

Cryogenic heat load and refrigeration capacity management at the Large Hadron Collider (LHC)

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The Large Hadron Collider (LHC) is a 26.7 km high-energy proton and ion collider based on several thousand high-field superconducting magnets operating in superfluid helium below 2 K, now under commissioning at CERN. After a decade of development of the key technologies, the project was approved for construction in 1994 and the industrial procurement for the cryogenic system launched in 1997, concurrently with the completion of the R&D program. This imposed to base the sizing of the refrigeration plants on estimated and partially measured values of static and dynamic heat loads, with adequate uncertainty and overcapacity coefficients to cope with unknowns in machine configuration and in physical processes at work. With the cryogenic commissioning of the complete machine, full-scale static heat loads could be measured, thus confirming the correctness of the estimates and the validity of the approach, and safeguarding excess refrigeration capacity for absorbing the beam-induced dynamic loads. The methodology is applicable to other large cryogenic projects such as ITER or the International Linear Collider (ILC).

MAIN FEATURES OF LHC CRYOGENICS

At the time of this conference, the eight 3.3 km long sectors of the Large Hadron Collider (LHC), some 100 m below Geneva, Switzerland, will have reached their operating temperature of 1.9 K, filled with some 80 t superfluid helium, the coolant which permits the several thousand superconducting magnets using Nb-Ti conductor to operate at high field and thus guide, focus and bring into collision the rigid 7 TeV proton beams in the accelerator, opening a new window on the structure of matter, the forces of nature and the history of our universe. The LHC features the largest helium cryogenic system in the world [1, 2], with 140 kW @ 4.5 K and 20 kW @ 1.8 K installed refrigeration capacity, a cold mass of 37'000 t with a cold surface area of 50'000 m², and some 130 t of total helium inventory. Each sector is cooled from a compound cryogenic refrigeration plant through cryogenic lines running down the access shafts and along the tunnel. Each plant consists of a 4.5 K refrigerator with 4 MW of installed compressor power, providing several cooling duties at different temperatures (Table 1), and a 1.8 K unit equipped with cold and warm sub-atmospheric compressors. Four of the 4.5 K plants were recovered from the previous LEP2 accelerator [3], operated until 2000, and adequately upgraded for LHC service [4], while four new ones were procured from industry, on the basis of a functional and interface specification issued in 1997 [5]. Following a development program of the specific technologies – cold hydrodynamic compressors, helium subcooling heat exchangers, thermodynamic cycle optimization – the eight 1.8 K units were also procured from industry on the basis of competitive tendering in 1998, and their design and performance validated on pre-series units [6]. The long lead times for industrial procurement of such complex plants, combined with the need for early refrigeration capacity at the location of the test station for LHC magnets, imposed to define the sizing of the plant [7] at a time when the thermal design of the machine components, although established from first principles and partial experimental work, was not fully validated, the final configuration of the accelerator was not yet established, and some of the basic processes for beam-induced heat loads still largely speculative. The management of risk associated with these uncertainties is the subject of this article.

Table 1 Installed cooling duties in the LHC sectors

Temperature level	High-load sector	Low-load sector	
50-75 K	33000	31000	[W]
4.6-20 K	7700	7600	[W]
4.5 K	300	150	[W]
1.8 K	2400	2100	[W]
3-4 K	430	380	[W]
20-280 K	41	27	[g/s]

ESTIMATED HEAT LOADS AND THEIR UNCERTAINTIES

Heat load was assessed and reviewed all along the project duration. Several exercises were formalised following the project definition: the Yellow Report (YR) in 1987 [8], the Pink Book (PB) in 1991 [9], the White Book (WB) in 1993 [10], the Yellow Book (YB) in 1995 [11] and two reviews in 1997 and 2000. The first review has frozen the values for the cryoplant specifications and the second one has established the reference data of the Design Report (DR) [2].

The first heat load assessment was made for the YR from first principles after defining the main levels of thermal shielding and heat interception. Thermal budgets were defined for the main components like the supporting system, the thermal shielding and the radiative insulation without knowing the final technology and configuration. At this stage, the machine layout, especially in the insertion regions was not fully defined and rough scaling had to be applied. To refine the heat load assessments, tests were performed on single components [12, 13], a full-scale cryostat thermal model [14], full-scale prototypes of magnet cryostats [15] and magnet strings [16], and pre-series of the cryogenic distribution line [17] from 1991 to 2001. Figure 1 shows the evolution of the static heat inleaks, of the dynamic heat loads and of the installed refrigeration capacity throughout the assessment exercises for the four main temperature levels.

