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Design principles and operational results of the cryogenic system for the ATLAS liquid argon calorimeter

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The ATLAS liquid argon calorimeter housed in three independent cryostats containing a total argon volume of about 78 m^3 has been installed in the underground cavern. The three detectors have been cooled down following stringent temperature gradient limits and have been filled with liquid argon. The cryostats are now in a stable condition for periods going up to almost two years. The temperature uniformity within each of the three detector volumes is found to be within 70 mK rms, while the temperature stability stays below 5 mK rms.

INTRODUCTION

ATLAS [1] is the largest of the five particle detectors constructed in order to study the interactions of proton or heavy-ion head-on collisions at the CERN Large Hadron Collider (LHC). The largest component of the central part of the ATLAS detector is a liquid argon ionization sampling calorimeter having a total cold mass of 550 tons. It is housed in three individual cryostats (one barrel and two end-caps) which are filled with a total volume of 78 m^3 of liquid argon at a temperature of 88.3 K. The commissioning of the calorimeter cryogenic installation started in 2005 following the installation of the various components in the 100 m underground experimental cavern. Between April 2006 and July 2007 the three calorimeters have been individually cooled down, and filled with liquid argon. Since then they have been kept at nominal running conditions.

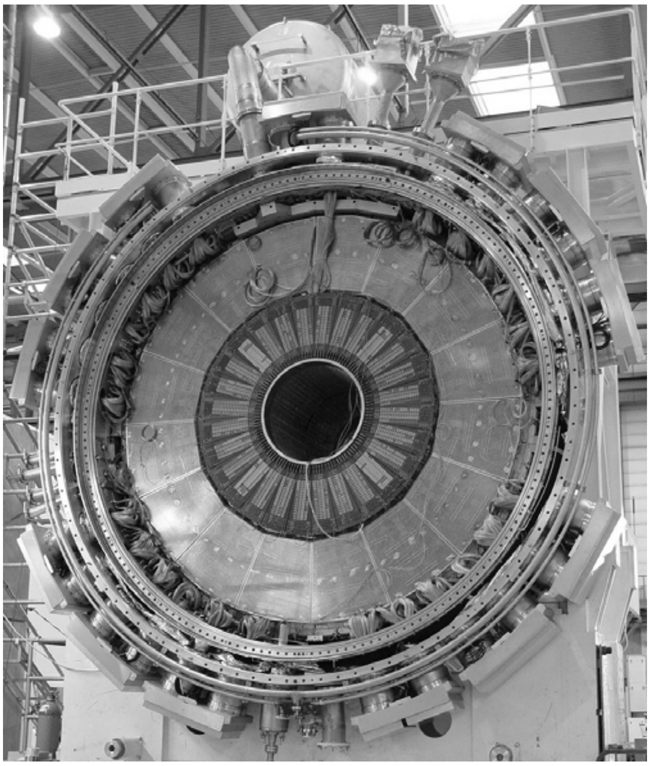

Figure 1, The end-cap calorimeter before final closure of the cryostat

THE ATLAS LIQUID ARGON CALORIMETERS

The barrel calorimeter [2] [3] consists of two detector wheels separated by a 4-mm gap. It is made of accordion-shaped lead absorber plates interleaved with copper electrodes. The two wheels weighing 120 t are placed in an aluminum cryostat immersed in a 40 m^3 liquid argon bath. For cooling purposes the barrel is equipped with 6 liquid nitrogen heat exchangers symmetrically distributed (4 at the outer circumference, 2 at the extremities). For minimizing the overall detector size and improving the “transparency” to particles emerging from the interaction point, the ATLAS central solenoid [4] is housed in the barrel cryostat. Both 219 t end-cap calorimeters (see Figure 1) consist of 4 detector wheels equipped with 2 heat exchangers. The cryostats are each linked via a transfer line to a dedicated expansion vessel in which the liquid/gaseous argon interface is located. An additional heat exchanger is placed in the gaseous volume of this expansion vessel in order to control the argon pressure.

The three cryostats are equipped with a total of 114 signal and 8 high-voltage feedthroughs distributed radially around the cryostat ends. Each signal feedthrough brings 2000 signal and calibration cables out of the liquid argon bath passing through an independent insulation vacuum.

Before final installation in the underground experimental cavern the various components and assemblies have undergone qualification tests. Between 1997 and 2004 the 128 individual detector modules have passed cold performance tests and calibration runs with a particle beam in test cryostats [5]. From 2001 to 2005 the detectors have been integrated in their cryostats and each calorimeter has been individually tested at the operating temperature, using a cryogenic system based on the same principle as the final system. This allowed validation of the cryostat design, of the cool down method and of the steady-state operation principles [6]. After transport to LHC Point 1 the calorimeters have been installed in their final location at the center of the ATLAS detector. The commissioning of the final cryogenic system started in March 2005 with the first transfer of liquid nitrogen into the 100-m underground cavern.

