EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
European Laboratory for Particle Physics

*Large Hadron Collider Project*

**LHC Project Report 331**

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LHC Division

Presented at the 1999 Cryogenic Engineering and International Cryogenic Materials Conference (CEC-ICMC'99), 12-16 July 1999, Montreal, Canada

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Geneva, 1 December 1999

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## ABSTRACT

The cooling capacity for the superconducting magnets in the Large Hadron Collider (LHC) at the European Laboratory for Particle Physics, CERN will be provided by eight helium refrigerators serving the eight 3.3 km long machine sectors. Of these eight refrigerators, four are already existing and are currently used for the Large Electron Positron Collider (LEP) project. These existing refrigerators have to be modified to serve the requirements for the LHC. Four new refrigerators providing cooling capacity down to 4.5 K will be added. All eight 4.5 K refrigerators will be completed by 1.8 K cooling stages. This presentation recalls the cryogenic architecture of the LHC, the constraints in process design resulting from it and from the desired capacity for steady state and transient operation. It then describes how these requirements were expressed in the technical specification for the four new 4.5 K refrigerators to be delivered between the years 2000 and 2002.

## INTRODUCTION

A detailed description of the total cryogenic system for the LHC is given in[1]. Figure 1 shows a simplified typical cryogenic block diagram for an even point of the LHC. It includes the existing[2] and the new 4.5 K refrigerator, the two 1.8 K refrigeration units, the gas storage tanks, the cryogenic interconnection box, the cryogenic distribution line and the magnet cryostats.

The refrigerators are divided into two units. A 4.5 K refrigerator covers the capacity for thermal shield cooling, current lead cooling, isothermal refrigeration at 4.5 K and cooling between 4.5 K and 20 K. Connected to this unit will be a 1.8 K refrigeration unit which cannot operate on its own but requires cooling capacity between 4.5 K and 20 K in order to supply the necessary refrigeration at 1.9 K for the LHC magnets.

Following the time schedule for the installation of the cryogenic equipment, the new 4.5 K refrigerators had to be purchased and delivered in advance of any other items, mainly to allow the testing of the 1.8 K refrigeration units. In the following we will describe the basic constraints that defined the specification for the new 4.5 K refrigerators of the LHC machine.

