The use of cryogenics has started at CERN in the 1960s for cooling high energy physics detectors requiring low temperature technologies to achieve the desired performances. From the 1980s onwards, cryogenics has also been used in CERN accelerators for cooling superconducting accelerating cavities and high field magnets. Today, cryogenics is largely used in the LHC project under construction at CERN for cooling the 27 km magnet ring which requires the largest 1.8 K helium refrigeration and distribution systems in the world as well as its two largest detectors (ATLAS and CMS), which incorporate a variety of cryogenic equipment. In addition, cryogenics is used for cooling specific experiments not related to the LHC complex. After a brief historical review, the present status and latest developments in cryogenics at CERN are reviewed.
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Introduction

The need for cryogenics at CERN [1] originated in the 1960’s in track sensitive chambers [2] (bubble chambers) of large dimensions (up to 35 m³) filled with liquid hydrogen, deuterium, neon or their binary mixtures and requiring the use of industrial scale cryogenic systems down to 20 K, soon followed by the construction of high spatial resolution (40 µm) chambers of smaller dimensions [3] (down to a few liters sensitive volume) operated at high repetition rate up to 30 Hz.

In parallel, the CERN fixed target experimental program required the construction of about 120 cryogenic targets (from 30 m³ down to few cm³) requiring cryogenics down to 20 K.

In the 1970’s the need of cryogenic technologies for detectors was extended in the 80 K range by the development of sampling ionization chambers (calorimeters with typical volumes of 2 to 4 m³) filled with liquid argon for measuring the energy of elementary particles [4, 5]. Helium cryogenics at 4.5 K was required by superconducting magnets [6, 7, 8] used as spectrometers for particle momentum analysis and for high-luminosity insertion superconducting quadrupoles at the ISR [9].

Later, in the 1980’s, the development of large colliders (electron-positron collider LEP) has created the need of a new generation of “particle transparent” spectrometers based on large superconducting solenoids [10] requiring refrigeration capacity in the kW range [11].

In the 1990’s, the successful development of 350 MHz superconducting accelerating cavities [12] represented for CERN cryogenics a major event implying the implementation in the 1990s of very large capacity 4.5 K helium refrigeration plants [13, 14]. At the opposite to large cryoplants, the achievement for polarized target experiments of very low temperatures led
to the development of powerful dilution refrigerators implying small scale but highly sophisticated technologies [15].

CERN management has decided at the end of 2001, in view of the Large Hadron Collider (LHC) construction, to close the LEP collider with its experimental facilities thus liberating most of the existing LEP cryogenic infrastructure for further re-use and upgrading for LHC. The LHC accelerator and its two large experiments ATLAS and CMS require helium cryogenic system as well as cryogenic test facilities of unprecedented size and complexity. In parallel, cryogenics is still used for cooling specific experiments not related to the LHC complex.

Figure 1 shows the cryogenic capacity evolution at CERN since the 1960’s.

Cryogenics for the LHC Collider

The LHC collider [16, 17] will be constituted of superconducting magnets to bend and to focus proton beams circulating in the former circular LEP tunnel (see Figure 2). The 27 km circumference of the LHC collider requires 7000 km of Nb-Ti alloy cable. In order to reach the nominal beam energy of 7 TeV, a bending field of 8.3 T is required, imposing to cool the magnet with superfluid helium down to 1.9 K [18].
subdivided into eight 3.3 km sectors (see Figure 3).

Cryogenic architecture

The transport of refrigeration capacity along a sector is made by a cryogenic distribution line, which feeds periodically the arc machine every 107 m via a jumper connection. To limit the thermodynamic penalty of the superfluid helium cooling loop, a maximum temperature difference of 0.1 K is imposed for heat extraction and pressure drop for transport across the whole 3.3 km sector.

Each sector is cooled by a dedicated cryoplant constituted of one conventional 4.5 K refrigerator having a equivalent unit capacity of 18 kW at 4.5 K coupled to a 1.8 K refrigeration plant having a unit capacity of 2.4 kW at 1.8 K. These cryoplants are located at five different tunnel access points. Figure 4 shows the corresponding cryogenic architecture. A cryogenic interconnection box interconnects the 4.5 K refrigerator, the 1.8 K refrigeration plant and the cryogenic distribution line. Except for sector 2-3 for which no adjacent cryoplant is available, these cryogenic interconnection boxes allow also redundancy of sector cooling.

