Performance of the ATLAS Tile Calorimeter

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Abstract. The ATLAS Tile hadronic calorimeter (TileCal) provides highly-segmented energy measurements of incoming particles. It is a key detector for the measurement of hadrons, jets, tau leptons and missing transverse energy. It is also useful for identification and reconstruction of muons due to good signal to noise ratio. The calorimeter consists of thin steel plates and 460,000 scintillating tiles configured into 5000 cells, each viewed by two photomultipliers. The calorimeter response and its readout electronics is monitored to better than 1% using radioactive source, laser and charge injection systems. The calibration and performance of the calorimeter have been established through test beam measurements, cosmic ray muons and the large sample of proton-proton collisions acquired in 2011 and 2012. Results on the calorimeter performance are presented, including the absolute energy scale, timing, noise and associated stabilities. The results demonstrate that the Tile Calorimeter has performed well within the design requirements and it has given essential contribution to reconstructed objects and physics results. In addition, the data quality procedures used during the LHC data-taking are described and the outcome of the detector consolidation in the maintenance period is also presented.

1. The Tile calorimeter in ATLAS

ATLAS [1] is a general purpose detector at one of four collision sites at the Large Hadron Collider (LHC) at CERN, Geneva, Switzerland. The experiment was designed to search for new physics with a wide range of final states, including signatures with missing transverse momentum, jets and leptons. The Tile calorimeter (TileCal) is the hadronic calorimeter in the central region of the detector, a sampling calorimeter composed of alternating pieces of plastic scintillator and steel absorber [2, 3]. To achieve the physics goals desired by ATLAS the energy resolution of the TileCal is expected to be: $\sigma/E = 50\%/\sqrt{E} \pm 3\%$. In addition the response is expected to be linear within 2% for jets up to 4 TeV.

As shown in Figure 1, the TileCal is composed of three physical volumes; a long barrel (LB) that spans $|\eta| < 1.0$, and two extended barrels each spanning $0.8 < |\eta| < 1.7$. Between the LB and EB there are gap and crack scintillators to help reconstruct energy otherwise lost in these transition regions. The TileCal provides full azimuthal coverage by further segmenting each partition into 64 wedge-shaped modules each spanning $\Delta \phi = 0.1$. There are three radial layers, with layer A closest to the beam line, followed by layers BC and D moving radially outward, as can be seen in Figure 2.

Light generated in the scintillating tiles is collected on two sides of the tile and transmitted via wavelength shifting fibers to photomultiplier tubes (PMTs) located together with the front-end electronics in long mechanical drawers on the outer radius of each module. The signal from one side of the tile is read by one PMT, connected to one electronic channel. Two channels,
which collect light from either side of the scintillator tile, are read out as one unit called a cell. There are a total of approximately 10k channels (or equivalently approximately 5k cells).

The analog signal of the PMT is processed by a so-called 3-in-1 card which provides signal shaping and amplification in bi-gain mode (with gain ratio of 1:64). The dynamic range covers energy deposits from 10 MeV to 800 GeV, where the upper limit corresponds to the low gain saturation, and the lower limit to the high gain precision (1 ADC counts). After amplification the signal from each gain is sent to a digitizer where the pulse is sampled every 25 ns, in sync with the LHC clock cycle. If the event is accepted by the trigger these samples are sent to the Read-out Driver (ROD) located with the off-detector back-end electronics where data integrity checks are made, along with real-time reconstruction of the signal.

