

## Chapter 9

# Cryogenics for the HL-LHC

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## 9 Cryogenics for the HL-LHC

### 9.1 Overview

The upgrade of the cryogenics for the HL-LHC will consist of the following:

- The design and installation of two new cryogenic plants at P1 and P5 for high luminosity insertions. This upgrade will be based on a new sectorization scheme aimed at separating the cooling of the magnets in these insertion regions from the arc magnets and considering the new feedboxes and superconducting links located in underground infrastructures.
- The design and installation of a new cryogenic distribution lines (QXL) at P1 and P5 in the LHC tunnel and in a new underground service galleries.
- The upgrade of the existing cryogenic plant (QSRA and QURA) cooling the LHC sector 3-4 located at P4.
- The cryogenic design support for superconducting devices, such as magnets, crab cavities, superconducting links, and the hollow electron lenses.

Some other options such as new cryogenic circuits at P7 for the HTS links and displaced current feedboxes or a new cryoplant in P4 have been discarded.

### 9.2 LHC machine upgrades

#### 9.2.1 Upgraded beam parameters and constraints

The main parameters impacting on the cryogenic system are given in Table 9-1. With respect to the nominal beam parameters, the beam bunch population will double and the luminosity in the detectors of the high luminosity insertions at P1 and P5 will be multiplied by a factor 5.

Table 9-1: LHC upgraded beam parameters for 25ns bunch spacing

Parameter	Unit	Nominal LHC	Nominal HL-LHC
Beam energy, $E$	TeV	7	7
Bunch population, $N_b$	protons/bunch	$1.15 \times 10^{11}$	$2.2 \times 10^{11}$
Number of bunches per beam, $n_b$	-	2808	2748
Luminosity, $L$	$\text{cm}^{-2} \text{s}^{-1}$	$1 \times 10^{34}$	$5 \times 10^{34}$
Bunch length	ns	1.04	1.04

These upgraded beam parameters will introduce new constraints to the cryogenic system.

- The collimation scheme must be upgraded. As some of the new collimators will work at room temperature but be installed on the cold region, cryogenic bypasses are required to guarantee the continuity of the cryogenic and electrical distribution.
- Hollow electron lenses will be installed for halo control.
- The increase of the level of radiation to the electronics could possibly require relocating power converters and related current feedboxes. New superconducting links will be required to connect the displaced current feedboxes to the magnets.
- To improve the luminosity performance by addressing the geometric luminosity reduction factor and possibly allowing the levelling of the luminosity, cryo-modules of crab-cavities (CC) will be added at P1 and P5.
- Finally, the matching and final focusing of the beams will require completely new insertion cryo-assemblies at P1 and P5.

### 9.3 Temperature level and heat loads

Heat loads to the cryogenic system have various origins and uncertainties. The heat loads deposited in the accelerator are the result of physical mechanisms, which are classified as static, resistive, beam-induced, collision-induced, or radiofrequency-induced. The nomenclature is based on the LHC Design Report [1].

An important effort has been done during the last years to estimate the future HL-LHC heat loads [2]. The heat loads values in Table 9-2 are categorized by temperature level and heat load type. Table 9-3 reports the heat load values for group of users. It indicates the total contribution from static, dynamic (nominal/ultimate), total load (nominal/ultimate) and design values.

Table 9-2: “Nominal heat load” table for the LSS.R5 for the HL-LHC. Preliminary values.

