Nuclear Inst. and Methods in Physics Research, A 1038 (2022) 166951

Contents lists available at ScienceDirect

Nuclear Inst. and Methods in Physics Research, A

journal homepage: www.elsevier.com/locate/nima

Upgrade of ATLAS hadronic Tile Calorimeter for the High-Luminosity LHC

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ARTICLE INFO

Keywords:
High-energy calorimetry
Hadronic calorimeter
Data acquisition system
ATLAS upgrade
High-luminosity LHC

ABSTRACT

The Tile Calorimeter (TileCal) is a sampling hadronic calorimeter covering the central region of the ATLAS experiment, with steel as absorber and plastic scintillators as active medium. The High-Luminosity phase of LHC, delivering an instantaneous luminosity up to 7.5×10^{34} cm^{-2} s^{-1}, is expected to begin in 2029. TileCal will require new electronics to meet the requirements of a 1 MHz trigger (calorimeter output rate), higher ambient radiation, and to ensure better performance under high pile-up conditions. Both the on- and off-detector TileCal electronics will be replaced during the shutdown of 2026–2028. The TileCal upgrade program has included extensive R&D and test beam studies. A Demonstrator module with reverse compatibility with the existing system was inserted in ATLAS in August 2019 for testing in actual detector conditions. The ongoing developments for on- and off-detector systems, together with expected performance characteristics and recent results of test-beam campaigns with the electronics prototypes will be discussed.

1. Introduction

High-energy physics experiments are built to explore and study the smallest known particles which are the fundamental building blocks of matter. In this context, the LHC (Large Hadron Collider) [1] has been designed to collide particles at CERN (European Organization for Nuclear Research) where two proton beams travel in opposite directions within a circular accelerator and collide, with a period of 25 ns. Dedicated experiments are built in particular points along the beam track to detect and measure the collision subproducts. The ATLAS (A Toroidal LHC ApparatuS) [2] detector is the largest experiment at LHC (a general-purpose experiment) with a large physics program. ATLAS records measurements of the particles created in collisions such as their tracks, energies, and their identities.

The ATLAS Tile Calorimeter (TileCal) [3] is the main hadronic calorimeter of the ATLAS experiment at LHC. From the construction point of view, TileCal is a sampling detector made of steel plates as absorber and scintillator tiles as active medium. TileCal absorbs energy from particles that are primarily hadrons and that pass through the ATLAS electromagnetic calorimeter. Physically, TileCal comprises three cylindrical parts: one central Tile barrel logically divided into two partitions (Long Barrel A and Long Barrel C) and two Tile extended barrels (Extended Barrel A and Extended Barrel C). Each part is composed of 64 modules to build the entire cylinder. The central barrel module and both extended barrels are further divided, respectively, into 45 and 16 cells with double readout. Fig. 1 illustrates the ATLAS calorimeter system.

The light produced by each scintillating tile is collected by wavelength shifting (WLS) fibers and transmitted to Photo-Multiplier Tubes (PMT) where a fast electric signal is produced composing each readout channel (see Fig. 2). This electric signal is further conditioned in the on-detector electronics through a shaper circuit [4] before being digitized at a sampling frequency of 40 MHz with 10-bit Analog-to-Digital Converters (ADCs) [5]. In total, almost 10,000 readout signals are available at every collision.

In the current TileCal electronics, the digitized data are stored in pipeline memories until a first level trigger acceptance signal is received. Then, the selected events are read out to the off-detector electronics. In the off-detector electronics, the Read-Out Drivers (ROD) gather the data coming from the front-end electronics at a maximum average trigger rate of 100 kHz [6]. After performing the energy and time reconstruction for each channel, RODs transmit the processed data to Read-Out Buffer in the ATLAS Level-2 trigger system. In total, 32 RODs are required for the complete TileCal readout system.

