Chapter 7

Cryogenic system

7.1 Overview

The LHC is unique among superconducting synchrotrons, because its operating temperature is below 2 K to maximise the field strength of the superconducting magnets with NbTi windings. The basic design as well as the main technical choices for the LHC cryogenic system have been described in Part III section 2 of the “White Book” [11] and in Part III section 2 of the “Yellow Book” [12].

The superconducting magnet windings in the arcs, the dispersion suppressors, and the inner triplets will be immersed in a pressurised bath of superfluid helium at about 0.13 MPa (1.3 bar) and a maximum temperature of 1.9 K [37]. This allows a sufficient temperature margin for heat transfer across the electrical insulation. As the specific heat of the superconducting alloy and its copper matrix fall rapidly with decreasing temperature, the full benefit in terms of stability margin of operation at 1.9 K (instead of at the conventional 4.5 K) may only be gained by making effective use of the transport properties of superfluid helium, for which the temperature of 1.9 K also corresponds to a maximum in the effective thermal conductivity. The low bulk viscosity enables the coolant to permeate the heart of the magnet windings. The large specific heat (typically 10^5 times that of the conductor per unit mass, 2×10^3 times per unit volume), combined with the enormous heat conductivity at moderate flux (3’000 times that of cryogenic-grade OFHC copper, peaking at 1.9 K) can have a powerful stabilising action on thermal disturbances. To achieve this, the electrical insulation of the conductor must preserve sufficient porosity and provide a thermal percolation path, while still fulfilling its demanding dielectric and mechanical duties. This cooling requirement applies during both ramping and stored-beam operation. In the case of fast current discharge, the temperature excursion may be larger but must still remain below the helium II/helium I phase transition (lambda line). In the long straight sections, with the exception of the inner triplets and the superconducting dipoles D1, the field strength and heat extraction requirements are such that operation at 1.9 K is not necessary. The superconducting windings of these magnets will be immersed in a bath of saturated helium at 4.5 K.

The cryogenic system must be able to cope with the load variations and a large dynamic range induced by the operation of the accelerator as well as being able to cool-down and fill the huge cold mass of the LHC, 37×10^6 kg, within a maximum delay of 15 days while avoiding

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thermal differences in the cryo-magnet structure higher than 75 K. The cryogenic system must be also able to cope with resistive transitions of the superconducting magnets, which will occasionally occur in the machine, while minimising loss of cryogen and system perturbations. It must handle the resulting heat release and its consequences, which include fast pressure rises and flow surges. The system must limit the propagation to neighbouring magnets and recover in a time that does not seriously detract from the operational availability of the LHC. A resistive transition extending over one lattice cell should not result in a down time of more than a few hours. It must also be possible to rapidly warm up and cool down limited lengths of the lattice for magnet exchange and repair. Finally, it must be able to handle, without impairing the safety of personnel or equipment, the largest credible incident of the resistive transition of a full sector. The system is designed with some redundancy in its subsystems.

7.2 General architecture

The main constraints on the cryogenic system result from the need to install the system in the existing LEP tunnel and to re-use LEP facilities, including four refrigerators. The limited number of access points to the underground area is reflected in the architecture of the system. The cooling power required at each temperature level will be produced by eight refrigeration plants and distributed to the adjacent sectors over distances up to 3.3 km. To simplify the magnet string design, the cryogenic headers distributing the cooling power along a machine sector, as well as all remaining active cryogenic components in the tunnel, are contained in a compound cryogenic distribution line (QRL). The QRL runs alongside the cryo-magnet strings in the tunnel and feeds each 106.9 m-long lattice cell in parallel via a jumper connection (figure 7.1).

The LHC tunnel is inclined at 1.41% with respect to the horizontal, thus giving height differences of up to 120 m across the tunnel diameter. This slope generates hydrostatic heads in the cryogenic headers and could generate flow instabilities in two-phase, liquid-vapour, flow. To avoid these instabilities, all fluids should be transported over large distances in a mono-phase state, i.e., in the super-heated-vapour or supercritical region of the phase diagram. Local two-phase circulation of saturated liquid can be tolerated over limited lengths, in a controlled direction of circulation. Equipment is installed as much as possible above ground to avoid the need for further excavation, but certain components have to be installed underground near the cryostats. For reasons of safety, the use of nitrogen in the tunnel is forbidden, and the discharge of helium is restricted to small quantities only.