Component	Q1	Q2A	Q2B	Q3	CP	D1	Intercon.	DFX	DFM	D2	CC
Length (m) (thermal shield)	10.140 (10.640)	9.785	9.785	10.140	6.01 (6)	7.370	6.930 (6 unit *)	2.535 (3.034)	4.000	13.025 (14.025)	2 module units †
<b>Cold Mass</b>											
Temperature (K)	1.9	1.9	1.9	1.9	1.9	1.9	1.9	4.5	4.5	1.9	2
Total Heat Load (W)	138.9	122.7	157.5	163.9	97.4	97.1	38.2	4.1	4.5	46.7	89.9
Avg. Heat Load (W/m)	13.7	12.5	16.1	16.2	16.2	13.2	5.5 W pu	1.6	1.1	3.6	45.0 W pu
Static (W/m)	1.7	1.7	1.7	1.7	1.8	2.2	0.3 W pu	1.6	1.1	0.6	18.9 W pu
Resistive (W/m)	0.7	0.4	0.4	0.7	3.9	0.1	0.0 W pu	0.0	0.0	0.0	0.0 W pu
Beam Induced (W/m)	0.3	0.2	0.2	0.3	0.0	0.1	2.2 W pu	0.0	0.0	0.2	0.0 W pu
Collision Induced ‡ (W/m)	11.0	10.3	13.8	13.5	10.5	10.7	3.0 W pu	0.0	0.0	2.8	0.0 W pu
RF Cavity (W/m)	-	-	-	-	-	-	-	-	-	-	26.1 W pu
<b>Beam Screen</b>											
Temperature (K)	60-80	60-80	60-80	60-80	60-80	60-80	60-80	-	-	4.5-20	4.5-20
Total Heat Load (W)	223.1	97.3	144.8	133.0	66.9	74.0	375.8	0.0	0.0	49.8	46.0
Avg. Heat Load (W/m)	22.0	9.9	14.8	13.1	11.1	10.0	54.2 W pu	0.0	0.0	3.8	23.0 W pu
Static (W/m)	0.1	0.1	0.1	0.1	0.2	0.2	0.0 W pu	0.0	0.0	0.0	9.3 W pu
Resistive (W/m)	0.0	0.0	0.0	0.0	0.0	0.0	0.0 W pu	0.0	0.0	0.0	13.6 W pu
Beam Induced (W/m)	5.1	2.9	4.4	5.1	0.6	2.3	42.4 W pu	0.0	0.0	3.7	0.0 W pu
Collision Induced ‡(W/m)	16.8	6.9	10.2	7.9	10.3	7.6	11.9 W pu	0.0	0.0	0.2	0.0 W pu

Component	Q1	Q2A	Q2B	Q3	CP	D1	Intercon.	DFX	DFM	D2	CC
<b>Thermal Shield</b>											
Temperature (K)	60-80	60-80	60-80	60-80	60-80	60-80	60-80	60-80	60-80	60-80	60-80
Total Heat Load (W)	66.6	53.2	53.2	54.3	133.8	103.2	22.2	24.9	28.0	133.1	609.0
Avg. Heat Load (W/m)	6.3	5.4	5.4	5.4	22.2	14.0	3.2 W pu	8.2	7.0	9.5	304.5 W pu
Static (W/m)	6.3	5.4	5.4	5.4	22.2	14.0	3.2 W pu	8.2	7.0	9.5	206.9 W pu
RF Cavity (W/m)	-	-	-	-	-	-	-	-	-	-	97.6 W pu
“-“ = not applicable; W pu = Watts per unit. * Length of each interconnection unit is 1 m, except between Q3-CP which is 1.8 m and CP-D1 which is 1.13 m. † A module unit contains 2 crab cavities.											

Table 9-3: Total heat loads divided by group of users, LSS.R5 and IP5. Preliminary values.

Group*	IT	D2	CC	LSS_R5		IP5	
Cold mass length (m)	62.7	17	-	79.7		159.4	
Thermal shield length (m)	63.7	18	-	81.7		163.4	
Number of units (-)	-	-	2	2 (CC)		4 (CC)	
<b>Cold Mass</b>							
Temperature (K)	1.9	1.9	2	1.9-2		1.9-2	
Total Design + flash (W)	1416.7	100.2	149.6	1667		3333	
Total Design (W)	1173.3	83.0	127.6	1384		2768	
Total Ultimate (W)	1103.4	68.7	89.9	1262		2524	
Total Nominal (W)	779.4	50.7	89.9	920		1840	
Dynamic - Ultimate (W)	1033.4	54.4	52.2	1140		2280	
Dynamic - Nominal (W)	709.4	36.4	52.2	798		1596	
Static (W)	70.0	14.3	37.7	122		244	
<b>Beam Screen</b>							
Temperature (K)	60-80	4.5-20	4.5-20	60-80	4.5-20	60-80	4.5-20
Total Design (W)	1685.0	74.7	97.0	1685	172	3367	343
Total Ultimate (W)	1424.1	50.9	46.0	1424	97	2846	194
Total Nominal (W)	1115.0	49.8	46.0	1115	96	2228	192
Dynamic - Ultimate (W)	1415.8	50.9	27.3	1416	78	2830	156
Dynamic - Nominal (W)	1106.7	49.8	27.3	1107	77	2211	154
Static (W)	8.4	0.0	18.7	8	19	17	37
<b>Thermal Shield</b>							
Temperature (K)	60-80	60-80	60-80	60-80		60-80	
Total Design (W)	744.9	229.6	913.5	1967		3935	
Total Ultimate (W)	496.6	153.1	609.0	1312		2623	
Total Nominal (W)	496.6	153.1	609.0	1312		2623	
Dynamic - Ultimate (W)	0.0	0.0	195.2	195		390	
Dynamic - Nominal (W)	0.0	0.0	195.2	195		390	
Static (W)	496.6	153.1	413.8	1116		2233	

