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EXERGY ANALYSIS OF THE CRYOGENIC HELIUM DISTRIBUTION SYSTEM FOR THE LARGE HADRON COLLIDER (LHC)

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Abstract

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ABSTRACT

The Large Hadron Collider (LHC) at CERN features the world's largest helium cryogenic system, spreading over the 26.7 km circumference of the superconducting accelerator. With a total equivalent capacity of 145 kW at 4.5 K including 18 kW at 1.8 K, the LHC refrigerators produce an unprecedented exergetic load, which must be distributed efficiently to the magnets in the tunnel over the 3.3 km length of each of the eight independent sectors of the machine. We recall the main features of the LHC cryogenic helium distribution system at different temperature levels and present its exergy analysis, thus enabling to qualify second-principle efficiency and identify main remaining sources of irreversibility.

KEYWORDS: cryogenics, helium, distribution, exergy, LHC

INTRODUCTION

With the emergence of superconductivity as a key technology of high-energy particle accelerators, cryogenic refrigeration has to be distributed in increasing power over longer and longer distances [1], ensuring over the entire length or circumference of the machines the low temperatures that enable correct operation of the superconducting devices and the small temperature gradients that constitute the basic condition for high thermodynamic efficiency [2]. Cryogenic distribution losses are also important for projects of limited geographical extension, but requiring high flow-rates of supercritical or two-phase helium as coolant, such as superconducting analysis magnets for high-energy physics and magnetic confinement fusion devices. A significant fraction of the capacity and operation costs of the refrigeration plants thus ends up in distribution losses, through two basic thermodynamic mechanisms: first-principle losses, i.e. heat inleaks and fluid friction in the transfer system, and second-principle losses, stemming from the fact that the cooling scheme is improperly matched in temperature to the cooling requirement. All distribution

losses lead to entropy generation, thus increasing the refrigeration load. Once expressed in terms of loss of exergy, they can be compared whatever the physical process which caused them, thus allowing technical arbitration among competing solutions and global thermodynamic optimization of the process. A good example of the exergetic method of analysis applied to a large cryogenic helium refrigeration plant, is given in reference [3]. We are however not aware of this method having been applied to cryogenic distribution.

METHODOLOGY

Exergy E is a thermodynamic function of state introduced by Rant [4] to describe the maximum amount of mechanical work which can be extracted – i.e. by the Carnot cycle - from a quantity of heat Q at temperature T, given an environment providing an infinite heat sink at temperature T_0.

$$\Delta E = Q \ (1 - T_0/T) \tag{1}$$

It is equivalent to the concept of useful energy ("énergie utilisable") introduced by Gouy [5]. The exergy analysis method for thermodynamic processes was promoted by Borel [6], while Bejan equivalently advocated minimization of entropy generation [7].

Conversely, E represents the minimum amount of mechanical work which is required to extract a heat quantity Q at temperature T – by a Carnot refrigerator – and reject it in the environment at temperature T_0. At cryogenic helium temperatures, exergy is clearly dominated by the $-T_0/T$ term, so that a refrigeration duty results in a loss of exergy.

For non-isothermal cooling duties, exergy can be expressed in differential form for each value of temperature and then integrated between the boundary temperatures T_1 and T_2. For example, in the case of a steady flow of fluid of constant specific heat,

$$\Delta E = Q \ [1 - (T_0/T_2 - T_1) \ \ln T_2/T_1] \tag{2}$$

Thus all cooling duties in a complex cryogenic system can be expressed in "useful" exergy losses ΔE_{useful}. The real exergy loss ΔE_{real} in the cryogenic distribution circuit providing each cooling duty will however be higher than ΔE_{useful}. For steady-state flow, the real exergy loss can be calculated from the definition of exergy as a function of state

$$e = h - T_0 \ s \tag{3}$$

where h and s are the enthalpy and entropy per unit mass of the fluid. The real exergy loss can then be calculated from the thermodynamic functions at the process points

$$\Delta E_{real} = m \ (\Delta h - T_0 \ \Delta s) \tag{4}$$

In the following, thermodynamic functions of helium are taken from the software package HEPAK 3.4 [8], and T_0 is taken as 290 K which corresponds approximately to the average ambient temperature. For each cooling loop, an exergetic efficiency η of the cryogenic distribution can thus be estimated