Figure 7.2 shows the general layout of the cryogenic system with five "cryogenic islands" at access Points 1.8, 2, 4, 6 and 8, where all refrigeration equipment and ancillary equipment is concentrated. Equipment at ground level includes electrical substations, warm compressors, cryogen storage (helium and liquid nitrogen), cooling towers, and cold boxes. Underground equipment includes lower cold boxes, 1.8 K refrigeration unit boxes, interconnecting lines, and interconnection boxes. Each cryogenic island houses one or two refrigeration plants that feed one or two adjacent tunnel sectors, requiring distribution and recovery of the cooling fluids over distances of 3.3 km underground.

Figure 7.3 shows the general architecture of the system. A refrigeration plant comprises one 4.5 K refrigerator and one 1.8 K refrigeration unit. The 4.5 K refrigerator is either one of the

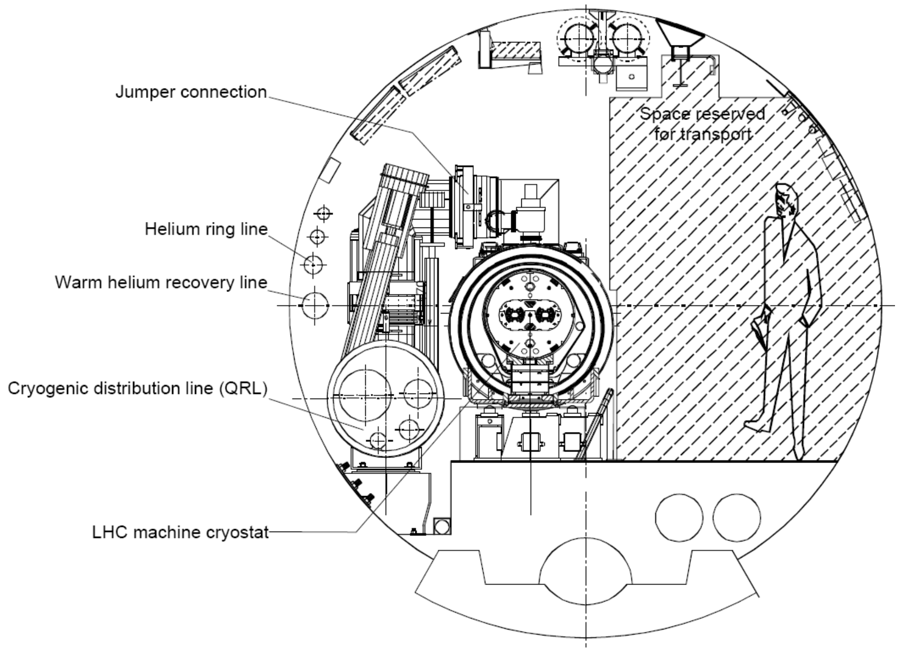

Figure 7.1: Transverse cross-section of the LHC tunnel.

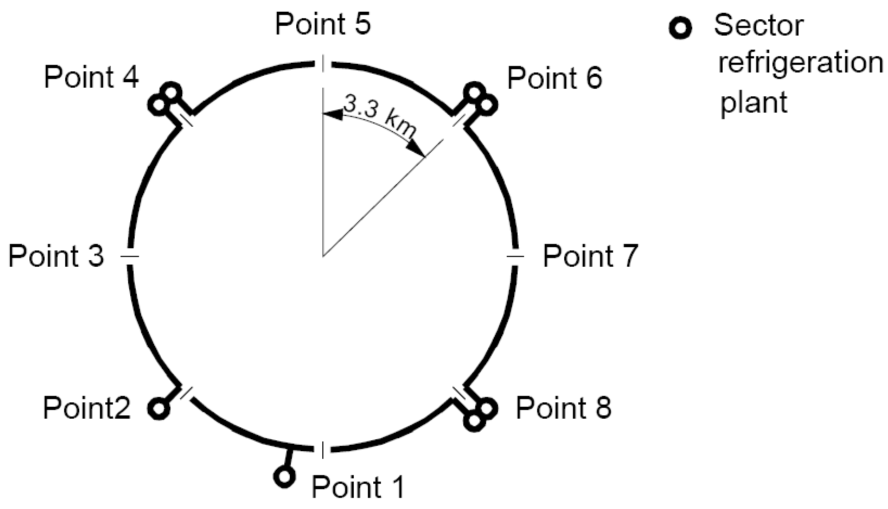

Figure 7.2: General layout of the cryogenic system.

four split-cold-box refrigerators recovered from LEP, or one of the four new integrated-cold-box refrigerators. At each cryogenic island, an interconnection box couples the refrigeration chains and the cryogenic distribution lines. Due to lack of space for two refrigeration plants at Point 2 and the need at Point 1.8 for a large refrigeration capacity for cryo-magnet testing, the 4-point symmetry was broken, and two refrigeration plants at Points 4, 6 and 8, but only one plant at Points 1.8 and 2, were installed. The drawback of this architecture affects Sector 2-3, which has only limited redundancy.