2. Signal reconstruction and calibration
The TileCal recorded almost 30 fb$^{-1}$ of data during Run 1 at the LHC. The digital data from each channel, sampled every 25 ns, were reconstructed using the Optimal Filtering (OF) algorithm [5].
The channel amplitude, $A$, and time, $\tau$, were reconstructed according to:

$$A = \sum_{i=1}^{n=7} a_i S_i, \quad A\tau = \sum_{i=1}^{n=7} b_i S_i$$

(1)

where the weights $a_i$ and $b_i$ were derived using the known pulse shape and sample autocorrelation matrix. The weights were applied based on the expected time of the pulse peak (where $\tau = 0$). The phase $\tau$ was measured with respect to time-of-flight of the particle. For events where $\tau \neq 0$ the reconstructed amplitude underestimated the true amplitude by a known function, and hence a correction was applied to recover the true pulse amplitude. Within a phase $\tau \pm 10$ ns the average difference in amplitude after correction was seen to be $< 1\%$.

A series of calibration constants, $C_i$, were used to convert the reconstructed channel peak amplitude in ADC-counts ($A$) to energy ($E$):

$$E = A \cdot C_{\text{ADC} \to \text{pC}, \text{CIS}} \cdot C_{\text{pC} \to \text{GeV}, \text{TB}} \cdot C_{\text{Cs}} \cdot C_{\text{laser}}$$

(2)

The constant $C_{\text{pC} \to \text{GeV}, \text{TB}} = 1.05$ pC/GeV, was the global electromagnetic scale of the TileCal, set using 11% of the modules in a test beam of electrons [4]. The other three calibration constants, $C_{\{\text{CIS}, \text{Cs}, \text{laser}\}}$ were derived using dedicated calibration systems, and maintained this electromagnetic scale across the calorimeter.

The conversion between ADC counts and pC, represented by $C_{\text{ADC} \to \text{pC}, \text{CIS}}$, was made for each channel using a charge injection system, where a known charge was injected into the 3-in-1 cards and the response was measured. The injected charge spanned a range of values scanning both the high gain and low gain range. This system was also used to monitor the front-end electronics and correct for non-linearities. The charge injection calibration was performed twice per week, and over the LHC Run 1 showed the front-end electronics were extremely stable. In 2012 the variation of the charge injection response was 0.04% across all channels.

The constant $C_{\text{Cs}}$ was extracted using a $^{137}$Cs source that was moved through every tile, emitting 0.662 MeV photons to illuminate the scintillator. This system and associated constant were used to calibrate the scintillators, PMTs, and correct for residual cell differences. Cesium calibrations were taken monthly and were shown to have a precision of 0.3%. Figure 3 shows the change in response of the cells to the cesium source as a function of $\eta$ for each radial layer as a function of time in 2012. Cell A13 ($|\eta| = 1.3$) was the cell most exposed to radiation from proton collisions (from the cells shown in the plot), and displayed a maximum variation of 3.5% across the 2012 LHC run period.

**Figure 3.** Change in response of cells to the cesium calibration source (in %) as a function of cell $\eta$ from March 2012 to November 2012, corresponding to the 2012 LHC proton collision run. Sample refers to the radial layer, with A being the inner-most layer.
The final calibration constant in Equation 2, $C_{\text{laser}}$, was calculated using a laser calibration that system sent pulses of light directly to the PMTs. It was used to monitor and measure the individual PMT gain variations between the monthly cesium scans. Laser calibrations were typically taken twice per week and during collision data-taking laser pulses were sent to the PMTs in LHC bunch crossings without protons to monitor channel timing. The stability of the calibration system was better than 0.5% over the period of one month.

Special care was taken to calibrate the gap and crack scintillators, cells E1-E4 in Figure 2, as they were exposed to the most amount of radiation of any TileCal cells. The cesium source could not enter the crack scintillators, cells E3 and E4. However using the laser calibration system the cell E4 exhibited a variation of 8% in response over the 2012 period.

All of these variations in response were monitored with the respective calibration systems and corrected such that the global electromagnetic scale of the calorimeter was maintained.

The initial channel time was set using laser events, where all channels were illuminated at the same time, and with single LHC beam events. In beam “splash” events a single LHC proton beam was incident on a collimator 150 m upstream of the ATLAS detector. The result of this impact was a spray of many high energy particles depositing significant amounts of energy in all channels. Using the beam splash events taken in 2011 and after correcting for particle time of flight the reconstructed cell times across the entire calorimeter were found to be within 0.5 ns of each other. This timing precision was verified using jets from proton collisions.