The High-Luminosity Large Hadron Collider (HL-LHC) project aims to increase the potential for discoveries after 2027 [7]. The goal is to increase luminosity by a factor of almost 10 beyond the LHC's design value, reaching an instantaneous luminosity of 7.5×10^{34} cm^{-2} s^{-1}. These upgrades will lead to an expected average number of collisions per bunch crossing up to 200, providing a total integrated luminosity of 4000 fb^{-1} by around 2040. In order to cope with such unprecedented operation conditions imposed by the new ATLAS trigger and data acquisition systems [8], the TileCal readout electronics needs to be completely revised. Some of the detector components such as the steel absorbers and the scintillating tiles will not be replaced.

2. The TileCal new electronics

In the ATLAS upgrade program, both on- and off- detector electronics of the TileCal will undergo major upgrade in order to meet

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https://doi.org/10.1016/j.nima.2022.166951
Received 28 March 2022; Accepted 31 May 2022
Available online 8 June 2022

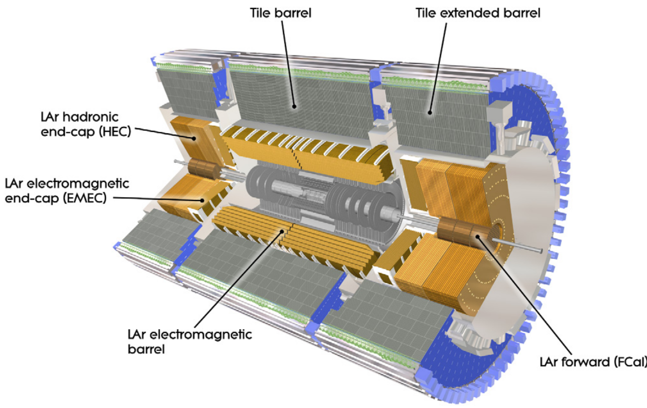

Fig. 1. The ATLAS calorimeter system [2].

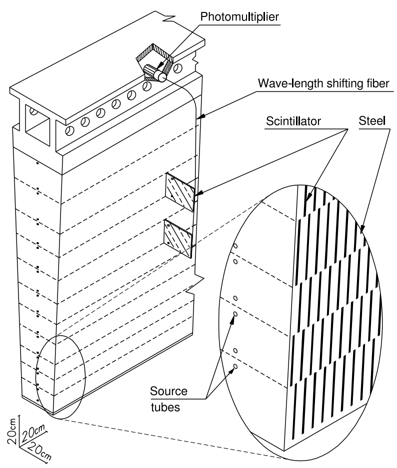

Fig. 2. Components and mechanical structure of a TileCal module [2].

the requirements of the HL-LHC, especially high radiation levels and 1 MHz trigger output, as well as good performance for reconstructed jets, tau leptons and missing energy in the environment with high pile-up conditions [9].

The photomultiplies (PMTs) and on-detector electronics of a module will be housed within a new modular configuration. This configuration consists of three-meter long drawers, so-called Super Drawers (SD). Each SD is itself composed of either four (for the long barrel drawers) or three (for the extended barrel drawers) mechanically attached independent Mini-Drawers [10]. The SD are located at the outer radius of the TileCal to minimize the radiation effects. The new configuration simplifies installation and manipulation. The mini-drawers contain the on-detector electronics required for the acquisition of the PMT signals as well as a high-speed interface with the off-detector electronics and a high voltage distribution system for the PMTs. The modularity, redundancy and robustness achieved by the new configuration improve the reliability of the on-detector acquisition system [11].

A Main Board (MB) is placed on top of each Mini-Drawer structure and is responsible to receive the PMT signals and digitize them before sending these data to the Daughter Board (DB). The DB synchronizes the digitized data and sends them to the TileCal Pre-Processor (PPr) at a rate of 40 MHz [12]. The full new read-out system and processing chain are shown in Fig. 3.