(\*) *italic* values are indicating Design Heat Load values

The design heat load values consider margins and technological requirements. They can be calculated by using the following equations:

$$\dot{Q}_{installed} = MAX[F_{ov} \cdot (F_{un} \cdot \dot{Q}_{static} + \dot{Q}_{dynamic\ nominal}) ; F_{un} \cdot \dot{Q}_{static} + \dot{Q}_{dynamic\ ultimate}] \quad (9-1)$$

$$\dot{Q}_{installed} = MAX[F_{ov} \cdot \dot{Q}_{nominal} ; \dot{Q}_{ultimate}]$$

The first equation is valid for the cold mass (1.9–2 K) and beam screens (4.5–20 K and 60–80 K). The second equation is valid for the thermal shield (60–80 K) and current leads (20–293 K). A detailed study is available on [2]. Figure 9-1 gives a global view of the heat load at 1.9 K.

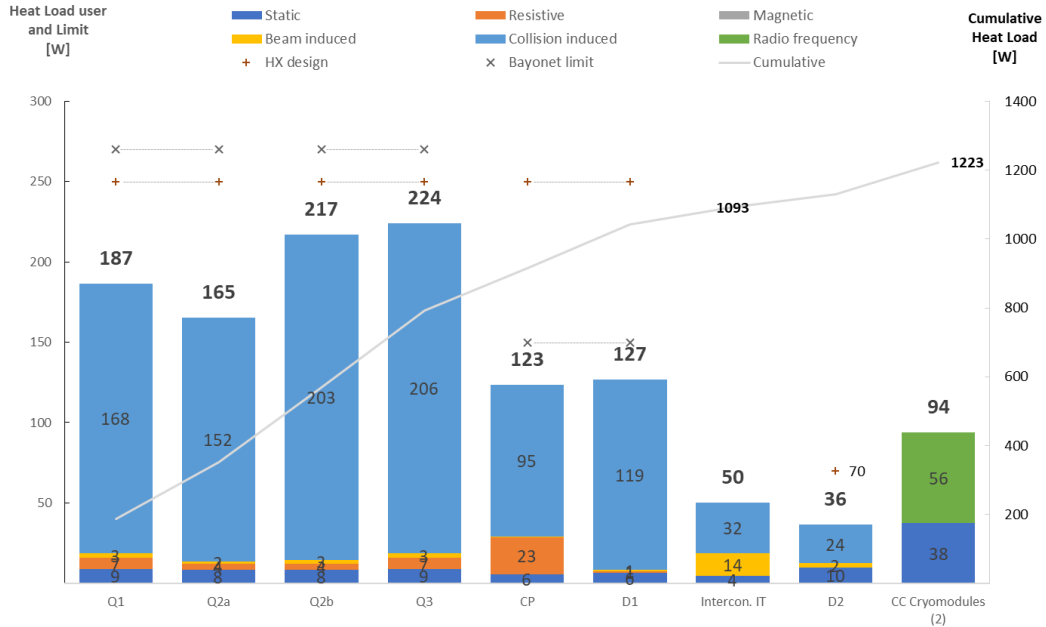


Figure 9-1: Total heat load for users at 1.9 K. Preliminary values.

