Detailed study of the cryogenic jumper connections between the cryogenic distribution line and the superconducting magnets of the High Luminosity LHC upgrade at CERN

F. Merli, S. Claudet, D. Ramos, A. Lees, A. Perin, H. Prin and M. Sisti

CERN, Technology Department, Cryogenic Group, Geneva, Switzerland

E-mail: Fabio.Merli@cern.ch

Abstract. The High Luminosity upgrade of the Large Hadron Collider (HL-LHC) project will require a new cryogenic system to cool the new superconducting components in the final focusing regions for the ATLAS and the CMS experiments. New superconducting magnets operating in pressurized HeII at 1.9 K will replace the existing ones and each magnet will generate heat loads of several hundred watts. The liquid and gaseous helium needed for the magnets will be supplied by new multi-header cryogenic distribution lines (QXL). The connections between the magnets and the QXL are performed at specific service modules via cryogenic jumpers, which must provide high flexibility while being compatible with the limited space in the LHC tunnel. This article describes the development of the QXL jumpers and presents their final configuration. It covers the mechanical and thermal-hydraulic validation, including a test campaign carried out to characterize the bending stiffness of the metallic flexible hoses used for cryogenic lines.

1. Introduction

The HL-LHC is a major upgrade of the LHC particle accelerator with the aim to increase its luminosity by a factor 5 to 7 [1]. To achieve this goal, about 150 m of the accelerator will be replaced on each side of the Interaction Points holding ATLAS (IP1) and CMS (IP5) experiments. The upgrade of the focusing system foresees to install new Inner Triplets (IT) Quadrupoles (Q1, Q2a, Q2b, Q3), sextupole-octupole-decapole Corrector Package (CP) [2], separation and recombination Dipoles (D1, D2), Crab Cavities [3] and cold powering system (DFX, DFM) [4].

To cool the new and reconfigured Cryogenic Beam Line Components (CBLCs), new cryogenic infrastructure will be installed including two new helium refrigerators [5] and two new cryogenic distribution systems [6], each consisting of two distribution lines to supply liquid and gaseous helium at various temperature and pressure levels.

The QXL is vacuum insulated and contains five cryogenic headers surrounded by a Thermal Shield (TS) actively cooled at 80 K: a liquid supply line at 4.6 K, a pumping line at 15 mbar and 4 K, a return line at 20 K and supply/return lines for TS and beam screens (BS) circuits between 60 K and 80 K. Each QXL consists of segments installed in the new HL-LHC service galleries and in the existing LHC tunnel. The segment in the tunnel includes Service Modules (SMs) housing the cryogenic instrumentation, control valves, heat exchangers and heaters needed to provide local cooling of the CBLCs.

2. QXL IT jumpers

In the IT region, three SMs provide local cooling of the continuous cryostat that includes the Q1, Q2a, Q2b, Q3, CP and D1 magnets. The cold masses of the IT magnets are immersed in a common static bath of pressurized HeII cooled by five cooling loops, each including a sub-cooling heat exchanger and control valves installed in the QXL SM and bayonet heat exchangers in the magnet, in the configuration shown in Figure 1. The IT magnets also share common circuits for the Beam Screens (BS) and Thermal Shields (TS) cooling. Finally, the static bath of HeII is connected to the QXL return line at 20 K for overpressure protection in case of quench.

