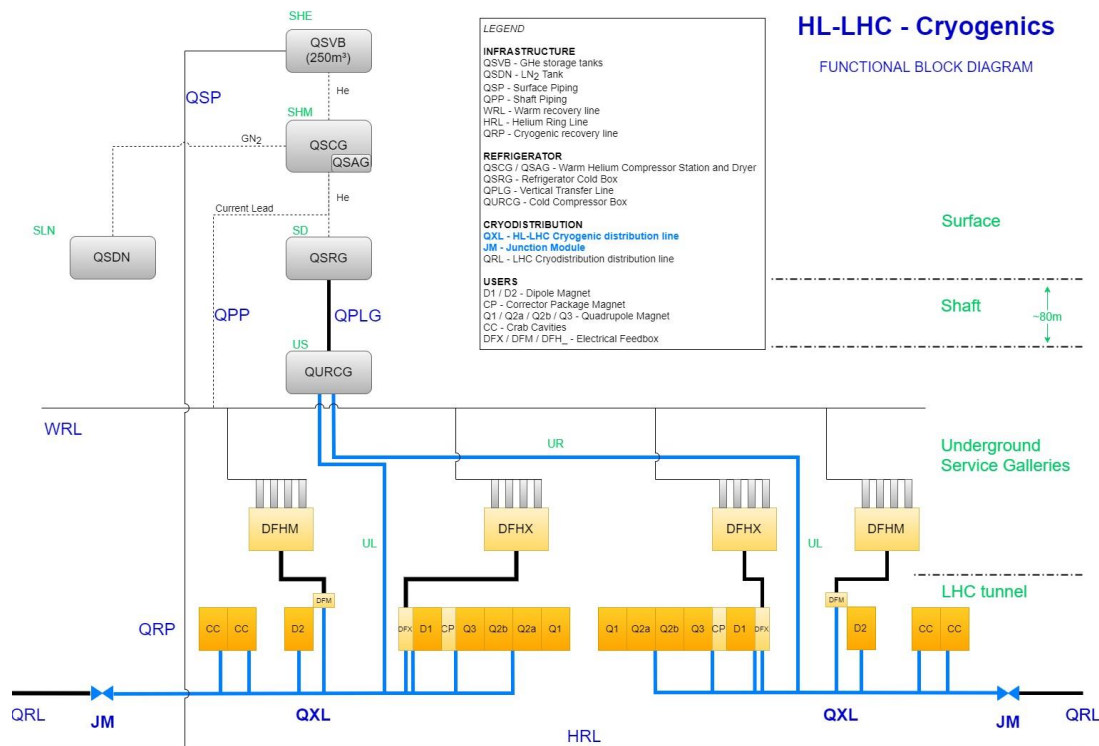


Figure 1. Schematic of the cryogenic architecture, QXL highlighted in blue.

The HL-LHC cryogenic system is divided in three systems, the Refrigerator, the Cryogenic Distribution Lines (QXL) and the Infrastructure.

The Refrigerator consists mainly of the warm compressor station and the refrigerator cold box located at the surface, and the cold compressor box located underground. Two multi-header QXL for each of P1 and P5 will be connected to the cold compressor box and will distribute helium at different temperature levels, pressures, and mass flows to and from the HL-LHC machine components. Each QXL has a total length of approximately 750 m; its main interfaces are:

- The 16 cryogenic interfaces with the magnets, crab cavities, and cryogenic powering equipment in the LHC tunnel;
- The two interfaces with the new refrigerator in the underground service galleries;
- The two interfaces with the existing LHC cryogenic distribution system (QRL).

3. HL-LHC QXL Main Functional Requirements

The QXL will provide cooling between 1.9 K and 80 K to the new HL-LHC machine equipment listed below:

- Q1-Q2A-Q2B-Q3 (inner triplet), CP and D1: superconducting Nb₃Sn Quadrupoles, Corrector Package Magnet and NbTi separation Dipole to focus the beams before collisions, correct orbits and separate the beam after collisions.
- D2: superconducting recombination dipole magnets based on NbTi conductors to separate and combine the beams after and before collisions.

- CC: special superconducting radio-frequency cavities (crab cavities) used to tilt and un-tilt the particle bunches before and after the collisions to maximize the cross section of the colliding bunches. There are two cryomodules per beam holding two cavities each.
- Cold powering system: electric feedboxes DFX/DFM/DFH and the superconducting link to power the superconducting magnets

The main functionalities of the cryogenic system of the HL-LHC are:

- Controlled cool-down and warm-up in maximum 15 days, defined by the refrigerator capacity and compatible with the cool-down and warm-up of the LHC sectors.
- Operation of the magnets in pressurized Helium II (1.9 K) and crab cavities at 2 K
- Cooling of beam screens at two different temperature levels: 60 K – 80 K and 4.5 K – 20 K
- Cooling of the thermal shield at 60 K – 80 K
- Supply of gaseous and liquid helium to the cold powering system
- Quench buffering during quench (energy discharged up to 39 MJ in the triplet magnets) and recovery to nominal operation in maximum 12 hours. The latter is defined by the capacity of the selected cold compressors and is compatible with the targeted cryogenic availability for LHC.
- Sectorization of the QXL and the existing QRL for fallback operation

The future HL-LHC heat loads were analysed during the last years [2] and dynamic heat load of about 3 kW at 1.9 K were found to be the dominant contribution. Taking into account these values and its shorter length, the static heat loads of the QXL represent a much smaller fraction of the total heat loads than for the existing QRL: this allows to accept heat loads to the QXL cold header (Table 1) that are approximately twice the values specified for the existing QRL [3], allowing for a more cost-effective design.