### 9.4 Impact on existing sector cryogenic plants

With new cryogenic plants dedicated to the cooling of cryogenic equipment in P1 and P5, the cooling duty of the existing sector cryogenic plants will be reduced and more equally distributed. Figure 9-2 and Figure 9-3 shows the required cooling capacities for the different temperature levels and compares them to the nominal cooling requirements and to the installed capacities. The low-load sectors equipped with upgraded ex-LEP cryogenic plants have lower installed capacity than the four cryogenic plants specially ordered for the LHC high-load sectors. For the HL-LHC, sufficient capacity margin still exists providing that the beam scrubbing of dipole beam-screens is efficient (dipole off).

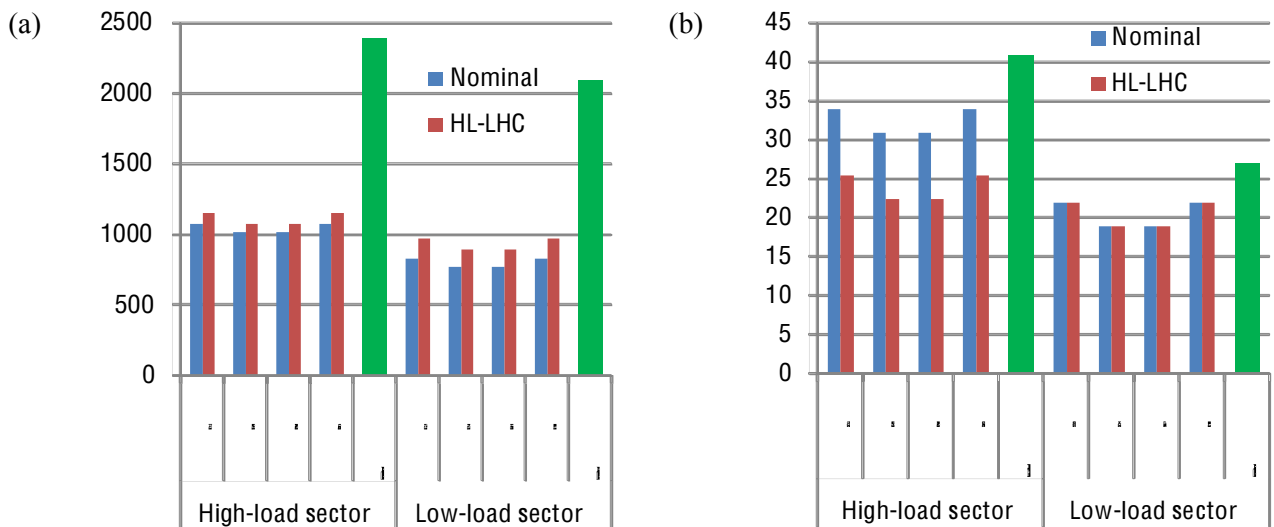


Figure 9-2: Cooling capacity requirement of sector cryogenic plants. (a) Cold mass; (b) current leads

