PROCEEDINGS OF SCIENCE

The ATLAS Tile Calorimeter, its performance with 13 TeV proton-proton collisions, and its upgrades for the high luminosity LHC

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The Tile Calorimeter (TileCal) is the central hadronic calorimeter of the ATLAS experiment at the LHC. Jointly with the other calorimeters it is designed for reconstruction of hadrons, jets, tau-particles and missing transverse energy. It also assists in the muon identification. A summary of the upgrades and performance results for TileCal using pp collisions from the initial LHC Run II at 13 TeV will be presented. For the high luminosity era a major upgrade of the TileCal electronics is planned, and the ongoing developments for on- and off-detector systems, together with expected performance characteristics and recent beam tests of prototypes, will be described.

XXIV International Workshop on Deep-Inelastic Scattering and Related Subjects
11-15 April, 2016
DESY Hamburg, Germany

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PoS(DIS2016)265

1. Introduction

The Tile Calorimeter spans over the central region ($|\eta| < 1.7$) in the ATLAS experiment [1], which explores the proton-proton (and also lead-lead) collisions at the LHC. TileCal is a sampling device made of alternating layers of steel plates and active scintillating tiles. Mechanically, the calorimeter is divided into a central long cylinder and two shorter cylinders flanking it on both sides. Each cylinder consists of 64 wedges (modules), as shown in Fig. 1.

The readout cells are organized into 3 radial layers. In the $\eta - \phi$ plane, the cell segmentation is $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$ (0.2×0.1 in the outermost radial layer). Each cell is readout by two photomultipliers (PMTs), which provides redundancy and improves the readout uniformity in the azimuthal direction.

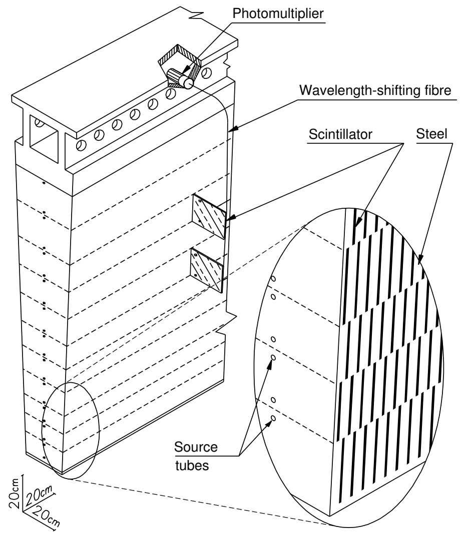

Figure 1: The sketch of one TileCal module shows its geometry and the principle of the signal readout [2]. Light from tiles is collected on both edges by wavelength-shifting fibers, which route the light to the PMTs housed in the outer part together with the front-end electronics. The readout cells are defined by grouping the fibers onto a PMT.

1.1 Signal processing

The current signal processing scheme is sketched in Fig. 2. The analog pulses from PMTs are shaped, split into two branches (high- and low-gain, gain ratio 64:1) and sampled every 25 ns with 10-bit analog-to-digital converters (ADCs) [3]. The digitized samples are stored in pipeline memories and sent off-detector only if the event is accepted by the first trigger level[1]. The energy, time and quality factors are then reconstructed in Read-Out Drivers (RODs) for each channel and are used in the high level trigger decision chain as well as for the offline data processing.

1.2 Calibration

TileCal uses three dedicated systems to calibrate different stages of the signal propagation:

[1]The ATLAS L1 trigger is based on analog signals from calorimeters and trigger system. TileCal contributes with summed analog signals, each corresponding to the calorimeter region $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$.

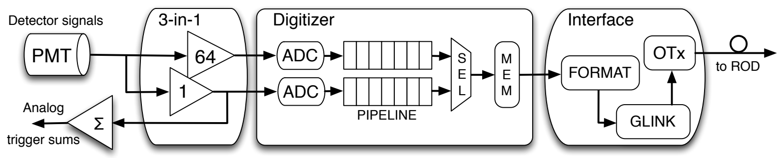

Figure 2: The scheme of the signal path in the current TileCal front-end electronics [3]. The slow integrator readout used for Cs calibration and minimum bias signal processing is not displayed.