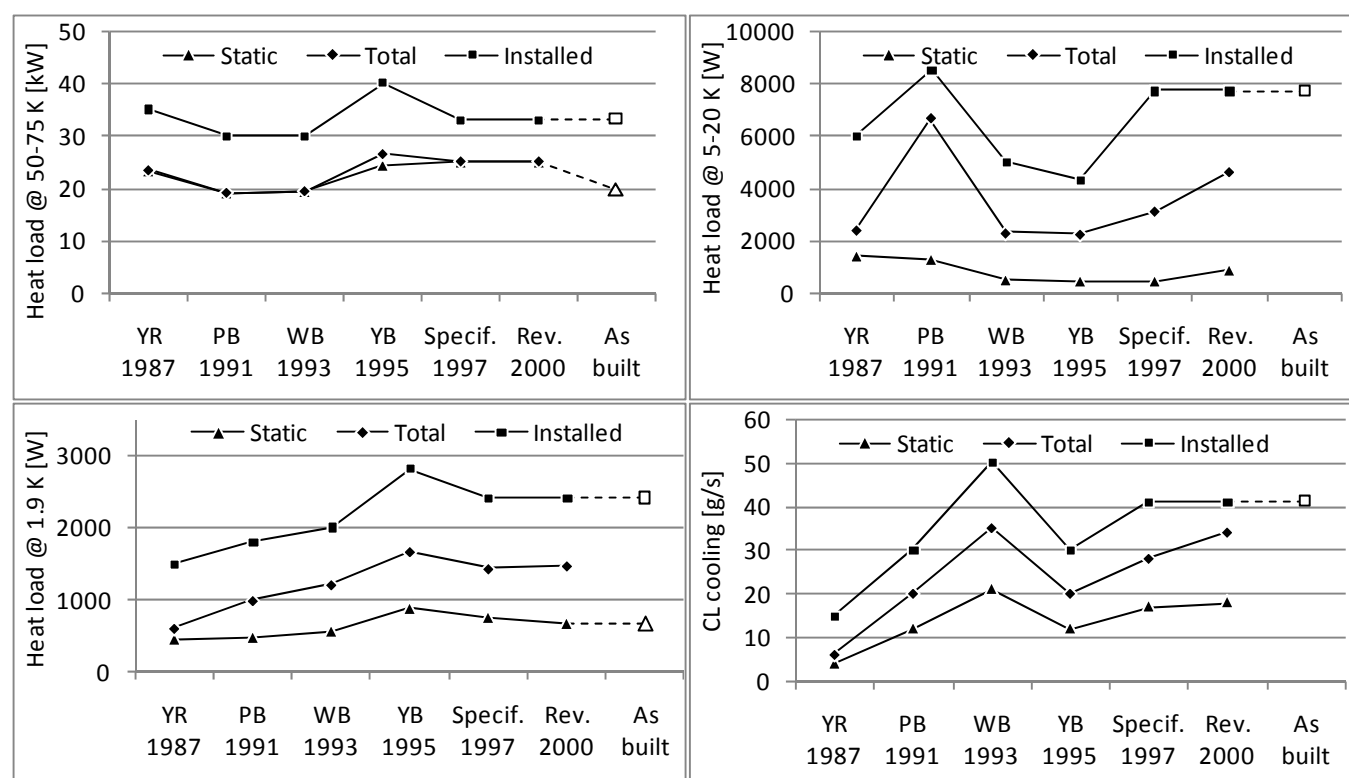


Figure 1 Evolution of estimated static and total heat loads, and of installed refrigeration capacity per sector

The heat loads at the 50-75 K temperature level are mainly driven by static heat inleaks of thermal shields and support heat intercepts. The main changes are due to the introduction in 1995 of the separate

cryogenic distribution line, which increases the overall thermal shield surface area. Moreover an early design of HTS current leads attached to this level added a dynamic heat load.

The heat loads at the 5-20 K temperature level are driven by the beam-induced heating falling on the beam screens and by the heat intercepts. The first peak observed corresponds to the ambitious beam energy and beam current parameters proposed in 1991. The increase observed after 1995 corresponds to energy deposition from photo-electrons resonantly accelerated by the beam potential (“electron cloud”), a now predominant phenomenon neglected in the previous estimates.