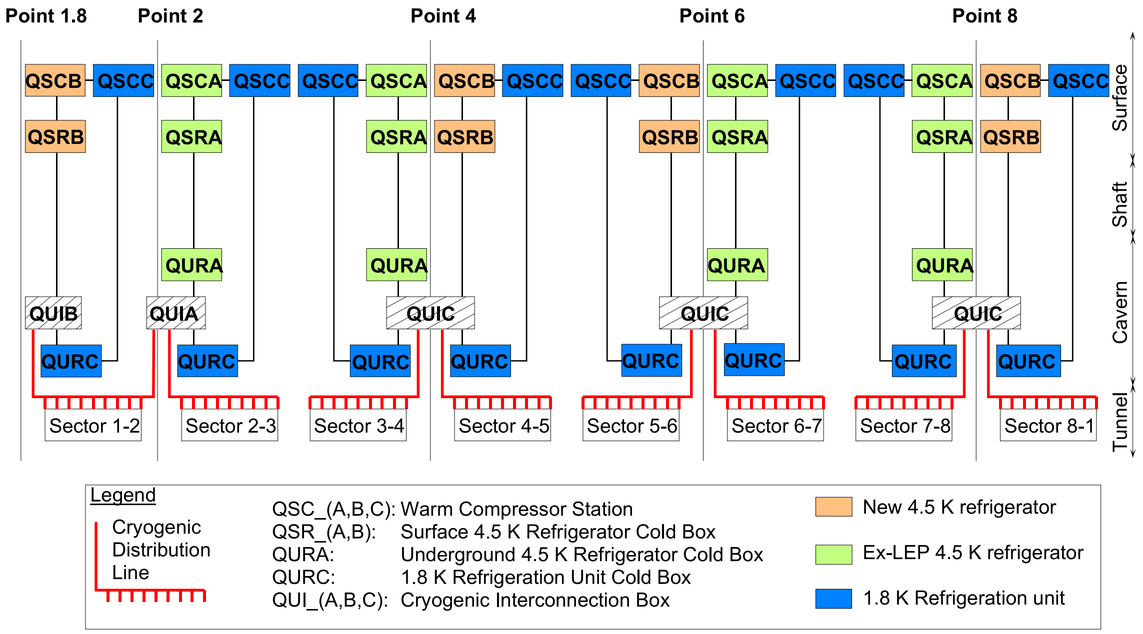

Figure 7.3: General architecture of the cryogenic system.

7.3 Temperature levels

In view of the high thermodynamic cost of refrigeration at 1.8 K, the thermal design of the LHC cryogenic components aims at intercepting the main heat influx at higher temperatures; hence the multiple-staged temperature levels in the system. The temperature levels are:

- 50 K to 75 K for the thermal shield protecting the cold masses,
- 4.6 K to 20 K for lower temperature interception and for cooling the beam screens that protect the magnet bores from beam-induced loads.
- 1.9 K quasi-isothermal superfluid helium for cooling the magnet cold masses,
- 4 K at very low pressure for transporting the superheated helium flow coming from the distributed 1.8 K heat exchanger tubes across the sector length to the 1.8 K refrigeration units,
- 4.5 K normal saturated helium for cooling some insertion region magnets, RF cavities, and the lower sections of the HTS current leads,
- 20 K to 300 K cooling for the resistive upper sections of the HTS current leads [38].

To provide these temperature levels, use is made of helium in several thermodynamic states: figure 7.4. The cryostats and cryogenic distribution line (QRL) combine several techniques for limiting heat influx, such as low-conduction support posts, insulation vacuum, multi-layer reflective insulation wrapping, and low-impedance thermal contacts, all of which have been successfully applied on an industrial scale.

