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 a multi-purpose detector built for analyzing LHC collision data. In July 2012, ATLAS announced the discovery of the Higgs boson, the last undiscovered particle in the Standard Model of Particle Physics. The ATLAS Liquid Argon (LAr) Calorimeter played a crucial role in the discovery by providing accurate measurements of Higgs final state objects such as photons, electrons and jets. The LAr detector is a sampling calorimeter consisting of four subsystems: an electromagnetic barrel, electromagnetic endcaps, hadronic endcaps, and forward calorimeters. The purity and temperature of the liquid argon remained well above the required levels throughout the data-taking period. Overall the calorimeter performed very well, with over 99% of data it collected in 2012 proton-proton collisions being suitable for physics analyses. In order to ensure good LAr detector performance at future higher luminosity LHC operation, several upgrades are being planned and implemented.

KEYWORDS: Noble liquid detectors (scintillation, ionization, double-phase); Calorimeter methods; Ionization and excitation processes

1On behalf of the ATLAS Liquid Argon Calorimeter Group.
1 Introduction

The Large Hadron Collider (LHC) is a proton-proton collider located on the Swiss-French border near Geneva. The ATLAS detector [1] is one of two multi-purpose detectors used for taking LHC collision data. 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. The high particle multiplicities at unprecedented energies provided a challenging environment for ATLAS. Figure 2 shows the mean number of interactions per LHC bunch crossing, \(\langle \mu \rangle\), in 2011 and 2012. 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) calorimeters [2] played an essential role in the discovery by providing precise measurements of Higgs final states such as photons, electrons and jets.
2 Design requirements of the Liquid Argon Calorimeter

The design for the LAr calorimeter in ATLAS was largely motivated by requirements on searches for the Higgs boson in which the final states contain photons, electrons, jets and missing transverse energy. These particles must be accurately identified, necessitating fine lateral and longitudinal segmentation in the calorimeter.

The energy resolution of the calorimeter is described in equation (2.1):

$$\frac{\sigma_E}{E} = a\sqrt{E} \oplus b\frac{E}{E} \oplus c$$

Here $a$ is the coefficient of the sampling term, representing the statistical shower development, $b$ is the noise term, and $c$ is the constant term. To meet the mass resolution required for the Higgs searches the sampling term is required to be 10% for the electromagnetic calorimeter, 50% for the hadronic calorimeter and 100% for the forward calorimeters. The constant term, which dominates the calorimeter resolution at high energy, is required to be 0.7% for the electromagnetic calorimeter, 3% for the hadronic calorimeter, and 10% for the forward calorimeters. Measurements performed in test beam studies show that these resolution requirements have been met [1].

The position of particles in the angular direction is required to be resolved within $50\,\text{mrad}/\sqrt{E}$ to allow for precise vertex identification. The LAr calorimeter must also have a fast shaping time and minimal dead time needed to cope with the 40 MHz bunch crossing rate at the LHC. Minimal coherent noise (<5% of the incoherent noise) and a linearity of 0.1% is required. Finally, the calorimeter must be capable of sustaining high radiation doses. In order to satisfy the linearity, stability and radiation hardness requirements, liquid argon was chosen as the active material.

3 The Liquid Argon Calorimeter design

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 electromag-
The liquid argon subsystems: the hadronic endcap, the electromagnetic endcaps and barrels with their accordion geometry design, and the forward calorimeter with its rod matrix geometry [4].

The EMB (Electromagnetic Barrel) 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 allows for 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 matrix absorber (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.

4 The Liquid Argon Calorimeter readout chain and energy reconstruction

The high voltage system generates an electric field across the liquid argon gap, between the absorbers and readout electrodes. Figure 4 shows the layout of the electrodes and absorbers in the barrel. When a charged particle crosses the liquid argon gap, it ionizes the argon along its track, and the applied electric field collects the freed argon electrons onto the electrodes. The resulting ionization signal has a triangular shape, as shown in figure 5, and a drift time of $\sim 450$–$600$ 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 such that the summed area of the positive and negative lobes of the pulse shape is 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 5.

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 digitized path. 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 take $2 \mu s$ to decide whether to retain or discard a particular event.