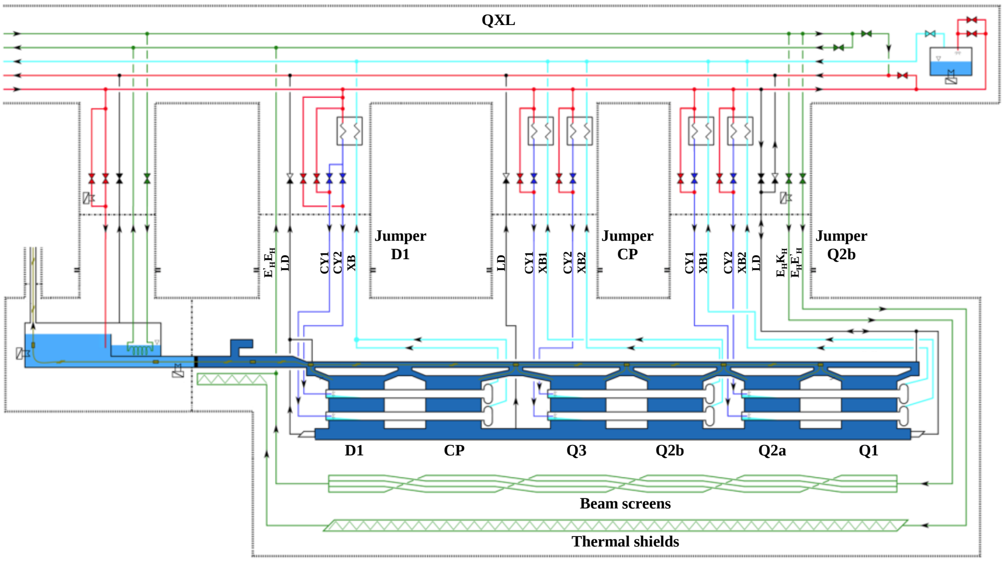

Figure 1. IT magnets cooling loops Process Flow Diagram. Nomenclature defined in Table 1.

The cryogenic requirements result in 5 to 7 pipes, ranging in inner diameter from 14 mm to 84.9 mm, that need to be routed to the magnets through three cryogenic jumpers (Q2b, CP and D1). The functions, the inner diameters and the operating conditions of these cryogenic lines are listed in Table 1.

Table 1. QXL IT jumpers functions, inner diameters and operating conditions.

Cryogenic line		ID [mm]	p [bar]	T [K]
Q2b	1.9 K gas pumping (XB1, XB2)	72.1	0.019	1.85
	1.9 K liquid supply (CY1, CY2)	14	1.6	1.85
	Quench, cooldown, warm-up (LD)	44.3	1.3	1.9
	BS supply (E_HK_H)	23.7	19	60
	TS supply ($E_HE'_H$)	23.7	19	60
CP	1.9 K gas pumping (XB1, XB2)	72.1	0.019	1.85
	1.9 K liquid supply (CY1, CY2)	14	1.6	1.85
	Quench, cooldown, warm-up (LD)	44.3	1.3	1.9
D1	1.9 K gas pumping (XB)	84.9	0.019	1.85
	1.9 K liquid supply (CY1, CY2)	14	1.6	1.85
	Quench, cooldown, warm-up (LD)	44.3	1.3	1.9
	BS & TS return (E'_HF_H)	23.7	18	80

3. Design of the cryogenic jumpers

As the HL-LHC magnets are designed to be re-aligned in operational conditions through a Full Remote Alignment System (FRAS) [7], the connection with the QXL shall be flexible enough to allow their movement without readjustment of the QXL SM while in cryogenic conditions.

In addition, the QXL jumpers shall compensate initial misalignments and accommodate relative displacements due to differential thermal contractions, which results in the required displacements listed in Table 2. The loads caused by these displacements shall not impair the alignment within few tenths of millimeters of the magnet cryostat. An additional functional requirement is to integrate a vacuum barrier to separate the QXL and the magnets insulation vacuum. These requirements combined with the significant space limitations in the LHC tunnel pose significant challenges requiring a particular care in the design of the connection.

Table 2. QXL IT jumpers design displacements along three axes (all values are expressed in mm, the LHC tunnel axis is parallel to Y and Z is the vertical direction)

	Vacuum Vessel						Cryogenic lines					
	Tolerances + FRAS			Thermal contraction			Tolerances + FRAS			Thermal contraction		
	X	Y	Z	X	Y	Z	X	Y	Z	X	Y	Z
Q2b	± 25	± 25	± 35	2	3	2	± 35	± 25	± 40	3	12	2
CP	± 25	± 25	± 35	2	2	2	± 35	± 25	± 40	3	2	2
D1	± 25	± 25	± 35	2	8	2	± 35	± 25	± 40	3	15	2

The solution employed for the existing LHC distribution lines (QRL) [8] consists in an elbow configuration with an articulated three-bellows system for the Vacuum Vessel (VV) and two flexible hoses integrated in the internal piping, as shown in Figure 2.