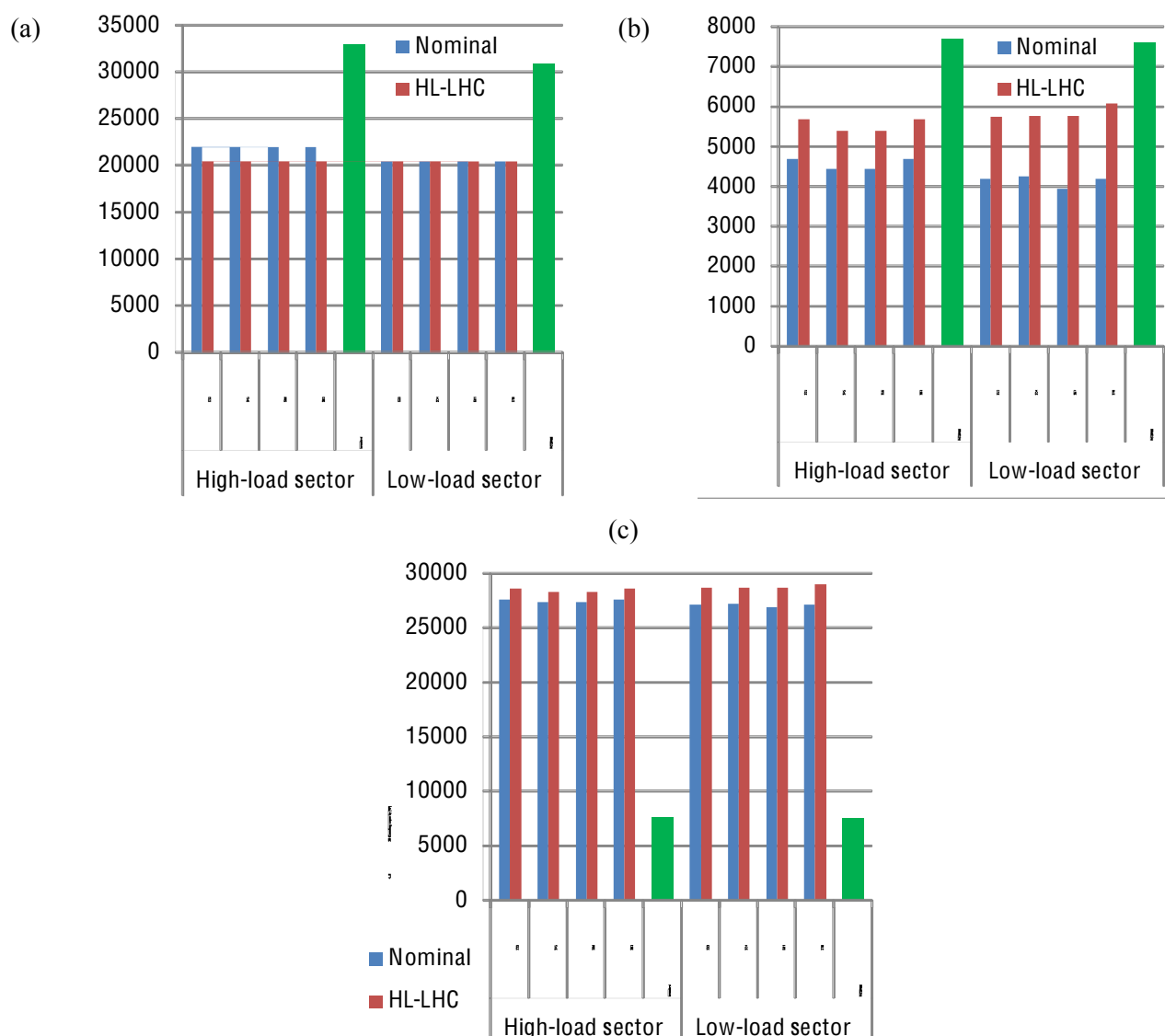


Figure 9-3: Cooling capacity requirement of sector cryogenic plants. (a) thermal shields; (b) beam screen (dipole off); (c) beam screen (dipole on).

### 9.5 Point 4 cryogenics

The initial baseline considered the installation of a new cryoplant in P4. Later on, was decided to evaluate an alternative scenario for the refrigeration part. The alternative scenario consisted of an upgrade of one of the existing refrigerator of P4 (equivalent of 2 kW@4.5 K with respect to the existing plant capacity of 16.5 kW@4.5 K) [6] to fulfil the required cooling capacity of existing SRF modules with sufficient margin, while keeping or adapting the distribution system depending on the alternative. As a complement, a new mobile refrigerator with a cooling capacity allowing RF tests of a single cryo-module during long shut-downs was then considered, as all other cryogenic sub-systems would be stopped for maintenance and major overhauling, but was finally abandoned.

The upgrade of the ex-LEP refrigerator included mainly:

- Replacement of 7 expansion turbines.
- Modification of one existing turbine.
- Modification of the required piping inside the boxes or for instrumentation and service panels.

The upgrade was successfully completed during the Long Shutdown 2.

The modification of the cryogenic distribution line to allow the installation of the hollow electron lenses is under study. The schematic layout can be seen in Figure 9-4 [5].