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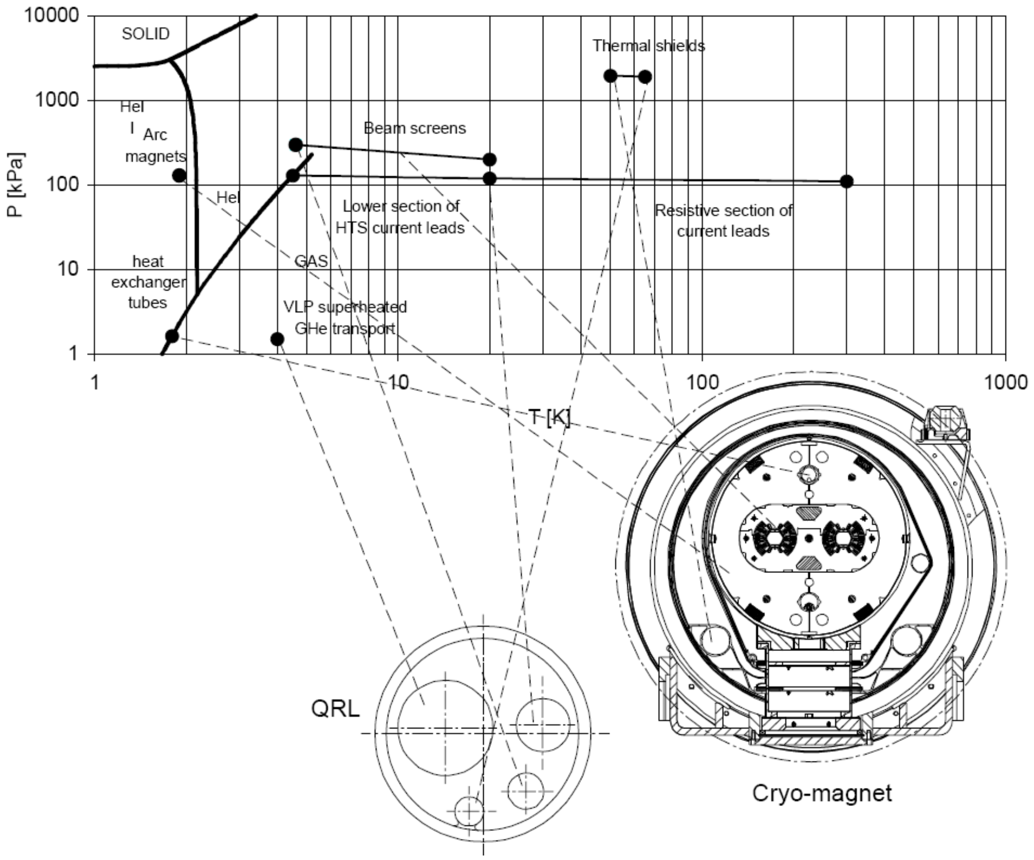

Figure 7.4: Thermodynamic states of helium in the LHC cryogenic system.

7.4 Cooling scheme

7.4.1 Arc and dispersion suppressor cooling loops

The cooling flow scheme for the arcs and DS regions is shown in figure 7.5. The first level of thermal shielding and heat interception in the magnet cryostats and the QRL is provided by forced circulation of gaseous helium under pressure at a temperature between 50 K and 75 K, through headers E and F respectively. The cryo-magnets operate in a static bath of pressurised helium II, cooled by heat exchange with flowing saturated helium II. Low-pressure vapour resulting from the vaporisation of the saturated helium II is returned to the refrigerator by header B. Supercritical helium is distributed by header C and is used to a) fill the cryo-magnet baths, b) to produce — after subcooling and Joule-Thomson expansion — the saturated helium II flowing in the full cell length heat exchanger tube and c) feed line C' that cools the cold heat intercepts in the support posts at about 5 K, in series with the beam screens that operate between about 5 K and 20 K. The resulting gaseous helium is returned to the refrigerator by header D.