3. Run 1 operations

Table 1 shows a summary of the colliding proton beam conditions delivered to ATLAS by the LHC during Run 1. In 2011 and 2012 the bunch spacing between beam bunches filled with protons was 50 ns, so out-of-time pileup effects were visible in the calorimeter due to the concomitant presence of signals from nearby proton bunch collisions in the TileCal readout window. The instantaneous luminosity was increased with time, and with it an increase in the average number of interactions per bunch crossing. Multiple interactions in one bunch crossing gave rise to in-time pileup effects.

In ATLAS the data were grouped according run numbers, where one run number was typically assigned to a proton fill, with intermediate changes to a new run in the case of significant detector configuration changes. Within one run the data were split into units called luminosity blocks, typically one minute long. Each ATLAS subsystem had a team of experts and automatic scripts reviewing the data taken by their respective system in real time, and promptly thereafter. For situations of poor data quality, where the data reconstructed was not judged of sufficient quality to be used for physics analysis, luminosity blocks were flagged as unusable.

Table 1. LHC beam conditions during the Run 1 proton collision program. In the table B.C. stands for bunch crossing. Not shown is proton collision data from 2009 where 14 nb\(^{-1}\) of data were recorded with a center of mass energy at 900 GeV.

|                      | 2010 | 2011 | 2012 |
|----------------------|------|------|------|
| Max. center of mass energy [TeV] | 7    | 7    | 8    |
| Delivered int. luminosity [ pb\(^{-1}\)] | 0.0481 | 5.5  | 22.8 |
| Min. bunch spacing [ns] | 150  | 50   | 50   |
| Max. avg. interactions per B.C. | 4    | 17   | 36   |
Figure 4. Percentage of faulty cells (called masked channels) that were not reconstructed from TileCal as a function of time across Run 1 (left); and the $\eta - \phi$ location of these masked cells at the end of Run 1 (right), where the z-axis represents the actual number of cells.

3.1. Tile calorimeter operation during Run 1

The fraction of good data that was recorded by TileCal was 100% in 2010, 99.2% in 2011, and 99.6% in 2012. The largest causes of the inefficiency were due to problems causing four or more consecutive modules to not be properly read out due to busy processes inside the back-end electronics or trips of PMT high voltage power-supply sources that power PMTs in four consecutive modules. Another large source of data integrity problems during Run 1 was a channel timing problem affecting an entire partition, where channels were reconstructed with a delay of 25 ns. The loss of data due to this channel timing problem was recovered when the data were re-reconstructed with updated detector conditions correcting for the known time shift.

There were additional operational problems that did not cause a total loss of data. These were situations where some fraction of the data from the detector was compromised but the information regarding the event could be recovered using information from neighboring modules. One such problem was failures of the low voltage power supplies (LVPS), that were located at the end of the electronics drawers on the detector, and provided power to the front-end electronics in that one module. Two types of failures were possible, one case where the LVPS failed to turn back on and required a hardware intervention for replacement and/or repair, and a second case where the LVPS simply tripped and was restarted successfully.

For the first case, in 2011 the TileCal lost approximately one LVPS per month, and in 2012 one LVPS was lost every two months. In these cases the channels associated to the problematic module were removed from the reconstruction, and energy from neighboring modules was interpolated to assign energies to the missing channels. The fraction of dead cells as a function of time in Run 1 is shown in Figure 4 (left). Large jumps in the fraction of dead cells represented moments when a LVPS turned off and could not be restarted. Smaller steps correspond to single cell problems arising from other less dramatic sources of channel failures. Maintenance periods allowed replacement of the LVPS and/or repair of the faulty readout cells, corresponding to steep reductions in the figure. At the end of Run 1 there were six LVPS that were off, dominating the 2.9% of cells that were faulty. The physical location of these faulty channels can be seen in Figure 4 (right).