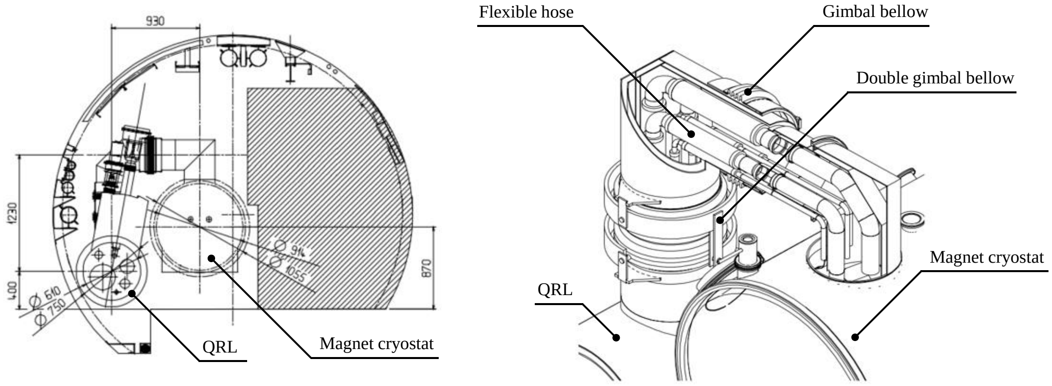

Figure 2. QRL cryogenic jumper connection.

The larger pipes needed for the HL-LHC require a larger VV, resulting in stiffer compensation components. Further, in the HL-LHC magnets the position of the longitudinal fixed supports was moved to the center of the cold mass, resulting in higher differential thermal contraction. Thus, the QRL configuration could not be adopted as such for the HL-LHC jumpers.

Retaining the basic principles of the QRL jumper design, the HL-LHC jumpers adopt an articulated three-bellows system for the VV and flexible hoses for the cryogenic lines. An additional horizontal segment was introduced to fit more flexible hoses and to relocate the VV gimbal bellow to increase the access to the jumper interconnection, as shown in Figure 3.

To minimize the differential thermal contraction in normal operating conditions and in case of Loss of Insulation Vacuum (LIV), the jumper vacuum barrier and the ground support of the QXL SM were positioned on the side of the magnet cryostats longitudinal fixed supports. Aligning the internal and external QXL supports in longitudinal direction results in having no consequences on the magnet cryostat in case of LIV in the cryogenic lines.

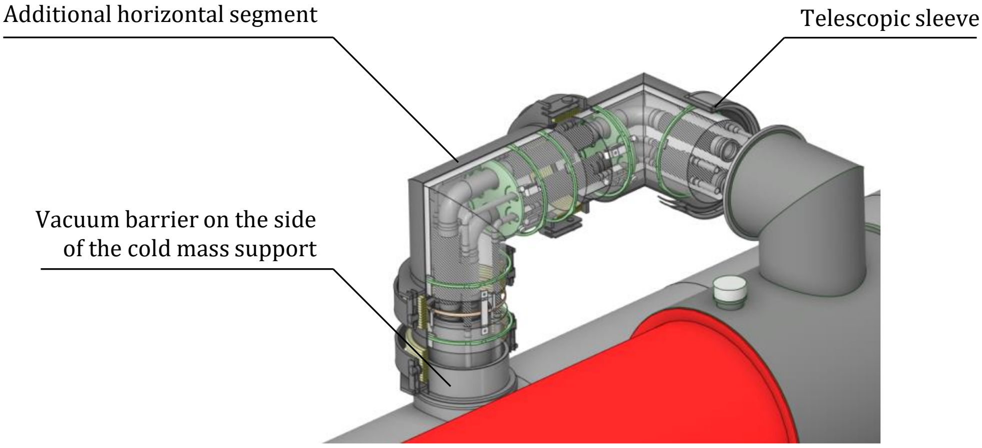

Figure 3. QXL (Q2b) cryogenic jumper connection.

The cryogenic lines are surrounded by three TS sections fixed to the VV and linked by joints aligned with the VV gimbal bellows. In the Q2b and D1 jumpers, the TS is cooled by the BS-TS inlet and return lines, while in the CP jumper it can only be cooled by conduction through the vacuum barrier.

