Performance of the ATLAS Tile Calorimeter in $pp$ collisions at the LHC

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Abstract. The Tile Calorimeter is the central section of the ATLAS hadronic calorimeter at the Large Hadron Collider. This detector is instrumented for the measurements of hadrons, jets, tau leptons and missing transverse energy. Scintillation light produced in the tiles is transmitted by wavelength shifting fibers to photomultiplier tubes (PMTs). The resulting electronic signals from approximately 10000 PMTs are measured and digitized before being transferred to off-detector data-acquisition systems. After an initial setting of the absolute energy scale in test beams with particles of well-defined momentum, the calibrated scale is transferred to the rest of the detector via the response to radioactive sources. The calibrated scale is validated in situ with muons and single hadrons whereas the timing performance is checked with muons and jets. The data quality procedures used during the LHC data-taking and the evolution of the detector status during the LHC Run 1 are presented. The energy and the time reconstruction performance of the digitized signals is summarized and the calorimeter response to hadrons is investigated with collision data.

1. Introduction
The ATLAS Tile Calorimeter (TileCal) is the barrel hadronic calorimeter of the ATLAS experiment at the Large Hadron Collider (see figure 1). Covering the pseudorapidity region -1.7 < $\eta$ < 1.7, together with the electromagnetic calorimeter TileCal provides precise measurement of hadrons, jets, taus and missing transverse energy. The performance requirements driven by the ATLAS physics programme are a jet energy resolution of $\sigma/E = 50%/\sqrt{E(GeV)} \pm 3\%$ and a response linearity within 2% up to 4 TeV.

The TileCal is a sampling calorimeter using plastic scintillator as active material and low-carbon steel as the absorber. It is divided into a long barrel (LB) in the central region (-1.0 < $\eta$ < 1.0) and two extended barrels (EB) spanning 0.8 < |$\eta$| < 1.7. The barrel and extended barrel cylinders are segmented into 64 wedges (modules) in $\phi$ and in three longitudinal layers (A, BC, D) for a total thickness of approximately 7$\lambda$. Light emitted by the scintillating tiles is transported via wavelength shifting fibers to photomultiplier tubes (PMTs). Each TileCal three dimensional cell is read out by two PMTs on either $\phi$ side, providing redundancy and improved uniformity. The calorimeter granularity is $\Delta \eta \times \Delta \phi = 0.1 \times 0.1$ for A and BC cells and 0.2 x 0.1 for D cells. In the electronics readout, the signals from the PMTs are shaped and amplified.

1 Pseudorapidity $\eta$ is defined as $\eta = - \ln \tan(\theta/2)$, where $\theta$ is the polar angle measured from the beam axis. The azimuthal angle $\phi$ is measured around the beam axis, with positive (negative) values corresponding to the top (bottom) part of the detector.
in two gains with relative ratio 1:64. Each signal is digitized at a rate of 40 MHz and stored in the front-end pipeline memory. Upon arrival of a first level trigger accept, seven samples from the appropriate gain are sent to the back-end electronics for energy and time reconstruction.

A detailed description of ATLAS and TileCal is provided in [1] and [2], respectively.

![Cut-away view of the ATLAS calorimeters](image)

Figure 1. A cut-away view of the ATLAS calorimeters. The Tile Calorimeter consists of one central barrel and two extended barrels.

2. Detector operations

2.1. Data quality

In 2012 ATLAS recorded 21.3 fb$^{-1}$ of pp collision data. Out of these, 95.5% were declared good for physics. The data quality efficiency for TileCal alone was 99.6%, with the main sources of inefficiency being problems with timing and with the readout system.

TileCal achieved this high data quality efficiency thanks to an effective monitoring system. A Data Quality Monitoring Framework (DQMF) collects information about the quality of the data in real-time and performs automatic checks. When problems are detected, a flag is raised in a graphical user interface to alert the shifter who can take immediate action. In addition, automatic recovery procedures are implemented in the Data Acquisition (DAQ) and Detector Control Systems (DCS) to minimize the need for manual intervention and the recovery time.

2.2. Low Voltage Power Supplies

An example of the importance of automatic recovery procedures is given by trips of the Low Voltage Power Supplies (LVPS). The LVPS power the front-end electronics of each module and therefore LVPS trips result in a full module being off. During the LHC Run 1, LVPS trips occurred at a rate of about 0.6 trips/pb$^{-1}$ and the recovery time to power on LVPS and resume data-taking was about two minutes.