During Run 1 there were frequent trips of the LVPS that were correlated with the integrated luminosity. Studies showed the rate of LVPS trips were approximately one every picobarn in 2011, and one every two picobarns in 2012. As in the case of permanent faulty channels, energy was interpolated from neighboring cells to account for the energy deposited in cells belonging to a module with a tripped LVPS. An automatic recovery mechanism was in place to recover...
tripped LVPS during physics runs. During the 2011-2012 maintenance period 40 new versions of the LVPS were installed, and of the 14k LVPS trips in 2012 only one was from one of these new LVPS.

4. Run 1 performance with single particles

The performance of the TileCal, and hence the methods used to reconstruct, calibrate, and correct for problematic regions of the detector, was evaluated with single isolated particles.

Single isolated muons were used to study the electromagnetic scale across the detector, using the ratio of the energy deposited to the path length traveled by the muon in a cell, $dE/dl$. For muon energies below 100 GeV this ratio is approximately constant. This quantity was studied across the physical detector volume, between cells in the same layer, between layers, by its stability over time, and compared with Monte Carlo (MC) predictions.

Figure 5 shows the $dE/dl$ distribution for cosmic muon data taken in 2008 and MC simulations for one typical cell. The cosmic muons were selected with momentum in the range $10 < p < 30$ GeV to ensure the dominant energy loss was from ionization. For all cells in a given layer the variation in the response was found to be $\pm 2\%$, validating the calibration corrections implemented to account for cell-to-cell variations.

For all cells in a given layer the truncated mean of $dE/dl$ was computed for data and MC. The truncated mean was defined such that 1% of the entries in the upper side of the $dE/dl$ were neglected from the calculation, in order to reduce contributions from rare (non-ionizing) energy loss mechanisms. This ratio of data/MC is shown in Table 2 for each layer in each partition for the three years of cosmic muon data studied. The results show the layers were well inter-calibrated, except for LB layer D, which was approximately 4% over calibrated with respect to the other layers. The response to cosmic ray muons was constant in time, validating the calibration constants that corrected for the scintillator and PMT response variations.

The performance of the TileCal was also studied using single isolated charged hadrons, using the ratio of the energy measured by the TileCal, $E$, to the momentum as measured by the inner detector, $p$, for a single track. A signal compatible with a minimum ionizing particle in the LAr calorimeter was required, to avoid any bias of the TileCal response due to interactions in upstream material. The $E/p$ distributions are shown in Figure 6 for data taken in 2011 and MC simulations as a function of $\eta$ (left) and momentum (right). The data and MC agree within 3 %, except in the transition region between the LB and EB ($0.8 < |\eta| < 1.1$) where
Table 2. The data/MC ratio for the truncated mean of dE/dl averaged over all cells of a given layer, shown as a function of time from cosmic ray muons collected in 2008, 2009, and 2010. The error bars represent the statistical and systematic uncertainties.

| Radial layer | $R_{2008}$ | $R_{2009}$ | $R_{2010}$ |
|--------------|------------|------------|------------|
| LB-A         | 0.966 ± 0.012 | 0.972 ± 0.015 | 0.971 ± 0.011 |
| LB-BC        | 0.976 ± 0.015 | 0.981 ± 0.019 | 0.981 ± 0.015 |
| LB-D         | 1.005 ± 0.14 | 1.013 ± 0.014 | 1.010 ± 0.013 |
| EB-A         | 0.964 ± 0.043 | 0.965 ± 0.032 | 0.988 ± 0.014 |
| EB-B         | 0.977 ± 0.018 | 0.966 ± 0.016 | 0.988 ± 0.014 |
| EB-D         | 0.986 ± 0.012 | 0.975 ± 0.012 | 0.982 ± 0.014 |

deviations up to 10% are seen. As a function of particle momentum the agreement deviates above about 15 GeV, which is the transition point for the gain of the electronics readout. The transition region between the low energy parametrization model and quark-gluon string model in the Geant4 physics list (QGSP\_BERT) used in the simulation happens for hadrons with energies in the range 12-25 GeV [6, 7].