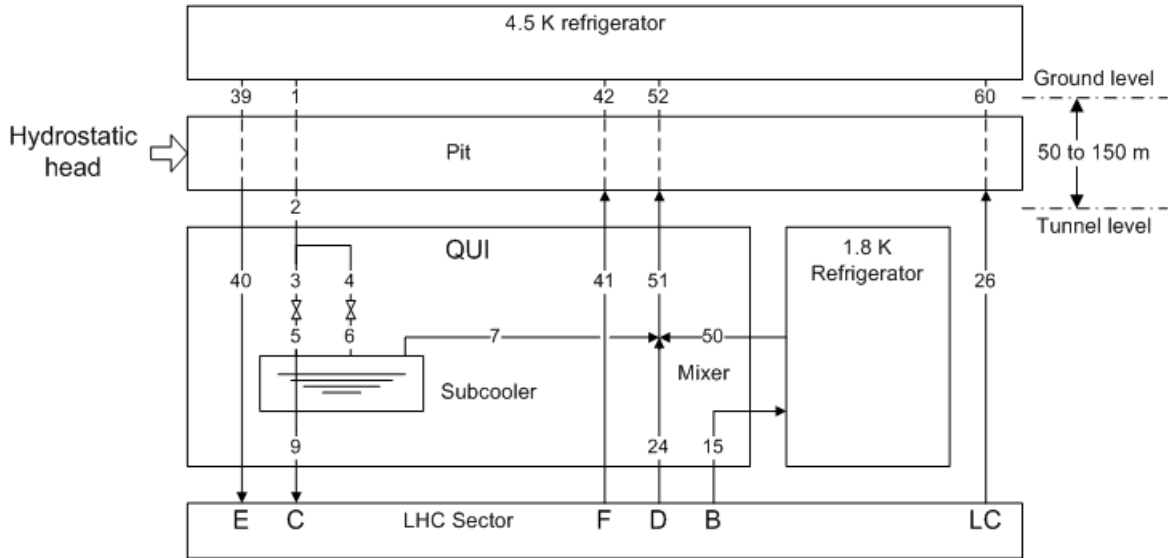$$\eta = \Delta E_{useful}/\Delta E_{real} \tag{5}$$

FIGURE 1. Simplified flow diagram for helium distribution between the refrigerators and a LHC sector

LHC SECTOR HEAT LOADS AND REFRIGERATION CAPACITIES

Every one of the eight 3.3 km-long sectors of the LHC machine is cooled by one dedicated refrigerator down to 4.5 K and one cold compressor unit for the cooling at 1.8 K. Of the eight 4.5 K refrigerators four were upgraded from the existing installations recovered from the LEP project [9], four were built new [10]. Every 1.8 K refrigeration unit [11] is connected to a 4.5 K refrigerator. The overall architecture of the cryogenic system is given in reference [12]. FIGURE 1 schematically shows how a sector is connected to the 4.5 K and 1.8 K refrigerators via the cryogenic interconnection box QUI.

The nominal exergetic capacities in nominal conditions for the 4.5 K and 1.8 K refrigerators can be obtained from the interface conditions at their cold end [10, 11] using equation (4). The resulting values are given in TABLE 1.

EXERGY ANALYSIS OF THE NOMINAL PROCESS

The nominal values of cooling duties, as defined in [13], and process points for the cryogenic distribution in the machine tunnel of a sector of the LHC are shown in FIGURE 2. Points B, C, D, E and F correspond to the interfaces with the tunnel interconnection box, while LC is the inlet to the gaseous helium return line of the current leads. The helium properties and flow rates at the interface points of the sector are given in TABLE 2.

TABLE 1. Nominal exergetic capacity of the refrigerators for a LHC sector

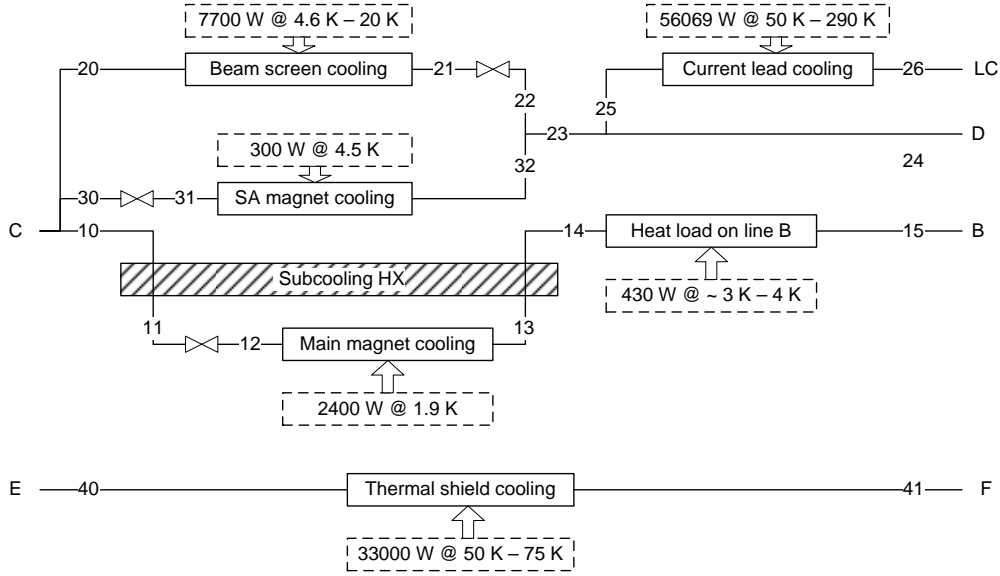| Refrigerator	Total exergetic capacity [kW]	Equivalent capacity at 4.5 K [kW]
4.5 K refrigerator	1149	18.1
1.8 K refrigerator	45.9	0.72

