Status of the ATLAS Liquid Argon Calorimeter; Performance after 2 years of LHC operation

Hass AbouZeid on behalf of the ATLAS Collaboration
Department of Physics, University of Toronto, 60 St. George St., Toronto, Ontario, M5S 1A7, Canada
E-mail: ossama.abouzeid@cern.ch

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 pseudo-rapidity 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 without any gap. Copper and tungsten were chosen as passive material for the hadronic calorimetry; whereas a classic 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 particle flow is higher. All detectors are housed in three cryostats kept at about 88 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 9 fb$^{-1}$ (as of June, 2012) of data have been collected at a center of mass energy of 7 and 8 TeV. During all these stages, the calorimeter and its electronics have been operating almost optimally, with performances very close to the specifications.

Figure 1. Delivered and recorded luminosity for 2011 proton-proton run [3].

Figure 2. Delivered and recorded luminosity for 2012 proton-proton run (as of June 4th) [3].
1. Introduction
The ATLAS [1] Liquid Argon (LAr) calorimeters [2] have been installed and fully operational since the cosmic-ray data-taking in 2006. Since then, with the first LHC collisions coming in 2009, the Liquid Argon calorimeters have collected over 9 fb$^{-1}$ of proton-proton collision data as of June 4th, 2012 (see figures 1,2) [3]. Throughout this time, the LAr calorimeters have also exhibited excellent performance and operational stability.

The LAr calorimeters, shown in figure 3, are sampling calorimeters, with liquid argon as the active medium. They are composed of 4 different sub-systems that cover different regions of pseudo-rapidity and are constructed with different absorber materials. Properties of these various sub-systems are summarized in Table 1. These 4 sub-systems are contained inside three separate cryostats. The barrel cryostat houses the electromagnetic barrel (EMB) calorimeter, while the two end-cap cryostats contain the electromagnetic end-cap (EMEC), hadronic end-cap

![Figure 3. ATLAS Liquid Argon Calorimeter [2]](image)

| Sub-system | Coverage     | Absorber | Channels | Layers                        |
|------------|--------------|----------|----------|-------------------------------|
| EMB        | 0 < $|\eta|$ < 1.475 | Pb       | 109568   | 3 (+ presampler)              |
| EMEC       | 1.375 < $|\eta|$ < 3.2 | Pb       | 63744    | 3: $|\eta|$ < 2.5 (+ presampler $|\eta|$ < 1.8) 2: $|\eta|$ > 2.5 |
| HEC        | 1.5 < $|\eta|$ < 3.2 | Cu       | 5632     | 4                             |
| FCal       | 3.1 < $|\eta|$ < 4.9 | Cu/W     | 3524     | 3                             |

Table 1. Summary of LAr sub-system properties.
(HEC) and forward (FCal) calorimeters. In total these cryostats contain 80 m$^3$ of liquid argon kept at 88 K.

2. Signal Readout

Ionization from charged particles crossing the liquid argon gap in the calorimeters drifts through a high electric field generated by the LAr high-voltage system in between the absorber plates and readout electrodes. This gives rise to a triangle shaped ionization pulse with a steep rise, and slowly falling tail shown in figure 4. This analog triangular signal is then processed by the front-end boards, giving a bi-polar pulse (superimposed on figure 4), and digitized at 40 MHz. A pulse shape from a cosmic muon event, showing the agreement between predicted and actual pulse shape is shown in figure 5. The digitized samples are then sent to the read-out drivers, where the amplitude and timing of the digitized signal are computed. The equations for the amplitude (in ADC counts) and time of the signal are as follows:

$$A = \sum_{i=1}^{N} a_i (s_i - p), \quad \tau = \frac{1}{A} \sum_{i=1}^{N} b_i (s_i - p)$$

where $N$ is the number of samples (5 for standard data-taking), $s_i$ are the digitized samples in ADC counts, $p$ are the pedestals and $a_i$ and $b_i$ are the Optimal Filtering Coeffecients (OFCs) [4]. Both the pedestals and OFCs are obtained by calibration runs taken in between LHC physics fills. The energy (in MeV) of the pulse is then obtained by applying a series of constants – taken from calibration runs, and test beam results – to the amplitude $A$.

The timing of the signal in the calorimeter is used for both physics studies and to suppress unwanted backgrounds. By studying the timing of the signal one can differentiate between energy deposited in the calorimeter by an event that was triggered on and an event from a neighbouring LHC bunch crossing. The timing can also be similarly used to determine the direction of the energy flow and therefore veto cosmic events, or study long-lived exotic particles which may decay far from the interaction vertex (non-pointing photons, or other particles). The overall timing resolution of the EM barrel calorimeter is shown in figure 6.

The readout channels from the Liquid Argon calorimeter along with the ATLAS Tile calorimeter form trigger tower cells for the Level-1 Calorimeter (L1Calo) trigger. The L1Calo trigger is a hardware based trigger which shares part of its readout with the calorimeter (LAr + Tile) readout. Once the pulse coming from the calorimeter is shaped by the front-end electronics, the readout paths split. The L1 portion of the readout sends the analog pulse to be

![Figure 4](image)

**Figure 4.** The ionization pulse from the calorimeter before shaping and after shaping [4].

![Figure 5](image)

**Figure 5.** The ionization pulse from the calorimeter after electronics shaping [5].
Figure 6. Timing Resolution from Middle Layers Cells from the LAr EM Barrel Calorimeter (2011 data). Includes 200ps contribution from intrinsic beam spread [6].

