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# The ATLAS Liquid Argon Calorimeter: an overview

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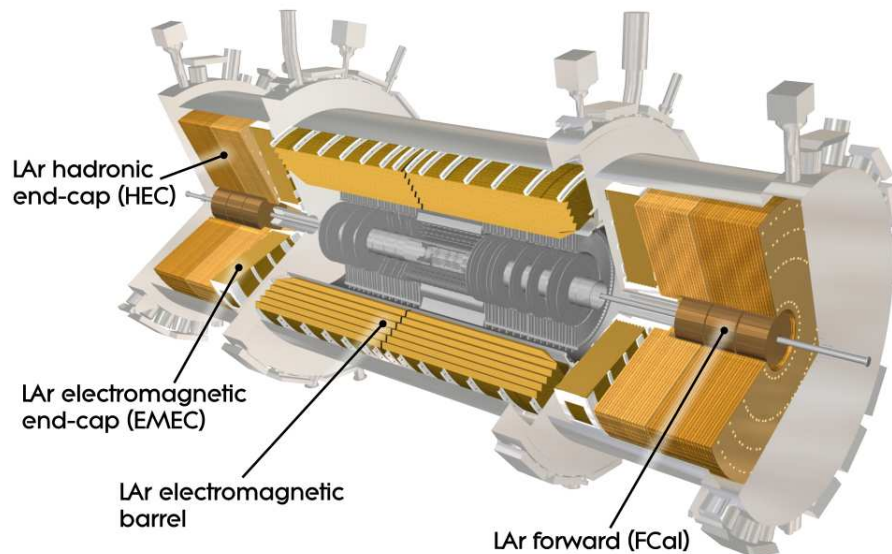
**Abstract.** The various cryostats with the ATLAS LArg calorimeter are installed in the ATLAS cavern since several years. Following this, an effort to install and commission the front end read-out electronics (infrastructure, crates, boards) has been ongoing and is converging, in time for LHC start. After the mechanical installation of the LArg calorimeter 99.9 % of the read-out channels were working, hence great care was taken to assure the same high level of quality after the installation of the read-out electronics. Following cautious procedures and with continuous testing-campaigns of the electronics at each step of the installation advancement, the result is a fully commissioned calorimeter with its readout and a small number of non-functional channels.

## 1. Introduction

An new energy frontier will soon open at CERN with the start-up of the Large Hadron Collider (LHC) providing proton onto proton collisions at nominal center of mass energy of 14 TeV. With a very high collision rate, it will deliver an integrated luminosity ranging from 10 to 100 fb<sup>-1</sup> a year. These performances will allow, using the detectors located around the collision points to study the production of heavy particles, interactions resulting in the productions high transverse momenta particles, even with low production cross-sections. A prominent example is the possible discovery of the Higgs boson, which within the Standard Model provides the mechanism giving mass to the particles. A good energy resolution and a good linearity are needed to fully exploit the collisions.

## 2. Physics requirements for the ATLAS LArg Calorimeters

The performance requirements for the Electromagnetic (EM) calorimetry in ATLAS [2] has been driven by the potential production of the Higgs boson in LHC collisions. The two channels decay channels  $H \rightarrow \gamma\gamma$  and  $H \rightarrow 4e^\pm$  were used to benchmark the design choices in the EM calorimeter design. The accordion design provides a large acceptance and uniform response over the full azimuthal range with no gaps for services, whereas the liquid Argon active medium is intrinsically resistant to radiations. To address the large dynamic range requirement going from 30 MeV to 3 TeV, the radiation hard front end electronics implements three gains for each readout channel. The contribution to the energy resolution of the stochastic term for EM showers should be  $10\% \sqrt{E}$ , and the constant term around 0.7 %, which requires very precise mechanics, in terms of absorbers and electrode positions, as well as a calibration system for the readout system reaching an accuracy of 0.25 %. To address the precise measurement of the W-mass, an excellent linearity of the calorimeter response, of order 0.1 %, is needed. This is accomplished with a presampler, as well as 3 longitudinal segmentations of the calorimeter,



**Figure 1.** Schematic drawing of the ATLAS LAr calorimeter system. In the middle the barrel cryostat hosts two electromagnetic wheels, at each end the end cap cryostats host two concentric electromagnetic wheels, two hadronic wheels and three forward calorimeter wheels.

