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CRYOGENICS FOR THE LARGE HADRON COLLIDER EXPERIMENTS

J. Bremer, D. Delikaris, N. Delruelle, F. Haug, G. Passardi and G. Perinic

Abstract

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ABSTRACT

High Energy Physics experiments have frequently adopted cryogenic versions of their apparatus to achieve the desired performance. Among the four new experiments for the CERN Large Hadron Collider (LHC) the two largest, ATLAS and CMS, include spectrometers using 4.5 K superconducting magnets and detectors filled with liquid argon at 87 K, respectively for particle momentum and energy measurements. These detectors are of unprecedented size and complexity and the definition of the associated cryogenic systems is the result of a collaboration between CERN and several external institutes all around the world. A review of the various systems is presented with particular emphasis to the basic cooling principles, the special cryogenic features and the operation scenarios.

INTRODUCTION

The design of detectors for High Energy Physics experiments is based on large magnets generating the field required by particle momentum measurements. Both resistive and superconducting (s.c.) magnets are used and the choice is dictated by economy and/or number of radiation lengths (a parameter indicating the "transparency" of the mechanical structure along the path of the elementary particles). Following these design criteria two, ATLAS and CMS [1],[2], of the four experiments for LHC (Fig.1) have adopted 4.5 K s.c. magnets whilst the others, ALICE and LHC-B, have retained the resistive version.

The CMS experiment is built around a single large s.c. solenoid [3] (length 13 m, inner diameter 5.9 m, uniform field of 4 T), whilst the magnetic configuration of ATLAS is based on a "thin" central solenoid [4] (length 5.3 m, inner diameter 2.4 m, uniform field of 2 T) surrounded by a large s.c. toroid [5] consisting of three separate magnets, the Barrel and two End-Caps. They generate a toroidal field in a cylindrical volume (length 26 m, external diameter 20 m) covering the entire ATLAS detector. At the exception of the ATLAS solenoid operated at 8000 A, all the others are powered up to 20000 A. The total stored electromagnetic energy is 4.4 GJ (60% in CMS and the remaining in the ATLAS magnets together).

Particle energy measurements are carried out by means of detectors called calorimeters transforming the energy into measurable signals (ionisation charge or scintillation light). The ionisation principle was chosen for ATLAS and liquid argon selected among the possible ionisation media as it is the best suited fluid, fully compatible with the LHC radiation environment, to satisfy the detector requirements [6]. This choice implies cooling in the range 84 to 89 K of the calorimeter made of three large detectors: the Barrel and two End-Caps, their respective cryostats are filled with 45 m^3 and 2x19 m^3 of liquid argon. All together they cover a cylindrical inner structure of a length of 13 m and an external diameter of 9 m.

All these detectors are in advanced stage of technical specification and of construction.

1. CRYOGENIC SYSTEMS

The LHC experiment cryogenics can be sub-divided into three parts: internal, proximity and external.

Internal cryogenics means any cryogenic device like heat exchangers, thermal shields, supports, feedthroughs located inside the cryostat housing a magnet or detector.

Proximity cryogenics means the links, from a conceptual and an operational point of view, to a given cryostat. It includes phase separators, expansion volumes, current leads turrets, cryogenic pumps, distribution valve boxes, transfer lines and safety devices. All these links located on top of the corresponding detector or near-by are installed in the main caverns (typically 100 m underground) housing the experiments.