Refrigeration at 4.5 K

The four Ex-LEP 4.5 K refrigerators [19] will be upgraded for LHC requirements and four new 4.5 K refrigerators [20] have been produced by two industrial companies and already delivered to CERN. Following reception tests, the new refrigerators have been accepted [21] and are presently in operation. The new 4.5 K refrigerators are equipped with a 600 kW liquid nitrogen pre-cooler used to cool down a LHC sector from ambient to 80 K in less than 10 days [22] as well as switchable 80 K adsorbers and 300 K molecular sieve full-flow dryers preventing helium circuit pollution and guaranteeing a continuous operation for more than 6000 hours. The same functions will be added on the four Ex-LEP 4.5 K refrigerators which will be consolidated in 2005 and 2006. Each 4.5 K refrigerator simultaneously produces 33 kW between 50 K and 75 K for thermal shielding, 28 kW between 4.6 K and 20 K for heat interception, beam screen cooling and 1.8 K refrigeration unit boosting as well as 41 g/s between 20 K and 280 K for HTS current leads cooling [23]. At installed capacity, the electrical power input of the warm compression station of these refrigerators is about 4 MW, which yields a coefficient of performance of 230 W at 300 K per W at 4.5 K.

Refrigeration at 1.8 K

Two pre-series 1.8 K refrigeration units [24] have been ordered from two industrial companies and already delivered to CERN for extensive qualification tests. The two pre-series [25, 26] have successfully passed the qualification tests. These units compress a very-low-pressure helium flow of 125 g/s from 1.5 kPa to a pressure above atmosphere. The compression is realized by a set of cold axial-centrifugal compressors in series with a warm volumetric compressor. This combination of cold and warm compressors allows a turndown capability higher than 3 as well as a transient flow-rate variation higher than +/- 10 g/s per minute. At installed capacity, the electrical power input of the warm compressor station of these units is about 500 kW, which yields, also taking into account the capacity produced by
the 4.5 K refrigerator boosting the units, a coefficient of performance of 950 W at 300 K per W at 1.8 K. The series and spare cold compressor cartridges have also been intensively tested using the pre-series units as test benches [27]. Figure 5 shows the pressure ratio and isentropic efficiency measured at installed capacity of the 35 cold compressors for the 2 companies. In terms of isentropic efficiency, a considerable improvement has been achieved. In addition the five cold compressors of a given compression stage are fully interchangeable without any specific mechanical or electronic tuning.

Figure 5  Measured cold compressor performance (uncertainty on efficiency: +/- 5 points).

Cryogenic distribution

The five cryogenic interconnection boxes have been delivered to CERN and are under installation and commissioning. These boxes contain all the cold valves for interconnecting the different cryo-plants to the tunnel cryogenic distribution line. They also integrate one or two 600 kW electrical heaters to warm up a LHC sector from 1.9 K to ambient in less than 12 days.

The four vertical transfer lines [28] connecting the new 4.5 K refrigerators to the interconnection boxes have been delivered to CERN and are under installation and commissioning. The thermal compensation unit of these lines, which have lengths between 80 and 150 m, are located at ground level avoiding the integration of bellows in the vertical part.

The cryogenic distribution line [29] feeds periodically each of the LHC sector over its 3.3 km. Two sectors are under installation. In 2004, the discovery of major non-conformities has stopped both the installation and the fabrication of the lines. The problems encountered are now solved and activities have restarted with corrective actions to recover the delay.

Local transfer lines are connecting the different underground cold boxes. They are relatively short (maximum length of 30 m) but due to space constraint have many bends and shuffling modules. Two out of 12 lines have been delivered, installed and commissioned.

Electrical feed boxes and superconducting links

The LHC accelerator is electrically sectorized and has to be powered at each sector end. A total current of about 1.7 MA has to enter or leave the cryogenic environment via current leads having current varying from 120 A to 13 kA. The current leads, using high-temperature superconductors, are grouped in electrical feed boxes [30] located at the extremity of each magnet string. In total, 44 boxes are required to feed the arc, matching-section and inner-triplet magnet strings. The first two boxes are under manufacturing at CERN. The assembly and installation will be performed in the framework...
of a collaboration agreement between Russia and CERN. Figure 6 shows an electrical feed box for arc magnets constituted of two current lead modules and of a shuffling module acting as magnet arc termination.

![Image of electrical feed box](image)

Figure 6 Electrical feed box for the LHC accelerator

In some locations, where it is impossible to place power converters close to the magnet strings to be powered, the converters and the corresponding electrical feed box are located at a distance of up to 500 m and the connection to the magnet strings is performed via superconducting links housing low-temperature superconductor bus-bars cooled below 5.2 K. In total, 5 superconducting links are required for the LHC. They are under manufacturing and will be installed end of 2005.