In the new architecture, the output signals of the Tile detector cells will be digitized using the radiation hard on-detector front-end electronics, and then transferred off-detector for every bunch crossing for further processing. High Voltage Active Dividers (HVADs) are located at the end of every PMT. The function of the dividers is to distribute

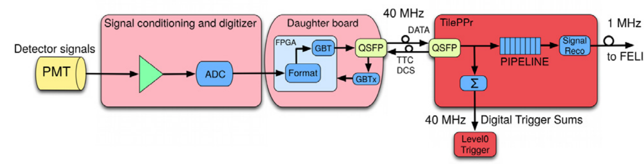

Fig. 3. The HL-LHC upgrade TileCal signal readout chain [14].

the proper input high-voltage power received from the high voltage system amongst the 8 PMT dynodes with an allowed variance of the set voltage of 0.5 V in the range of 600 to 900 V. Active components are used within the HVADs in addition to passive components thereby ensuring the PMT response linearity requirement of better than 1% at high luminosity [13].

Front End board for the New Infrastructure with Calibration and signal Shaping (FENICS) are attached to every HVAD. FENICS is a readout electronics board that is responsible for the amplification and shaping of the analog signals received from an individual PMT. The two main roles of a FENICS are to read the fast signals using two gains and to read the average current using six gains. The modular front-end electronics feature radiation-tolerant commercial off-the-shelf components and redundant design to minimize single points of failure. The timing, control and communication interface with the off-detector electronics is implemented with modern Field Programmable Gate Arrays (FPGAs) and high speed fiber optic links running up to 9.6 Gb/s.

All interfaces between the TileCal and Trigger and Data AcQuisition (TDAQ) system are implemented in the TDAQ interface (TDAQi) modules. The TDAQi constructs the trigger primitives and interfaces with the trigger. It also communicates with the Front End LInk eXchange (FELIX) system which is responsible for interfacing between TileCal and the ATLAS TDAQ. The Trigger FPGAs compute trigger objects for electrons, jet, global, and muon triggers and the results are transmitted digitally through low latency high-speed optical links to the Level-0 trigger.

A special version of the upgrade electronics, called Demonstrator, was built as a TileCal spare module to read out signals at the test beam campaigns [15]. It comprises a hybrid module (using both MB and DB components) that serves as a test case for the new components while ensuring compatibility with the current system. The Demonstrator system exhibited stable links between the on- and off-detector electronics as well as being well integrated with the TDAQ software used for the legacy system. It is worth mentioning that the Demonstrator readout achieves a 17-bit dynamic range using a two-gain 12-bit fast ADC readout with ratio of 1:32. In the legacy system, the readout provides a 16-bit dynamic range also with a two-gain ADC readout with a ratio of 1:64.

3. Preliminary results

Test beam campaigns took place during 2015–2021. The purpose of such activities was to evaluate and validate the proposed new TileCal electronics to be used in the HL-LHC operation. For example, Fig. 4 shows the distributions obtained using experimental and simulated data samples considering electron beams of 20, 50 and 100 GeV incident in a particular TileCal cell. It can be seen that, for each energy condition, both distributions agree, proving the efficient selection of experimental electron samples.

Furthermore, tests with projective muons were also carried out. High energy muons traverse the entire TileCal modules for any angle of incidence, thereby allowing a study of the module response in great detail through their entire volume. It should be stressed that the energy deposited in the calorimeter by high energy muons is still smaller than electron energy depositions with the same energy scale. Fig. 5 shows

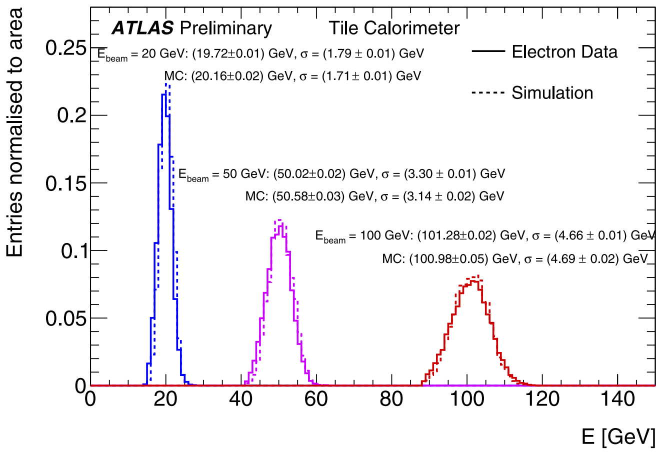

Fig. 4. Distribution of total electron deposited energy for different beam energies. The solid line corresponds to data, while the dotted line shows the simulation result [16].