The performance of such a scheme depends critically on the thermo-hydraulic behaviour of the two-phase helium II flowing in quasi-horizontal tubes. This has been modelled at CERN and CEA Grenoble and demonstrated that over a large range of vapour quality, most of the tube cross-section is occupied by the vapour flow, which then controls the overall pressure drop. For

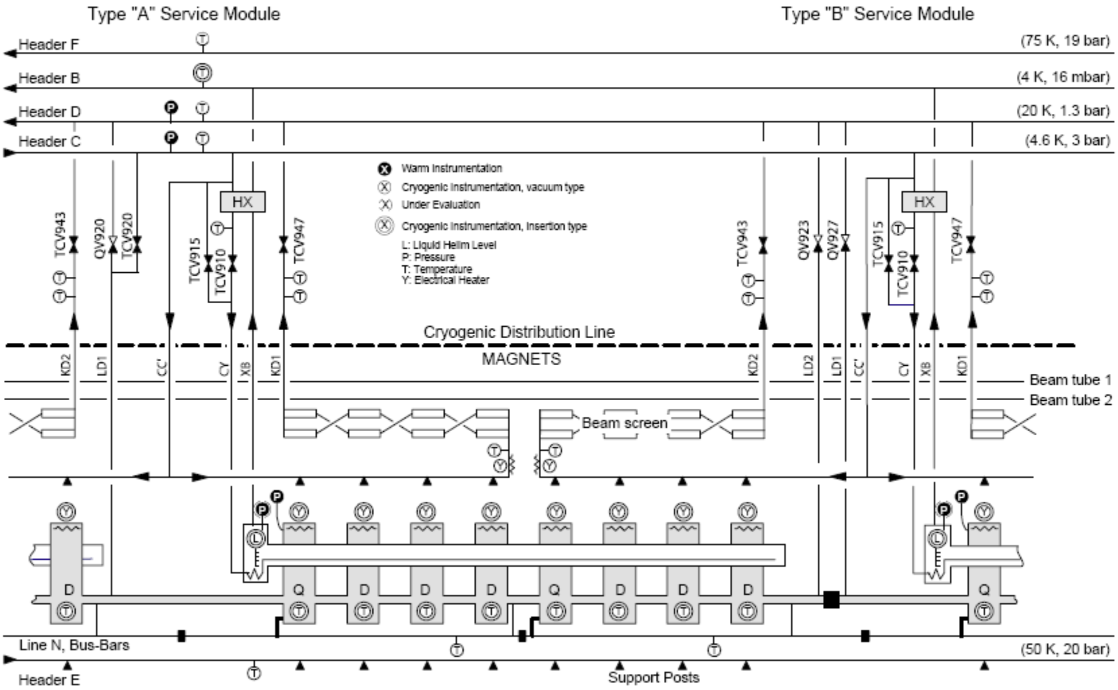

Figure 7.5: Thermodynamic cryogenic flow scheme and instrumentation of an LHC lattice cell.

vapour velocities of up to a few m s^{-1}, the drag between the two phases remains small, so that the liquid flows separately from the vapour, almost as if in a single phase open channel. Under these conditions, the heat transfer is mainly controlled by the wetted area inside the tube, which can be adequately predicted by simple models. Other important factors controlling the heat transfer across the tube wall are the conductivity of the tube and the Kapitza thermal resistance at the solid-liquid interfaces. By using a 53.4 mm inner diameter tube of OFHC copper with a wall thickness of 2.3 mm, the total transverse impedance when fully wetted can be kept down to about 0.3 mK m^2 W^{-1}, and the practical heat transfer capability of the partially wetted bayonet heat exchanger is thus typically a few mK m W^{-1}. The final validation of this cooling scheme was performed on a full scale magnet string equivalent to one LHC cell.

Within a sector, the tunnel slope results in elevation differences up to 50 m, equivalent to a hydrostatic head of up to 70 kPa (700 mbar). To avoid the negative effects of this hydrostatic head, the cold masses within a sector have been sub-sectorised by adding hydraulic restrictions every two or three cells (figure 7.6). These restrictions also limit the propagation of resistive transitions caused by warm helium flowing from magnet to magnet. The cryogenic vacuum is also sub-sectorised in order to limit the extent of a degraded vacuum zone caused by a possible helium leak from the internal circuit. On the cryo-magnet side, the vacuum barriers are in the SSS cryostats every two cells, and, in the QRL, vacuum barriers are placed every four cells. The jumper connection between the QRL and the magnet cryostats always contains a vacuum barrier. The two sub-sectorisation schemes also make it possible to warm-up and re-cool-down a limited length of the machine (up to 600 m) for minor interventions. The removal of magnets, however, requires the complete sector to be warmed up.