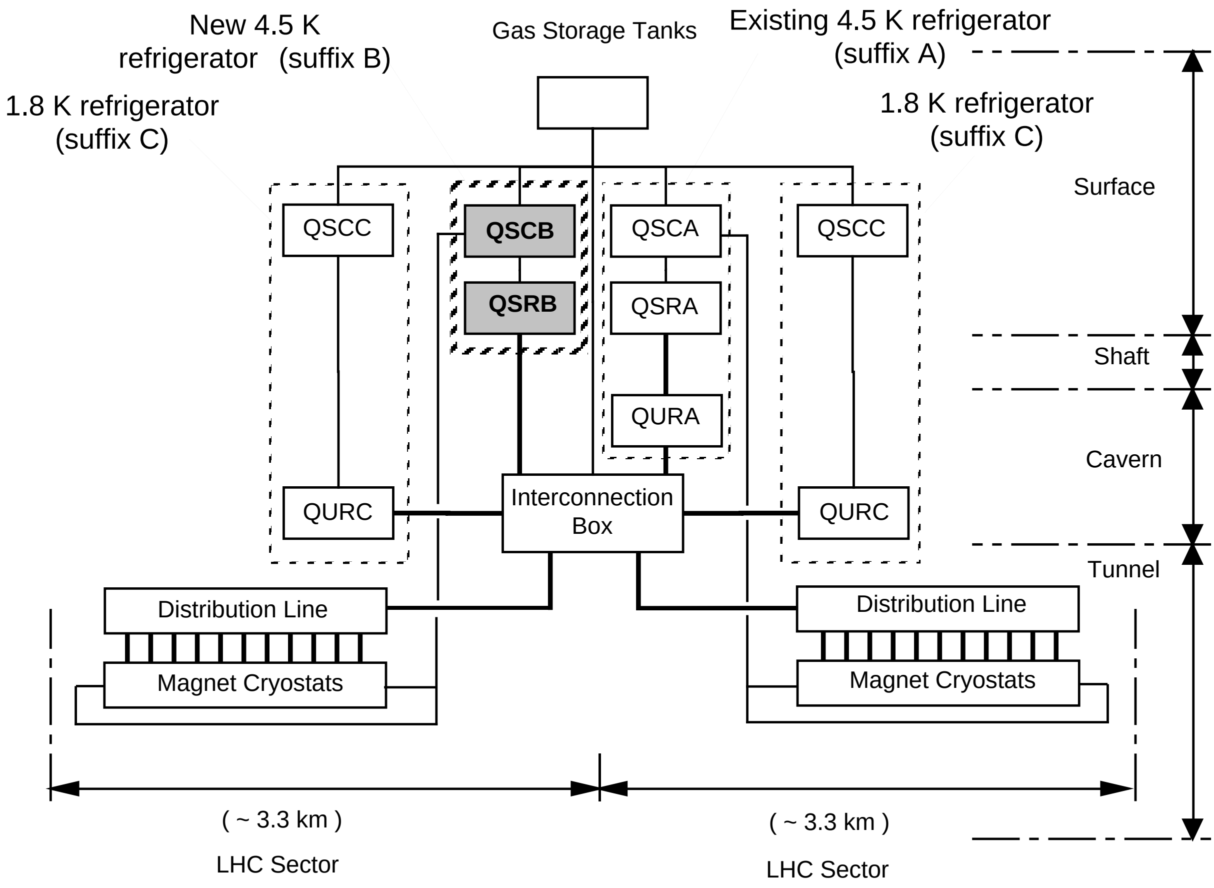


**Figure 1**. Simplified block diagram of the cryogenic installation in a typical even point of the LHC

## DESIGN BASIS

The design for the new 4.5 K refrigerators is based on several constraints, which are defined partly by technical requirements proper, and partly by interface considerations. As concerns the latter, the new cold boxes must be comparable to the existing, ones in order to allow for both types to integrate equally into the LHC cryogenic system.

### Division between 1.8 K and 4.5 K Refrigeration

In order to allow the identical 1.8 K refrigeration units to combine equally well with the new 4.5 K refrigerators for LHC and the existing LEP refrigerators, it was decided, at an early stage of the conceptual design studies, to separate the refrigerators for all LHC points into two systems: a 4.5 K unit and a 1.8 K unit[3]. As a consequence the new 4.5 K refrigerators need to interface with the rest of the cryogenic system at the temperature levels of 75 K, 50 K, 20 K and 4.5 K, like the already existing LEP cold boxes.

### Given Interfaces

A principle block diagram of a new 4.5 K refrigerators together with the 1.8 K refrigeration unit, the cryogenic interconnection box and the cryogenic distribution system of the LHC machine is given in Figure 2. As for the LHC no high-density vapour at 4.5 K flows back from the magnet ring to the cold boxes, it was decided to install the cold boxes completely at ground surface. This allows to save precious space at the underground level compared to the existing LEP cold boxes, which are of split design[4].