The layout of the cryogenic lines at the jumper interface is determined by the piping configuration of the magnets and it is compatible with LHC-validated methods and tools for the interconnection. A telescopic sleeve on the VV ensures access for automatic orbital TIG welding machines for installation and maintenance activities.

4. Design validation

4.1 Flexibility

Detailed FEM analyses were performed to assess the flexibility of the proposed configuration and to evaluate the interface loads exerted by the jumper VV and cryogenic lines to the magnet cryostats. Multi-point constraints (MCPs) were used to represent the gimbal bellows of the VVs. The model includes a portion of the magnet's cryostat to assess the induced stress field and the reaction loads on the support jacks to check impacts on its stability.

To model the internal cryogenic lines, flexible hoses were represented as elastic beams with specified section properties. A representative characterization of the hoses bending stiffness was obtained by performing a dedicated test campaign. A scheme of the experimental set-up and a plot of the test results are shown in Figure 4. The bending stiffness was evaluated by measuring the reaction forces exerted by the hoses under imposed lateral displacements ΔL. The hoses were tested at room temperature at different pressure levels.

The results indicate that at constant pressure the bending stiffness varies roughly proportionally to the cube of the hose diameter. The internal pressure originates frictional forces between the bellow and the braids resulting in increased stiffness of the flexible hoses. For increasing pressure the hose bending stiffness (EI) was found to depend on two parameters, increasing roughly linearly with the pressure and with the hose diameter.

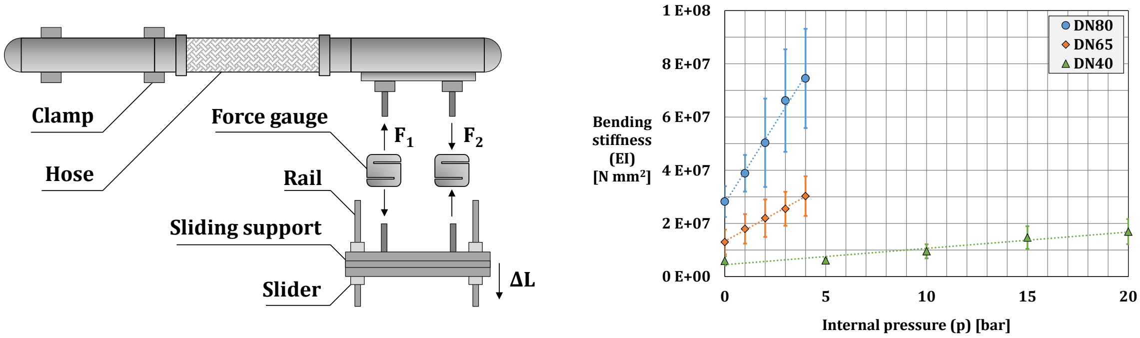

Figure 4. Flexible hoses bending stiffness characterization test set-up (left) and test results (right).

The design validation of the VV compensation system resulted in the requirements for the gimbal bellows to operate in a range of ±16° and to have a torsional stiffness lower than 15 Nm/°. The design of cryogenic lines was validated by verifying that the specified displacements are accommodated with minimum bending radii of the flexible hoses compliant with the limits prescribed by typical manufacturers' specification.

Finally, it was verified that the loads exerted by the QXL jumper are compatible with the high alignment precision requirements of the magnet cryostats. The calculated interface loads for the VV and the main cryogenic lines of the Q2b jumper are listed in Table 3.

Table 3. Q2b jumpers interface loads

Interface	Fx [N]	Fy [N]	Fz [N]	Mx [Nm]	My [Nm]	Mz [Nm]
VV	850	1950	2500	950	1350	1100
XB1	200	350	200	100	50	100
XB2	300	500	250	100	50	150
LD	100	150	100	50	50	50

4.2 Thermal-hydraulic performance

To ensure proper cooling and thermal stability of the superconducting magnets, the pressurized He II bath temperature shall not exceed 1.9 K. The corresponding saturation pressure equal to 23 mbar, coupled with the pumping pressure of 15 mbar at the cold compressor inlet, imposes a maximum pressure drop along the QXL pumping line and its branches lower than 8 mbar. The choice of two DN65 pumping lines (XB1 and XB2) for the Q2b and CP jumpers and of a DN80 line for the D1 jumper ensures a maximum pressure at the inlet of the bayonet heat exchangers lower than 20 mbar for the operating case corresponding to the nominal heat loads [9] of the IT magnets.

