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CRYOGENICS AT CERN

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The use of cryogenics at CERN was originated (in the 1960s) by High Energy Physics detectors requiring low temperature technologies to achieve the desired performance and indicates a sustained trend during the entire evolution of the CERN experimental program. More recently (in the 1980s) the need of cryogenics for CERN accelerators has shown an impressive increase due to the development of superconducting accelerating cavities and high field bending magnets. Today, the two largest detectors (ATLAS and CMS) of the LHC accelerator ask for a considerable variety of cryogenic equipments and the 27 km LHC magnets ring requires the largest 1.8 K helium refrigeration and distribution systems in the world. The status of CERN cryogenics is briefly reviewed including those systems not related to the LHC complex.

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INTRODUCTION AND HISTORICAL OVERVIEW

The use of cryogenics at CERN originated in the 1960s in track-sensitive chambers (bubble chambers) requiring the use of industrial scale 30 K cryogenic systems. The largest CERN bubble chamber BEBC [1] used a variety of cryogenic fluids filling the sensitive volume (35 m^3) namely liquid hydrogen, deuterium, neon and their binary mixtures. The complexity (as a single unit) of the BEBC cryogenic system is still unequalled at CERN. The construction of large bubble chambers was followed by high spatial resolution (40 µm) chambers of smaller dimensions [2], down to a few liters sensitive volume, operated at high repetition rate up to 30 Hz.

In parallel, the need for targets or multi-targets (up to ten) for particle beams interacting with simple and high density nuclei have led to the construction of non sensitive chambers (most of them filled with liquid hydrogen or deuterium) ranging again from very large (30 m^3) down to a few cubic centimeters. About 120 targets requiring 20 K cryogenics have been constructed, in more than 30 years, to satisfy the CERN fixed target experimental program.

In the 1970s the need for cryogenic detectors was extended in the 80 K range by the development of sampling ionization chambers (calorimeters) filled with liquid argon for measuring the energy of elementary particles [3]. Several calorimeters (typical volumes 2 to 4 m^3) were built at CERN for fixed target physics [4] and the first proton-proton collider ISR [5].

Helium cryogenics, mostly at 4.5 K, was requested by superconducting (s.c.) magnets used as spectrometers for elementary particle momentum analysis and, in the 1970s, was extended to accelerator technologies for radiofrequency beam separators of the SPS complex and for high-luminosity insertion s.c. quadrupoles at the ISR [6] requiring respectively 300 W@1.8 K and 1.2 kW@4.5 K cryoplants. In total six s.c. solenoids and one dipole [7], [8], have been constructed for the CERN fixed target physics program. The largest solenoid (3.5 T, 4.7 m inner diameter) was associated with BEBC. The corresponding combined He/H_2 refrigerating system had a cooling capacity of 6.7 kW@4.5 K. Collider physics experiments, with the ISR first and later, in the 1980s, with the large electron-positron collider LEP have created the need of a new generation of "particle transparent" spectrometers which could satisfy this specific demand of particle detectors only in their s.c. version. One solenoid was installed in the ISR [9] and larger solenoids [10], requiring each 800 W@4.5 K helium cryogenics [11], were built for two (DELPHI and ALEPH) of the four LEP experiments.

The successful development of 350 MHz s.c. accelerating cavities [12] represented for CERN cryogenics a major event implying the implementation in the 1990s of very large capacity 4.5 K helium refrigerating plants. By means of 288 s.c. cavities installed on both sides of the four beam collision points, LEP energy was upgraded from 45 GeV to 104 GeV per beam. The associated cryogenic system [13], [14] consisted, in its final upgraded version, of: 4x18 kW@4.5 K cryoplants, 2 km of helium distribution with an inventory of 9.6 tons helium.

At the opposite to large cryoplants, the achievement for polarized target experiments of very low temperatures (below the range of ^{3}He evaporating systems) led to the development of dilution refrigerators implying small scale but highly sophisticated technologies [15].

CERN has decided at the end of 2000, in view of the construction of the Large Hadron Collider LHC, 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, which will require the largest 1.8 K refrigeration and distribution system in the world.

CRYOGENICS FOR FIXED TARGET PHYSICS

Cryogenic activities associated to sensitive and non sensitive chambers are today very minor at CERN. In fact, bubble chambers do not meet the present requirements of modern detectors in terms of repetition rate, trigger capability, selectivity and reconstruction time of events and only a few non sensitive targets are under design and construction.

On the contrary, noble-liquid calorimetry is in wide use at CERN. In particular, one experiment [16], 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 m^3 liquid krypton cryostat [17]. 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 same is valid for s.c. spectrometers still in use for fixed target physics. Today, four magnets are in operation for running experiments or beam test set-ups of new detectors for LHC. Each of these facilities need helium plants of typically 400 W@4.5 K. Cooling of these magnets is achieved either by flow into hollow conductors of saturated helium forced by reciprocating pumps [18] or by saturated helium bath.

Polarized target experiments are still part of the CERN physics program with an experiment COMPASS continuing the tradition of very low temperature applications for High Energy Physics initiated with the development of dilution refrigerators in the 1960s. COMPASS uses solid targets made of 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 s.c. solenoid.

