Performance of the ATLAS Liquid Argon Calorimeter after three years of LHC operation and plans for a future upgrade

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ABSTRACT: The ATLAS experiment is designed to study the proton-proton collisions produced at the Large Hadron Collider (LHC) at CERN. Liquid Argon sampling calorimeters are used for all electromagnetic calorimetry covering the pseudorapidity region up to 3.2, as well as for hadronic calorimetry in the range 1.4-4.9. The electromagnetic calorimeters use lead as passive material and are characterized by an accordion geometry that allows a fast and uniform azimuthal response. Copper and tungsten were chosen as passive material for the hadronic calorimetry; whereas a parallel plate geometry was adopted at large polar angles, an innovative one based on cylindrical electrodes with thin argon gaps was designed for the coverage at low angles, where the particles flow is higher. All detectors are housed in three cryostats kept at 88.5 K. After installation in 2004-2006, the calorimeters were extensively commissioned over the three years period prior to first collisions in 2009, using cosmic rays and single LHC beams. Since then, around 27 fb$^{-1}$ of data have been collected at a unprecedented center of mass energies between 7 TeV and 8 TeV. During all these stages, the calorimeter and its electronics have been operating with performances very close to the specification ones. After 2019, the instantaneous luminosity will reach 2-3×10$^{34}$ cm$^{-2}$s$^{-1}$, well above the luminosity for which the calorimeter was designed. In order to preserve its triggering capabilities, the detector will be upgraded with a new fully digital trigger system with a refined granularity. In 2023, the instantaneous luminosity will ultimately reach 5-7×10$^{34}$ cm$^{-2}$s$^{-1}$, requiring a complete replacement of the readout electronics. Moreover, with an increased particle flux, several phenomena (liquid argon boiling, space charge effects...) will affect the performance of the forward calorimeter (FCal). A replacement with a new FCal with smaller LAr gaps or a new calorimeter module are considered. The performance of these new calorimeters is being studied in highest intensity particle beams. This contribution covers all aspects of the first three years of operation. The excellent performance achieved is especially detailed in the context of the discovery...
of the Higgs boson announced in July 2012. The future plans to preserve this performance until the end of the LHC program are also presented.

**KEYWORDS**: Calorimeters; Large detector systems for particle and astroparticle physics; Liquid detectors
1 Introduction

The ATLAS detector [1] is one of two multi-purpose detectors used for taking LHC collision data. After a long commissioning phase, ATLAS started recording data from proton-proton collisions at 7 TeV centre-of-mass energy in 2010. In this year the LHC operated at a modest luminosity with little or no pile-up. In the following two years the instantaneous luminosity delivered by the LHC was substantially increased. For the 2012 run, the centre-of-mass energy was increased to 8 TeV.

1.1 LHC and ATLAS

The amount of integrated luminosity delivered by the LHC, recorded by ATLAS, and considered suitable for physics analyses is shown in figure 1. In proton-proton collisions, ATLAS recorded 45 pb\(^{-1}\) at a centre of mass energy, \(\sqrt{s}\), of 7 TeV in 2010, 5.25 fb\(^{-1}\) at 7 TeV in 2011, and 21.7 fb\(^{-1}\) at 8 TeV in 2012 [2]. In all years the LHC used 50 ns bunch spacing. The high peak luminosity 7.73\(\times\)10\(^{33}\) cm\(^{-2}\) s\(^{-1}\) (with nominal being 10\(^{34}\) cm\(^{-2}\) s\(^{-1}\)) and high pileup environment (figure 2 shows the mean number of interactions per LHC bunch crossing, \(<\mu>\), in 2011 and 2012) creates very challenging environment for the detectors.

Despite these challenging conditions, in July of 2012 ATLAS announced the discovery of the Higgs boson, responsible for giving particles mass within the Standard Model of Particle Physics. The Liquid Argon (LAr) Calorimeter played an essential role in the discovery by providing precise measurements of Higgs final states such as photons, electrons and jets.
1.2 The Liquid Argon Calorimeter design principles

The design for the LAr calorimeter in the ATLAS detector was largely motivated by requirements on searches for the Higgs boson in which the final states contain photons, electrons, jets and missing transverse energy.