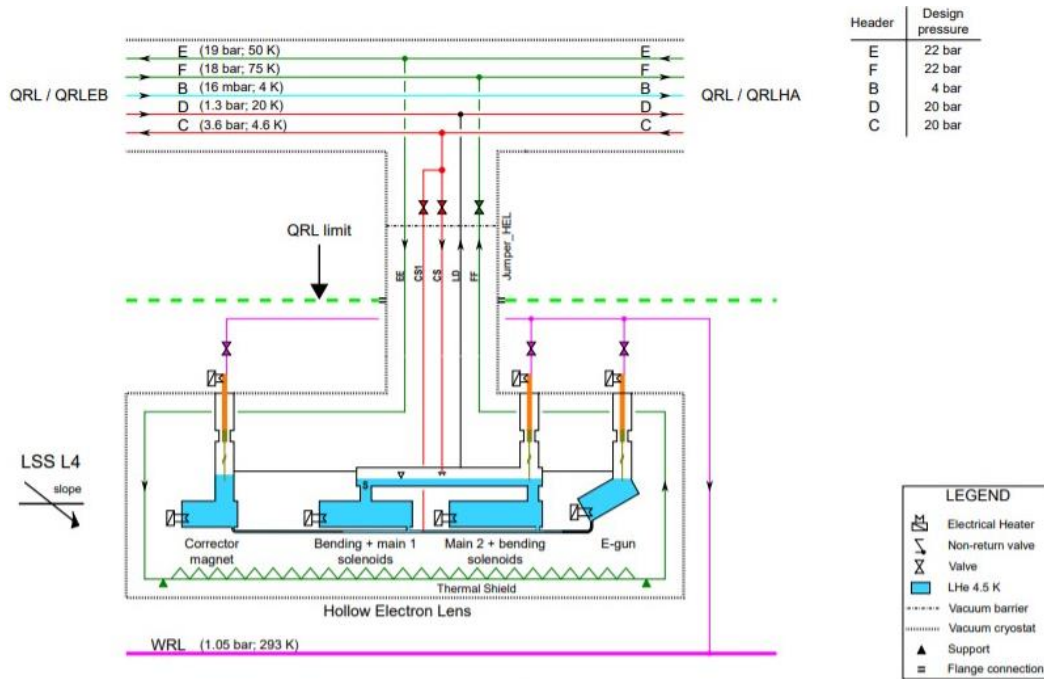


Figure 9-4: Layout of the possible cryogenic layout at P4 (Hollow e-lens)

### 9.6 New cryogenics for high luminosity insertions at Point 1 and Point 5

The new HL-LHC cryogenic system will require new cryo-plants of about 15 kW at 4.5 K including 3 kW at 1.8 K. They will encompass new refrigeration plants and distribution lines. Figure 9-5 illustrates the architecture of the system. A full analysis of both systems have been done in order to optimize the cost and the sourcing strategy.