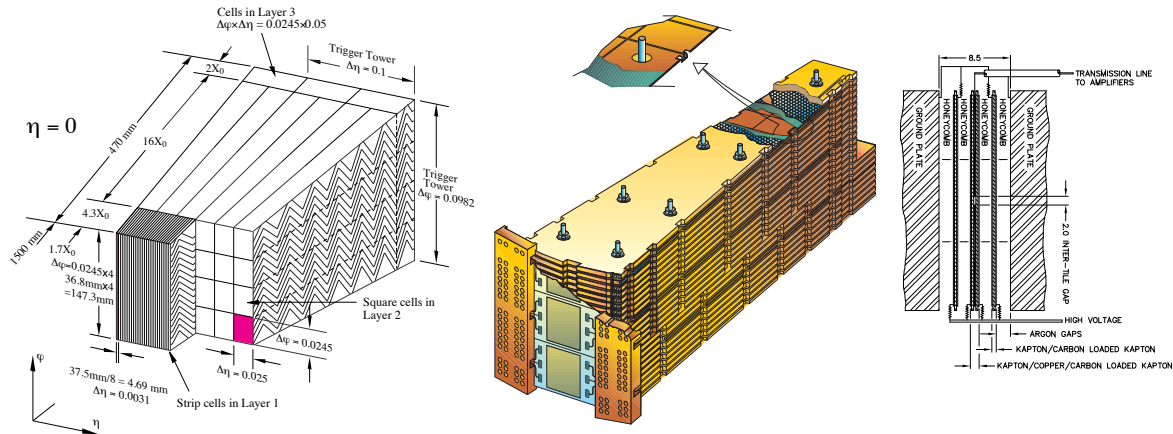
which allow for correction for the upstream material using a layer weighting technique. The requirement for good particle identification, of electrons versus jets, and photons versus  $\pi_0$ , is achieved through a fine granularity of the detector, especially in the first sampling, allowing a fine position and angular resolution ( $50\text{mrad}/\sqrt{E}$ ).

The potentiality that super-symmetric particles may be produced in LHC collisions invites for excellent missing energy determination. Therefore the ATLAS LAr calorimeters have an almost  $4\pi$  acceptance, and sets the energy resolution criteria for the LAr hadronic and forward regions to  $50\%/\sqrt{E}$  for the pseudo rapidity range  $|\eta| < 3$  and  $100\%/\sqrt{E}$  in the pseudo rapidity range  $3 < |\eta| < 4.9$ .

The very fine granularity and longitudinal segmentation of the calorimeter allow through layer weighting technique, when estimating the energy offline, to correct for the non compensating nature of the calorimeter. Finally the LHC 40MHz bunch frequency makes pile-up an important background. To minimize its contribution, and making use of the fast rise time of the ionisation signal, bipolar shaping is applied in the front end electronics.

### 3. The Atlas Liquid Argon Calorimeters

Three large aluminum cryostats host the LAr calorimeters as displayed in Figure 1. The three cryostats are surrounded by a barrel hadronic calorimeter build out of iron absorbers and scintillating tiles as active material, This calorimeter, TileCal, is described in a separate contribution at this conference [1]. The design and construction of the barrel and endcap EM calorimeter is precisely documented in the paper [3], and [4] respectively.



**Figure 2.** On the right side, schematic section of the EM barrel detector, displaying the granularity of the three samplings, in the middle a schematic view of a section of the HEC module. On the left side the signal gap structure in the HEC.