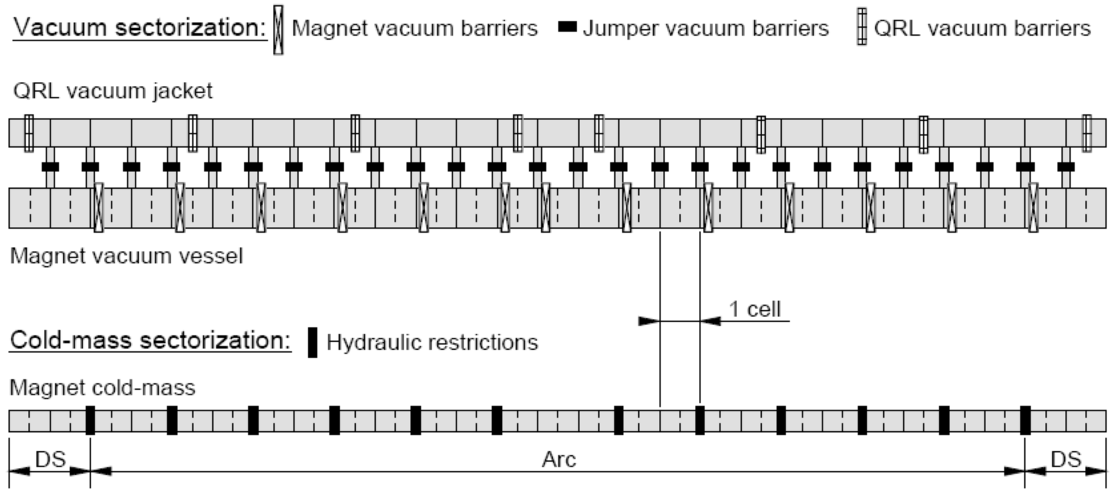

Figure 7.6: Cold-mass and cryogenic vacuum sub-sectorisation.

7.4.2 Matching section cooling loops

The special magnets in the matching sections that do not require 1.9 K operate in baths of saturated helium I at 4.5 K. These magnets are generally a single quadrupole or dipole with correctors (standalone), or a single quadrupole and dipole in series with correctors (semi-standalone). Figure 7.7 shows the basic cooling scheme. There is an actively cooled heat intercept at about 70 K. The cold mass is filled and the liquid level actively maintained by helium supplied from QRL header C. The vapour outlet is into the QRL header D, whose pressure of about 0.13 MPa (1.3 bar) directly determines the corresponding magnet's saturated liquid bath temperature at about 4.5 K. The stand-alone and semi-stand-alone magnets receive their powering through a dedicated interface, which in the majority of cases connects to a local DFB or to a superconducting link.

7.4.3 Inner triplet cooling loops

The inner triplet quadrupoles in the IRs are subject to heating due to secondary beam particles of up to 10 W m^{-1} in the high luminosity insertions of Points 1 and 5, and up to 2 W m^{-1} in the low-luminosity insertions in Points 2 and 8. Although this represents a much higher heat load than in the arcs, the quadrupoles can be cooled by a scheme similar to that in the standard arcs. A large-diameter, corrugated, copper heat exchanger tube inside a stainless steel tube is placed outside and parallel to the cold mass in the cryostat. Figure 7.8 shows the cryogenic flow scheme and instrumentation for a high luminosity insertion inner triplet.

7.5 Cryogenic distribution

The central nodes of the cryogenic distribution system are situated in the underground caverns. These are the cryogenic interconnection boxes (QUI) which provide the connection between the different cryogenic sub-systems at each of the five feed-points: surface 4.5 K cold boxes, underground 4.5 K lower cold boxes, 1.8 K refrigeration unit boxes, and the QRL. The upper cold boxes