- Cesium system measures the signal induced by ^{137}Cs radioactive source that passes through all tiles in special runs. It calibrates the optics and the PMTs. The signal is read out through dedicated slow electronics. This readout path is shared with minimum bias system that averages the physics signals from collisions over several ms and is used for monitoring and luminosity measurements.
- Laser pulses are used to measure the PMT response combined with the fast readout electronics that is also used for physics data. Laser events are also used during the physics data taking for monitoring the time calibration.
- Charge injection system (CIS) calibrates the fast readout electronics by injecting pulses of specified charge into it. The amplitude-to-charge conversion coefficient C_{CIS} is measured with this system.

The response of individual channels is calibrated at electromagnetic (EM) scale by the formula

$$E\ [\mathrm{GeV}] = A\,[\mathrm{ADC}] \times C_{\mathrm{Cs}} \times C_{\mathrm{las}} \times C_{\mathrm{CIS}}\,[\mathrm{pC/ADC}]\,/\,C_{\mathrm{TB}}\,[\mathrm{pC/GeV}], \tag{1.1}$$

where A is the reconstructed pulse amplitude, C_{Cs}, C_{las} and C_{CIS} represent the corresponding system calibration constants. The last element C_{TB} was measured with electron beams of known energies in beam tests [4].

2. Performance

The TileCal performance has been assessed in beam test measurements [4], cosmic rays data taking [2] and finally in the LHC collisions.

High energy muons traverse the whole calorimeter, therefore they represent a very good tool to assess the response uniformity and to validate the EM scale across all radial layers. Isolated muons originating in cosmic rays as well as in pp collision are used for this purpose. An example of the W-decay muon response is shown in Fig. 3. Similar results were obtained in other analyses, the maximum difference between radial layers of 4 % was found [5, 6]. The EM scale was also checked with cosmic muons over three consecutive years, a stability better than 1 % in the central long cylinder was found [5].

Figure 4 shows the spectrum of the energy deposited in TileCal cells in the proton-proton collision data at two different center-of-mass energies $\sqrt{s} = 13$ TeV and 0.9 TeV. Superimposed is the minimum bias MC, which describes the data very well.

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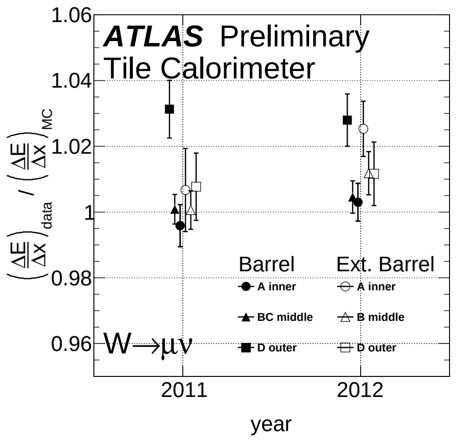

Figure 3: The isolated muons from W-decay are used as a probe of the EM scale. The plot shows their response dE/dx in individual layers relative to the MC prediction [6].

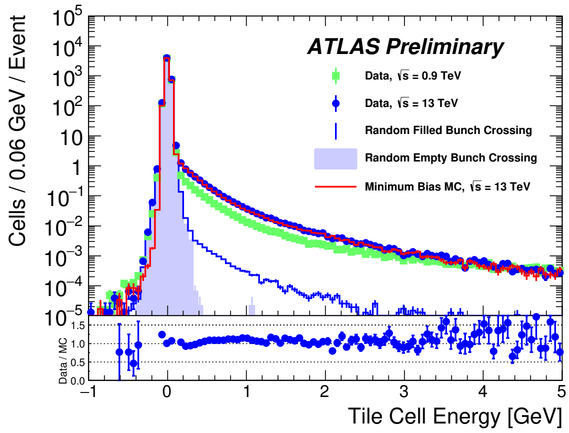

Figure 4: The spectrum of the energy deposited in the TileCal cells in the proton-proton collisions at two indicated center-of-mass energies [6]. Events with just one reconstructed primary vertex are displayed. The difference between the two energies is due to the increase of binary parton interactions with $\sqrt{s}$. The symmetric blue-shaded area corresponds to electronic noise.

3. Upgrade plans

During the Long Shutdown 1 (2013–2015), also referred to as Phase-0 upgrade, TileCal replaced all low voltage power supplies. New power supplies are more robust — the number of trips dramatically reduced and the non-Gaussian tails in the noise distribution were significantly suppressed.

During the Phase-1, scheduled for 2019–2020, the gap and crack scintillators[2] are planned to be replaced due to material ageing.