### 3.1. EM calorimeters

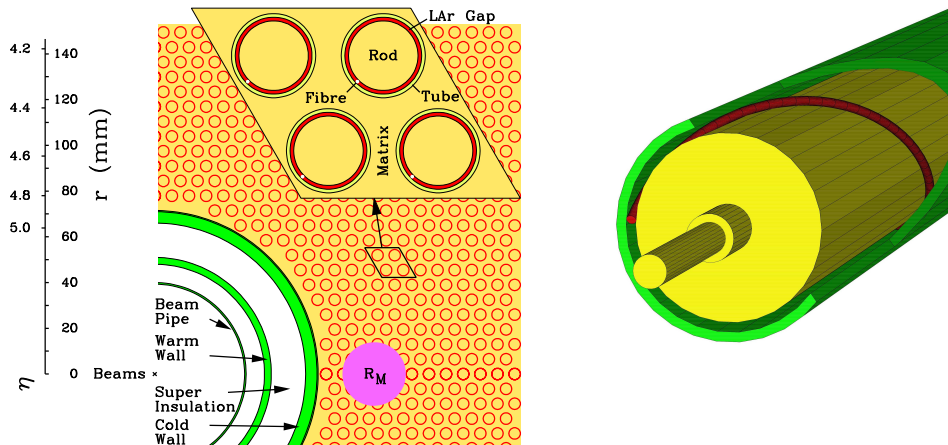
The Barrel EM calorimeter consists of two wheels of 1024 steel clad lead absorbers, interleaved with the same number of electrodes held in place by a 2.1 mm high honey comb structure, which defines the gap size. The electrode itself is build out copper etchings on polyimide, two outer conductive layers distribute the high voltage over the electrode outer surfaces, whereas a central layer, in between the two isolating foils collects the signals through capacitive coupling. When the nominal potential difference of 2000V between the electrodes and the absorbers is applied, the charges induced by ionisation in the argon drift in 450 ns towards the electrodes. The barrel calorimeter extends in pseudo-rapidity to 1.475, for a total thickness of 22  $X_0$ . The readout electrodes are etched with readout pads defining three different sections in depth, and signals from adjacent electrodes are collected together, defining the geometry presented left in figure 2. The EM endcap detector extends the pseudo rapidity coverage from  $1.375 < |\eta| < 3.2$ , and is build similarly to the EM barrel out of accordion shaped absorbers and electrodes, assembled together to form two concentric wheels in each endcap cryostat, build out of 256 absorbers for the inner wheel, and 768 four the outer wheel. The presampling detectors are build by instrumenting a small gap of argon in front of the precision detectors, however the layout of the electrodes in different between barrel and endcap.

### 3.2. Hadronic End cap calorimeters (HEC)

The wheels of the hadronic section are build out of 32 modules. Each of them is a alternation of 25 mm thick copper absorbers (50 mm in the second wheel), and signal collection gaps. Such a gap, as can be seen in figure 2, is subdivided in 4 sub-gap, of 1.8 mm each, by three electrode of same nature as the EM electrodes. Two adjacent sub-gaps act as an electrostatic amplifier, allowing to operate at lower voltage than with a single gap. The signal is collected from the central electrode. The total depth of the hadronic section amounts 10 absorption length.

### 3.3. Forward calorimeters (FCAL)

The forward calorimeter wheels consist of a first copper followed by two tungsten matrices, traversed by cylindrical holes. The holes house the gaps and the electrodes which are build out of signal collecting tubes which in turn contain a copper (respectively tungsten ) rod. The tube and the rod are kept in place by a fiber spiraled around them as illustrated in figure 3, the



**Figure 3.** Left, schematic section of a fraction on the FCAL detector. Right, detail of the assembly of an electrode, with the signal collection tube, and the inserted rod, maintained by the plastic fiber.

fiber diameter defines the gap size of 0.25 mm, 0.375 mm and 0.5 mm respectively for the three wheels.