THE PROCEDURES DURING COOL-DOWN

Between April 2006 and July 2007 the three calorimeters have been individually cooled down to liquid argon temperature following procedures identical to those qualified at the test facility. These procedures, whose basic principles are recalled here, have been fully detailed in [6] [7].

In order to avoid excessive mechanical stresses or displacements the calorimeters have been cooled down while ensuring very limited temperature gradients over the fragile composite structure of the detectors. Seven cooling criteria have been defined for the barrel and eleven for the end-caps [8] [9]. Worth mentioning is the temperature dependence of some end-cap temperature gradients which become more stringent when cold (< 6 K @ 93 K).

Before cooling the calorimeters, rinsing cycles were carried out in order to remove the impurities present in the cryostats and detectors. The cold vessels were pumped with an oil-free pump and then filled with helium (end-caps) to enhance heat transfer or argon gas (barrel). Argon was preferred as the contact gas for the barrel since the estimated cool-down time was acceptable (total energy to be extracted 6.9 GJ compared to 15.7 GJ for each end-cap) and pumping of helium at cold could, in this way, be avoided. These purging cycles were repeated until the remaining traces of water and oxygen were respectively below 250 and 10 ppmv.

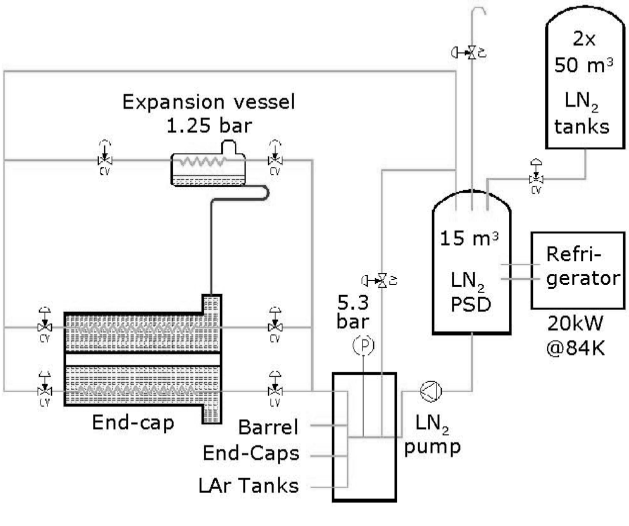

Figure 2, Simplified flow diagram of the nitrogen

From ambient temperature, the cooling was first achieved by forced convection of gaseous nitrogen in the heat exchangers whose inlet temperature was decremented and by free convection of gaseous helium (argon) in the end-cap (barrel) cryostat. At about 120 K the heat exchange became ineffective and the cooling was switched to a circulation of vaporizing liquid nitrogen in the heat exchangers. The cool-down rate was limited by an interlock triggered by the cooling criteria.

When the detectors were at about 90 K, the end-cap cryostats were purged with argon gas after which a total of 40 m^3 (barrel) and 2 x 19 m^3 (end-caps) of argon was condensed into the cold volumes. Argon was not filled in liquid phase to minimize the displacement of any dust remaining in the 2-mm gaps between electrodes. The argon gas was taken from two 50-m^3 liquid argon storage tanks which had been previously filled with argon passed through a mechanical and an Oxysorb filter in order to purify the liquid. Before filling the cryostats the O_2-equivalent purity in the argon tanks was less than 0.2 ppmv.

During liquid cooling and argon condensing stages liquid nitrogen was supplied by two 50-m^3 storage tanks installed at ground level, to a 15-m^3 Phase Separator Dewar (PSD) located in the underground experimental area (see Figure 2). The liquid nitrogen circulation through the heat exchangers was driven by a centrifugal pump providing a flow of up to 250 g/s. The pressure after the pump was regulated to 5.3 bar by means of a control loop, returning part of the flow directly to the PSD. The inlet valves of the heat exchangers were controlling the decrease of the detector temperature, while the outlet valves were regulating the nitrogen pressure so as to prevent or allow argon condensation. The nitrogen vaporized in the process was vented to the outside atmosphere.

Figure 3 shows the variation of the end-cap A calorimeter mean temperature and temperature gradient during cool-down. The 15.7 GJ total heat capacity from ambient down to 90 K [6] was extracted in 9 weeks at the average speed of 0.13 K/h while keeping the average temperature gradients below 20 K.