Figure 7. Energy as measured by the L1Calo trigger system vs the full calorimeter readout electronics for the LAr EM Calorimeter [6].

summed with approximately 60 other readout cells, forming a trigger tower with granularity of $\Delta \eta \times \Delta \phi \approx 0.1 \times 0.1$. These summed analog pulses are then sent to the L1 electronics, which must then make a decision whether or not to keep or discard the event within 2 $\mu$s. Figure 7 shows the agreement in energy calculated between these two different readout paths. The L1Calo energy resolution is designed and operates such that $\sigma_{E_{T}(L1Calo)} < 5\%$ for $E_{T}(Calo) > 10$GeV.

3. LAr Monitoring and Stability

3.1. Liquid Argon Temperature and Purity Monitoring

Deviations of the temperature of the liquid argon from 88K can have adverse affects on both the energy resolution and the energy response of the calorimeters. The energy response has a linear relationship with the temperature, with a 2% signal decrease for each degree Kelvin.

Figure 8. Relative variation in gain per front end board over 3 month period [6].

Figure 9. Pedestal variation per front-end board over 3 month period [6].
This is due to both a change in the drift time in the liquid argon and a change in the density that accompanies the temperature variation. In order to monitor the temperature of the liquid argon, > 400 Precision PT100 temperature probes are installed throughout the 3 cryostats. Monitoring of these temperature measurements over long periods of time show that the LAr cryostats display an overall temperature stability of 59 mK, which is well within the design specifications of < 100 mK.

The liquid argon is also closely monitored for impurities, in particular O₂. The design specifications dictate that the purity be better than 1000 ppb. Each cryostat contains 10 purity monitors that each have two radioactive sources (²⁰⁷Bi and ²⁴¹Am). Using these purity monitors, it was found that the levels of impurities are far below the operational limit and are approximately 200 ppb in the barrel and 140 ppb in the endcap cryostats.

3.2. Calibration Stability
Figures 8 and 9 show the long term stability of the calibration constants and therefore the electronics (which, as mentioned previously, play an important part in determining the energy deposited in the calorimeters) for the LAr EM calorimeters. The pedestal variations are below 0.03 ADC counts (corresponding to 0.3 MeV for the EM calorimeter) and the relative variation in gain is < 10⁻³ for all LAr sub-systems.

4. Physics with the Liquid Argon Calorimeters
In order to provide meaningful physics results in the challenging LHC environment, the LAr calorimeter must meet the following important design goals: have excellent linear response over a broad range of energies, be able to reconstruct and model an event’s missing transverse energy ($E_{\text{miss}}^T$) well, and provide excellent performance with electron and photon objects. The results from the ATLAS physics program over the past 2 years of operations strongly vouches for the excellent performance of the LAr calorimeters in physics analysis.

4.1. Linearity of Response and Electron Performance
Figures 10 and 11 [7] show that the calorimeter response is very good over a wide range of transverse momentum ($p_T$). While the electrons from the $J/\psi$ decay are relatively low energy compared to the much harder spectrum of the Z-boson di-electrons, the agreement with the Monte Carlo simulation is excellent in both cases.

Figure 10. Invariant mass spectrum for electron pairs around 90 GeV, showing a clear Z-boson resonance [7].

Figure 11. Invariant mass spectrum for electron pairs around the 3 GeV mass window, showing a clear $J/\psi$ peak [7].
4.2. $E_{\text{miss}}^T$ Modelling
Similarly, in figure 12, the $E_{\text{miss}}^T$ spectrum is shown in the WW diboson analysis [8]. This spectrum is seen to be well modelled, even up into the tails.

4.3. Photon Performance
Finally, figure 13 [9] shows the invariant mass distribution for diphoton events in the Standard Model Higgs search. The figure shows the invariant mass for di-photon events, and also for the main backgrounds that can fake photon-like signals.

5. Summary
Although the LHC has been delivering physics data only since 2009, the ATLAS Liquid Argon calorimeters have been installed and taking cosmic ray data as of 2006. Since that time, the LAr calorimeters have exhibited excellent operational stability and the physics performed with the calorimeters shows excellent understanding and modelling of both the calorimeter and the underlying physics processes at the LHC.

References
[1] ATLAS Collaboration. The ATLAS experiment at the CERN Large Hadron Collider, JINST 3 (2008) S08003.
[2] ATLAS Collaboration. Readiness of the ATLAS Liquid Argon Calorimeter for LHC Collisions, Eur. Phys. J. C 70 (2010) 723.
[3] https://twiki.cern.ch/twiki/bin/view/AtlasPublic/LuminosityPublicResults
[4] H. Abreu et al., Performance of the electronic readout of the ATLAS liquid argon calorimeters, JINST 5 (2010) P09003.
[5] ATLAS Collaboration. Drift Time Measurement in the ATLAS Liquid Argon Electromagnetic Calorimeter using Cosmic Muons, Eur. Phys. J. C 70 (2010) 755-785.
[6] https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ApprovedPlotsLAr
[7] ATLAS Collaboration. Electron performance measurements with the ATLAS detector using the 2010 LHC proton-proton collision data, Eur. Phys. J. C72 (2012) 1909.
[8] ATLAS Collaboration. Measurement of the $W^+W^-$ Production Cross Section in Proton-Proton Collisions at $\sqrt{s} = 7$ TeV with the ATLAS Detector, ATLAS-CONF-2012-025.
[9] ATLAS Collaboration. Search for the Standard Model Higgs boson in the two photon decay channel with the ATLAS detector at the LHC, Phys. Lett. B705 (2011) 452-470.