The heat loads at the 1.9 K temperature level are driven by the static heat inleaks, by resistive dissipation in superconducting cable splices, by beam-gas scattering and by secondary particles escaping the detectors during collisions. The static heat inleaks remained about constant; the increase due to the better definition of the equipment has been compensated by the optimisation and the simplification of the cooling scheme. Concerning the dynamic heat loads, the increase observed is coming from the proper assessment of energy deposition by secondary particles, as well as from the increase in the number of magnet electrical circuits (three main 13 kA circuits from 1995 instead of one previously).

The last load concerns the cooling of the current leads which were based until 1994 on conventional technology, thus requiring pure liquefaction cooling. With the multiplication of the number of electrical circuits and the emergence of industrial HTS materials with controlled properties, HTS current leads were first proposed in 1995, requiring reduced liquefaction duty at 4.5 K and non-isothermal cooling between 50 K and 300 K in addition to the 50-75 K loads. Later, a new type of HTS lead was developed needing only reduced liquefaction at 4.5 K and non-isothermal cooling between 20 K and 300 K. This new design increased the flow-rate requirement but simplified the cooling scheme and the lead design [18, 19].

Figure 2 shows the evolution of the ratio of installed refrigeration to total estimated heat load for the different cooling duties. This ratio was initially taken at 2.5 in the early conceptual design of 1987. As the LHC design evolved towards more detail and less uncertainty, concomitant with the appearance of previously unknown or neglected phenomena, the ratio gradually decreased. With the exception of current lead cooling, it however remains above 1.5, thus providing adequate overcapacity for ensuring smooth long-term operation of the cryogenic plants, an essential condition of reactivity in transients, e.g. quench recovery, and a buffer for potential loss of capacity in time. The remaining capacity ratio for current lead cooling is 1.2, i.e. 20 % above the most recent assessment; since then, all the leads were individually tested, yielding heat loads according to the specification, and are now operated in the LHC.

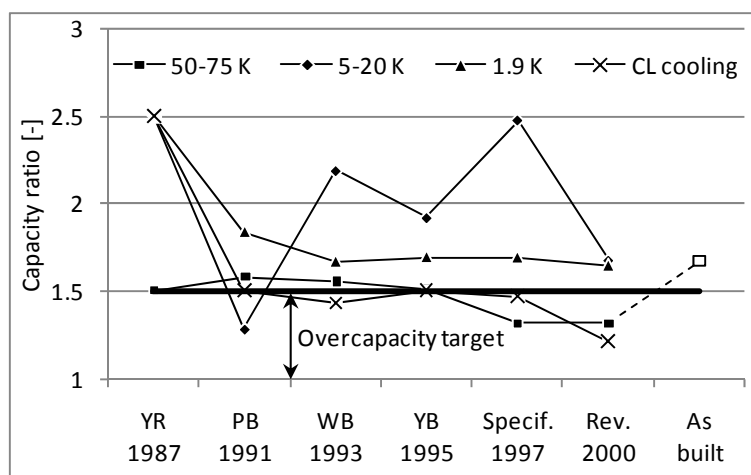


Figure 2 Evolution of installed refrigeration to total heat load ratio per sector for the different cooling duties

SPECIFIED AND MEASURED CRYOPLANT PERFORMANCE

Conversion of sector cooling duties into refrigeration capacities

For the 4.5 K refrigerators the cooling duties listed in Table 1 had to be converted into refrigeration capacities at the cold box interface [20], taking into account the cryogenic architecture of each sector. This led to the specified capacities given in Table 3. The high-load sectors of the LHC are supplied by four new 4.5 K refrigerators, while the low-load sectors reuse upgraded refrigerators of the LEP collider.

Table 3 Required refrigeration capacity for the 4.5 K refrigerators

Temperature level	Unit	New refrigerator	Upgraded refrigerator from [19]	Upgraded refrigerator specified 2004
50-75 K	[W]	33000	31000	31000
4.5-20 K	[W]	20700	16700	19500
4.5 K	[W]	4400	3500	4150
20-280 K	[g/s]	41	27	27

For the 1.8 K units, the required capacity equals the cooling duty in Table 1 as no conversion was necessary. All units were specified to satisfy the more demanding needs of a high-load sector.