**Magnet test station**

Before installation in the LHC tunnel, all superconducting cryo-magnets have to be tested to verify their electrical, mechanical and cryogenic performance. For this purpose a magnet test station has been built at CERN [31]. Until end of 2006, about 1800 cryo-magnet must be tested and the capacity of this station has been design for testing at 1.9 K an average rate of 15 magnets per week. 12 test benches are operated 24 hours per day and 7 days per week to meet this rate. Every week, about 400 tons of magnet cold masses are cooled down and warmed up from 300 K to 1.9 K. The test station is coupled to a new LHC 4.5 K refrigerator and the 1.9 K refrigeration capacity of about 500 W is produced by LHC prototype cold compressors in series with warm pumping units.

![Image of test station](image)

Figure 7 Test station of LHC accelerator magnets

**Cryogenics for the LHC Experiments**

Four main physics experiments are under construction around the LHC (see Figure 8). In the case of the magnets for particle spectrometers, the final choice (superconducting vs. resistive) was dictated by economy and/or “transparency” of the mechanical structure along the path of particles crossing the detector volume. These basic design criteria have led CMS and ATLAS [32, 33], the two largest LHC experiments, to construct superconducting spectrometers at 4.5 K of unprecedented size whilst for the other two experiments, ALICE and LHC-B, the resistive version was preferred.

![Image of LHC experiment layout](image)

Figure 8 LHC experiment layout
ATLAS and CMS experiments, in diametrically opposite locations on the LHC ring, have independent refrigeration plants separated from the cryogenics of LHC accelerator. However the control systems are highly standardized to allow future operation and maintenance of all LHC cryogenics by a single team sharing common resources.

**CMS experiment**

CMS is built around a single large solenoid [34] (length 13 m, inner diameter 5.9 m, uniform field 4 T) powered up to 20 kA with a total stored electromagnetic energy of 2.6 GJ and cooled at 4.5 K by the indirect method greatly simplifying the cryostat design. The helium flow in the cooling channels is driven by a thermosiphon effect [35]. The CMS calorimeter uses scintillation light as detectable signals to measure the particle energies and does not need cryogenic technologies.

**ATLAS experiment**

ATLAS is based on a "thin" central solenoid [37] (length 5.3 m, inner diameter 2.4 m, uniform field of 2 T) surrounded by a toroid consisting of three separate magnets [38], the barrel and two end-caps, generating a toroidal field in a cylindrical volume (length 26 m, external diameter 20 m) covering the entire ATLAS detector. All these magnets, at the exception of central solenoid, are powered up to 20 kA and the total stored electromagnetic energy is 1.8 GJ.

For ATLAS calorimetry, an innovative design of the internal absorber/electrode structure (the so called "accordion") has allowed the construction of the largest detector in the world using liquid argon as ionization medium that meets the LHC physics requirements in term of hermeticity, time and uniformity responses. Three large calorimeters [39] (a barrel and two end-caps) cover a cylindrical structure of a length of 13 m and an external diameter of 9 m and the corresponding cryostats are filled with 45 m³ and 2x19 m³ of liquid argon. The calorimeters are operated at 87 K in sub-cooled conditions to prevent bubble formation by means of heat exchangers placed inside the liquid argon volumes and cooled by a two-phase flow of liquid nitrogen forced by centrifugal pumps [40].

The barrel detector has been cooled down, tested and warmed up during spring and summer 2004. During cool-down and warm-up, the temperature differences in the composite structure of the detector must be kept within
strict limit (20 K) to avoid excessive mechanical stresses or relative displacements. During normal operation a temperature gradient of less than 0.7 K is mandatory across the liquid argon bath (see Figure 10).

As for CMS, the superconducting magnets of ATLAS are cooled at 4.5 K. For the solenoid [41, 42], the helium flow in the cooling channels is driven by a thermo-siphon effect, whilst for the toroids the two-phase helium mixture is forced by centrifugal pumps [43]. The three first barrel toroidal magnets have been individually tested at ground level in 2004. During cool-down, the thermal stresses have to be limited by controlling a maximum temperature difference across the magnet below 50 K (see Figure 11).

ATLAS will use two helium and one nitrogen refrigerators [44] independent from each others providing non isothermal cooling for current leads and thermal shield in addition to base load isothermal refrigeration at 4.5 K for the magnets and 84 K for the calorimeters. The total cooling capacity of these plants is 8.7 kW at 4.5 K. The cold mass of all detectors is 1275 tons and, in total, 165 GJ must be extracted to achieve the corresponding operating temperature levels. The helium refrigerators have integrated liquid nitrogen/gaseous helium heat exchangers to provide 60 kW capacities for cooling the magnets from 300 K down to 100 K. Furthermore, ATLAS calorimeters need additional 30 kW capacity for 300 K to 100 K cool-down provided by the internal heat exchangers cooled by liquid nitrogen. By means of buffer volumes of cooling liquids, back-up cryogenic facilities are implemented to allow in case of failure of the refrigerating systems the slow dumping of the stored electromagnetic energy in 2 hours as well as the continuation of the cooling of the calorimeters for at least one day.