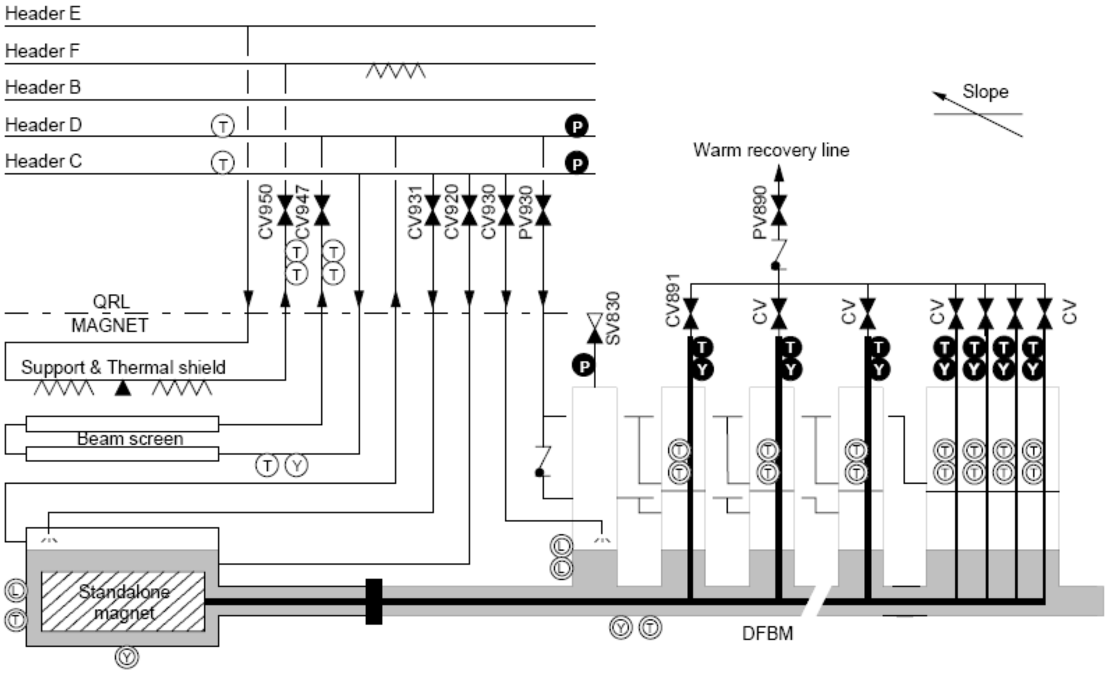

Figure 7.7: Cryogenic flow scheme and instrumentation of a 4.5 K standalone magnet.

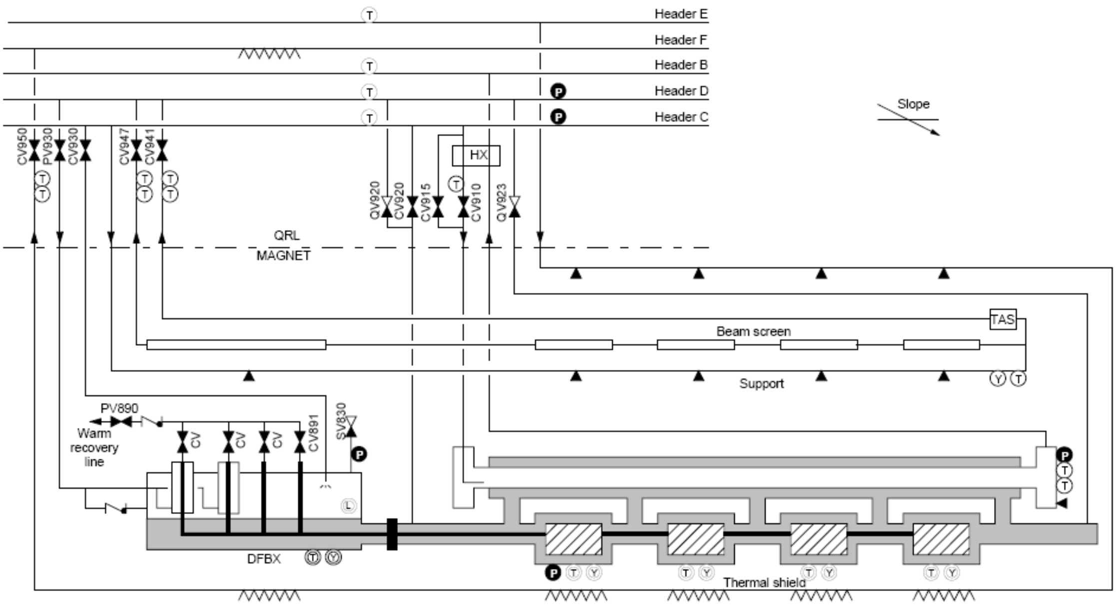

Figure 7.8: Cryogenic flow scheme and instrumentation of an inner triplet cell.

of the new 4.5 K refrigerators are linked to the interconnection boxes via four vertical helium transfer lines that pass down the main LHC shafts. The QUIs are located between 80 m and 145 m below ground, depending on the access point. The lower cold boxes of the refrigerators recovered from LEP and those of the 1.8 K refrigeration units are connected to the interconnection boxes

Table 7.1: Installed refrigeration capacity in the LHC sectors.