To meet the mass resolution required for the Higgs searches the sampling term of the energy resolution is required to be less than 10% for the electromagnetic calorimeter. The constant term, which dominates the calorimeter resolution at high energy, is required to be less than 0.7% for the electromagnetic calorimeter. Measurements performed in test beam studies show that these resolution requirements have been met [1].

The LAr calorimeter, shown in figure 3, is a sampling calorimeter consisting of four subsystems:

- the electromagnetic barrel (EMB) covering a pseudorapidity range of $|\eta| < 1.475$
- the electromagnetic endcap (EMEC), covering a range of $1.375 < |\eta| < 3.2$
- the hadronic endcap (HEC), covering the region of $1.5 < |\eta| < 3.2$
- forward calorimeters (FCal) covering the region $3.1 < |\eta| < 4.9$

The EMB is enclosed in the barrel cryostat, while the endcap cryostats contain the EMEC, HEC and FCal. The EMB and EMEC were constructed using an accordion geometry, with copper and kapton electrodes and lead as the absorbing material. The electrodes are positioned between the absorber plates by honeycomb spacers. This design provides good hermeticity, azimuthal uniformity and fast response. The calorimeter is segmented into three longitudinal layers for $|\eta| < 2.5$ and two coarser-granularity layers for $|\eta| > 2.5$. A finer granularity presampler, covering the range $|\eta| < 1.8$, provides an estimate of the energy loss in front of the calorimeter. The HEC is segmented into four layers constructed in parallel-plate geometry. It has copper absorbers and copper and kapton electrodes. The FCal consists of three modules constructed of electrode rods parallel to the beam pipe, sitting in a metal absorber matrix (figure 3). The LAr gap between the rods and
matrix are smaller than in the rest of the LAr detector in order to endure the high particle fluxes in the forward regions. The first module of the FCal, consisting of a copper matrix, is used for electromagnetic measurements. The two latter modules, consisting of tungsten matrices, are used for hadronic measurements.

1.3 The Liquid Argon Calorimeter readout and calibration

When charged particles in the calorimeter shower cross the liquid argon gaps, they ionize the argon along their tracks. The applied high-voltage separates the electrons and the ions; they drift to the electrodes. During their drift, the electrons induce an electrical signal that is read out.

The resulting ionization current signal has a triangular shape, as shown in figure 4, and a drift time of 450-600 ns in the barrel. Since this drift time spans 18-24 LHC bunch crossings, the signal must be shaped and contracted in order to mitigate the effects of overlapping interactions. The 1524 front-end boards (FEBs), located concentrically around the LAr calorimeter, shape the signal in such a way that the area of the positive and negative lobes of the pulse are summed to zero. The shaping is performed in three different gains in order to meet the large dynamic energy range expected for physics signals. The readout chain is schematically represented in figure 4.

After the signal is shaped, it is transmitted through two paths, an analog path which leads to the Level 1 (LVL1) calorimeter trigger system and a digitizing chain. In the analog path a sum is performed over approximately 60 readout cells creating energy collections called trigger towers. The summed analog pulses are then analyzed by the hardware based LVL1 electronics which takes 2.5 \( \mu s \) to decide whether to retain or discard a particular event.

In the digitizing path, shaped analog signals are stored in a switched capacitor array (SCA) and digitized with 12-bit analog-to-digital converters (ADC). For each triggered event, 5 ADC samples are sent out. The signal amplitude is reconstructed online (in digital signal processors) using an optimal filtering technique [4].
The amplitude $A$ and the time offset $\tau$ are computed by the formulas:

$$A = \sum_{i=0}^{5} a_i (s_i - p)$$

$$A \tau = \sum_{i=0}^{5} b_i (s_i - p)$$

where $a_i$ and $b_i$ are the optimal filtering coefficients, $s_i$ are the ADC samples and $p$ is the pedestal in ADC counts. In addition, a quality factor is computed that measures how well the actual pulse shape matches the reference pulse shape. The optimal filtering coefficients are derived from the predicted pulse shape and the noise auto-correlation. The pulse shape as well as the pedestal and the amplification of the readout chain can be measured using an electronic calibration system. This system injects well-known exponential pulses at the beginning of the readout chain near where the physics pulse is produced. The injection is performed by calibration boards located in the same crates as the FEBs.