The cryogenic architecture of the ATLAS helium refrigeration is given in Figure 12. The two helium refrigerators have been installed and are under commissioning with the corresponding proximity cryogenic system.

In addition, the ATLAS experiment requires longitudinal displacements of several meters without interrupting the cryogenic operation of the end-cap magnets and calorimeters for periodic access to the electronics placed near the central part. Several flexible transfer lines with a complex system of guidance will be implemented to satisfy these unique requirements. Furthermore for the calorimeters, the demand of uninterrupted cooling is extended over several years, because liquid argon emptying/refilling might affect the detector calibration. To guarantee uninterrupted operation, the 84 K nitrogen refrigerator has a back-up of liquid nitrogen storage dewars.
Cryogenics for Specific Experiments

**NA48 experiment**

The NA48 experiment [45] using noble liquid calorimetry is still in operation at CERN. This experiment extends the range of the application from liquid argon to liquid krypton which, because of its very high density, combines the function of "passive particle absorption", thus avoiding the use of lead or uranium plates, and "active read out" via ionization of the liquid. The cooling fluid for this detector is saturated liquid nitrogen and heat is extracted from the calorimeter by re-condensing the evaporated krypton via an intermediate bath of liquid argon feeding by gravity the corresponding 10 m³ liquid krypton cryostat [46]. This cascade cooling allows operation of the liquid nitrogen system at about only 0.5 MPa since argon has a triple point (84 K) lower than krypton (116 K).

The cryogenic operation of NA48 has to be guaranteed with 100 % of availability to avoid the detuning of the detector. As a consequence, redundant systems have been implemented for the cryogenics and utilities. This experiment has been in operation at CERN for 10 years without any stop.

**COMPASS experiment**

Polarized target experiments are still part of the CERN physics program with an experiment COMPASS continuing the long tradition of very low temperature applications for high energy physics initiated with the development of dilution refrigerators in the 1960s. COMPASS uses solid targets either ammonia or $^6$LiD. Nuclear spin polarization is achieved by microwave irradiation of the target kept at less than 1 K in a field of 2.5 T generated by a superconducting solenoid.

A new solenoid superconducting magnet offering a larger acceptance with respect to the first one has been designed and constructed and is presently under reception test at CEA (France) before delivery and integration at CERN.

**CAST experiment**

A novel experiment called CAST consisting of a solar telescope aiming at the detection of axions, hypothetical particles constituting a prime candidate for galactic dark matter, is also in operation. The experiment uses a decommissioned 10 m, 9.5 T LHC superconducting dipole prototype to catalyze the solar axions into photons. The LEP Delphi refrigerator (800 W at 4.5 K) is re-used to provide the necessary cooling capacity to the superfluid helium cryogenic system of the magnet [47].

A phase 2 will start in 2005 to increase the detector performance by filling the two dipole apertures with helium 4 and helium 3.

**Conclusion**

Cryogenics is a key technology for cooling specific components like detectors or entire complexes like accelerators and is mandatory for enabling them to reach their scientific objectives through technical performance.

The need for large industrial scale 4.5 K refrigerators has been introduced in the 1980's
by the use of superconducting accelerating cavities. Today, with the construction of the Large Hadron Collider using high field magnets, additional efficient large-scale 1.8 K refrigerators are required and have been developed with industry. This superconducting accelerator which is distributed all around a ring of 27 km has also required specific breakthroughs in cryogenic distribution and electrical feeding technologies. To match the installation rate of the LHC machine, a large cryogenic test station has been designed and constructed and is presently in continuous operation.

CERN detectors are quantitatively less demanding for cryogenics in comparison with the accelerators, however their cryogenic needs have generated a variety of different application with a range of temperature from 130 K (liquid krypton calorimeters) down to a few tenth of mK for polarized targets. The CMS and ATLAS experiments of LHC, which are using large solenoid and toroid magnets, have required to push away thermo-siphon cooling technology and to develop large cryogenic circulating pumps with industry.

During the past 10 and over the next 20 years around 2000, a strong CERN effort in cryogenics was and will be required for these unique accelerator facilities including their final consolidation and operation.

Reference

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