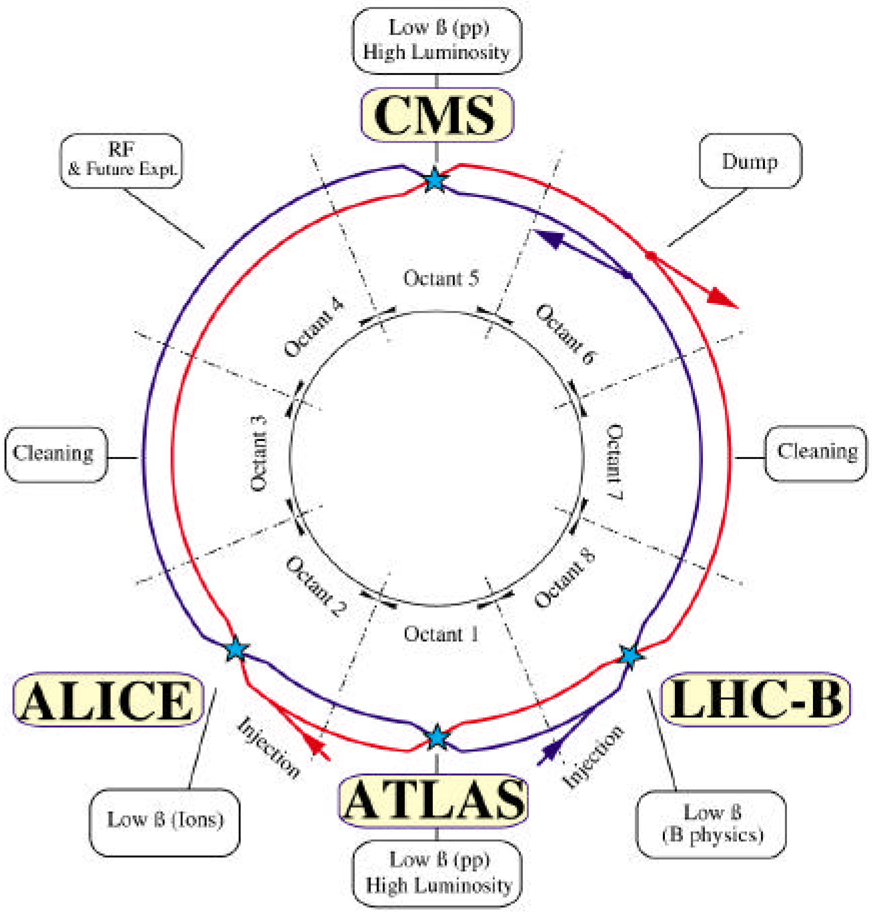

Figure 1: Schematic layout of the Large Hadron Collider (LHC) with its four experiments

External cryogenics means all devices needed to generate the cooling capacity at different temperature levels and in the various operating modes. Included are compressors, refrigerators, cryogens to boost the cooling capacity and all auxiliaries. These external components are located in service caverns near the main ones and in surface buildings at the vertical of the underground areas.

ATLAS and CMS detectors, in opposite location on the 27 km ring of the collider, have independent cryogenic systems in turn separated from the very large 1.8 K system of LHC, however unified control systems will be adopted to allow operation and maintenance of all LHC cryogenics by a team sharing common resources.

1.1 Internal cryogenics

Cooling of all magnets is achieved by the indirect method which greatly simplify the cryostat design. For the two solenoids (CMS and ATLAS [7],[8]), the helium flow in the cooling pipes is driven by the hydrostatic pressure difference between the pure liquid supply and the two-phase mixture in the return pipes (thermosyphon). The CMS solenoid uses a typical U shaped geometry with several parallel return channels, whilst the ATLAS solenoid has a single pass serpentine cooling pipe running parallel to the axis on each side of the magnet. For the ATLAS toroid, where the thermosyphon could not be applied because of the unfavourable geometry and the complex helium internal distribution, the two-phase helium mixture is forced by centrifugal pumps (total flow of 1200 $g \cdot s^{-1}$). Both systems (thermosyphon and pumps) provide the high flow rate that should ensure hydraulic stability in the two-phase helium by combining a mass flow per unit area higher than 4 $g \cdot s^{-1} \cdot cm^{-2}$ with a vapour mass fraction at the outlet of the coils of less than 10% [9]. In all cases helium is supplied to the coils circuits at 4.5 K, hydrostatic or pumps heads will add subcooling at inlet of 0.2 to 0.4 K. For the CMS solenoid and the ATLAS Barrel toroid double (one redundant) cooling piping is implemented since, for these systems, dismounting or access for repair of the internal cryogenics after final underground assembly cannot be envisaged.

Cooling of calorimeters [10] is achieved by evaporation of two-phase nitrogen flowing through pipes placed in the liquid argon volumes. Nitrogen circulation is driven again by pumps (total flow of 100 $g \cdot s^{-1}$) providing a flow rate corresponding to the thermal loads plus 10 % to ensure wet operating conditions of the heat exchangers over all their length. Pressure and, therefore, temperature of the cooling pipes can be varied between 90 and 84.1 K as function of operating conditions. They will set the temperature of the calorimeters at about 87 K creating subcooled conditions by 5 to 8 K depending on the height of the cryostat. Thus argon gas bubbling, being detrimental for the functioning of the detector, is prevented. Furthermore, the cooling pipes are located in such a way to control the temperature gradients over the overall calorimeter volumes within 0.6 K for minimising possible non uniformity in the detector response due to differences of the liquid argon density.

All magnets have thermal shields cooled by a high pressure flow of helium at about 60 K whilst no thermal shields are foreseen for the calorimeters. The ATLAS solenoid is a special case since the Barrel calorimeter is housed in the same cryostat and externally shields at 87 K the solenoid. This complex solution was imposed by the requirement of minimum radiation length along the path of elementary particles.

Cooling from ambient to the operating temperature is carried out via the same pipes used during normal operation. In case of the magnets, by means of high pressure helium at a temperature 40 K lower than that one of the cold mass and, in the case of the calorimeters, by means of liquid nitrogen in all the cool-down temperature range. In the first case, heat is extracted by conduction through the magnet structure made of aluminium and, in the second case, by convection and/or conduction through the argon gas gaps and the structure of the detector made of various materials (copper, lead, kapton). To improve the overall heat transfer and the corresponding cool-down time of the calorimeters (a factor 2 to 3), the argon gas can be temporarily replaced by helium or condensation of argon allowed below 120 K.