The amplitude, $A$, is then used in the calculation of cell energies as shown in equation (1.1):

$$E_{\text{cell}} = F_{\mu A \rightarrow \text{MeV}} \cdot D_{\text{DAC} \rightarrow \mu A} \cdot \frac{M_{\text{calibration}}}{M_{\text{physics}}} \cdot R \cdot A$$

The $F_{\mu A \rightarrow \text{MeV}}$ factor is obtained from test beam and describes the amplitude of the current pulse per one MeV of energy deposited in the detector. The $D_{\text{DAC} \rightarrow \mu A}$ factor represents the amount of current obtained from a calibration board for a given DAC setting. The $M_{\text{calibration}}/M_{\text{physics}}$ is a factor applied to compensate the difference in shapes between calibration and physics pulses. This difference would otherwise introduce biases in the energy reconstruction. The factor is calculated by comparing the maximum amplitudes of the calibration and physics pulses. The $R$ factor quantifies the gain of each cell and is obtained from Ramp calibration runs in which the timing of the pulses is kept constant and the amplitude is varied.

2 The Liquid Argon Calorimeter performance

The performance of the calorimeter and quality of the results crucially depend on a proper monitoring of both hardware and data quality.
2.1 The Cryogenic and HV systems

During operation the liquid argon temperature and purity are continuously monitored in order to ensure accurate energy measurements. A change in temperature of the order of 1 K induces a 2% change in the energy measurement due to the changes in the drift time and the liquid argon density. For this reason there are 508 PT100 probes in the LAr calorimeter to monitor the temperature which remains at approximately 88.5 K. The temperature uniformity between different probes is of the order of 50-60 mK (see figure 5), well below the design requirement of <100 mK. Impurities within the liquid argon, such as $O_2$ can also degrade the signal. For this reason 30 purity monitors, immersed in the liquid argon, are read out every 10 to 15 minutes. The measured impurities are approximately 140-200 ppb (figure 5), well below the design specification of <1000 ppb.

2.2 Operational performance

The electromagnetic part of the Liquid Argon Calorimeter has a total of 173312 channels of which 76 (0.04%) cannot be read out because of technical defects either inside the cryostat or in the read-out electronics. For the HEC the number of non-operational channels is 22 out of 5632 (0.39%), for the FCal it’s 8 out of 3524 (0.23%). In total 0.06% of all Liquid Argon Calorimeter readout channels are unusable.

Even though, there were no substantial problems with the detector systems, or cryogenics over the whole period, there were a few intermittent problems, which were taken into account in Monte Carlo for data analysis:

- 2010: Thirty FEBs lost optical connection to the data acquisition system (broken optical transmitters), which was around 5% acceptance loss. Broken and suspicious transmitters were replaced during 2010/2011 winter stop. There have been no problems since then;

- 2011: Six FEBs and one calibration board in the EM barrel lost trigger, clock and control signals due to a burnt fuse on controller board. The most important FEBs (layer 2) were fixed within few weeks, the rest were repaired six month later during winter shutdown;

![Figure 5. Liquid argon temperature stability (left) and purity evolution (right).](image)
Figure 6. Example of a typical coherent noise event observed in the EMECA partition in run 205071 - CosmicCalo stream (left) and the $Y_{3\sigma}$, percentage of channels with signal above $3\sigma$ of electronic noise measured in CosmicCalo stream (right) [5].

- 2012: A leak has developed in part of FEBs cooling system. As a consequence, 4 FEBs were turned off in endcap. Coverage loss was 4.5% of the hadronic and 1.2% of the electromagnetic channels. The problem was fixed after couple of weeks (therefore was not included in MC). There have been no more problem seen since then;

- 2013: Water leak from Tile Cs calibration system stopped one HEC LV power supply, recovered, Cs calibration system is under review now.

2.3 Data quality and physics measurements

During the LHC’s three years of operation the percentage of LAr data considered good quality for physics analyses increased, despite the increase in instantaneous luminosity that can lead to more challenging operating conditions. In 2012 proton-proton collisions, more than 99% of data were suitable for physics, compared with 97% in 2011 and 90% in 2010. The improved efficiency is attributed to the improved treatment of high-voltage (HV) trips and noise bursts which were responsible for data losses (in 2012) of 0.46% and 0.2%, respectively.

