PROCEEDINGS OF SCIENCE

# Performance of the ATLAS hadronic Tile calorimeter

**Pavol Bartoš**[*†] **on behalf of the ATLAS Collaboration**
*Comenius University, Bratislava, Slovakia*
*E-mail:* pavol.bartos@cern.ch

The Tile Calorimeter (TileCal) of the ATLAS experiment at the LHC is the central hadronic calorimeter designed for energy reconstruction of hadrons, jets, tau-particles and missing transverse energy. TileCal is a scintillator-steel sampling calorimeter and it covers the region of pseudorapidity < 1.7. The scintillation light produced in the scintillator tiles is transmitted to photomultiplier tubes (PMTs). Signals from the PMTs are amplified, shaped and digitized by sampling the signal every 25 ns. Each stage of the signal production from scintillation light to the signal reconstruction is monitored and calibrated.

Results on the calorimeter operation and performance are presented, including the calibration, stability, absolute energy scale, uniformity and time resolution. These results show that the TileCal performance is within the design requirements and has given essential contribution to reconstructed objects and physics results.

*Fourth Annual Large Hadron Collider Physics*
*13-18 June 2016*
*Lund, Sweden*

*Speaker.

†Work supported by the Ministry of Education, Science, Research and Sport of the Slovak Republic.





PoS(LHCP2016)204

## 1. Introduction

The Tile Calorimeter (TileCal) is the central hadronic calorimeter of the ATLAS experiment at the LHC [1]. It is partitioned into three physical volumes: a long barrel (LB) that spans pseudorapidity region of $|\eta| < 1.0$ and two extended barrels (EB) each spanning region of $0.8 < |\eta| < 1.7$. The barrel cylinders are divided into 64 modules each spanning $\Delta\phi \approx 0.1$. In general, each LB (EB) module is composed of 45 (32) photomultiplier tubes (PMTs), which are connected to an electronic channel. Each TileCal cell is read out by two PMTs. There are in total approximately 5000 cells, which are organized into three longitudinal layers with total thickness of $7\lambda$ (interaction lengths). The size of the cell is $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$ in the inner and middle longitudinal layers and $\Delta\eta \times \Delta\phi = 0.1 \times 0.2$ in the outer layer.

The light from the scintillator tiles is transmitted by wavelength shifting fibers to PMTs. The analog signals from the PMTs are shaped and amplified in bi-gain mode with gain ratio of 1:64 and sampled by a 10-bit ADC each 25 ns. The dynamic range covers energy deposits from 10 MeV to 800 GeV. The lower limit corresponds to the high gain precision (1 ADC count), while reaching the upper limit leads to low gain saturation (the saturated signal can be reconstructed, but with lower precision).

## 2. Signal calibration

The digitized signal is reconstructed using the optimal filtering algorithm [2]. To convert the reconstructed amplitude, $A$, in ADC-counts into the energy, $E$, several calibration factors are used:

$$E = A \cdot C_{\mathrm{ADC}\to\mathrm{pC}} \cdot C_{\mathrm{pC}\to\mathrm{GeV}} \cdot C_{\mathrm{Cs}} \cdot C_{\mathrm{laser}} \tag{2.1}$$

The global constant $C_{\mathrm{pC}\to\mathrm{GeV}}$ was set during a test beam using 11% of the modules [3]. The other three factors ($C_{\mathrm{ADC}\to\mathrm{pC}}$, $C_{\mathrm{Cs}}$, $C_{\mathrm{laser}}$) are obtained from dedicated calibration systems for each channel separately. Due to variations in the PMT responses and/or aging of optical components these factors can evolve in time.

The *Charge injection system* (CIS) determines the conversion factor $C_{\mathrm{ADC}\to\mathrm{pC}}$ for the low- and high-gain regimes by comparing a known injected charge with the response of the electronics. Figure 1 shows the average of the CIS conversion factor obtained from all low-gain channels, except for approximately 1% of channels with no response or fluctuating conversion factor, over three months period in fall 2015. The RMS values in the plot are indicative of the fluctuation present in calibrations. The conversion factor in the presented period is stable at the per mille level.

The *Laser system* monitors the PMTs and downstream electronics by sending well calibrated light pulses into the PMTs. By modifying the light amplitude it is possible to monitor both gain regimes. The factor $C_{\mathrm{laser}}$ is used to correct for individual PMT gain variations. During the Long Shutdown of the LHC (2012-2015), a new Laser II system has been developed. The results of using the system during Run 2 shows higher stability ($< 1\%$) then in Run 1. Such a stability is compatible with the expectations of the Laser II project [4].

The *Cesium system* circulates a radioactive source ($^{137}$Cs) through all cells. The response is then read out using the integrator readout path. It is used to calibrate optical components and to monitor PMTs. Figure 2 shows a deviation of $C_{\mathrm{Cs}}$ from the expected Cs response. The spread

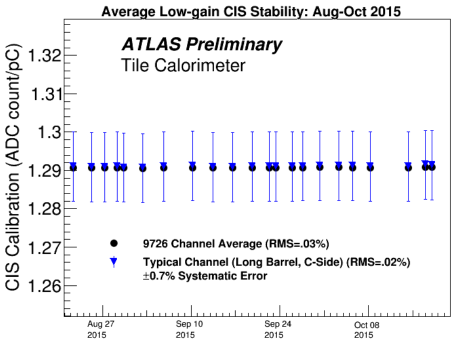


**Figure 1:** The CIS calibration constant average of all low-gain channels as a function of time [4].

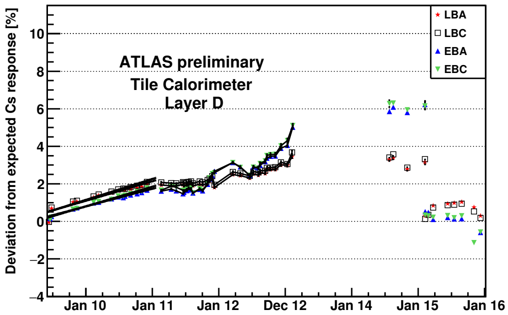


**Figure 2:** Variation of Tile Calorimeter response over period of six years measured in Cesium calibration runs averaged over all cells in a given sample [4].