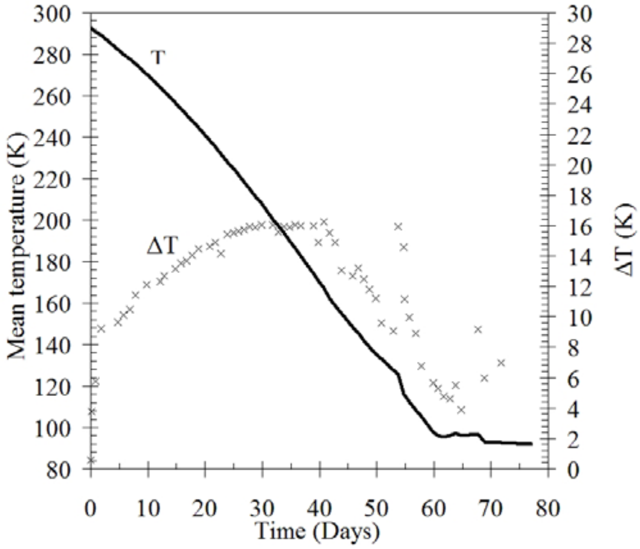

Figure 3, End-cap A mean temperature and ΔT variation during cool-down

THE STEADY-STATE OPERATIONAL PERFORMANCE

In steady-state operating conditions the cooling power is provided by the vaporization of liquid nitrogen flowing through the same heat exchangers. The pressure in the expansion vessels is regulated to 1.25 bar (89.3 K saturation) by using the liquid nitrogen heat exchanger placed in the gaseous volume. In order to prevent gas bubble formation which would be detrimental to the detector, the temperature of the argon bath in the cryostats is lowered to about 88.3 K thus creating a sub-cooled liquid. The inlet valves of the internal heat exchangers are set such that dry-out of part of the exchanger is prevented while the outlet valves regulate the saturated nitrogen pressure. The liquid/gas mixture is returned to the PSD and the gas is re-liquefied by a 20 kW @ 84 K nitrogen refrigerator (see Figure 2). In addition, the minimum pressure in the closed nitrogen circuit is set to 2.2 bar in the phase separator, well above the argon triple point.

The temperature of the warm flange of each individual feedthrough is regulated during the complete process by electrical heaters in order to avoid condensation on the electrical connections.

The barrel, end-cap A and end-cap C calorimeters have been in nominal running conditions for respectively 24, 17 and 10 months with performance fully satisfactory for detector physics operation. Figures 4 and 5 show the steady state operational conditions of the barrel calorimeter. The non-uniformity of the argon baths is during test periods of several weeks found to be less than 70 mK rms and the temperature stability over time less than 5 mK rms for each of the 232 temperature probes of the barrel (calibrated PT100 platinum resistors). Maintaining the temperature of the liquid in sensitive parts of the calorimeters uniform and stable in time is extremely important since temperature variations directly affect the energy measurements (2 %/K). Because of the temperature uniformity, the liquid argon bath is sub-cooled by 4.2 to 7.7 K

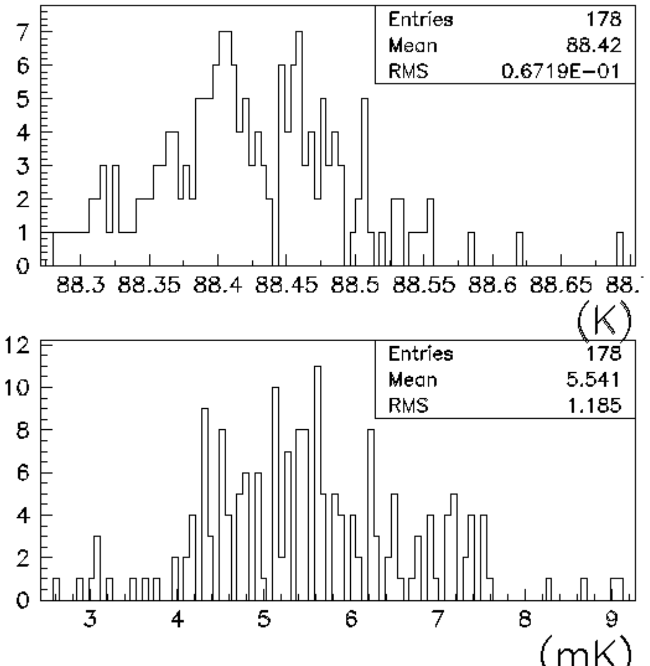

Figure 4, Statistical occurrence of average temperature in the barrel (top). Stability measurements in barrel over 24 hours (bottom) depending on the depth in the cryostat. Finally the argon purity measured by monitors located in the liquid argon bath is between 0.1 and 0.3 ppmv of O_2-equivalent, without any significant degradation over time.