Figure 6. Ratio of the energy deposited in TileCal ($E$) to the track momentum ($p$) for isolated charged tracks as a function of $\eta$ (left) and particle momentum (right).

5. Activities during the LHC long shutdown 1
In March 2013 the LHC entered a Long Shutdown (LS) period lasting for nearly two years so the accelerator could be commissioned to higher center of mass energy and luminosity. During this time the TileCal community took the opportunity to repair and improve many aspects of the subsystem. On the front-end, each of the 256 modules was opened, consolidated, inspected, and/or repaired to address problems detected during Run 1, such as corrupted data, channels with large noise, etc. Once the module was closed an extensive sign-off procedure was employed to ensure all problems identified were addressed and that no new problems were introduced in the process. There was a mobile test bench used to test the front-end electronics for a single module on the detector, there was a detector verification system used to test the full readout of a single module, and finally full calibration sets using the charge injection and laser systems were taken twice a week to extensively check and monitor every channel in TileCal.
All of the LVPS were replaced by the newer version which has increased tolerance to radiation and as a consequence fewer trips, as demonstrated by the 40 LVPS installed in 2012. For Run 2 these new LVPS will significantly reduce the number of trips, and therefore also reduce instances of corrupt data that sometimes followed the recovery of a LVPS. These new LVPS also exhibit lower electronic noise that follows more closely a single Gaussian distribution. The electronic noise for cells in layer A as a function of $\eta$ is shown in Figure 7 for the old (nominal Run 1) and new LVPS.

![Figure 7](image.png)

**Figure 7.** The electronic noise as a function of cell $\eta$ with the original LVPS (2011) and with LVPS installed during the LS period from 2013-2015. The cell noise is shown for the case where both channels contributing to the cell were read out in high gain.

Other activities undertaken by the TileCal community during the LS were an update of the mechanical aspects of the cesium system, and the laser calibration system to improve the light mixing to avoid non-uniformities in the light distribution thereby yielding more precise calibration constants. In Run 2 eight additional E3 and E4 cells (per EB) will be read out, where in Run 1 those readouts were used for the Minimum Bias Scintillator Trigger (MBTS) system. In addition trigger systems were updated to allow the TileCal layer D to be used in coincidence with the muon trigger system to reduce the muon trigger fake rate.

6. Summary and outlook

The ATLAS TileCal performed very well in the LHC Run 1, both in operation, calibration, performance and stability. Analysis of single particles demonstrate the success of the reconstruction and calibration methods to correct for changes over time from irradiated scintillators, aging PMTs, and cell-to-cell variations. During the LHC LS (2013-2015) the TileCal community has been quite active in upgrading and improving many components of the system. The precision of the calibration constants directly contributes to the energy resolution of reconstructed objects, such as jets, and missing transverse momentum, and correct modeling of the calorimeter in MC is essential as many searches use MC for background estimation techniques. The LHC Run 2 is just around the corner, and the TileCal will play an essential role for quests for new physics at higher energy regimes.

References

[1] ATLAS Collaboration 2008 JINST 3 S08003
[2] ATLAS Collaboration 1996 CERN-LHCC-96-42
[3] ATLAS Collaboration 2010 Eur. Phys. J. C 70 1193
[4] ATLAS/TileCal Collaboration 2009 NIM A606 362-94
[5] Cleland W E and Stern E G 1994 NIM A338 467-97
[6] Agostinelli S et al. 2003 NIM A506 250-303
[7] Allison J et al. 2006 IEEE Transactions on Nuclear Science 53 270-8