Measurement principle and equipment

In order to test the refrigeration capacities in proper conditions, special test cryostats were built for the 4.5 K refrigerators [21] and for the 1.8 K refrigeration units [22]. The heat loads at the different temperature levels were applied by means of calibrated electrical heaters.

According to the specification, all refrigerators had to provide the specified capacities in order to pass the tests. The necessary electrical power input to the cycle compressors to reach the tested capacity was not limited. The actual electrical power consumption necessary to pass the tests was compared to the guaranteed value in the original proposal, and the difference converted into a commercial bonus or malus, through a shared-incentive formula. The performance measurements were only carried out once all transients and other specified operational features of the different refrigerators had been demonstrated.

Results

Table 4 shows the results of the reception tests for the new 4.5 K refrigerators. For the refrigerator located at PA18, the specified heating capacity could not exactly be applied to the test cryostat due to a problem with the 400 V AC supplied by CERN.

Table 4 Measured and guaranteed performance of the new 4.5 K refrigerators in installed capacity mode

LHC location	PA18	PA4	PA6	PA8
Supplier	Air Liquide	Air Liquide	Linde	Linde
Guaranteed energy consumption [kW]	4204	4204	4275	4275
Measured energy consumption [kW]	4297	4474	3964	4095
Measured cryogenic capacity [% of specified]	97.3	101.5	100.1	99.3
COP [W/W]	248	247	222	231

For the upgraded refrigerators recovered from LEP, the specified performance given in Table 3 which dated from 1997, was revised in 2004 and considerably increased as result of the growth in calculated heat loads. As these refrigerators have no interface that would allow the connection to a test cryostat, it is not possible to measure their final capacity. Only tested was the performance of the upgraded turbines in order to verify that it meets the specification.

The first 1.8 K unit from each of the two suppliers - called “pre-series unit” - was validated by extensive testing at CERN before launching the production of the following series units. Both pre-series units were successfully tested, demonstrating a COP of about 900 W/W and lower power consumption than guaranteed [23]. In addition, all cold compressor cartridges of the series units as well as spare cartridges were tested, using the pre-series units as test benches, to properly assess their performance as components. They all performed reproducibly to better than 2 % [24].

MEASURED HEAT LOADS ON LHC SECTORS

Static heat loads to the superconducting magnet baths at 1.9 K were measured on sectors as they became available during commissioning. The magnets operate in static pressurized superfluid helium (HeII) baths at 1.3 bar, delimited by hydraulic restrictions every 214 m. Heat is removed from the pressurized HeII

through heat exchange with saturated HeII at 16 mbar in a separate cryogenic circuit, in which the helium supplied at about 3.6 bar, 5 K by the cryogenic plant is subcooled in a counter-flow heat exchanger, expanded to saturation and vaporized by the heat load. The superheated vapour is returned to the suction side of the cold compressors in the cryogenic plant [1].

The cooling scheme permits two independent methods of assessing the heat load to the 1.9 K level. One is local, by measuring the change in internal energy during natural warm-up of a hydraulically isolated 214 m long section with active cooling stopped and temperatures remaining below the superfluid helium transition [25]. The other method is global, by measuring the return flow of superheated helium vapour at 16 mbar to the cryogenic plant from the complete sector, and correcting for the applied electrical heating in the HeII baths (Figure 3).