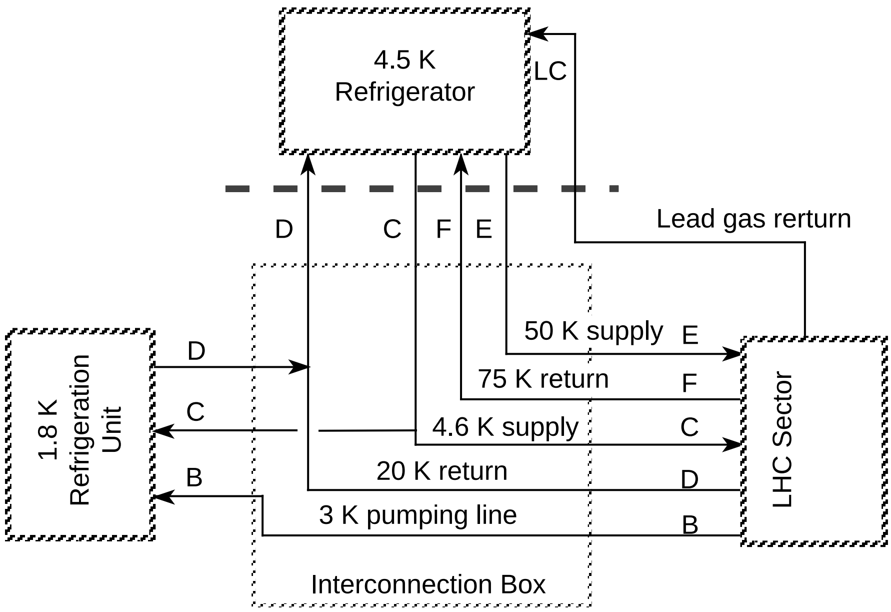


**Figure 2**: Simplified cryogenic block diagram for a new 4.5 K refrigerator including cryogenic interconnection box, 1.8 K refrigeration unit and the cryogenic distribution system of the machine.

The interface from the new 4.5 K refrigerator cold box to the LHC machine consists of five lines: 4.6 K supply (line C), 20 K return (line D), 50 K supply (line E), 75 K return (line F) and lead gas return at 280 K (line LC).

**Cooling Requirements**

Following the design of the different elements in the LHC machine, the required cooling capacities including contingency for overcapacity and uncertainty[5] are listed in Table 1.

**Table 1.** Required cooling for the LHC machine sectors

| Temperature level | 50-75 K [W] | 4.6-20 K [W] | 4.5 K [W] | 1.9 K [W] | 3-4 K [W] | 20-280 K [g/s] |
|---|---|---|---|---|---|---|
| High-load sector | 33000 | 7700 | 300 | 2400 | 430 | 41 |
| Low-load sector | 31000 | 7600 | 150 | 2100 | 380 | 27 |

As shown in Table 1, the cooling requirements are not identical for the different sectors. The sectors identified as "Low-load" sectors will be supplied by the existing LEP refrigerators which will undergo a final upgrade during the years 2001 to 2003 and be completed with a 1.8 K refrigeration unit. The new 4.5 K refrigerators consequently had to be specified in order to cover the load of the "High-load" sectors. The values for mass flows and helium properties which are to be supplied at the interface shown in Figure 2 are listed in Table 2.

**Table 2:** Property and mass flow data at the interface of the new 4.5 K refrigerator

| Line | | C | D | E | F | LC |
|---|---|---|---|---|---|---|
| Temperature | [K] | 4.6 | 20 | 50 | 75 | 280 |
| Pressure | [bar] | 3.0 | 1.3 | 18.5 | 16.0 | 1.1 |
| Flow | [g/s] | 235 | 194 | 251 | 251 | 41 |

### Operation Modes

Due to the daily operation cycle of the LHC machine, four steady state operation modes which differ by the required capacity are defined [6]. To this adds a "75 K standby" mode at which only the shield cooling circuit between 50 and 75 K is operated, in order to keep the cold masses below 80 K during extended periods in which no physics is possible. Additionally the refrigerator has to cover the transient operation modes of cool-down and warm-up. At the end of the cool-down the magnets will accumulate about 50000 L of liquid helium, which results in the quasi steady-state mode of "liquid fill".

### Liquid Nitrogen Pre-cooling

Large capacity of liquid nitrogen pre-cooling was never used at cryogenic installations of CERN. The magnets of the LHC machine will have a total mass to be cooled of 4500 tons per sector [7]. In order to limit the time for a machine cool-down to reasonable values, a liquid nitrogen pre-cooler for a capacity of 600 kW will be installed in each 4.5 K refrigerator. This unit will be used for the cool-down of the machine and to boost the liquefaction rate during the "liquid fill" mode at the end of the cool down. During all operation cycles with the magnets in cold conditions no pre-cooling with nitrogen is desired in order to eliminate the environmental impact by nitrogen deliveries during long term operation.

## SPECIFIED REQUIREMENTS

### Capacity Requirements

Figure 3 shows how the cooling loops for the LHC machine are seen from a 4.5 K refrigerator. The refrigerator must be able to cope with the simultaneous cooling loads for each of the steady-state operation modes resulting from the operation modes of the machine described above and listed in Table 3 as "Installed", "Normal", "Low-intensity", "Injection standby" and "75 K standby".

The identification numbers of the heat loads listed in Table 3 refer to Figure 3.