#### 4. Installation and commissioning in the experimental hall

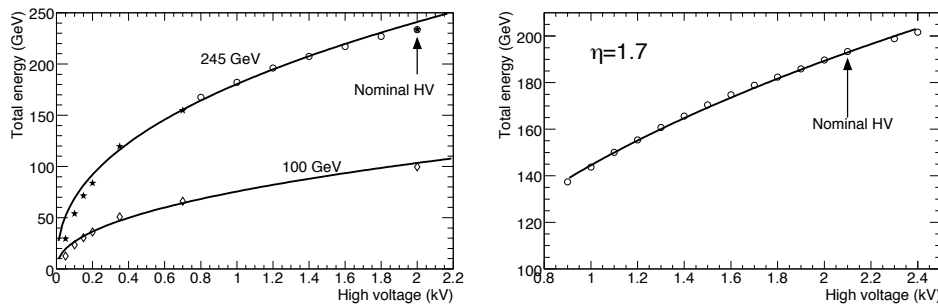
After construction of the detectors and cold testing at the surface, each of the cryostat have been lowered into the ATLAS experimental hall, in October 2004, December 2005 and April 2006 respectively for the barrel cryostat, and for each the two endcap cryostats.

##### 4.1. cryogenics

All three cryostats have been connected to the cryogenic system and cooled down to the operating temperature of 87K. During the cool down, great care was taken to maintaining minimal temperature gradient across the instrument to prevent mechanical tress on the detector. Following its cool down each cryostat was filled with liquid Argon, via condensation of gaseous Argon, this minimizes the turbulences in the Argon bath and the risk to alter the high voltage distribution system. As the signal response is depending on the active medium temperature (2 %/K), the uniformity of the temperature inside the detector volume is important. The temperature of the detector is closely monitored through a large array of precision PT100 sensors, and the dispersion of the temperatures across the detector shows a satisfactory value of order 70 mK, and very stable over time. Also electronegative contamination can affect the quality of the calorimeter response. The contamination is monitored in each cryostat an found to be below 250 ppb in all three cryostats.

##### 4.2. High voltage system

The high voltage system is build out of 157 commercial modules, in the ATLAS counting room, providing individual setting and monitoring of about 4700 channels. On the detector side, redundancy is achieved as different sides of electrodes are powered from different high voltage channels/module. During the commissioning phase, a number of problematic regions in the EMEC and presampler detectors could be cured by injecting a significant charge on the problematic channel. Other techniques have been implemented to address the remaining



**Figure 4.** EM calorimeter response as function of the high voltage setting in test beams. Left for the barrel for 245 GeV electrons (circles), 100 GeV electrons (diamonds), and right for 193 GeV electrons in an endcap module. Start show the results at nominal high voltage, scaled to the corresponding voltage value.