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, has been recently approved. The experiment uses a decommissioned 10 m, 9.5 T LHC s.c. prototype to catalyze the solar axions into photons. The LEP DELPHI refrigerator (800 W@4.5 K) is re-used to provide the necessary cooling capacity to the superfluid helium cryogenic system of the magnet [19].

CRYOGENICS FOR THE LHC COLLIDER

The LHC collider [20], [21] will be constituted of s.c. magnets designed to bend and to focus proton beams circulating in the former circular LEP tunnel. The 27 km circumference of the LHC collider requires 7000 km of Nb-Ti alloy cable, one of the s.c. materials of technical interest. In order to reach the nominal beam energy of 7 TeV, a bending field close to 8.3 T is required, imposing to cool the magnet with superfluid helium down to 1.9 K [22]. To maintain the 27 km ring of magnets at such a temperature, the cryogenic system will have to produce and distribute a total refrigeration power, unprecedented in size and complexity, of 144 kW@4.5 K and 20 kW at 1.9 K. A total magnet cold-mass of 36000 tons has to be cooled down to 1.9 K and the helium inventory of the collider is about 96 tons two thirds of which dedicated to the magnet filling. The LHC collider is subdivided in eight 3.3 km sectors.

The transport of refrigeration capacity along a sector is made by a cryogenic distribution line [23], 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.

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 1 shows the LHC collider cryogenic system layout as well as 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.

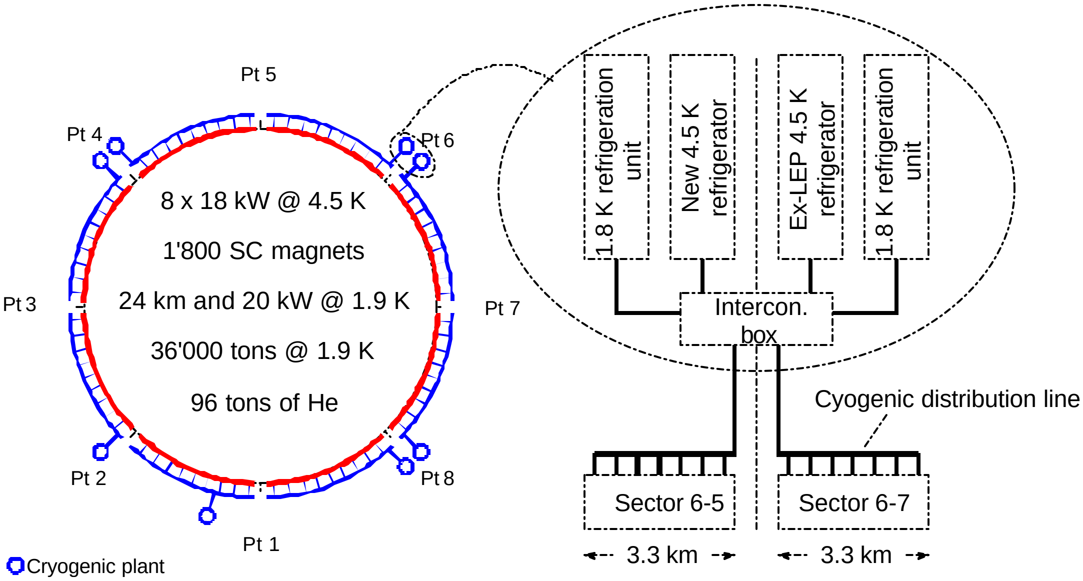

Figure 1 Cryogenic layout and architecture of the LHC collider

The four Ex-LEP 4.5 K refrigerators [24] will be upgraded for LHC requirements and four new 4.5 K refrigerators [25] have been ordered from two industrial companies and already delivered to CERN. Following reception tests, the first refrigerator has been accepted [26] and is presently in operation at point 1.8. These 4.5 K refrigerators are or will be equipped with a 600 kW liquid nitrogen precooler used to cool down a LHC sector from ambient to 80 K in less than 10 days [27] as well as switchable 80 K adsorbers and 300 K molecular sieve dryers preventing helium circuit pollution and guaranteeing a continuous operation for more than 6000 hours. 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 [28]. 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.

Two preseries 1.8 K refrigeration units [29] have been ordered from two industrial companies and already delivered to CERN for extensive qualification tests. The first preseries [30] has successfully passed the qualification tests; the other preseries [31] is under commissioning. 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 [32]. 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.

CRYOGENICS FOR LHC COLLIDER PHYSICS

The LHC collider physics program foresees four experiments (Figure 2). In the case of the magnets for particle spectrometers, the final choice (superconducting vs. resistive) is dictated by economy and/or "transparency" of the mechanical structure along the path of elementary particles crossing the detector volume. These basic design criteria have led CMS and ATLAS [33], [34], the two largest LHC experiments, to construct s.c. spectrometers at 4.5 K of unprecedented size whilst for the other two experiments, ALICE and LHC-B, the resistive version was preferred.