In the digitized path, shaped analog signals are stored in a switched capacitor array (SCA) and digitized in five samples once the decision from the LVL1 trigger arrives indicating an event should be retained. The five samples are then sent via optical transmitters to back end electronics located in a room beside the detector. The backend electronics consist of digital signal processing chips which compute the peak time and quality factor of the pulse shapes and energy of cells. The quality factor quantifies how well the pulse shape obtained matches the expected pulse shape from a physics signal. The energy is obtained from the amplitude of the pulse shape, $A$, which is shown in equation (4.1).

$$A = \sum_{j=1}^{5} a_j (s_j - p) \tag{4.1}$$

Using the amplitude, the timing offset, $\tau$, is computed as shown in equation (4.2).

$$A\tau = \sum_{j=1}^{5} b_j (s_j - p) \tag{4.2}$$

The factors in equations (4.1) and (4.2) are obtained from electronics calibrations carried out by injecting 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 $a_j$ and $b_j$ factors are Optimal Filter Coefficients (OFCs) derived from the pulse shape and the noise autocorrelation [4]. They are obtained from Delay calibration runs in which the amplitude of the pulses is kept fixed but the timing of injection is varied. The pedestal, $p$, is an electronics baseline describing the mean value of the signal per cell in the absence of an energy deposit. It is calculated from Pedestal calibration runs, in which there is no signal injected into the detector and the amount of noise is measured.

The amplitude, $A$, is then used in the calculation of cell energies as shown in equation (4.3).

$$E_{cell} = F_{\mu A \rightarrow \text{MeV}} \cdot D_{\text{DAC} \rightarrow \mu A} \cdot \frac{M_{\text{calibration}}}{M_{\text{physics}}} \cdot R \cdot A \quad (4.3)$$

The $F_{\mu A \rightarrow \text{MeV}}$ factor is obtained from test beam and describes the amplitude of the current pulse obtained per MeV of deposited energy 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 for 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.

### 5 The Liquid Argon Calorimeter performance

#### 5.1 Liquid Argon monitoring

During operation the liquid argon temperature and purity are constantly monitored in order to ensure accurate energy measurements. A change in temperature on 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 on the order of 50–60 mK, 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, well below the design specification of $< 1000$ ppb.

#### 5.2 Operational performance

During its operation the LAr calorimeter performed exceptionally and contributed only negligibly to ATLAS offline efficiency losses. There were some minor hardware problems which typically persisted for several weeks. In 2010, 30 FEBs lost connection to the data acquisition system due to broken optical transmitters. This resulted in a small acceptance loss. The broken and suspicious transmitters were replaced in 2010 and 2011 and have functioned properly since then. In 2011, 6 FEBs and a calibration board in the EMB lost their connection due to a burnt fuse on one of the electronics boards. After the replacement of the burnt fuse such problems did not reappear. Finally in November of 2012, a leak in part of the front end cooling developed. The result was the shutdown of 4 FEBs, affecting 4.5% of the HEC channels and 1.2% of the EMEC channels. The leak was attributed to a loose connector which was fixed a few weeks later. The loss of acceptance due to each problem was simulated in the Monte Carlo.
5.3 Data quality

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 was 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.

5.3.1 High-voltage trips

The power supplies providing high voltage to the detector electrodes trip when too much current is drawn. Most modules ramp the voltage back up automatically. During the ramping stage the data are recoverable after HV energy scale corrections are applied offline [7]. The only data lost are those taken between the near-instantaneous voltage drops and the start of the ramp. In order to minimize the losses, sensitive channels that trip regularly usually have their voltages lowered by a few hundred volts from their nominal operating point (1 kV–2 kV). In order to decrease the rate of HV trips in sensitive detector areas more robust HV power supplies were installed at the beginning of 2012. These modules are able to switch to current controlled mode and tolerate short current spikes without tripping. Figure 6 shows the percentage of luminosity lost due to HV trips as a function of the integrated luminosity in 2012. The drastic decrease in data lost after the first data point is a result of the new module installation. The smaller increase near 12 fb$^{-1}$, in figure 6, is attributed to the hardware failure of a module which caused six HV trips in one LHC data taking period. Following replacement of the problematic module, the rate of HV trips returned to its baseline value. Higher rates of HV trips are correlated with large increases in instantaneous luminosity. Based on this observed behavior, when running resumes in 2015, the rate of HV trips is expected to stabilize after the initial increase in luminosity at the beginning of the data taking period.