A major upgrade is planned for Phase-2 (2024–2026), when the whole readout electronics should be replaced. The main features of the new electronics include:

- Fast and more modern electronics with higher radiation tolerance is needed for the high luminosity[3] LHC operation.
- High bandwidth is required to achieve better precision and finer granularity of the ATLAS trigger. All signals will be digitized and sent off-detector at the bunch-crossing rate, the first level trigger decision will use these data.
- The current drawer will be split into 4 operationally independent units called mini-drawers, which increases the redundancy and reliability of the front-end electronics.

[2]These single-scintillator cells cover the transition region between the central long cylinder and short cylinder (gap) and between the central and end-cap EM calorimeter (crack) respectively.

[3]In the HL-LHC era, the instantaneous luminosity is supposed to increase by a factor 5 to 10 relative to the LHC design value.

The scheme of the new electronics chain is displayed in Fig. 5. Each mini-drawer operates 12 channels. It consists of a Main Board, a Daughter Board, High Voltage board and 12 Front-End Boards (FEBs) corresponding to each readout channel.

The Daughter Board, being controlled by two Kintex-7 Field-Programmable Gate Arrays, communicates with the off-detector electronics (sROD) [7]. It interfaces the digitized data at the bunch-crossing frequency from FEBs to the sROD and it receives slow control commands and routes them to the Main Board.

The sROD provides data to the first level trigger and stores the digitized samples for signal reconstruction if the event is accepted by trigger.

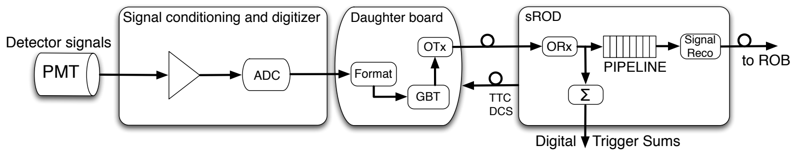

Figure 5: The scheme of the signal processing in TileCal planned for the Phase-2 upgrade [5].

3.1 Front-End Board

The analog pulses from PMT are conditioned and digitized in the FEB. Currently, three options of FEB are being investigated and tested:

- The so-called “modified 3-in-1” FEB [8] represents the solution closest to the currently operating version. The pulses are split into two branches (designed gain ratio 32:1), shaped and digitized with 12-bit ADCs. This FEB options also provides CIS and slow integration for the Cs and minimum bias system.
- Charge integrator and encoder (QIE) [9] is based on the ASIC chips. Pulses are not shaped but directly integrated. Four branches of different gains are foreseen, each being digitized with a 6-bit ADC.
- FATALIC uses a combination of two ASIC chips. Pulses are split into three branches (gain ratio 64:8:1), shaped and sampled by 12-bit ADCs.

3.2 Demonstrator

In order to test the new electronics in real conditions, a hybrid front-end electronics prototype called demonstrator has been constructed. The demonstrator combines a fully functional Phase-2 readout system with the analog trigger signals of the current system. The demonstrator thus allows for testing the new electronics in parallel to the current-style data-taking.

The analog signals from PMTs are digitized in the Main Board and transferred to the Daughter Board, which formats and transfers the data off-detector to the PreProcessor (PPr) through parallel optical links using GBT protocol. The PPr stores the digital data in pipeline memories and in parallel it computes digital sums and provides them to the calorimeter L1 trigger system. Upon the reception of the L1 accept signal, the digital signals are processed and also transmitted to the currently used ROD in parallel.

The demonstrator is currently undergoing intensive tests and further developments in laboratories. All three FEB options are explored. Control and calibration tests are implemented. Apart from the laboratory tests, a TileCal module equipped with the demonstrator has already been exposed to particle beams at SPS at CERN in autumn 2015 and data were successfully recorded. Two other beam test periods are planned in 2016. After successful tests the demonstrator should be inserted in one TileCal module at the next ATLAS detector opening to gain more experience with the new system before the mass production and final installation during Phase-2 upgrade.

4. Conclusions

The ATLAS Tile Calorimeter has performed very well so far in Run-1 and Run-2. The design specifications are met, the calibration systems achieved a precision better than 1 %. The EM scale settings were validated with in-situ measurements. The calorimeter thus provides good data essential for many physics analyses.

Complete replacement of the readout electronics is foreseen for the high luminosity LHC era. Intensive tests and revisions of many components is ongoing to improve their performance. The front-end electronics prototype has been built and tested in laboratory as well as with the particle beams. More tests are scheduled in 2016 so that the prototype is ready to be inserted into one TileCal module at the next ATLAS detector opening.

Acknowledgments

The support from Ministry of Education, Youth and Sports of the Czech Republic is acknowledged.

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