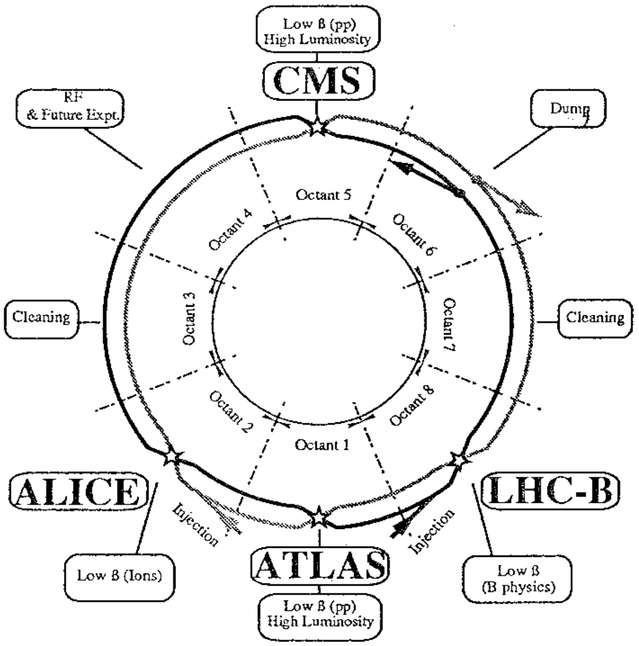

Figure 2 Schematic layout of the Large Hadron Collider with its four Experiments

CMS is built around a single large solenoid [35] (length 13 m, inner diameter 5.9 m, uniform field 4 T). ATLAS is based on a "thin" central solenoid [36] (length 5.3 m, inner diameter 2.4 m, uniform field of 2 T) surrounded by a toroid consisting of three separate magnets [37], 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 ATLAS central solenoid, are powered up to 20000 A and the total stored electromagnetic energy is 4.4 GJ (60% in CMS and the remaining in the ATLAS magnets together).

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 [38], 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 m^3 and 2x19 m^3 of liquid argon. All the other calorimeters for LHC experiments use scintillation light as detectable signals to measure the particle energies and do not need cryogenic technologies.

The s.c. magnets of the LHC experiments are cooled at 4.5 K by the indirect method greatly simplifying the cryostat design. For the two solenoids of CMS and ATLAS [39], [40], the helium flow in the cooling channels is driven by a thermosyphon effect, whilst for the ATLAS toroids the two-phase helium mixture is forced by centrifugal pumps [41], [42]. The calorimeters are operated at 87 K in subcooled 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 [43].

ATLAS and CMS experiments, in opposite location on the 27 km ring of LHC, have independent external refrigerating plants in turn separated from the 1.8 K cryogenics of LHC, however the control systems are highly standardized to allow future operation and maintenance of all LHC cryogenics by a single team sharing common resources.

ATLAS will use two helium and one nitrogen refrigerators [43], [44] independent from each others and CMS a single helium refrigerator [45]. They will provide 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 10.3 kW@4.5 K (84 % in ATLAS). The cold mass of all detectors is 1500 tons (85% in ATLAS) and, in total, 200 GJ (82% in ATLAS) must be extracted to achieve the corresponding operating temperature levels. The helium refrigerators of ATLAS and CMS have integrated liquid nitrogen/gaseous helium heat exchangers to provide respectively 60 kW and 30 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 cooldown provided by the internal heat exchangers cooled by liquid nitrogen. Back-up cryogenic facilities (by means of buffer volumes of cooling liquids) are implemented to allow in case of failure of the refrigerating systems: a) the magnets slow dump of the stored electromagnetic energy in few hours, b) the continuation of the cooling of the calorimeters for at least one day.

In particular the ATLAS experiment requires longitudinal movements 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 emptying/refilling might affect the detector calibration. To guarantee uninterrupted operation conditions, the 84 K nitrogen refrigerator has a back-up of liquid nitrogen storage dewars.

CONCLUSION AND FUTURE PERSPECTIVES

Cryogenics is a key technology for CERN and its use continuously follows the demand of High Energy Physics allowing specific components like detectors or entire complex like accelerators to achieve the desired scientific or technical performance at an acceptable cost. Several systems could not even be conceived without adopting solutions using low-temperature technologies.

Two important technological breaktroughs, the s.c. accelerating cavities and high field bending magnets have made feasible respectively the energy upgrading of the LEP collider and the present construction of LHC. In the first case introducing at CERN the need of large industrial scale 4.5 K helium plants and, in the second case, both increasing the equivalent 4.5 K cooling power of LEP by almost a factor three and expanding the application of superfluid helium cryogenic technologies to an unprecedented level. 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, whilst future long-term perspectives will strongly depend on the next generation of accelerators.

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. Furthermore, we have shown over the past 40 years a rather constant trend of application of cryogenics for CERN experiments following the continuous innovation of particle detector technologies. A very recent promising example of this innovation capability are the silicon detectors for particle tracking purposes [46] showing, when operated below 130 K under heavy radiation load, a recovery of the collection efficiency of the charges induced by the incident particles. This might lead to the construction of large particle trackers requiring innovative cryogenic technical solutions.

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