To deal with the HV trips, most of the channels were run in "auto-recovery" mode, bringing the operational HV back after the trip automatically, with HV values stored in conditions DB, from which offline corrections are computed and applied during reconstruction. Some adjustment of operational voltage (lowering) was done for frequently tripping channels (energy also corrected offline) and more robust HV modules (Current Control mode instead of trip) have been deployed in the critical regions.

When operated with beam, the ATLAS Liquid Argon Calorimeter experiences occasional large bursts of coherent noise. These bursts are usually very short, 90% are less than 5 $\mu$s long, with many channels exhibiting noise well above standard level; an example of such burst measured in bunch crossing without LHC collisions is shown in figure 6 (left). Using the shape quality factor rejects the core events (those with at minimum 30 channels on at least 5 FEBs with bad quality)
Figure 7. Mean FEB timing in individual subdetectors (left) and single cell timing resolution (right) after per-channel offline timing corrections [6].

Figure 8. Time (left) and pile-up (right) stability of EM energy reconstruction [7].

affected by the noise bursts and using the time veto on events around identified core noise events (in 2012 a conservative 250 ms window was used) allowed good rejection with low inefficiency, as shown in the right plot of figure 6. The amount of luminosity lost by time veto was around 0.2% during 2012 data taking.

Stable and precise timing is needed to measure out-of-time signals, in order to suppress cosmic-ray and beam-induced backgrounds. The individual FEBs were aligned and stability of timing throughout 2012 is shown on left plot of figure 7. The timing dispersion measured online between FEBs has $\sigma \sim 0.10 - 0.17$ ns. The offline channel-level corrections, calculated from $W\rightarrow e\nu$ events brings overall timing resolution to $\sim 300$ ps (right plot on figure 7) for large energy deposits, which includes $\sim 220$ ps correlated contribution from the beam spread.

The calibration and stability of the energy measurements in the LAr calorimeter are monitored by measuring properties of well-known physics events. One example is the ratio of the electron
energy in the calorimeter and momentum of the electron tracks in the inner detector for $W \rightarrow e\nu$ events. Another example is the invariant mass of the electrons in $Z \rightarrow ee$ events which is expected to peak at 91.18 GeV. In order to compare these two measurements, the data points of each measurement are normalized to their mean values. The resulting values are shown in figure 8 as a function of the date (left plot) and average number of interactions per bunch crossings (right). This figure shows that the normalized, or relative energy scale, is stable on the per-mil level.

3 The Liquid Argon Calorimeter upgrade

In 2012, the LHC was already running at close to design luminosity. In the upcoming run (also called Run-2) there are plans to exceed it. After three years of operations, the second shutdown (LS-2) is scheduled, after which there is a plan to achieve luminosity $\sim 3 \times 10^{34}\text{cm}^{-2}\text{s}^{-1}$ (in so called Run-3). The ambitious plan of a High Luminosity LHC (HL-LHC), which should start in 2025 or later, with luminosity up to $5 \times 10^{34}\text{cm}^{-2}\text{s}^{-1}$ is already proposed.

The Liquid Argon detector was not designed to run at such luminosities and some components can / may not survive the absorbed dose corresponding to planned integrated luminosity of $\sim 3000\text{fb}^{-1}$. Therefore, upgrade plans are being prepared, accordingly grouped in 3 phases (0-2). Phase-0, which is currently ongoing, consists mainly of consolidation of the electronics and installation of demonstrator hardware for the Run-2.

The Phase-1 upgrade should cope with increasing trigger rates, with the LVL1 rate limited to 100 kHz. The current EM trigger selection would yield a rate of 270 kHz in Run-3 luminosity and pile-up conditions. We need to reduce it to 20 kHz, in order to meet the global rate limit, without important acceptance and efficiency loss.

Phase-2 changes should address issues with performance of the readout electronics, possible problems with HEC GaAs cold electronics and the issues for the FCal, where ion buildup affects the electric field in the gap, where higher currents cause significant voltage drop across resistors inside the cryostat and the high ionization load leads to heating of the modules which could potentially boil the LAr.

3.1 Phase-1 upgrades

To maintain the performance at the luminosity levels expected after the Phase-I upgrade, the present granularity provided to the trigger system is not sufficient to identify EM objects accurately in the presence of increased QCD background [8].