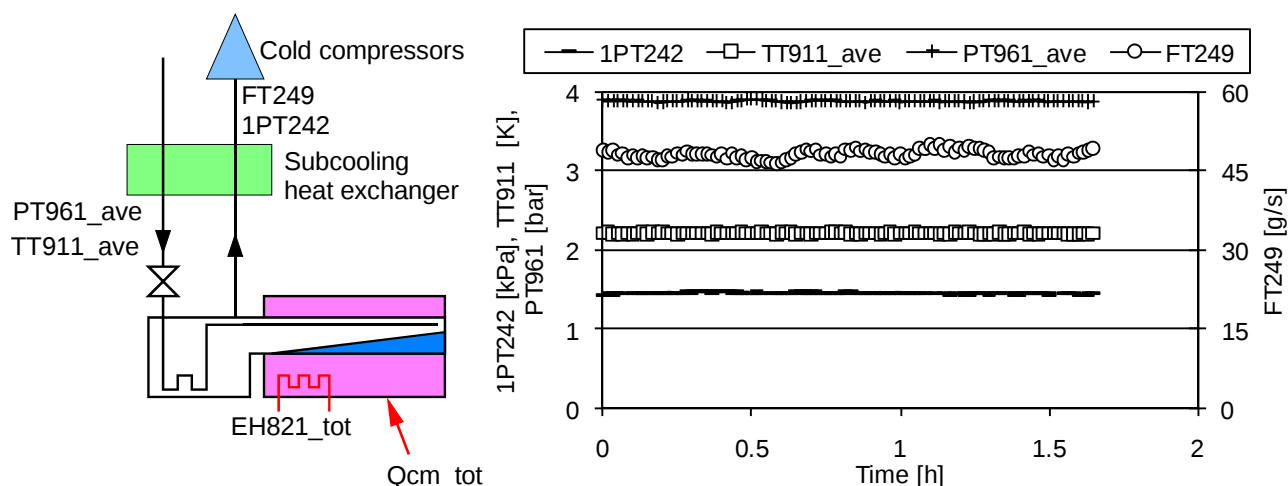


Figure 3 Principle of global heat load measurement at 1.9 K of LHC sector

The average nominal budgeted heat load at 1.9 K is 0.21 W/m. The local method was applied to parts of sectors 2-3, 5-6 and 7-8, yielding results of up to 33 % below nominal for particular sections. The global method was applied to sectors 5-6 and 7-8 [26]. Measurements give 0.20 and 0.21 W/m, respectively, in good agreement with the estimates. Static heat load to the thermal shield of the magnets and cryogenic line in the tunnel (50-75 K level) were assessed by measuring the enthalpy change of the helium along a complete sector and evaluating the corresponding mass flow. The resulting 6.5 ± 0.6 W/m is 18 % below the budgeted value. Figure 4 summarizes the sector heat load estimates and measurements.

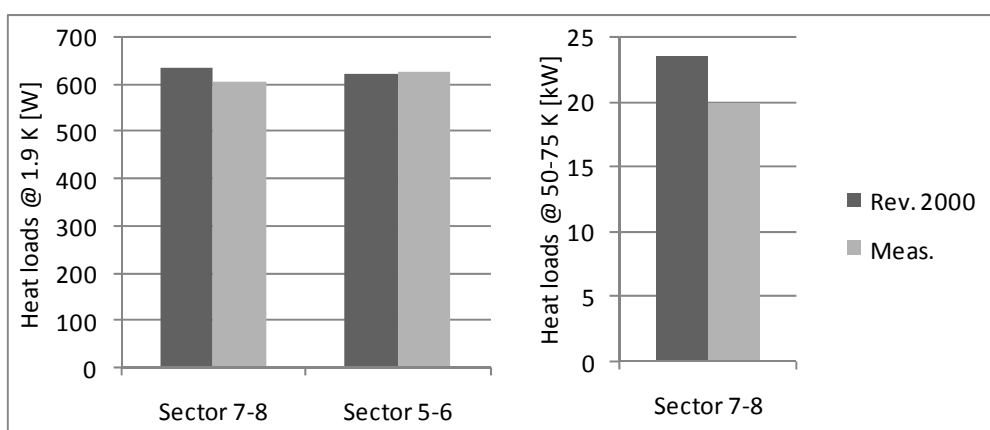


Figure 4 Estimated and measured sector heat loads at 1.9 K and 50-75 K

CONCLUSION

Definition and specification of helium cryogenic plants for large projects must be made early, in view of procurement lead times and in some cases, of the interest of using them for reception testing of components. The risk incurred, to freeze refrigeration capacity before the heat loads of the project are

comprehensively assessed and the dynamic effects fully understood, can be mitigated by the adoption of a contingency factor coping with such uncertainty. Moreover, plant overcapacity is needed for operational flexibility, reactivity and possible upgrade, and should not be unduly used as contingency for uncertainty in heat loads. The LHC experience has shown that a contingency factor of 2.5 on estimated heat loads at the beginning of the project was just sufficient to meet the final overcapacity target of 1.5. This available overcapacity was confirmed by the measured static heat loads on complete sectors. The LHC approach should be easily transposable to projects like ITER or ILC, characterized by large dynamic loads (nuclear heating, eddy currents, RF losses), for which the remaining differential between installed capacity and achieved static heat loads will eventually set the performance limit of the machine.

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