Table 1. HL-LHC QXL operational requirements.

	Header B	Header C	Header D	Header E _H	Header F _H
Nominal Temperature (K)	4	4.6	20	60	80
Nominal Pressure (bar)	0.015	4	1.3	21	20
Maximum flow rate (g/s)	178	212	10	82	82
Maximum heat load (avg) (W/m)	0.2	0.1	0.3	0.5	3
Maximum total heat load (W) per point	148	74	222	370	2220

4. HL-LHC QXL Operating Conditions and Architecture

The operating conditions of the cryogenic circuits in the QXL are specified in Table 1 and the global architecture of the QXL is shown in Figure 2.

The QXL will be made of a sequence of straight interconnected sub-assemblies.

This vacuum insulated multi-header cryogenic distribution line contains five process pipes

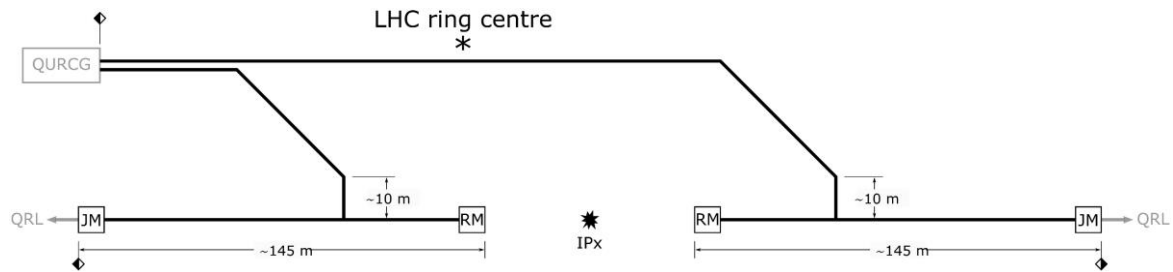


Figure 2. Schematic of the HL-LHC QXL architecture at each location.

in a single vacuum envelope, thermally shielded by an actively cooled thermal shield.

Naming, function, design pressure and nominal diameters of process pipes and vacuum vessel are given in Table 2. Header B and D diameters are different in the LHC tunnel and the underground galleries, to match the requirements of quench buffering for D and low pressure drop for B with the given volume availability for the vacuum vessel. Header D diameter is maximized in the LHC tunnel, where a smaller B is acceptable thanks to the left/right splitting of

Table 2. HL-LHC QXL process pipes and vacuum vessel main characteristics.

	Header B	Header C	Header D	Header E _H	Header F _H	Vacuum vessel
Function	Pumping line	4.6 K He supply line	20 K He return line	Thermal shield supply line	Thermal shield return line	-
Design pressure (bar)	4	20	20	25	25	1.4 – 1.5
Nominal diameter (ISO DN) – LHC tunnel	200	65	200	40	50	650 mm (nominal)
Nominal diameter (ISO DN) – HL-LHC galleries	250	65	125	40	50	650 mm (nominal)

the QXL when entering the tunnel, and the subsequent reduction in mass flow.

At each point, a portion of the QXL will be installed in the new underground service galleries for a total length of approximately 460 m per point. At each side of P1 and P5, approximately 150 m of the QXL will be installed in the LHC tunnel. This portion of the line, installed in the long straight sections around each IP, will be connected to the branches of the QXL coming from the Service Galleries through dedicated access vertical cores and will interface with the existing LHC cryogenic distribution line QRL. The QXL will be installed in two phases. The first phase will be carried out independently from the LHC machine operation, reducing the duration of the second phase, which requires the LHC machine dismantling foreseen during Long Shutdown 3

The HL-LHC devices will be connected to the QXL at specific service modules that include a cryogenic jumper, cryogenic valves, heat exchangers and instrumentation to control and monitor the helium supply and return. On the IP side, the QXL will be terminated with a Return Module (RM), where the inner headers will be interconnected. At the other extremity, the QXL will be connected to the existing QRL by a Junction Module (JM).