To improve the trigger resolution, the readout channels will be grouped into so-called Super-Cells which allow finer granularity in $\eta \times \phi$ space and in layer depth than the currently used trigger towers. The presampler and the outermost layers will stay with the previous granularity of $\eta \times \phi = 0.1 \times 0.1$, whilst the first and second EM layers will have 4 times finer granularity resulting in $\eta \times \phi = 0.025 \times 0.1$ Super-Cell sizes.

The analog pulses from the Super-Cells will be sent from the front-end electronics to a new LAr Trigger Digitizer Board (LTDB). The LTDB will contain new ADC chips, which should have very low power consumption and should be radiation hard with 40MHz speed and 12 bits range. Two such ADC chips (one commercial, one custom design) are currently under tests. The LTDB is designed for digital precision of 32 MeV in Front and 125 MeV in Middle layers of the EM
calorimeter. The LTDB then sends the signal to the LAr Digital Processing System (LDPS), with a speed of $\sim 25$ Tbps, which is responsible for reconstruction of Super-Cell transverse energy and peaking time. The energy and peaking time values will then be sent ($\sim 41$ Tbps) to the LVL1 Calorimeter trigger.

With the increase of the luminosity expected for the next phases of the LHC operation, the levels of pile-up may reach the limits when it cannot be handled by the Optimal Filter technique [4]. New signal processing techniques might be necessary to keep the optimal performance of the detector. One of the first tested implementations is the Wiener Filter. For the application to energy reconstruction, the Wiener Filter is trained to produce an output sample proportional to the amplitude of the signal. For detecting the presence of the signal, the filter is trained to produce the following sample to the peak one to be at half the peak value. This filter is intrinsically pile-up robust and bunch train independent. In figure 9 the signal detection efficiency is compared with three different Optimal Filters techniques [8].

Using higher granularity in trigger should maintain or even increase efficiency, whilst the reduced transverse energy ($E_T$) thresholds will increase the acceptance for measuring Higgs properties and looking for new physics including SUSY and extra dimensions. Using some shower shape variables (like $R_\eta$, which is calculated by taking the ratio of the core of the energy deposit, to the total energy deposit in the middle layer of the calorimeter) will allow better discrimination of electrons and jets and keep $E_T$ thresholds low (28 GeV), as shown in figure 10. Applying rejection criteria similar to those used offline will allow rejection of backgrounds from QCD jets. An example of this is shown in figure 11 for hadronic $\tau$ decays.

### 3.2 Phase-2 upgrades

For the Phase-2 upgrades, front-end and back-end electronics will be replaced in order to cope with higher radiation levels and to upgrade the trigger system. New FEBs will be installed to provide analog to digital conversion of all signals at a rate of 40 MHz, multiplex and serialize the digital data and transmit them to the back-end electronics via high-speed optical links for final energy processing.
reconstruction. The back-end electronics will have to be modified in order to receive digitized data from the new FEBs. This change from the analog signal readout design, to one where all the calorimeter cells are digitized at 40 MHz will drastically improve LVL1 bandwidth and latency [9].

The LVL1 trigger developed for Phase-1 becomes a LVL0 trigger in Phase-2.

Ongoing studies [10] will determine whether the HEC electronics will require replacement due to radiation damage. This replacement would require opening the cryostats since the HEC electronics are located inside the cryostats. Figure 12 shows changes in the signal from the same energy deposit in the typical cell from a degraded HEC preamplifier (expected HL-LHC dose is slightly higher than one measured in green). The most worrying issue is non-linearity in the preamplifiers, because 4 preamplifiers are summed and calibrated together. Effects, caused by such degradation, on physics signals are currently under study.

Another main concern is the degradation in FCal performance due to increasing heat and space charge effects caused by higher particle flux and ionization. The heat production could (in the worst case) boil the liquid argon, and because precise calculations of heat convection in the complicated geometry between FCal and HEC are not available, a special mock-up will be built, to allow measurements of the heat flow that can be used to validate simulations. In addition, the FCal HV protection resistors are large and will produce big voltage drops at the high currents that will be present at higher luminosities. The two plans currently being explored to remedy these problems. The first plan involves replacing the FCal by a new detector (sFCal) with smaller LAr gaps, lower value HV resistors and adding a cooling loops. The second plan consists of placing a complementary calorimeter, referred to as the Mini-FCal, in front of the existing FCal [9]. The choice will also depend on whether opening the endcap cryostats will be needed for HEC electronics replacement.