To prevent LVPS trips in Run 2, a new production of upgraded power supplies has been installed in the detector during the long LHC shutdown in 2013. The upgraded LVPS have already been tested under the LHC running conditions: 40 of them were installed in the detector in December 2011 and only one trip was observed in the whole of 2012 (compared to the about a hundred trips typically observed for old LVPS in the same area of the detector). The new LVPS also benefit from reduced electronic noise.
2.3. Detector status during Run 1
In TileCal, cells that deliver corrupted data are masked. The evolution of masked cells during 2011 and 2012 is shown in figure 2. The fraction of masked cells changed over time, increasing during the periods when the LHC was operational and decreasing to almost 0% during the maintenance period when the front-end electronics could be accessed and repaired. At the end of the LHC Run 1, in February 2013, about 3% of TileCal cells were masked. The majority of these were due to six modules being powered off because of failures in the LVPS. During the current LHC shutdown of 2013-2014, TileCal is undergoing major maintenance interventions to repair and consolidate all 256 modules and replace all LVPS with the upgraded ones. These activities aim to ensure high performance, high quality and robust operations during Run 2.

![Evolution of Masked Cells: 2013-02-10](image)

**Figure 2.** Percentage of masked TileCal cells as a function of time, from December 2010 to February 2013. A sharp increase in the fraction of masked cells corresponds to the loss of an entire module, for example due to failures in the LVPS. The sudden decrease between December 2011 and January 2012 corresponds to the maintenance period, when the front-end electronics could be accessed and repaired.

3. Performance
In TileCal, the Optimal Filter (OF) algorithm is used to reconstruct the pulse amplitude and time for each channel. The reconstructed channel energy is derived from the signal amplitude after appropriate calibration factors. The OF requires an initial knowledge of the time phase between the pulse peak and the LHC clock signal. The performance of the energy reconstruction is checked by comparing two different methods applied online and offline, see figure 3(a). The bias due to the phase variation can be reduced applying a correction using the time of the pulse. After the correction, online and offline energy reconstruction agree within 1% in the time range [-10 ns, 10 ns], as shown by the blue points.

Precise timing is crucial for accurate jet energy reconstruction. The 10000 TileCal channels were synchronized using the laser calibration system, cosmic ray events, beam splashes and collision events, as described in [2]. The cell time resolution is measured in data using muons and jets and found to be better than 1 ns for energies above 4 GeV, as shown in figure 3(b).

The inclusive cell energy response can be validated at the electromagnetic scale using collision events. Figure 4(a) shows the average cell energy as a function of $\phi$. The response is uniform in $\phi$ and the data is well described by the simulation. Furthermore, an in-situ method is used to probe the calorimeter response to single isolated hadrons that shower in TileCal. The calorimeter response is characterized by the ratio $E/p$, where $p$ is the charged particle momentum measured...
Figure 3. (a) Relative difference between the online and the offline cell energy reconstruction as a function of the cell time. (b) Cell time resolution measured in collision data on jets and muons as a function of the cell energy.

Figure 4. (a) Average cell energy as a function of $\phi$ in collision events at $\sqrt{s} = 7$ TeV. Only cell energies above 500 MeV at the electromagnetic scale are considered. Non-diffractive minimum bias Monte Carlo events with the same energy cut are superimposed. (b) Mean value of $E/p$ as a function of $\eta$ for data at $\sqrt{s} = 7$ TeV and minimum bias Monte Carlo simulation. $E$ refers to the energy deposited in TileCal by isolated charge particles with momentum $p$. The bottom plot shows the ratio data/Monte Carlo.

with high accuracy in the inner detector and $E$ is the energy of three-dimensional clusters around the track extrapolated to the calorimeter. The $E/p$ ratio measured in 2011 data at $\sqrt{s} = 7$ TeV is shown in figure 4(b) as function of $\eta$. The data is well described by the simulation, except in the region around $|\eta| = 1$ where a discrepancy of 10% is observed.
4. Conclusion
The ATLAS Tile Calorimeter has been performing very well during the first LHC run, achieving a high data quality efficiency. By the end of the LHC Run 1, 97% of the detector was operational. At present, major interventions are ongoing in the ATLAS cavern to replace the problematic LVPS and ensure that the detector is in the best conditions for the beginning of Run 2. The performance of TileCal has been studied with collision data and shown to be good.

References
[1] ATLAS Collaboration 2008 *JINST* 3 S08003
[2] ATLAS Collaboration 2010 *Eur. Phys. J. C* 70 1193