5. Conceptual design of the main QXL sub-assemblies

5.1 Service Module

The Service Module (SM) is a portion of the QXL which provide the function of connecting the QXL to the user. It includes control valves, instrumentation, subcooling heat exchangers and the relevant connecting circuits. The mechanical and hydraulic connection to users is performed via flexible cryogenic jumpers [4]. The typical jumper includes a vacuum barrier and flexible hoses and bellows to compensate the interface movement. Where the user interface is longitudinally shifted with respect to the jumper position, an additional extension to the jumper will be installed and will connect to the jumper with an interconnection. The SM connect to their adjacent QXL sub-assemblies via interconnections. In the given volume, the internal piping maintains the longitudinal continuity of the QXL Headers, while branch connections to jumpers and valves are mounted on the SM. The positions and orientations of the cryogenic valves guarantee their accessibility and maintainability considering the given tunnel cross-section. There will be 8 SM on each side of the two IPs, for a total of 24 new SM in total to be installed in the LHC tunnel.

5.2 Return Module

The Return Module (RM) is a portion of the QXL located at the IP extremity acting as the end-of-the-line element. It includes control valves, instrumentation and a sub-atmospheric phase separator. Four new RM will be installed in the LHC tunnel.

5.3 Junction Module

The Junction Module (RM) is a portion of the QXL located at the non-IP extremity on the line. The JM functions as the return module of both the QXL and the QRL, and as a sectioning element. It includes control valves, sectioning valves, instrumentation and sub-atmospheric phase separators. The JM incorporates two vacuum barriers, separating the vacuum of the QXL from that of the QRL and enabling independent operation and maintenance on the two sides. To limit the heat load between the QXL and the QRL process piping, an omega-shape circuit will be realized for each Header in the interconnecting region between the QXL-side and the QRL-side. Four new JM will be installed in the LHC tunnel. For transport reasons, the JM is split in two sub-assemblies, the JM-QXL and the JM-QRL.

5.4 Additional sub-assemblies

Additional sub-assemblies are part of the QXL, including the straight spool Pipe Element (PE) and the Tee Element, which is the mechanical and hydraulic connection of the QXL in the underground galleries and the QXL in the LHC tunnel.

6. Integration of the QXL in the HL-LHC environment

The integration of the QXL in the HL-LHC environment is one of the biggest challenges due to the peculiarities of the civil infrastructure and density of equipment in the LHC tunnel.

This aspect was considered since the first studies and once the QXL functional requirements were mature enough, the preliminary volume occupancy of each sub-assembly was defined and

the volume reserved in the HL-LHC global integration 3D model. Based on the QRL experience and available data, guidelines were established. Vacuum vessel outer diameter of 650 mm and 770 mm were selected for pipe elements and service modules respectively. A minimum distance of 350 mm between medium-size control valve installed in a row was accounted for the estimation of the total length of SM. As the QXL is installed between the magnets and the tunnel wall, accessibility for maintenance and inspection purposes is crucial and was considered since the beginning. Bridge platforms positioned on top of the LHC equipment will be installed in specific positions. In addition, horizontal flat platforms anchored to the top part of the QXL vacuum vessel are required to make the movements safer and easier and the time of intervention shorter. The future HL-LHC radiation environment played an important role in the definition of the QXL layout. A dose between 100 kGy and 1 MGy on the QXL is estimated and exclusion zones for sensitive equipment on the QXL (e.g., instrumentation) are defined in correspondence to the dose peaks. The final design of the first QXL sub-assemblies (pipe elements in the HL-LHC underground galleries) is now coming to an end. The preliminary volume occupancy in the HL-LHC global integration 3D model will be shortly replaced with the “as-designed” 3D model.

7. Conclusions and Challenges

The HL-LHC QXL is built upon the solid foundation of lessons learnt from the LHC and the QRL. It encompasses mechanical and thermal design, manufacturing, installation and maintenance, associated to a strong global cryogenic architecture and operability.

Qualified industrial manufactures were involved since the early stage of the tendering process. A concept and installation feasibility study was performed in 2021 with four out of five qualified industrial partners when the CERN concept was confirmed to be solid and room for improvement was identified. The 2022 tendering phase was affected by severe market turbulence. CERN adapted to the complex situation by proposing flexible and cost-effective solutions based on international indices for raw material, production and consumer to share the risks.

A contract for the procurement of the QXL was signed in December 2022 with the polish company KrioSystem Sp. z o.o.. The design phase is currently ongoing, and the first sub-assemblies are entering the manufacturing phase. The installation, planned in two phases to minimise its duration in the LHC tunnel, is planned to start end-2024 in the HL-LHC underground galleries, and be completed during the Long Shutdown 3 in the LHC tunnel. The QXL is foreseen to be cold-tested and its performance assessed in standalone mode prior to the installation of the HL-LHC machine components

References

- [1] Brüning O and Rossi L 2024 *The High-Luminosity Large Hadron Collider* Second Edition (World Scientific)
- [2] Gahier V and all 2024 Cryogenic architecture and heat loads for the High-Luminosity upgrade of the Large Hadron Collider at CERN (Paper presented at this conference)
- [3] Erdt W, Riddone G, Trant R 2000 The cryogenic distribution line for the LHC: functional specification and conceptual design *Advances in Cryogenic Engineering* 45 1387-1393
- [4] Merli F and all 2024 Detailed study of the cryogenic jumper connections between the cryogenic distribution line and the superconducting magnets of the High Luminosity LHC upgrade at CERN (Paper presented at this conference)