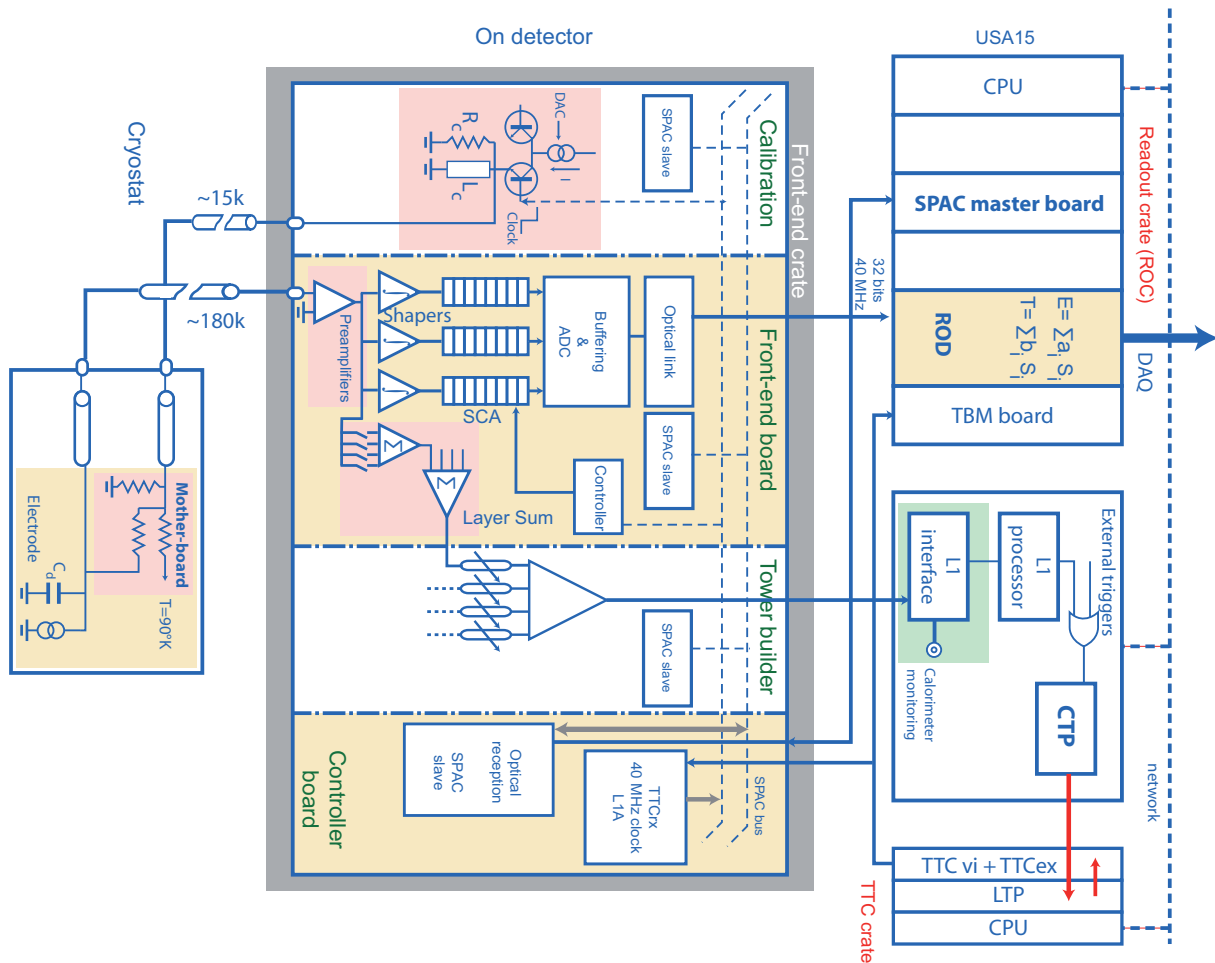
problems like powering individual sectors of an electrode from an individual channel for problems observed during construction. For remaining problematic region, some half gaps are not powered, which results in a signal reduction by a factor 2 that can be corrected for offline at the reconstruction level. Alternatively some half gaps can be powered from dedicated modules, allowing to flow a DC current through a problematic region, but keeping enough constant high voltage to operate the faulty sector, again this can be corrected for. Overall less than 1 % of the sectors are at reduced voltage, and all detector sectors are good for physics. Studies at test beam validate the corrections procedures for non nominal high voltage settings, see figure 4, showing the good agreement of data and the fitted  $E = aV^b$  function.

#### 4.3. Electronics

The LArg electronics, composed of the on detector electronics, so called front end, and off detector electronics, so called back end. It provides precision measurements of the energy in each readout channel for the triggered bunch crossings up to a rate of 75 kHz, and analogue inputs to the first level trigger system proportional with the energy in trigger towers of  $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$ . A schematic description of the system is provided in figure 5.

The radiation hard front end electronics ( $10^{12}$  n/cm<sup>2</sup>/year, 20 Gy/year), has been installed and extensively tested. It is located in 58 crates mounted on the cryostats. It consists of Calibration boards which inject precisely known pulses through high precision resistors onto the detector for EM and HEC, or later in the signal path for FCAL. The signals from the detector are collected on the 1524 Front End boards [6], after amplification and shaping, the signals are summed on one side to prepare the trigger inputs. These signals are further treated and time aligned in dedicated tower builder boards. On the other side after shaping through bipolar filters with 3 gains for each channel in ratios 1/10/100, signals are then stored in an analogue memories. Upon reception of a level 1 accept signal, signals are extracted from the memories, digitized on 12 bits analogue to digital converters and sent to the off detector system for further processing over 1.6 Gbits/s links. For each trigger received up to 32 time samples can digitized on the incoming signals. This is the readout mode used mainly for commissioning noise studies, and recording of cosmic signals, whereas 5 samples is used for physics.