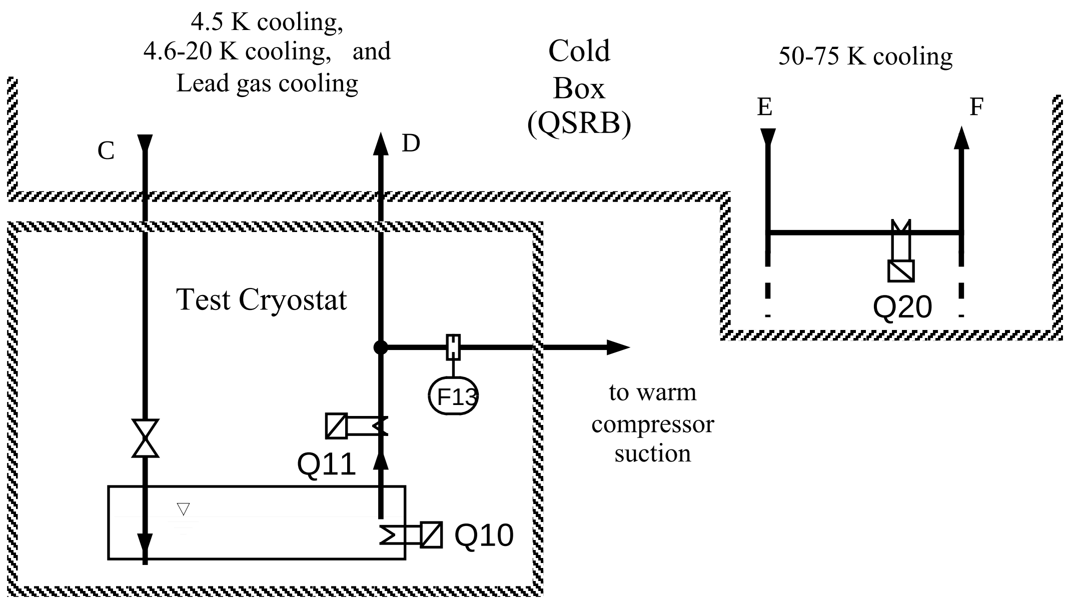


**Figure 3.** The LHC cooling capacities as seen from the 4.5 K refrigerator

**Table 3.** Cryogenic capacity requirements for a 4.5 K refrigerator in all steady-state LHC operation modes

| Operation mode | Q10<br>4.5 K<br>isothermal<br>[W] | Q11<br>4.5 - 20 K<br>non isothermal<br>[W] | Q20<br>50 - 75 K<br>non<br>isothermal<br>[W] | F13<br>20 - 280 K<br>lead<br>cooling flow<br>[g/s] |
|---|---|---|---|---|
| Installed | 4400 | 20700 | 33000 | 41 |
| Normal | 2600 | 12400 | 22000 | 27 |
| Low-intensity | 1600 | 7700 | 22000 | 27 |
| Injection standby | 1200 | 5700 | 22000 | 11 |
| 75 K standby | 0 | 0 | 22000 | 0 |

As the purchasing rules of CERN, based on the concept of "conforming bid" do not allow to account for high safety margins in the process design of the different bids, the specification stipulates that the T-s diagram of the "Installed" mode must show 5% over–capacity on each load in order to compensate for manufacturing uncertainties, plus an additional 500 W capacity for regulation purpose in the phase separator of the cold box. The ambient-temperature compressor station was specified to satisfy the flow and pressure requirements resulting from this process calculation.

**Test Cryostat**

In order to limit the number of interfaces between CERN and the supplier that could influence the measured capacity during the reception test, and in view of tedious discussions in the past concerning such measurements, we decided to include in the specified supply a test cryostat dedicated only to the reception test. The supplier has to bear all heat loads which are generated by this test cryostat. CERN accepts only the electrical heating capacity and the measured flow rate in the test cryostat as achieved capacity of the refrigerator. A simplified flow scheme of this test cryostat is included in Figure 3.