A small prototype of the first layer of the planned FCal replacement, with smaller LAr gaps,
was tested [11] and on figure 13 the stability of the signal is shown as a function of proton beam intensity, up to values exceeding those expected at the HL-LHC. The other option would be a small calorimeter in front of the high-η part of the existing FCal, in order to absorb some of the energy in this region of very high particle flux. Various possibilities were studied, like warm option with either diamond sensor or with Cu absorber and high-pressure Xenon gas (which would require basic R&D on gas properties up to 10 bar). The currently favoured solution is a cold option, with Cu absorber and liquid argon as active medium, with FCal-like design and small LAr gaps as proposed for the sFCal.

4 Summary

The ATLAS LAr Calorimeter has achieved excellent performance and stability during the first three years of LHC operations, without significant hardware or software problems. The LAr working group was constantly improving the hardware, monitoring and data quality procedures, which results in an excellent achievement that over 99% of the data collected by the LAr calorimeter are considered as a good quality for physics analyses in 2012. The calorimeter calibration was stable as a function of time and average number of interactions per bunch crossing.

There is ongoing consolidation work on the FEBs, low voltage power supplies that power the FEBs and online software to prepare the calorimeter for running in 2015.

An upgrade of the trigger read-out of the LAr calorimeters will allow very good performance for identification of interesting physics objects to be maintained, while efficiently suppressing backgrounds. A prototype of new trigger read-out is explored in laboratory now, and will be installed this year on ATLAS to demonstrate the functionality of the system with a small part of the detector already by the 2015 data taking period.

Phase-2 upgrade plans for the 2023 upgrade, which will require replacement of front-end electronics, possible replacement of HEC cold electronics and a solution to degradation of the
FCal performance, are intensively studied and a road map to take decisions and to prepare more detailed plans is already set.

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References

[1] ATLAS collaboration, The ATLAS Experiment at the CERN Large Hadron Collider, 2008 JINST 3 S08003.

[2] https://twiki.cern.ch/twiki/bin/view/AtlasPublic/LuminosityPublicResults.

[3] ATLAS collaboration, The Readiness of the ATLAS Liquid Argon Calorimeter for LHC Collisions, Eur. Physics J. C70 (2010) 723 [arXiv:0912.2642].

[4] W.E. Cleland, E.G. Stern, Signal Processing considerations for liquid ionization calorimeters in a high rate environment, Nucl. Instrum. Meth. A 338 (1994) 467.

[5] The ATLAS collaboration, Monitoring and data quality assessment of the ATLAS liquid argon calorimeter, CERN-PH-EP-2014-045, submitted to JINST [arXiv:1405.3768].

[6] https://twiki.cern.ch/twiki/bin/view/AtlasPublic/LArCaloPublicResults2010.

[7] ATLAS collaboration, Electron energy response stability with time in 2012 data with 13 fb⁻¹, https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/EGAMMA/PublicPlots/20121106/ATL-COM-PHYS-2012-1593/index.html, ATL-COM-PHYS-2012-1593;

ATLAS collaboration, Electron energy response stability with pile-up in 2012 data, https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/EGAMMA/PublicPlots/20120611/StabilityPlots/ATL-COM-PHYS-2012-782/index.html, ATL-COM-PHYS-2012-782.

[8] ATLAS collaboration. ATLAS Liquid Argon Calorimeter Phase-I Upgrade Technical Design Report, CERN-LHCC-2013-017.

[9] ATLAS collaboration. Letter of Intent for the Phase-II Upgrade of the ATLAS Experiment, CERN-LHCC-2012-022.

[10] F Adamov et al., Upgrade plans for the Forward and Hadronic-Endcap Calorimeter of ATLAS for the high luminosity stage of the LHC, ATL-COM-LARG-2013-002.

[11] Hilum ATLAS Liquid Argon Endcap Collaboration, Liquid argon calorimeter performance at high rates, Nucl. Instrum. Meth. A 669 (2012) 47.