1.2 Proximity cryogenics

The proximity cryogenics takes the cooling capacity provided by the external cryogenics and distributes it to the various sub-systems. By means of centrifugal pumps (ATLAS toroids and calorimeters) or of thermosyphon (CMS and ATLAS solenoids) the two-phase mixture is forced through the internal cooling pipes. In the first case, the excess of liquid is returned to phase separators placed on the wall of the main cavern near-by the detector and, in the second case, is returned to phase separators placed on top of the detectors to favour thermosyphon effect.

In case of failure of the external cryogenics, the proximity systems are designed to have a sufficient autonomy to allow: a) the magnets slow dump of the stored electromagnetic energy in a few hours; b) the continuation of the cooling of the calorimeters for at least one day. This is achieved by a sufficient liquid capacity of the phase separators with their associated back-up dewars: 15000 litres of liquid nitrogen for the calorimeters and 12000 and 6000 litres of liquid helium for respectively ATLAS and CMS magnets. Furthermore, the liquid argon volumes of the three calorimeters are linked to corresponding expansion/phase separator vessels (volume 10% of the total) since no gas is allowed inside the detectors.

ATLAS experiment requires longitudinal movement of several meters of the magnets and calorimeters End-Caps for periodic (a few times per year) access to the electronics placed near the central part. The proximity systems include several flexible transfer lines with a complex system of guidance to perform these interventions with both the calorimeters and the magnets kept at their nominal cryogenic operating condition.

Only if required by major problems or hazard, the liquid argon contained in the calorimeter cryostats can be emptied in two dewars (each of 50000 litres capacity) installed in the main cavern and equipped with internal condensers for a closed circuit operation.

1.3. External cryogenics

To cope with the static and the dynamic thermal loads (ramp up and down of the magnets current and operation of the pre-amplifiers immersed in the liquid argon), ATLAS will use two helium and one nitrogen refrigerators independent from each others [10],[11] providing respectively:

- 3.6 kW isothermal capacity at 4.5 K and 15 g/s liquefaction for current leads
- 20 kW at 40 to 80 K for thermal shield cooling of the magnets
- 20 kW isothermal capacity at 84 K for the calorimeters.

and CMS will use a single helium refrigerator providing:

- 800 W at 4.5 K, 4 g/s liquefaction for current leads and 4.5 kW at 60 to 80 K for thermal shield cooling.

No liquid nitrogen supply from the surface is foreseen to achieve these performances and all the indicated cooling capacities include a 40 to 50 % margin.

The above refrigerators will also cope with the thermal recovery from the temperature (about 60 K) reached after a fast dump of the electromagnetic energy stored in the magnets. Both for ATLAS and CMS, the recovery time is expected to be less than 3 days.

Furthermore, in the case of the calorimeters the demand of uninterrupted cooling is extended over several years since emptying/refill of liquid might affect the detector calibration during a physics run. To satisfy this special requirement, nitrogen storage dewars installed at the surface can take over the supply of liquid during failure and annual maintenance work of the 84 K nitrogen refrigerator.

The cold mass of all the detectors is 1500 tons (85% in ATLAS) and, in total, 200 GJ (82% in ATLAS) must be extracted to cool them from ambient to the operating temperature. The helium refrigerators, designed for base-line operation, include additional heat exchangers to cool the high pressure helium flow to the magnets by means of liquid nitrogen supplied from the surface dewars (two for ATLAS and one for CMS each of 50000 litres capacity). These heat exchangers, integrated for CMS in the refrigerator cold box and for ATLAS in the thermal shield refrigerator, have a cooling capacity of respectively 30 and 60 kW in the range 300 to 100 K. For the calorimeters, no external heat exchangers are used since cooling-down is carried out directly by the liquid nitrogen flow through the internal cooling pipes operated in a way to provide 30 kW capacity. In all cases, the time required to reach from ambient the operating temperature is less than one month.

CONCLUSION

All the LHC detectors will pass surface tests prior to their final installation. The CMS solenoid will be fully assembled and tested with its final proximity and external cryogenic systems in a surface building at the vertical of the underground area. For ATLAS, a large test area with a dedicated cryogenic facilities [12] is now being prepared where the three calorimeters, the two End-Caps toroids and the central solenoid will be tested as single unit. For the Barrel toroid, the eight coils making the magnet will be tested in sequence because the very large dimension of the fully assembled magnet does not allow its mounting at the surface with further transfer underground. All these facilities are designed for providing basic cryogenic test conditions identical to those foreseen in the final configuration to fully validate the cooling principles.

Large experiments for High Energy Physics are the result of world-wide collaborations and, for the LHC detectors, this is also valid for the cryogenics. In total 10 external institutes from Europe, USA and Japan are collaborating with CERN in designing, constructing and testing the various systems of the internal, proximity and external cryogenics.

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