Over the past two-year operation period occasional temperature excursions of up to 0.25 K have been observed. They could be correlated either with an on or off powering of the end-cap cold electronics [2] (about 600 W heat load variation for each end-cap) or with a change of the liquid nitrogen conditions in the PSD (switch from refrigerator supply to surface storage tank supply). In the later case, corrective actions have been taken in order to minimize these variations: adjustment of the phase separator and tank pressure set points.

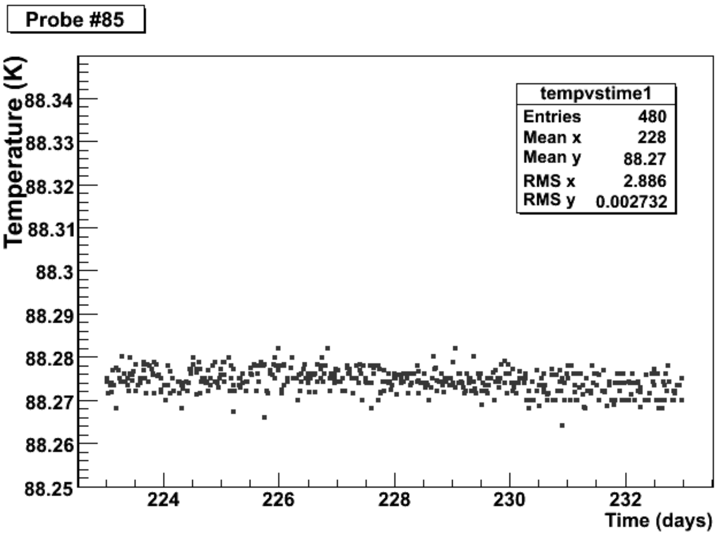

Figure 5, Temperature variation of one barrel probe over 1 week

The total heat load into the complete cryogenic system is measured to be about 9.2 kW. The heat load into the cryostats have already been measured in the test area [6] and come up to 1.9 kW and 2.5 kW for the barrel and each of the end-cap cryostats respectively. The above figures include the contribution of the end-cap cold electronics. The resulting additional 2.3 kW can be attributed to the heat load into the two 50 m^3 argon tanks, into the PSD, into a total of about 700 meters of transfer lines, into the nitrogen circulator and into the 5 valve boxes included in the installation.

SPECIAL FEATURE: UNINTERRUPTED FUNCTIONING OVER 15 YEARS

In order to minimize the thermal cycling and consequent risk of damaging or deforming the accordion structure of the calorimeters, it has been foreseen to keep the calorimeters filled with argon over the estimated 15 year lifetime of the ATLAS detector. The cryogenic system has thus been designed such that all maintenance, of the cryogenic as well as of the detector equipment, can be carried out while keeping the cooling operational.

Twelve-meter translation of the end-cap calorimeters

To allow access to the central part of ATLAS detector and especially to the electronics placed close to the cryostats, the two end-cap calorimeters have been equipped with a displacement system allowing them to translate over 12 meters. The cryogenic lines between the expansion vessels and the cryostats, the transfer-lines supplying liquid nitrogen to the heat exchangers, the signal cables and compressed air pipes have been designed to follow these displacements.

The argon transfer-line between the cryostat and the expansion vessel is a 35-m long flexible, having a DN 300 outer diameter and a 1.5-m bending radius which enables the storage of 12-m length on the service motorized platform. The line placed on this platform, is supported by fixed or mobile supports which guide its movement through