5.3.2 Noise bursts

Noise bursts occur when a large fraction of cells in a partition of the calorimeter are simultaneously affected by noise. They are observed only during collisions and usually last less than 5 µs. An example of such an event is shown in figure 7 in the EMEC. Noise bursts are suspected to be induced by the unshielded HV cables inside the cryostat. They are identified by using the quality factor, which distinguishes between pulse shapes from physics events and distorted ones due to noise. Events that lie within a conservative 250 ms time window around the burst are vetoed. The frequency of noise bursts increases with the instantaneous luminosity, but their length remains constant. Although more bursts are expected after the shutdown in 2015, the conservative time window used for the event veto can be shortened to reduce data loss.

5.4 Calibration with physics measurements

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 from the electron tracks in the inner detector in $W \rightarrow e\nu$ events.
Figure 6. The percentage of luminosity lost due to high-voltage trips, as a function of the integrated luminosity [7].

Figure 7. An example of an event affected by a noise bursts during empty LHC bunch in the EMEC [6].

Figure 8. The relative energy scale measured in $W \rightarrow e\nu$ and $Z \rightarrow ee$ events as a function of average interactions per bunch crossing on the left, and date on the right [8].

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 average number of interactions per bunch crossings and date. This figure shows that the normalized, or relative energy scale, is stable on the per-mil level.

6 Plans and upgrades

During the 2010–2012 data taking period, the LHC operated at a luminosity up to $7 \times 10^{33} \text{ cm}^{-1}\text{s}^{-1}$ at $\sqrt{s} = 7–8$ TeV. In the future the LHC will operate at higher luminosities and energies, presenting new challenges for ATLAS, such as higher radiation levels, trigger rates and particle multiplicities. During the 2013–2014 long shutdown the LHC is being commissioned to operate at its nominal design luminosity of $10^{34} \text{ cm}^{-1}\text{s}^{-1}$ and energy $\sqrt{s} = 13–14$ TeV in 2015. After operating for a three year period at this luminosity and energy, the LHC, and the experiments, will be upgraded in two phases. The first, Phase-1, refers to the 2018 upgrade needed to prepare for operating at
a luminosity of $2 \sim 3 \times 10^{34} \text{cm}^{-1}\text{s}^{-1}$ and $\sqrt{s} = 13\sim 14\text{TeV}$. The second, Phase-2, refers to the 2022 upgrade period needed to prepare for operating at a luminosity of $5 \sim 7 \times 10^{34} \text{cm}^{-1}\text{s}^{-1}$ and $\sqrt{s} = 14\text{TeV}$.

During the 2013–2014 shutdown, the LAr calorimeter has been kept in operation with the HV off and regular calibrations with HV at 100V performed to check the status of the system. During this time 10–20 FEBs are being extracted, repaired and reinstalled. The low voltage power supplies, that provide power to the FEBs, were replaced due problems with burnt out capacitors. There are also ongoing improvements in online software to prepare the detector for running at the re-start of the LHC in 2015.

### 6.1 Phase-1 upgrades

Phase-1 upgrades involve the implementation of finer granularity readout at the trigger level, which is needed to cope with the increasing instantaneous luminosity [9]. The finer granularity cells, called super cells, have the added advantage that they preserve layer information in the calorimeter. This is not the case with the current trigger tower energy calculation. The analog pulses from super cells will be sent from the front end electronics to a new LAr Trigger Digitizer Board (LTDB). The LTDB contains new ADC chips chosen for their low power consumption and radiation hardness. The 12 bit ADCs digitize the signals at a sampling frequency of 40 MHz. The LTDB then sends the signal to the LAr Digital Processing System (LDPS) which is responsible for reconstruction of super cell transverse energy and peaking time. The energy and peaking time will then be sent to the LVL1 Calorimeter trigger which decides which events to retain [9].

Super cells enable the possibility for online reconstruction algorithms at level 1 trigger to calculate variables that can be used to discriminate between electrons and jets. This allows for more efficient online rejection of dominant backgrounds such as QCD jets. One example of such a discriminating variable is $R_\eta$, 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 [9]. This distribution is very different for electrons and jets, as demonstrated by figure 9, which shows $R_\eta$ from simulation for a future data taking period at a luminosity of $3 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$, $\sqrt{s} = 14\text{TeV}$ and $\langle \mu \rangle = 80$. Other variables used for discrimination between electrons and jets are $w_{\eta,2}$, which characterizes the shower shape of the energy deposit in the middle layer, and $f_3$, which represents the ratio of the energy deposited in the back layer of the calorimeter to the total energy of a cluster [9]. Figure 10 shows LVL1 trigger rates as a function of the transverse energy from a Monte Carlo simulation assuming a luminosity of $3 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$, $\sqrt{s} = 14\text{TeV}$ and $\langle \mu \rangle = 80$. The blue line shows the expected rates if no discriminating variables are cut on. The black and green lines show that the trigger rates drastically decrease when such variables are utilized for online energy reconstruction. This figure demonstrates that in order to meet the LVL1 bandwidth of 20 kHz, the electron trigger thresholds are at approximately 25 GeV when the discriminating variables are applied, and over 35 GeV when they are not.

