Refrigeration assessment of the existing cryogenic plants for the high luminosity upgrade of the Large Hadron Collider (LHC)

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Abstract. The cryogenic system of the LHC will be upgraded by 2025 to comply with a considerable increase of beam induced heat loads deriving from higher beam currents and peak luminosity levels from the High Luminosity LHC. The current baseline foresees a modified sectorisation scheme with three additional cryogenic plants dedicated to cool the insertions at LHC’s points 1, 4 and 5, reducing the refrigeration duty of the existent adjacent plants. This paper assesses the refrigeration duty of the eight existing plants considering the modified sectorisation and increased heat load deposition. The accelerator loads and distribution losses are quantified for each plant and compared to the existing refrigeration capacity. The heat load values were obtained from the extrapolation of previous LHC assessments as well as from new calculations. Specifically for the LHC point 4 cryogenic equipment, based on updated refrigeration requirements, the upgrade of an existing plant is proposed as an alternative to the baseline scenario.

1. Introduction
The High-Luminosity Large Hadron Collider (HL-LHC) project is an upgrade of the LHC, with the objective of increasing the luminosity by 2030 to five times the LHC design value [1]. The LHC cryogenic system will be upgraded to comply with increased heat loads due to higher beam currents and to higher luminosity levels in the interaction regions of points 1 and point 5 [1]. The current baseline for the HL-LHC foresees a modified sectorisation scheme with three additional cryogenic plants: at point 1 and 5 for the high-luminosity insertions and at point 4 for the superconducting radio-frequency (SRF) cavities (Figure 1). To define the requirements of the cryogenic system, it is first necessary to assess the refrigeration duty and the overcapacity margin of the existing plants during nominal HL-LHC operation to then evaluate these margins for HL-LHC operation. This is accomplished by quantifying the accelerator loads and the distribution losses of each existing plant and comparing them to their respective refrigeration capacity. This paper presents the evaluation of the results considering the modified sectorisation and increased heat load deposition of the HL-LHC.

Figure 1. Cryogenic layout of the LHC machine including the three added cryoplants for the HL-LHC. [1]
2. Machine changes towards HL-LHC

2.1. Cryogenic Configuration

The cryogenic configuration of the LHC has eight cryogenic plants distributed in 5 cryogenic “islands” [2] (Figure 2). In the nominal configuration, each sector is cooled by a dedicated plant, but if necessary, interconnection boxes allow other configurations such as cooling two sectors with a single plant or combining refrigeration units of two interconnected plants. This study, however, only considers the nominal configuration with a single plant per sector. There will be four types of cryogenic plants for HL-LHC: type A and B already installed for the LHC and new type F and G planned for the HL-LHC (Table 1). In the LHC, type-A plants supply the four low-load sectors (S2-3, S3-4, S6-7, S7-8) and type-B plants the four high-load sectors (S1-2, S4-5, S5-6, S8-1).

In the HL-LHC, three new plants will take over the refrigeration of dedicated new superconducting devices; thus, reducing the refrigeration duty of five existing plants. Two new plants of type G will be installed at point 1 and 5 for the refrigeration of the high-luminosity insertions to the large ATLAS and CMS detectors, leading to the shortening of the sections served by existing type-B plants. The third new plant, of type F, will be installed at point 4 to cool the 400 MHz SRF modules with enough overcapacity to refrigerate future cryogenic equipment such as hollow electron lenses and harmonics of the SRF modules. This third new plant frees refrigeration power from the existing plants serving the two adjacent sectors (S3-4 and S4-5).

Besides these modifications, this study assumes that the cryogenic architecture of the existing cryogenic plants remains unchanged, excluding other modifications that have a minor impact on the heat loads like the new 11-T cryo-dipoles for the upgraded collimation scheme and the possible coating of short beam-screen regions for the mitigation of beam induced heat loads [1].

![Figure 2. Modifications in the LHC cryogenic configuration towards the HL-LHC.](image-url)

| Plant type | 4.5 K Refrigerator | Location | Served section |
|-----------|-------------------|----------|---------------|
| A         | LHCA              | Points 2, 4, 6, 8 | Low-load sectors |
| B         | LHCB              | Points 1.8, 4, 6, 8 | High-load sectors |
| F         | LHCF              | Point 4   | SRF modules   |
| G         | LHCG              | Points 1, 5 | High-luminosity insertions |