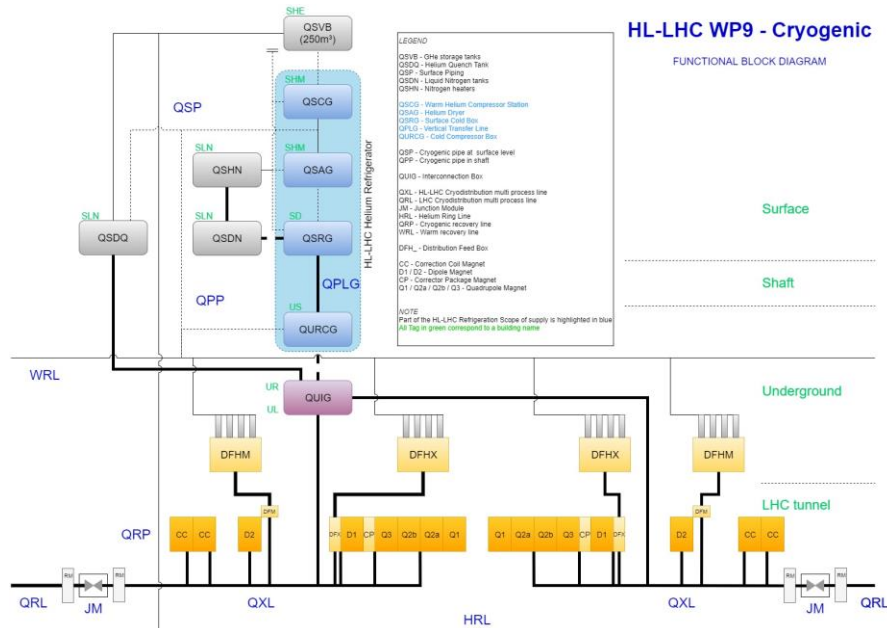


Figure 9-5: HL-LHC Cryogenic architecture at P1 and P5







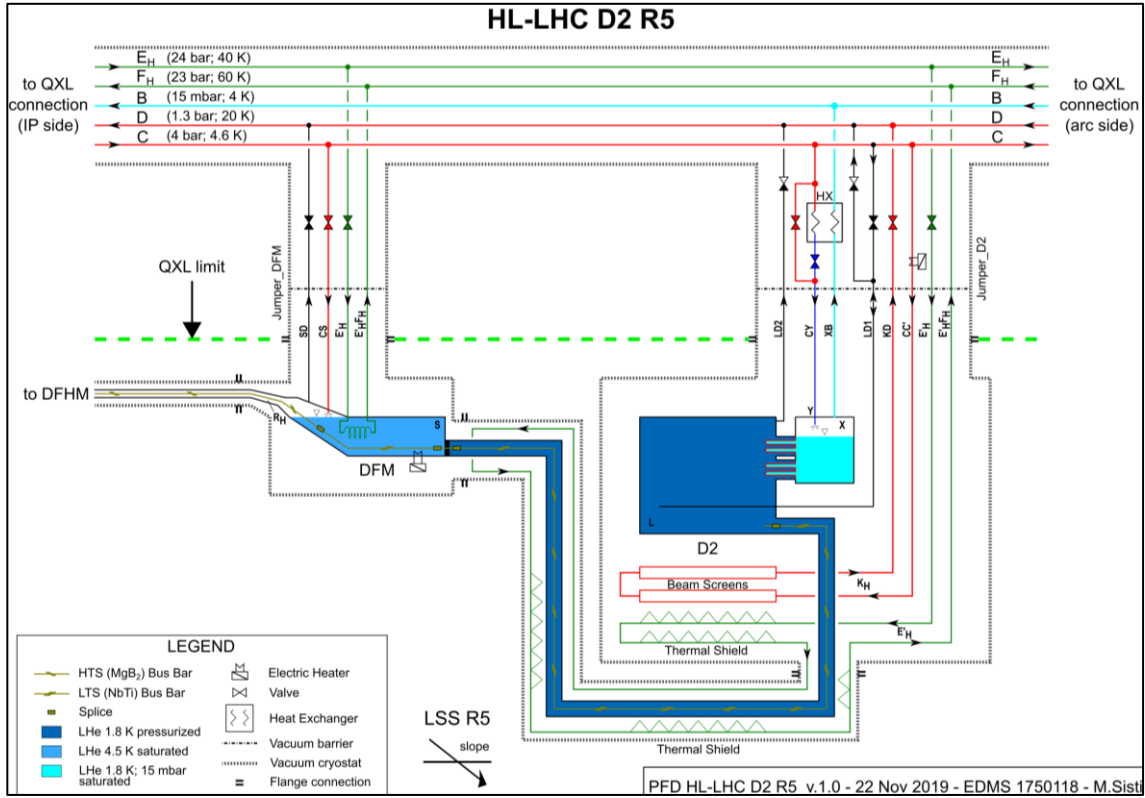


Figure 9-9: Detail of the distribution for the D2 magnet. [11]