### 6.2 Phase-2 upgrades

For the Phase-2 upgrades, front end and backend electronics will be replaced in order to cope with higher radiation levels and to upgrade the trigger system. New FEBs will be installed that
provide analog-to digital conversion of all signals at a rate of 40 MHz, multiplex and serialize the
digital data, and transmit it to the backend electronics via high-speed optical links for final energy
reconstruction. The backend electronics will have to be modified in order to receive digitized
data from the new FEBs. The change from the analog signal readout design, to one where the
calorimeter cells are digitized at 40 MHz means that LVL1 bandwidth and latency become almost
unlimited [10].

Ongoing studies will determine whether the HEC electronics will require replacement due to
radiation damage. This replacement will require opening the cryostats since, unlike in the EMB,
EMEC and FCal, the HEC electronics are located inside the cryostats.

Another main concern is the degradation in FCal performance due to increasing heat and
space charge effects caused by higher particle flux and ionization. In addition to this, the FCal HV
protection resistors are large and will produce large voltage drops at the high currents that will be
present at higher luminosities. The two plans currently being explored to remedy these problems
involve replacing the FCal by a new detector with smaller LAr gaps, or placing a complementary
calorimeter, referred to as the Mini-FCal, in front of the existing FCal [10]. This choice will also
depend on whether opening the endcap cryostats will be needed for HEC electronics replacement.

Three designs for the Mini-FCal have been considered. The first design involves diamond
sensors grown on ceramic plates, and placed between 12 circular, copper, absorber plates. Although
the diamond sensors are expected to work at the high particle fluxes expected, radiation can degrade
their signal amplitude down to 5% of its initial value. Another disadvantage to this design is that
diamond sensors are expensive to grow and the manufacturer of the prototype sensors has gone out
of business. The second option for the Mini-FCal is a copper parallel plate colorimeter using xenon
at high pressure (up to 10 bar) as the active medium. Xenon gas was chosen due to its high density
and specific ionization. Research on xenon properties, such as the electron-ion recombination rate,
must be conducted for the pressure range and electric fields needed for the Mini-FCal. A third

Figure 9. The simulated $R_\eta$ distribution for electrons in black and jets in red for luminosity of
$3 \times 10^{34}$ cm$^{-2}$s$^{-1}$ [9].

Figure 10. The simulated expected LVL1 trigger rates with and without discriminating variables for luminos-
ity of $3 \times 10^{34}$ cm$^{-2}$s$^{-1}$ [9].
design option under consideration is a LAr Mini-FCal, with the same electrode structure used in the FCal and smaller LAr gaps between the electrodes. However unlike the previous two design options, a LAr Mini-FCal must be placed inside a cryostat and this introduces additional material upstream of the detector which may degrade its performance.

7 Summary

The LAr calorimeter performed excellently during the three years of LHC operation. The conditions of the liquid argon remained stable throughout operation, and very few hardware problems were encountered. As a result, over 99% of the data the LAr calorimeter collected was considered good quality for physics analyses in 2012. The high efficiency in 2012 is attributed to efficient treatment of the main sources of data loss: HV trips and noise bursts. The calorimeter calibration was stable as a function of time and average number of interactions per bunch crossing as demonstrated by energy over ID momentum measurements in \( W \rightarrow e^+ e^- \) events, and invariant mass measurements in \( Z \rightarrow e^+ e^- \) events. 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. Phase-1 upgrade plans for the 2018 LHC upgrade period involve the implementation of finer granularity readout at the trigger level needed for lower trigger rates at the higher luminosity LHC operation. Phase-2 upgrade plans for the 2022 upgrade will require replacement of front end electronics, possible replacement of HEC cold electronics and a solution to degradation of the FCal performance.

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