The refrigeration layouts of the existing cryogenic plants (types A and B) are represented by simplified flow-schemes similar to references [4] and [5]. As shown in Figure 3, each sector is connected to a 4.5 K refrigerator and a 1.8 K refrigeration unit via the cryogenic interconnection box (QUI). Type-A refrigerators were recovered and upgraded from the Large Electron-Positron Collider (LEP) to purpose for the LHC [6] and have their interface to the cryogenic distribution underground, whereas more powerful type-B refrigerators were fabricated for the LHC [7] and have their interface at surface...
level. At the 4.5 K refrigerator, headers B, C, D, E and F correspond to the interfaces to the interconnection box, while header LC is the inlet of the room-temperature line returning from the current leads. The helium properties and flow rates at the interface points are listed in Table 2, with values similar to [4] but obtained with our most recent model. All 1.8 K refrigeration units [8], hereafter referred as cold compressor units, are considered to have identical performance. In type-B plants, an additional subcooler at the tunnel level is used to re-condition the incoming flow from the temperature increase due to hydrostatic compression.

**Table 2.** Temperature, pressure and flow at the interface of the A/B refrigerator (as [4] but with current model).

| Interface | Temperature [K] | Pressure [bar] | Flow-rate [g/s] |
|-----------|-----------------|----------------|-----------------|
| C         | 4.5             | 3              | 237 / 192       |
| D         | 17.3            | 1.3            | 196 / 165       |
| E         | 50              | 18.5           | 251 / 236       |
| F         | 75              | 16.0           | 251 / 236       |
| LC        | 290             | 1.05           | 41 / 27         |

**Figure 3.** Simplified helium distribution of a cryogenic plant of type A or B [5].

In our model, schematized in Figure 4, the complex cooling circuits along the 3.3 km long sector are represented as a lump power deposition in a point-like geometry with common inlet and outlet interface. This results in a total of eight cooling circuits, each at a different temperature level and with its own cooling requirements. Six of those circuits (solid lines) were used to define the refrigeration system of the LHC sectors [4] [3], whereas the other two (dashed lines) were added afterwards. The cooling capacity that is available on the sector circuits is listed in Table 3, while the additional cooling requirements are shown in Table 4.

**Table 3.** Cooling capacity of sector circuits (A/B) defined in the thermal budget of the LHC [4] [3].

| Cooling Circuit | Temperature Level [K] | Cooling Capacity [kW] | [g/s] |
|-----------------|-----------------------|------------------------|-------|
| Thermal shield  | 50-75                 | 33 / 31                | -     |
| Beam screen     | 4.5-20                | 7.7 / 7.6              | -     |
| Cold Mass       | 4.5                   | 0.30 / 0.15            | -     |
|                  | 1.8                   | 2.4 / 2.1              | -     |
| Pumping line    | 3-4                   | 0.43 / 0.38            | -     |
| Current lead    | 20-290                | -                      | 41 / 27|

**Table 4.** Additional cooling requirements on sector circuits (without contingency).

| Cooling Circuit | Temperature Level [K] | Cooling Requirement [kW] | [g/s] |
|-----------------|-----------------------|--------------------------|-------|
| SRF *           | 4.5                   | 0.76                     | -     |
| SC link **      | 4.5-290               | -                        | 2.8   |

* S3-4 and S4-5 only. ** S3-4 only.
2.2. Heat loads estimation

The heating power generated during the operation of the accelerator is the result of several physical mechanisms, which are classified in six types [3]. Static heat loads are heat-in leaks coming from the surroundings and are a function of the cryostat design. Resistive heating occurs in current leads and in splices of superconducting cables. Beam induced heat loads come from synchrotron radiation generated when charged particles are bent, from image currents induced at the resistive walls of the beam screens, from the impingement of photo-electrons accelerated by the beam potential, from continuous particle losses due to residual gas in the beam pipe, and from random particles escaping the collimation system. Collision induced heat loads are generated by the deposition of secondary particles escaping from the collision points. RF losses occur in the accelerating cavities and are the energy dissipation due to changing electromagnetic field.

Depending on the mechanism, the heat load depends on the cryostat design, the beam energy, the bunch population, number and length of the circulating bunches as well as on the luminosity in collision points [3]. As a consequence, and based on the change in machine parameters (Table 5), specific scaling laws can be used to extrapolate the heating power generated by each mechanism [9].

| Machine | Energy $E$ [TeV] | Bunch population $Nb$ [p+/bunch] | Bunch number $nb$ [-] | Bunch length $4\sigma_r$ [ns] | Luminosity $L$ [$10^{34}$ Hz / cm$^2$] |
|---------|------------------|----------------------------------|-----------------------|-------------------------------|----------------------------------|
| LHC     | 7                | 1.15E+11                         | 2808                  | 1.0                           | 1                                |
| HL-LHC  | 7                | 2.20E+11                         | 2748                  | 1.2                           | 5                                |
| Relative change | 1        | 1.91                             | 0.98                  | 1.2                           | 5                                |

* At the high-luminosity detectors ATLAS and CMS.