FIGURE 2. Simplified cryogenic process flow-scheme of LHC sector

The useful refrigeration duties are shown in the dashed-line boxes, while their application to the cooling fluid appear in solid-line boxes: these entities may differ when the cooling circuit is imperfectly matched in temperature to the refrigeration duty, or when there is an intermediate heat transfer process driven by an additional temperature gradient, e.g. the pressurized-to-saturated helium heat exchanger tube in the main magnets which requires transverse temperature gradient across its copper wall and longitudinal pressure drop along the length of the local cooling loop [14]. The useful exergy loss of each refrigeration duty, calculated from equations (1) and (2), is given in TABLE 3. The overall exergetic efficiency of the cryogenic distribution in the tunnel is 72%.

Helium properties and flow-rates at the process points enable to calculate exergy from enthalpy and entropy using equation (3). It is thus possible to track exergy losses along the different cooling loops, and to represent them on an exergy-flow diagram as given in FIGURE 3. We then proceed to discuss the losses in the different branches.

Main Magnet Cooling

This loop dominates the exergy budget of the whole system, with a useful exergy loss of 364 kW. Along the helium flow, the exergy losses are very similar among the different sources of irreversibility: the subcooling heat exchanger accounts for some 39.6 kW, the Joule-Thomson expansion for 44.7 kW and the heat load to the return line for 35.7 kW. The exergy loss through the pressurized-to-saturated helium heat exchanger tube in the magnets adds another 17.5 kW, thus yielding an overall exergetic efficiency of 73%.

TABLE 2. Helium properties and flow-rates at inlet and outlet of LHC sector

Interface	Temperature [K]	Pressure [bar]	Flow-rate [g/s]
B	3.79	0.015	125
C	4.60	3.00	214
D	16.9	1.30	48.0
E	50.0	18.5	251
F	75.0	16.0	251
LC	280	1.10	41.0

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TABLE 3. Exergy losses in cooling circuits in the tunnel of a LHC sector

Cooling circuit	Process points	ΔE_{real} [kW]	ΔE_{useful} [kW]	η [%]
Main magnets	10 to 15	501	364	73
Beam screens	20 to 22	271	205	76
Current leads	25 to 26	122	63.0	52
Stand-alone magnets and mixing	22 and 30 to 23	40.1	19.0	47
Thermal shields	40 to 41	145	122	84
Total	-	1079	774	72