between detector partitions (LB, EB) is small. The gap corresponds to the Long Shutdown of the LHC when the system was improved to be more stable and safe. In 2015, the high voltage of every PMT was adjusted to provide for the factor $C_{\mathrm{Cs}}$ to be 1.

The *Integrator System* monitors the instantaneous luminosity in the ATLAS by measuring the anode current for every PMT integrated over a long time (10 ms) with respect to the time between two bunch crossings (25 ns).

## 3. Calorimeter performance

The performance of the calorimeter has been studied in-situ employing cosmic ray muons and a large sample of proton–proton collisions acquired during the operations of the LHC. Prompt isolated muons of high momentum from electroweak $W$-boson decays are employed to study the energy response of the calorimeter at the electromagnetic scale. Studies with cosmic ray muons show that the energy deposited in the cell depends linearly on the track path length. The study using isolated muons from proton–proton collisions presents uniformity and stability of the electromagnetic scale (uncertainty of 3%) over Run 1 [5].

The calorimeter response to hadronic particles is evaluated with a sample of isolated hadrons using ratio of energy, $E$, deposited in a 3D cluster around the extrapolated tracks and the momentum, $p$, of the isolated hadron, which is precisely measured by the inner detector. The ratio as a function of the momentum, integrated over $\eta$ and $\phi$ is shown at Fig. 3. A discrepancy between the Minimum bias Monte Carlo and data is $< 5\%$ for the track momentum $< 9$ GeV.

## 4. Time calibration and resolution

The time calibration is important for the energy reconstruction; it aims to set the phase in each channel so that a particle from the interaction point gives a signal with measured time equal to zero. The most recent calibration was done in April 2015 using single beam data (splash events). The large signal essentially lighting up every cell of the calorimeter comes from high energy muons

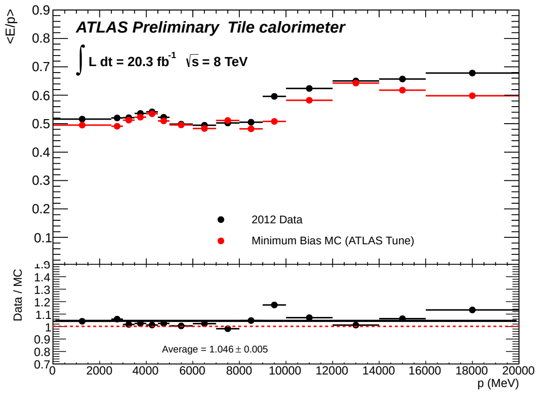


**Figure 3:** Calorimeter response characterized by energy over momentum ($E/p$) for isolated tracks, as measured with the Tile Calorimeter, using proton-proton collision data from 2012 in the Minimum Bias stream [5].

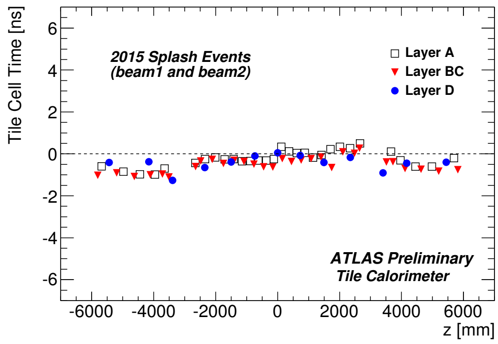


**Figure 4:** The average time over all cells with the same azimuth coordinate, $\phi$, is shown as a function of the cell position along beam axis, $z$, for all three radial samplings. Single beam data from 2015 is used. Timing corrections based on laser data had been applied [4].

flying parallel to the beam axis. Figure 4 shows the flat distribution (within 1.5 ns) of the average cell time as a function of cell position along the beam axis.

The study of the mean cell reconstructed time as a function of cell energy was done using 2011 collision data at $\sqrt{s} = 7$ TeV and 50 ns bunch spacing. The distribution obtained from events with isolated muons shows the mean time independence of the cell energy, as expected, while the mean time decreases with the cell energy in events with jets. It is probably caused by the slow hadronic component of the hadronic showers.

The collision data at $\sqrt{s} = 13$ TeV with 25 ns bunch spacing was used to study the time resolution. Both, events with jets and with isolated muons show similar results. The resolution is better than 1 ns for cell energies above 4 GeV. The same resolution was obtained with 50 ns bunch-spacing data.

## 5. Conclusions

The TileCal calibration systems were improved during the Long Shutdown and are more stable in Run 2. The performance in Run 1 and Run 2 is found to be within design requirements and is essential in object reconstruction.

## References

[1] The ATLAS Collaboration, The ATLAS experiment at CERN Large Hadron Collider, *JINST* **3** (2008) S08003.

[2] W.E. Cleland and E.G. Stern *NIM* **A338** (1994) 467-97.

[3] ATLAS/TileCal Collaboration, *NIM* **A606** (2009) 362-94.

[4] TileCal Public results, https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ApprovedPlotsTile

[5] TileCal Single particle response, https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ApprovedPlotsTileSingleParticleResponse