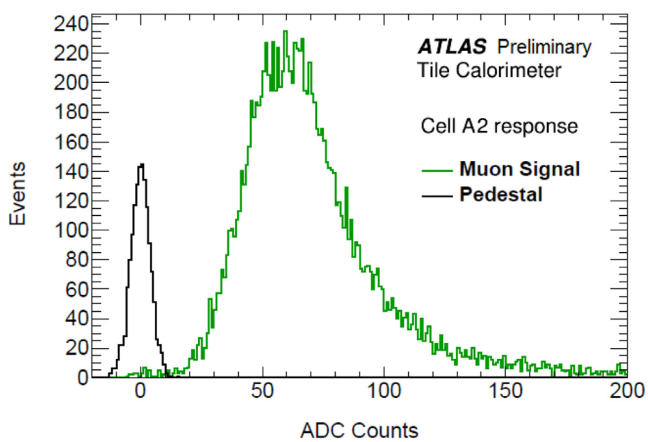

Fig. 5. Muon and pedestal energies (in ADC counts) considering muons hitting the Demonstrator system [16].

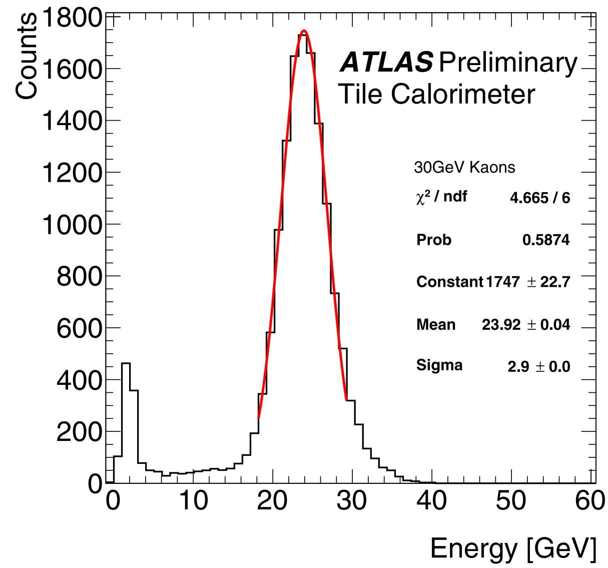

Fig. 6. Reconstruction of hadrons using the new electronics system [16].

the distribution of muon energies (in ADC counts) processed by the new electronics where the pedestal (electronic offset) distribution can also be seen for comparison.

Moreover, in order to achieve a good performance, the study of the response to isolated hadrons is also important for a hadronic calorimeter. In TileCal, the description of the response to hadrons is crucial to validate and improve the modeling of the jet energy characterization. Using the new electronics, the response of low energy hadrons (30 GeV Kaons) is shown in Fig. 6 where the energy distribution from the hadrons is well described through the fitted curve.

4. Conclusions

The High-Luminosity LHC, which should be operational from the beginning of 2029, will allow scientists to study known mechanisms in greater detail and observe rare new phenomena. However, the conditions imposed by the HL-LHC program requires a full replacement of some key on- and off-detector components. In this context, for the ATLAS TileCal a new electronics has been designed to operate during the HL-LHC. The new system has been tested and validated through test beam campaigns, using the so-called Demonstrator, populated with the new electronics which is fully integrated with the current system. The sensitive components have been radiation certified within the Demonstrator system. Test beam campaigns from 2015 to 2021 proved the good performance of the prototypes of new electronics installed in the Demonstrator module. More valuable experience of the new system will be gained through the next LHC operation period (Run-3), envisaging the installation towards the HL-LHC.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors are thankful to CNPq, CAPES, RENAFAE, FAPERJ and FAPEMIG (Brazil), and SNSF (Switzerland) for their support to this work.