The heat loads for the HL-LHC are estimated by extrapolating LHC values and by calculating values with updated thermal models [11] [12] (Table 6). Since the LHC Design Report [3] does not contain heat-load data with sufficient granularity (i.e. data tables for each mechanism), we recompiled the original data collected by the LHC’s Heat Load Working Group [13].

In the current LHC operation, the photo-electron effect contributes to a major fraction of the heating power deposited on the beam-screen circuits (30-80 % of the heat loads) [14]. However, due to high uncertainties in both the thermal model and the effectiveness of mitigation measures, we refrain to quantify their contribution for the future HL-LHC. We choose to exclude this mechanism from our heat-load balance and consider it part of the unknown factors to be covered by the refrigeration margin.

| Mechanism                  | Heat load data for the HL-LHC machine                          |
|----------------------------|---------------------------------------------------------------|
|                           | Extrapolated from [13] | Calculated with updated models |
| Heat-In leaks             | x1.00                                                           | -                               |
| Resistive heating         | x1.00 ($\sim E^2$)                                              | -                               |
| Synchrotron radiation     | -                                                              | Collected from [11] and [12].   |
| Image current             | -                                                              | Collected from [11] and [12].   |
| Photo-electron effect     | -                                                              | -                               |
| Beam scattering           | x1.87 ($\sim Nb \cdot nb$)                                     | -                               |
| Secondary particles       | x5.00 ($\sim E \cdot L$)                                       | -                               |
| RF losses                 | x1.00                                                           | -                               |

* Contribution considered as unknown due to high uncertainties in its evaluation.
Figure 5 shows the estimated heat loads for the nominal operation of the HL-LHC (vertical bars) with respect to the available cooling capacity of a type-A/B plant (dashed-dotted line). The estimation is without contingency and considers the different magnet types (main dipoles/quadrupoles, inner triplets, stand-alone magnets), the electrical feedboxes (DFB) and the cryogenic distribution line in the machine tunnel (QRL). The heat loads corresponding to the nominal operation of the LHC [13] are indicated for comparison (line segments).

With a few exceptions, the heat loads for a given circuit remain at similar levels across the eight plants. The substantial increase in beam-screen loads (4.5-20 K) is the most significant change between the LHC and the HL-LHC; especially because the reduced margin will have to cover a yet unknown amount of heating power due to photo-electron effect. Thanks to the modified sectorisation, there is only a moderate increment in the cold-mass loads (1.8 K) and an overall heat-load decrease for all other circuits on type-A plants.

Figure 5. Estimated heat loads for the nominal operation of the HL-LHC. Data is normalized with respect to the installed cooling capacity and is without contingency. Not shown are the additional heat loads from the SC link (LHC & HL-LHC) and from the SRF modules (LHC only).

3. Assessment of refrigeration duty on existing cryogenic plants

The assessment considers the losses of the distribution system and differentiates between useful and generated refrigeration power (Figure 6). The useful refrigeration power is the cooling power on a sector circuit (i.e. beam-screen circuit at 4.5-20 K) and assumes a perfect temperature match of the fluid to the cooling requirements. The term distribution loss derives from the efficiency of the distribution system and considers entropic losses due to pressure drop, flow mixing (i.e. at outlet of beam-screen circuit), flow re-conditioning and sub-cooling heat exchange. The sum of both corresponds to the refrigeration duty, which is defined as the cooling power provided by the 4.5 K refrigerator through its interface with the cryogenic distribution. The terms useful margin, margin loss and refrigeration margin are defined similarly.

Figure 6. Allocation of refrigeration power between the 4.5 K refrigerator and the equipment in the machine tunnel via the distribution system. The paths (not to scale) illustrate distribution losses as well as useful refrigeration power and margin.
Based on an exergetic analysis, the equivalent power at 4.5 K is used to compare the various physical processes such as the heat deposition at different temperature levels or the entropic losses along the distribution system. Figure 7 shows the refrigeration duty of the existing cryogenic plants for the nominal operation of the LHC (left bars) and for the HL-LHC (right bars). Since the SRF modules and the SC link were not part of the initial thermal budget of the LHC, their additional cooling requirements are covered by re-allocating a fraction of the refrigerator margin; in this work we use part of the margin originally allocated to the 1.8 K circuit. The refrigeration of the SRF modules in the LHC (S3-4 and S4-5) results in additional distribution losses caused by the mixing of the 4.5 K returning gas with the 20 K gas from the beam-screen circuits and from the cold compressor unit.