Stand-Alone Magnet Cooling

The stand-alone magnets operate in baths of saturated helium at 4.5 K, produced by Joule-Thomson expansion from the supercritical fluid tapped from C. The useful exergy loss is 19.0 kW, to which the expansion adds another 1.5 kW. An additional source of irreversibility is due to mixing the gaseous helium flows at 4.5 K (point 32) and 20 K (point 22), with a resulting temperature of 16.9 K (point 23): the corresponding exergy loss is 19.7 kW. The exergetic efficiency of this cooling loop is thus particularly low, 47%.
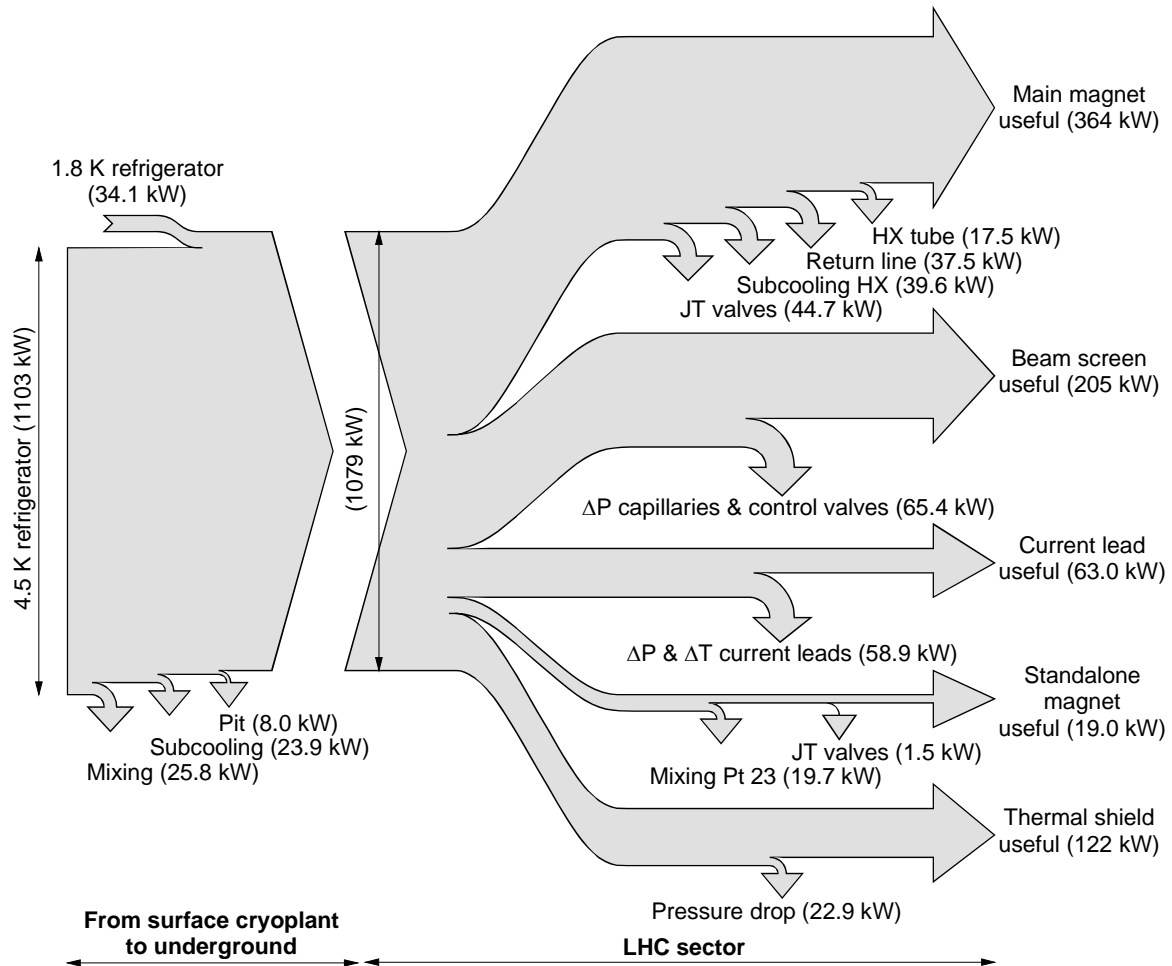

FIGURE 3 . Exergy-flow diagram of LHC sector including distribution from surface cryoplant to underground

Beam Screen Cooling

Non-isothermal cooling of the beam screens between 4.6 K and 20 K represents the second largest useful exergy loss in the system, with 205 kW. Pressure drop along the cooling capillaries of the beam screen and in the flow-control valves [16] amount to a large exergy loss of 65.4 kW: this is the price to pay for maintaining the thermodynamic state of the flowing helium well above the critical point, in order to limit the risk of instabilities. The exergetic efficiency of this cooling loop is 76%.

HTS Current Lead Cooling

The specification requires 41 g/s gaseous helium between (16.9 K, 1.3 bar) and (280 K, 1.1 bar), for cooling the upper section of the current leads from 50 K – maximum operating temperature of the HTS-to-copper junction, to 290 K. One may then calculate an equivalent refrigeration duty of 56.1 kW between the latter temperatures, and thus a useful exergy loss of 63.0 kW. The large temperature difference between lead and flowing helium – imposed by the limited heat exchange in practical current leads – and the pressure drop along the flow – including flow-control valves - yield an additional exergy loss of 58.9 kW. The resulting exergetic efficiency is thus only 52%.

Thermal Shield Cooling

In view of its high heat load between 50 K and 75 K, the thermal shield of the cryostat represents a significant useful exergy loss of some 122 kW. Pressure drop along the 6.6 km circuit (go and return) adds an exergy loss of 22.9 kW, this yielding an efficiency of 84% for this cooling loop.