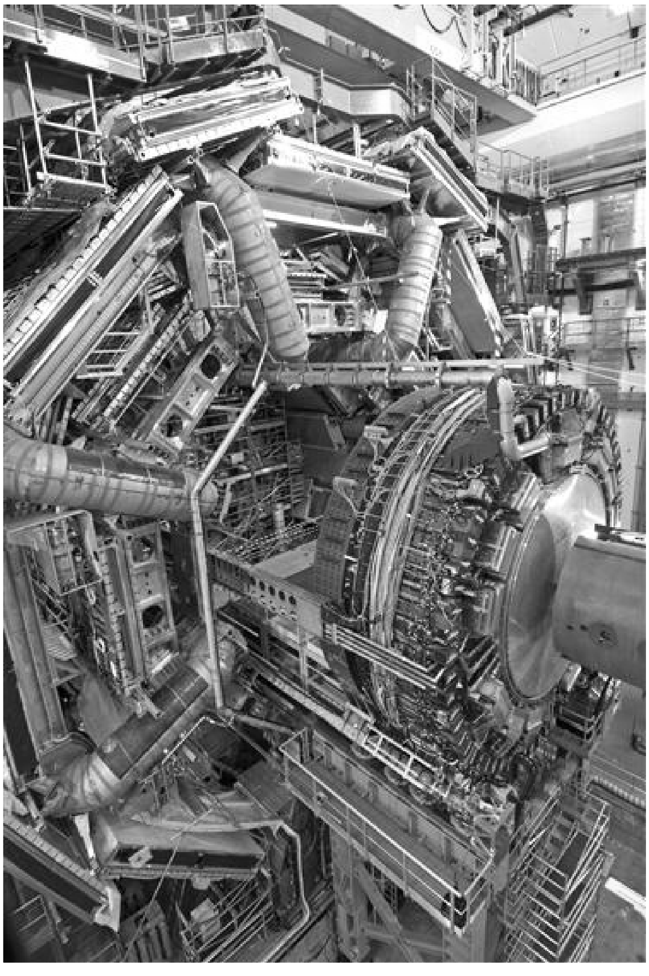

Figure 6, The end-cap calorimeter displaced to its extreme opening position with all services connected the detector central service gap.

Both end-cap calorimeter assemblies, each weighing about 1000 tons, have successfully made the 12-m translation on air pads with all their services connected (see Figure 6). During this operation the vacuum pumping lines and the transfer-lines used to empty the cryostats have to be disconnected. They can be reconnected at each of the three foreseen opening positions by mean of extra-sections.

Redundancies

The continuous functioning of the calorimeter cryogenic installation is ensured by several sets of redundancies:

- Three nitrogen centrifugal pumps are installed in parallel. One is running, the second is redundant while the third one can be dismounted for maintenance without affecting the operation of the others.
- Two 50 m^3 nitrogen storage tanks placed at ground level take over the supply of liquid nitrogen to the PSD during the annual refrigerator maintenance period or in case of refrigerator failure. In case of problem with the PSD or with the pumps, liquid nitrogen can directly be supplied from the ground level storage tanks to the distribution valve box located in the experimental cavern, via a vertical transfer-line. In this latter case, the 100 m pressure head is used to drive a nitrogen flow through the heat exchangers (see figure 2).
- All devices essential to the functioning of the system are powered by 2 electrical networks (French and Swiss networks) which are backed-up by diesel generators and uninterruptable power supplies (UPS) guarantying their functioning for up to two hours during power failures and test periods.
- In the same way, the compressed air supply for instrumentation and the cooling water used for the feedthrough heating system are backed up.

Even a loss of electrical power does not produce large perturbations. The vent valve of the expansion vessel vents the argon to the outside atmosphere, but time is afterwards needed to bring the system back to a stable state creating a delay on the physics data taking.

SAFETY ASPECTS

Under normal circumstances the liquid argon will stay in the cryostats. Special care has been taken to minimize the risk of a spillage of liquid argon in the underground cavern.

In case of an emergency the liquid can be emptied into two 50 m^3 liquid argon storage tanks installed in the underground area via a bottom dump valve placed inside the cryostat insulation vacuum. The tanks are positioned in such a way that the total argon volume of the cryostats can be transferred by gravity. A cryogenic pump can be used to speed up the process. To this purpose, these tanks are equipped with a liquid nitrogen condenser and kept cold over the life time of the experiment.

Additionally, all components containing large volumes of argon or nitrogen (the three calorimeters, the argon storage tanks and the PSD) are equipped with safety valves collected to a dedicated DN 500 pipe going directly to the surface and are placed in retention pits able to collect large spillage of liquid. The air is continuously extracted at the top of these pits by a ventilation system, so as to prevent diffusion of argon or nitrogen gas in the underground area and its subsequent risk of asphyxiation.

Finally, insulation vacuum levels are monitored and oxygen detectors are installed. They trigger evacuation alarms in the underground area.

CONCLUSION

The three liquid argon cryostats housing the ATLAS liquid argon detector system have been installed, cooled down and filled with argon in the underground area. The temperature of the argon baths have been regulated during test periods of several weeks to about 88.3 K with a temperature homogeneity within 70 mK rms in each of the three cryostats, while the temperature stability in time was better than 5 mK rms. The calorimeters have now been functioning for periods to up to two years during which the cryogenic system has demonstrated its high reliability judged from both the continuity in the operation and from the safety point of view.

ACKNOWLEDGMENT

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