Off detector the calorimeter data are processed in digital signal processors. These provide energy and time estimates through optimal filtering applied to the calorimeter raw signals, using preloaded coefficient determined from earlier electronic calibration runs. This has been demonstrated to operate without noticeable deadtime up to 90 kHz. The data is then further propagated to the ATLAS readout buffering system. The Analogue trigger input signals are



**Figure 5.** Block diagram of the LArg readout electronics, from left to right, the cold electronics, followed by the on detector electronics, and the off detector readout and trigger systems.

received off detector by a system allowing to adjust the gains before entering the Atlas trigger system. This system allows also to route signal from any trigger tower to a dedicated monitoring readout system and oscilloscopes for specific studies.

#### 4.4. Commissioning

From the start of the electronics installation, the system has been used to study the behaviour of the detector, its readout and and calibration system. Typical data being collected are random triggered data, data collected when pulsing the calorimeter, either varying the pulse amplitude, or the phase of the pulse with respect to the system clock. This allows to study respectively the baseline response and the noise, the gain and linearity of the response, and finally the signal shapes for each channel. Carefully analyses allowed to identify and fix problems on the readout electronics, as wheel as to establish the scheme for the electronics calibration during ATLAS operations. From these studies it appears the calorimeter suffers only 0.015 % of isolated dead channels, and the number of calibration lines without signal, requiring dedicated calibration strategies is down to 0.05 %.

Dedicated runs pulsing the calorimeter and recording the trigger data at the monitoring

readout in the trigger receiving system allowed to validate the integrity of the analogue signal path, to establish the gains by comparing the results with the signals obtained from the main readout. Also the relative timing of the trigger signal up to nano second precision has been established. A small number of mis-cablings could be identified and addressed in time.

Specific attention was spent on coherent noise in the calorimeter. The use of both the main and level 1 readout made it possible to identify a number of noise sources and their path into the cryostats. Additional filtering was added to some of the cryogenics services. A modification of the calorimeter grounding scheme at the level of the high voltage filtering system at their feed-through into the cryostat was needed. Also carefully routing and shielding the signal lines inbetween the cryostat feed-throughs and the front end electronics was important. Those actions addressed most of the coherent noise issues. In order to maintain the electrical isolation of the LArg cryostats with respect to other ATLAS systems, key for low noise in the detector, a dedicated system was used injecting a small current to the cryostats and verifying this current returns through the calorimeter ground connection. This system was crucial maintaining adequate grounding over the years of installation and cabling up of the detectors in the experimental hall.

The calorimeter is also tested using the signals induced by atmospheric muons, penetrating the earth and reaching the calorimeters. For this purpose a special trigger logic has been added to the Tile calorimeter electronics, and combined runs involving all of the available calorimeter system has been taken regularly starting from August 2006. Also a number of dedicated periods, aiming at integrating the different ATLAS detectors into a combined system, allowed to test operational strategies, procedures, developing appropriate monitoring. During these periods extensive time is devoted to collect cosmic muon data. Such data allows to validate the electronics calibration procedure, and to test the calorimeter response uniformity. Results from the Calibration runs taken in standalone mode and combined muon runs are presented a separate contribution in these proceedings [8].

## 5. Conclusions

At the time of this conference, the calorimeter installation has just been completed, and access to it is closed. Through careful testing at all stages of the installation of the detector, readout and services made it possible to deliver an instrument in very good condition: More than 99 % of the high voltage channels are at nominal high voltage, and all of the calorimeter is usable for physics. A very small amount of the signal lines, of order 0.015 % do not transmit signals to the readout, and 0.05 % of the calibration lines need refined strategies. A lot of experience has been accumulated over the commissioning period, resulting in available initial electronics calibration, readily tested on muon induced signals. Steadily moving towards a more and more routine operation of the calorimeter, the collaboration eagerly awaits first collisions from LHC later this year and the exciting physics to follow.

## Acknowledgements

The design, construction, and commissioning of the ATLAS liquid argon calorimeter wouldn't have been possible without the excellent contributions of our technicians. We are indebted to their great implication into the construction work. The installation of the ATLAS LArg calorimeter in the cavern was under the responsibility of the ATLAS technical coordination, we are grateful for this very good collaboration.

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