References

[1] L. Evans, P. Bryant, LHC machine, JINST 3 (2008) S08001, http://dx.doi.org/10.1088/1748-0221/3/08/s08001.

[2] The ATLAS Collaboration, The ATLAS experiment at the CERN large hadron collider, JINST 3 (2008) S08003, http://dx.doi.org/10.1088/1748-0221/3/08/s08003.

[3] The ATLAS Collaboration, Readiness of the ATLAS tile calorimeter for LHC collisions, Eur. Phys. J. C 70 (2010) 1193–1236, http://dx.doi.org/10.1140/epjc/s10052-010-1508-y.

[4] K. Anderson, A. Gupta, F. Merritt, M. Oreglia, J. Pilcher, H. Sanders, M. Shochet, F. Tang, R. Teuscher, H. Wu, G. Blanchot, M. Cavalli-Sforza, I. Korolkov, Design of the front-end analog electronics for the ATLAS tile calorimeter, Nucl. Instrum. Methods A 551 (2005) 469–476, http://dx.doi.org/10.1016/j.nima.2005.06.048.

[5] M. Tylmad, Pulse shapes for signal reconstruction in the ATLAS tile calorimeter, in: 2009 16th IEEE-NPSS Real Time Conference, 2009, pp. 543–547, http://dx.doi.org/10.1109/RTC.2009.5321656.

[6] A. Valero, Implementation and performance of the signal reconstruction in the ATLAS hadronic tile calorimeter, Physics Procedia 37 (2012) 1765–1771, http://dx.doi.org/10.1016/j.phpro.2012.02.500, Proceedings of the 2nd International Conference on Technology and Instrumentation in Particle Physics (TIPP 2011).

[7] G. Apollinari, O. Brüning, T. Nakamoto, L. Rossi, Chapter 1: High Luminosity Large Hadron Collider HL-LHC, CERN Yellow Report, 2017, pp. 1–19, http://dx.doi.org/10.5170/CERN-2015-005.1, arXiv:1705.08830.

[8] M. Ishino, ATLAS Trigger and DAQ upgrades for high-luminosity LHC, EPJ Web Conf. 164 (2017) 07003, http://dx.doi.org/10.1051/epjconf/201716407003.

[9] I. Tortajada, Upgrade of the ATLAS hadronic tile calorimeter for the high luminosity LHC, EPJ Web Conf. 170 (2018) 01001, http://dx.doi.org/10.1051/epjconf/201817001001.

[10] J. Abdallah, Upgraded electronics of the ATLAS hadronic tile calorimeter for the high luminosity LHC, JINST 15 (06) (2020) C06048, http://dx.doi.org/10.1088/1748-0221/15/06/c06048.

[11] F. Scuri, Upgrade of the ATLAS tile calorimeter for the high luminosity LHC, J. Phys. Conf. Ser. 1162 (2019) 012017, http://dx.doi.org/10.1088/1742-6596/1162/1/012017.

[12] F. Carrió, P. Moreno, A. Valero, Performance of the tile PreProcessor demonstrator for the ATLAS tile calorimeter phase II upgrade, JINST 11 (03) (2016) C03047, http://dx.doi.org/10.1088/1748-0221/11/03/c03047.

[13] D. Boumediene, ATLAS Tile calorimeter calibration and PMT response, JINST 15 (2020) C04051, http://dx.doi.org/10.1088/1748-0221/15/04/c04051.

[14] M. Mlynarikova, Upgrade of the ATLAS hadronic tile calorimeter for the high luminosity LHC, in: Proceedings of the 5th Conference on Large Hadron Collider Physics 2017, LHCP 2017, 2017, http://dx.doi.org/10.48550/ARXIV.1709.00099.

[15] E. Valdes Santurio, Beam tests on the ATLAS tile calorimeter demonstrator module, Nucl. Instrum. Methods A 936 (2019) 115–116, http://dx.doi.org/10.1016/j.nima.2018.10.066.

[16] The ATLAS Collaboration, ATLAS approved plots, URL https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ApprovedPlotsTileTestBeamResults.