Distribution from Surface Cryoplant to Underground

The cryogenic interconnection box QUI, shown in FIGURE 1 connects the cryogenic lines between the LHC sector, the 4.5 K refrigerator at ground level and the 1.8 K refrigerator at tunnel level. The cold compressor units deliver the flow of sub-atmospheric helium back at 20 K and 1.3 bar to the interconnection box.

The enthalpy variation in the vertical flow is the sum of the thermal load Q on the line and of the work of gravity across the elevation difference d, yielding per unit mass:

$$\Delta h = Q/m \pm g\, d \qquad (6)$$

with the + sign corresponding to downward flow, and the – sign to upward flow.

TABLE 4. Enthalpy variation due to work of gravity and thermal load in the vertical helium lines

Flow path	Δh total [J/g]	Estimated heat load [W]
1 to 2	1.63	35
39 to 40	1.61	35
41 to 42	-0.87	35
51 to 52	-1.29	150
26 to 60	-1.47	0

TABLE 5. Exergy losses in cryogenic distribution from surface to underground

Process	ΔE [kW]
Pit	8.0
Subcooling	23.9
Mixing (points 7, 24 and 50)	25.8
Total	57.8

TABLE 4 gives the enthalpy variations for the 150 m maximum depth of the LHC shafts, based on the estimated heat loads of the cryogenic lines. In all cases the enthalpy variations are dominated by the work of gravity. For the downward flow of subcooled helium the enthalpy increase is about 9% of the available enthalpy difference for two-phase cooling: it was therefore decided to include a subcooler in the distribution box in order to re-cool the helium before entering the sector.

One can then identify the corresponding losses, as listed in TABLE 5, and calculate the exergy flows, as shown in FIGURE 3. The overall efficiency of the distribution from the refrigerators to the inlet of the sector is 95%.

The exergetic load at the interface of the refrigerators results from the sum of all losses. The values for the total exergetic load of a sector on the two refrigerators, including the distribution are given in TABLE 6.

Comparing the calculated exergetic load on the refrigerators to the specified values given in TABLE 1, shows capacity margins of 4% for the 4.5 K refrigerator and of 35% for the 1.8 K refrigerator. In both cases these margins result from conservative assessment of the sector return temperatures.

FROM NOMINAL PROCESS TO REAL OPERATION

The above exergy analysis gives a good overview of the losses due to design choices. It is however not exact in every detail as it incorporates considerable simplifications. The sector losses are considered as lumped loads in a point-like geometry having one common inlet and outlet interface. In real, the loads are distributed over the 3.3 km long sector, each with different interface conditions as the thermodynamic states vary due to distributed heat loads, hydraulic friction, hydrostatic head and localized injections of 4.5 K vapour into the 1.3 bar return line.

A complete exergy analysis of a LHC sector would certainly be interesting in order to compare the real loads and losses along the sector to the design values, once the LHC machine reaches nominal operating conditions. This task however appears difficult as helium properties cannot be measured with sufficient precision using the installed industrial process instrumentation, and mass flow values are in most cases not measured at different locations along the sector.

TABLE 6. Total exergetic load on the refrigerators

Refrigerator	Process points	ΔE [kW]
4.5 K refrigerator	1, 39, 42, 52 and 60	1103
1.8 K refrigerator	15 and 50	34.1
Total load		1137
Total useful load		774

CONCLUSION

Thanks to the variety of its cooling duties, a 3.3 km long sector of the LHC provides an interesting field for application of the exergetic analysis method to cryogenic distribution. Cooling schemes and losses of very different nature can be compared in terms of their relative exergetic cost, while the absolute values of the exergy losses is an almost direct measure of the electrical power needed to run the corresponding refrigeration – within the efficiency factor of the real refrigerator with respect to the Carnot cycle. Hence, the total effective exergy loss of the sector of 1137 kW, combined with an overall efficiency with respect to the Carnot cycle of 27%, yields a power consumption of 4.2 MW. With a total useful exergy loss of 774 kW, the overall efficiency of cryogenic distribution in the tunnel of an LHC sector amounts to 68%. This good result can largely be attributed to the absence of circulation pump in the cooling loops. Still, the total exergy loss of 363 kW results in 1.3 MW extra power consumption of the refrigeration plant. We advocate application of the exergy analysis method to cryogenic systems as a powerful tool to render the design engineer second-law conscious and allow him to optimize cryogenic distribution.

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