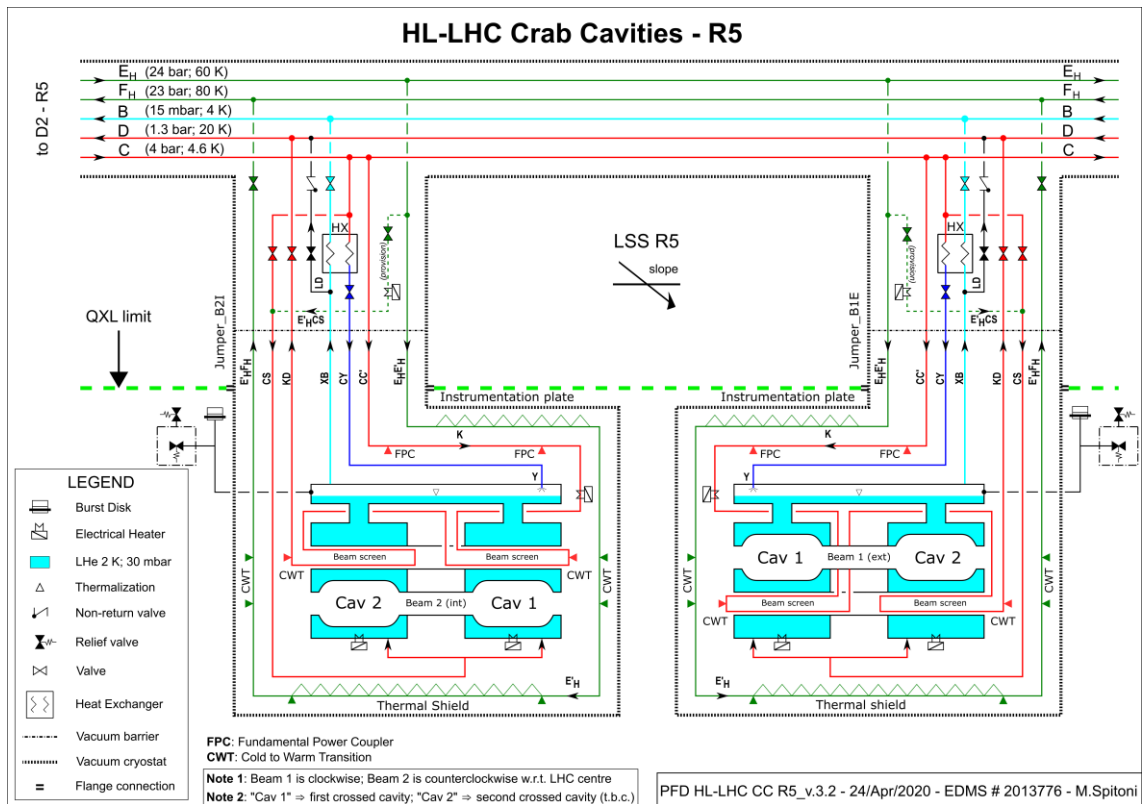


Figure 9-10: Detail of the distribution for the Crab Cavities [12].

Process flow diagrams for the Distribution Feed boxes are available on Refs. [13] [14].

## 9.7 References

- [1] LHC Design Report Volume I - The LHC Main Ring. Chapter 11. CERN, 2004, EDMS: [445856](#).
- [2] Updated heat load tables for the LSS.R5 for the HL-LHC, EDMS: [1610730](#).
- [3] Process flow diagram of HL-LHC IT L5, EDMS: [1963716](#).
- [4] Cryo distribution IP5, EDMS: [2025508](#).
- [5] Process Flow Diagram of HL-LHC Hollow e-Lens in P4, EDMS: [2314734](#).
- [6] IT-4472 Upgrade of the ex-LEP Refrigerator for HL-LHC - Point 4, EDMS: [2001440](#).
- [7] MS-4631 HL-LHC He Refrigerators, EDMS [2382454](#).
- [8] MS-4630 Supply of the Cryogenic Distribution Lines for the HL-LHC at P1 and P5, EDMS: [2381328](#).
- [9] Process flow diagram of HL-LHC IP5, EDMS: [2025508](#).
- [10] Process flow diagram of HL-LHC IT L5, EDMS: [1963716](#).
- [11] Process flow diagram of HL-LHC D2 L5, EDMS: [1750118](#).
- [12] Process flow diagram of HL-LHC Crab Cavities R5, EDMS: [2013776](#).
- [13] Process flow diagram of HL-LHC DFX L5, EDMS: [2322140](#).
- [14] Process flow diagram of HL-LHC DFM DSHM/DFHM R5, EDMS: [2373843](#).