Temperature level	High-load sector	Low-load sector
50-75 K [W]	33’000	31’000
4.6-20 K [W]	7’700	7’600
4.5 K [W]	300	150
1.9 K LHe [W]	2’400	2’100
4 K VLP [W]	430	380
20-280 K [g s^{-1}]	41	27

via 12 underground helium transfer lines. Finally, the QRL feeds helium at different temperatures and pressures to the cooling loops and other devices for each of the eight sectors, starting from the QUIs and running along the tunnel.

7.6 Refrigeration plants

The refrigeration capacity of the sectors listed in table 7.1 corresponds to ultimate operation, without contingency, assuming the heat load levels calculated in 1997. Since ordering the refrigerators, the electron cloud predictions have increased the heat loads. Consequently, the installed capacity can no longer cope with the estimated ultimate demand, but it still fulfills the nominal demand of about 5.3 kW per sector.

7.6.1 4.5 k refrigerators

The refrigeration of the LHC sectors requires mixed-duty operation of the cryogenic helium refrigerators, in order to fulfil a variety of isothermal and non-isothermal cooling duties. This amounts to a total equivalent entropic capacity of 144 kW at 4.5 K, thus making the LHC the world’s most powerful helium refrigeration system. In accordance with the policy for re-using as much as possible of the LEP equipment, CERN equipped the new “high-load” areas with four new refrigerators and upgraded four existing LEP refrigerators for the “low-load” areas.

7.6.2 1.8 k refrigerators

The efficient production of 1.8 K refrigeration in the multi-kW range can only be achieved through combined cycles making use of sub-atmospheric cryogenic compressors and heat exchangers. Considerable R&D was performed by CERN in liaison with CEA and industry before eight 1.8 K refrigeration units were procured industrially. The 1.8 K units are interconnected with the 4.5 K units.

7.7 Cryogen storage and management

Helium is mainly contained in the magnet cold masses, which require a minimum filling ratio of 15 l m^{-1} of superfluid helium for enthalpy buffering, and in the header C of the QRL. Figure 7.9 shows the helium inventory per sector. The total inventory is 96×10^3 kg. Initially, on-site helium

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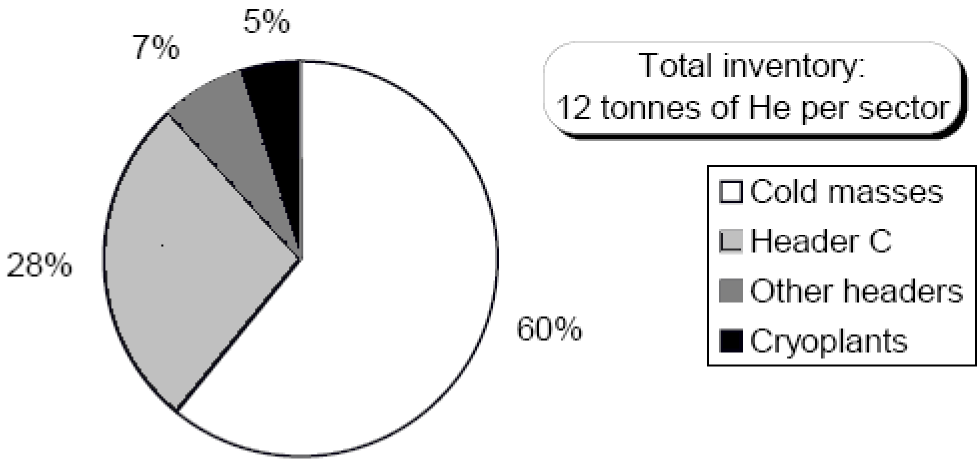

Figure 7.9: Helium inventory per sector.

storage was provided for half of this inventory, but in a second phase more storage is being added. CERN is also offering the possibility that gas-distribution companies can re-sell part of the helium inventory on the market during shutdowns, if the whole machine is warmed up and the on-site storage is insufficient.

CERN also needs liquid nitrogen for cool down operations and for the regeneration of purifiers. Liquid nitrogen is not used in the tunnel for safety reasons. For a normal cool down of a sector, the 600 kW pre-cooler will use a maximum of 1'260 ton of liquid nitrogen.