**Redundancies and Over-capacities**

No redundancy was specified for the refrigerators or any of their components except for the oil pumps of the compressor station. In view of the rather strong dependence of cooling requirements on LHC beam energy and intensity, it was accepted that in case of component failure, e.g. turbine or compressor, the supplied capacity will be reduced thus allowing operation of the collider at reduced performance. In fact the operation mode "Normal" which supplies the capacity to cover the nominal operation conditions of the machine represents only 60% of the cryogenic capacity installed. Moreover neighbouring refrigerators may be coupled at the level of the cryogenic interconnection box and a lack of capacity of one installation may be compensated by the capacity margin of the other one. As concerns the compressor flow, it is envisaged to install by-pass lines for the LP, MP and HP level and thus share compressor flow between the refrigerators installed on the same LHC point, if necessary.

**Gas Purification Equipment**

The level of impurities with which the refrigerators will have to cope are very difficult to assess. One has nevertheless to prepare for a high contamination by water during the first phase of each cool-down and the final phase of each warm-up. Besides this, contamination of oxygen, nitrogen and to a lesser extend, hydrogen and neon, must be accepted. In order to cope with the gaseous contamination we specified in each cold box two parallel, switchable adsorbers operating between 80 K and 70 K for each stream being cooled down to temperatures below 70K. Each of these adsorbers has to be sized to retain the impurities of the maximum possible helium flow in the relevant line contaminated by up to 50 ppm by volume of air, for a duration of 50 h. In addition one single adsorber has to be installed operating at about 20 K for each stream being cooled down to temperatures below 20 K. This adsorber has to be sized to retain the impurities of the maximum possible helium flow in the relevant line contaminated by up to 1 ppm by volume of hydrogen or neon, for a duration of at least 200 h. The necessary equipment for fully automatic switching, regeneration and cool-down of the adsorber beds has to be provided.

Original plans to provide each refrigerator with an external full-flow purifier operating at 80 K for water and air were abandoned. Instead of this it is envisaged now to provide dryer beds for continuous operation, handling the full flow upstream of each cold box. Therefore it is specified that under maximum operation condition a pressure drop of one bar must be respected in the interconnecting HP piping between the compressor station and the cold box to allow for the pressure drop in the future dryers.

## Liquid Nitrogen Pre-cooler

The liquid nitrogen pre-cooler was specified to be fully de-coupled from the main process heat exchangers in order to avoid problems in the case of return of large amounts of cold gas from the LHC machine, as well as to allow for operation even with a defective nitrogen heat exchanger. As the requirements are two-fold, for long-term cool-down operation and steady-state liquefaction boost, the connections to the main process lines are specified as shown in Figure 4. For cool-down operation the heat exchanger is used as indicated in Figure 4 A, for liquefaction boost as in Figure 4 B.

The heat exchanger is specified to have a nitrogen phase separator with included gas-liquid heat exchanger and a separate gas-gas heat exchanger.

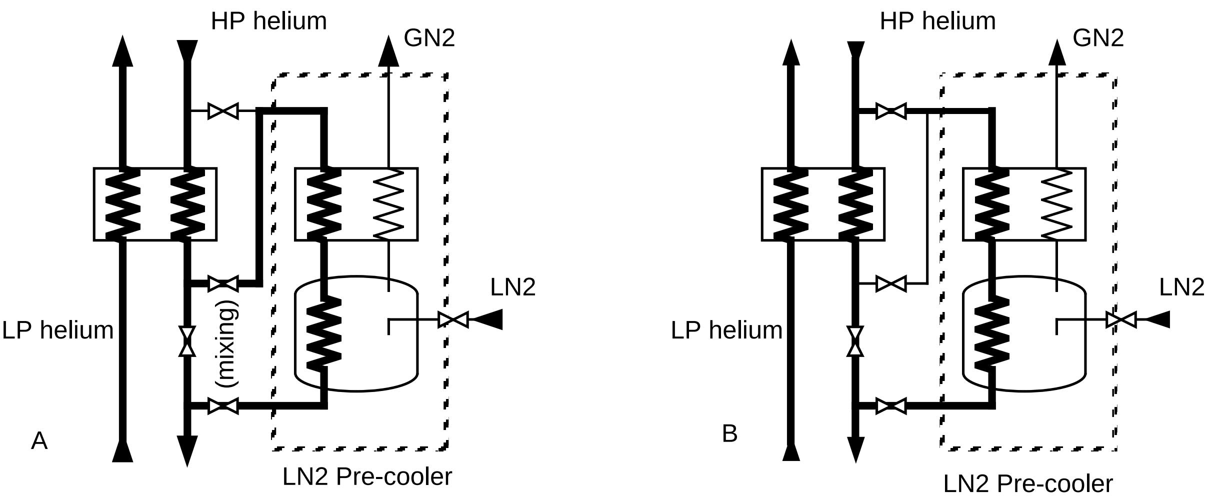


**Figure 4.** The specified process connections for the liquid nitrogen pre-cooler. A: Cool-down operation; B: Liquefaction boost