The assessment shows that most refrigerators will experience a limited increase in refrigeration duty of 10 % in average with respect to the LHC. The two exceptions are the plants cooling S3-4 and S4-5, because the exclusion of the SRF modules removed their related heat loads and distribution losses, leading to an average decrease of 6 %. Thanks to the modified sectorisation, all refrigerators of type-B will have a larger margin than those of type-A. The refrigerators serving S2-3 and S7-8 will have the lowest margin due to the heat loads from the low-luminosity insertions at point 2 and 8.

4. Alternative scenarios for point 4

The baseline scenario for point 4 is to feed the SRF modules with a dedicated cryogenic plant of type F, including a complex distribution scheme to keep the LHC sectorisation as backup. However, this solution increases the total number of cryogenic plants, potentially reducing the overall complexity and availability [15]. For this reason, and based on updated refrigeration requirements, we propose to cool the SRF modules with existing upgraded refrigerators at point 4 as a way to suppress the new dedicated plant of type F.

Table 7 shows the baseline scenario with two possible alternatives for point 4, and Figure 8 compares the corresponding refrigeration duty of the three types of plants (A, B and F). The refrigeration requirements of the SRF modules are 2 kW of useful cooling capacity, including an estimated 480 W of useful margin. In the baseline, all SRF modules are cooled by the type-F refrigerator, requiring the installation of a new plant with its respective distribution system. The refrigerator capacity of this plant is estimated in the order of 3 kW of equivalent power at 4.5 K, considering 25 % of distribution losses. In the alternative 1, all SRF modules are cooled by the type-B refrigerator (S4-5), requiring an upgrade of the refrigerator capacity and a modified distribution system at the SRF modules. The capacity upgrade of 19 % has the purpose to align the useful margin to the other plants, avoiding bottlenecks during operation. In the alternative 2, the SRF modules are cooled by both existing refrigerators (S3-4 and S4-5) as in the LHC configuration. The type-A refrigerator will require a capacity upgrade of 14 % to re-align its margin to the other plants. In contrast, the type-B refrigerator can use its margin to cover most of the additional loads, requiring only minor modifications, if any, to increase its capacity by 7 %.
Table 7. Possible refrigeration scenarios of the SRF modules at point 4.

| Plant type | Useful cooling capacity dedicated to the SRF modules [kW at 4.5 K] |
|------------|------------------------------------------------------------------|
|            | Baseline | Alternative 1 | Alternative 2 |
| A (S3-4)   | 0        | 0             | 1 (after upgrade) |
| B (S4-5)   | 0        | 2 (after upgrade) | 1             |
| F (point 4)| 2 (new plant) | -             | -             |

Schematics

Figure 8. Comparison of the refrigeration duty between the baseline and alternative scenarios at point 4.

5. Conclusions
The detailed heat-load estimation for the nominal operation of the HL-LHC has been completed, resulting in a comprehensive set of values for the existing cryogenic equipment and in the quantification of the available margins for the various cooling circuits in the machine tunnel. In addition, a thermal model of the cryogenic system has been built for the modified HL-LHC sectorisation, allowing the assessment of the refrigeration duty on the existing cryogenic plants. However, heat loads generated by the photo-electron effect were not quantified yet due to large uncertainties in their estimation.

The results show a considerable decrease in useful margin for the beam screen circuits (from ~5 kW to ~3.2 kW at 4.5 K to 20 K). This margin will cover a yet unknown, but significant, amount of heating power due to photo-electron effect. A possibility to increase this margin would be the re-allocation of the margin available on other circuits, but the efficiency of a margin transfer to the beam screen circuits requires further investigation. A re-assessment of our heat-load estimations would be necessary in case of a change in the beam parameters.

The assessment of the existing 4.5 K refrigerators shows a limited change in refrigeration duty between the LHC and the HL-LHC. The two refrigerators at point 4 will experience an average decrease of 6 % and the other 6 refrigerators an average increase of 10 %.

Our study shows the possibility to cool the SRF modules with existing upgraded refrigerators at point 4. This allows the suppression of one of the three additional plants for the HL-LHC, potentially increasing the overall availability and reducing complexity. For this reason, we propose two alternatives to the baseline scenario, each of them requiring an upgrade of the refrigerator capacity in order to align its margin to the other plants.

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