The thermal performance of the cryogenic lines, evaluated considering the heat inleaks coming from the very short vacuum barrier, the cryogenic spacers and the radiative heat exchange with the TS, ensures negligible heat loads to the bayonet heat exchanger lines (CYs and XBs) and to the quench line (LD) connected to the the pressurized HeII bath.

A major challenge for the cryogenic jumper design is to ensure the predicted thermal performance while providing the required flexibility. To verify that no contact would occur between lines at different temperatures and with the TS under the imposed displacements, a FEM clash and clearance analysis was performed including all the components from the vacuum barrier to the jumper interface. The analysis allowed to optimize the position and the size of the flexible hoses and the design of cryogenic spacers. An image of the model used for this analysis is shown in Figure 5.

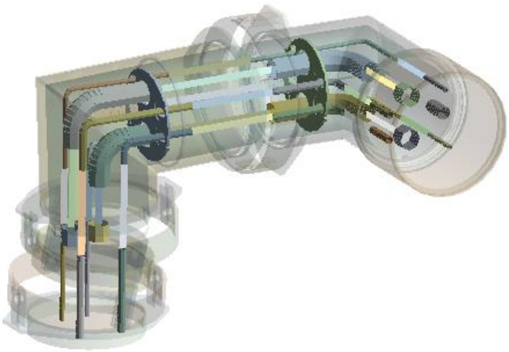

Figure 5. Q2b jumper clash and clearance analysis model.

5. Conclusions

This paper presents the design of the connection between the cryogenic distribution lines and the cryogenic beamline components for HL-LHC. The key design requirements and solutions for the QXL jumper are discussed, with reference to those of the QRL jumpers installed in the LHC tunnel.

The design of the new jumpers with the introduction of an additional horizontal segment increases the flexibility of the cryogenic connection and the access to the jumper interconnection easing the installation activities.

The design was validated by assessing the capability to fulfil all the requirements in the extremely limited space available while in nominal cryogenic conditions. Detailed FEM analyses were performed to ascertain that the jumpers can accommodate the design displacements while avoiding thermal contacts and that the loads applied to the magnet cryostats are compatible with their high precision alignment.

The article also reports a test campaign performed to provide a reliable characterization of the bending stiffness of flexible hoses, in the absence of available data from manufacturers.

References

[1] I. Béjar et al. (Eds.), "High-Luminosity Large Hadron Collider (HL-LHC): Technical Design Report", CERN Yellow Reports CERN-2020-010, Oct. 2020.

[2] D. Ramos et al, "Final design of the cryostat for the high luminosity LHC magnets", CEC 2021 (virtual), Jul. 2021.

[3] K Brodzinski et al., "Cryogenic design of the crab cavity modules for the High Luminosity LHC at CERN", CEC 2021 (virtual), Jul. 2021.

[4] A. Ballarino et al., "Conceptual study of the cryostats for the cold powering system for the triplets of the High Luminosity LHC", CEC 2017, Madison, Wisconsin, USA, Jul. 2017.

[5] E. Monneret et al., "Two new helium refrigerators for the LHC accelerator upgrade (HL-LHC) at CERN; From concept and tender to contract", CEC 2023, Honolulu, Hawaii, USA, Jul. 2023.

[6] M. Sisti et al., "The Cryogenic Distribution System for the High Luminosity LHC upgrade at CERN", ICEC 2024, Geneva, Switzerland, Jul. 2024.

[7] H. Mainaud Durand et al., "HL-LHC alignment requirements and associated solutions", IPAC 2017, Copenhagen, Denmark, May 2017.

[8] Erdt, W. et al., "The cryogenic distribution line for the LHC: functional specification and conceptual design", Advances in Cryogenic Engineering, 45 1387-1393, 2000.

[9] V. Gahier et al., "Cryogenic architecture and heat loads for the High-Luminosity upgrade of the Large Hadron Collider (HL-LHC) at CERN", ICEC 2024, Geneva, Switzerland, Jul. 2024.