## Liquid Helium Phase Separator

As no liquid helium storage dewar is foreseen, the helium phase separator is specified to have sufficient volume in order to store 50% of the total helium hold-up in the cold box and the compressor station. The subcooler must be operational with the phase separator filled at only 30%. Thus it is possible to react on capacity changes by storing liquid helium due to excess capacity in the phase separator.

## Process Control System

The process control system is not part of the supply for the refrigerators but will be purchased separately by CERN in order to allow a common process control system for the cryogenic equipment of the LHC machine. The supplier of the refrigerators has to deliver the necessary control logic in a pre-defined form compatible to international standards. The architecture of this control logic is based on the object-oriented philosophy validated already at CERN for the existing cryogenic installations of the LEP machine. The hardware safety as e.g. for turbo expanders and compressors is de-coupled from the main control system and must be provided with the supply. The necessary safety system may be based on logical relay arrangements or on the use of local process control units. The use of field bus connections is encouraged.

## Time Schedule

The time schedule specified for the four refrigerators is as given in Table 4.

**Table 4.** Time schedule for the 4.5 K refrigerators for LHC

| | First refrigerator | Second refrigerator | Third refrigerator | Fourth refrigerator |
|---|---|---|---|---|
| Location | LHC point 18 | LHC point 4 | LHC point 8 | LHC point 6 |
| Earliest delivery date | 15-04-2000 | 05-01-2001 | 01-04-2001 | 05-01-2002 |
| Final reception test date | 15-11-2000 | 30-06-2001 | 15-12-2001 | 01-07-2002 |

## Integrated Cost Estimate for Adjudication

According to the CERN purchasing rules a contract is awarded to the bidder with the lowest price for the equipment specified. For a cryogenic refrigerator the cost for electrical consumption are an important factor and shadow all other operation cost[8]. Thus an installation with low investment cost but bad coefficient of performance might prove more costly over the envisaged life time than an installation with high efficiency and higher investment cost. As for CERN the total cost of investment and operation is relevant we decided to leave the choice between efficiency and operation cost to the bidders.

For the specification of the new 4.5 K refrigerators for LHC, CERN therefore decided use a formula for adjudication that includes the cost for investment and the expected cost for power consumption over 10 years of operation. The bidders were required to provide guaranteed data for the electrical input power of the 3.3 kV supply in the operation modes “Low-intensity” and “Installed” The total cost of the supply was then calculated according to the formula below.

$$C = I + 4 * (1320 * P_{low} + 2640 * P_{inst}) \quad (1)$$

In this formula C represents the total cost, for adjudication purposes, in CHF for the four refrigerators, I the price in CHF as quoted by the bidder for the supply of the four refrigerators, $P_{low}$ the guaranteed 3.3 kV power consumption in kW for one refrigerator in the operation mode "Low-intensity” and $P_{inst}$ the guaranteed 3.3 kV power consumption in kW for one refrigerator in the operation mode "Installed". The factors 1320 and 2640 result from the expected 22000, respectively 44000 hours of operation during ten years at a cost of 0.06 CHF per kWh.

The 3.3 kV power consumption measured during the reception tests will be compared to the guaranteed values of the bids and the difference will result in a compensation payment by

CERN in case of lower power consumption than guaranteed, or by the supplier if the power consumption exceeds the guaranteed value.

## CONCLUSION

Following the specification for the new 4.5 K refrigerators for the LHC machine, CERN received two offers in February 1998. It was finally decided to split the supply in two and consequently two contracts for the supply of two 4.5 K refrigerators each were signed with Linde Kryotechnik AG, Switzerland and Air Liquide, France.

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