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Performance of the Tile Calorimeter Demonstrator system for the ATLAS Phase-II Upgrade

Edward Khomotso Nkadimeng[a,*] **and on behalf of the ATLAS Tile Calorimeter Group**

[a] *School of Physics and Institute for Collider Particle Physics, University of the Witwatersrand, Johannesburg, South Africa*

E-mail: edward.khomotso.nkadimeng@cern.ch

The HL-LHC will deliver five times the LHC nominal instantaneous luminosity, after a series of upgrades scheduled to take place in 2025 - 2027 during the long shutdown. The ATLAS TileCal will require the complete replacement of the readout electronics in order to accommodate its acquisition system to the increased radiation levels, trigger rates, and high pile-up conditions during the HL-LHC era. The upgraded readout electronics will digitize the PMT signals from every TileCal cell for every bunch crossing and will transmit them directly to the off-detector electronics. In the counting rooms, the off-detector electronics will store the calorimeter signals in pipe lined buffers while transmitting reconstructed trigger objects to the first level of trigger at 40 MHz. The TileCal upgrade project has undergone an extensive research and development program as well as several test beam campaigns. A Demonstrator module has been assembled using the upgraded on-detector electronics for data taking during Run 3. The Demonstrator module is operated and read out using a prototype TilePPr which also permits integrating the Demonstrator module into the present ATLAS TDAQ system. This contribution presents the status and performance of the Demonstrator module in the ATLAS experiment.

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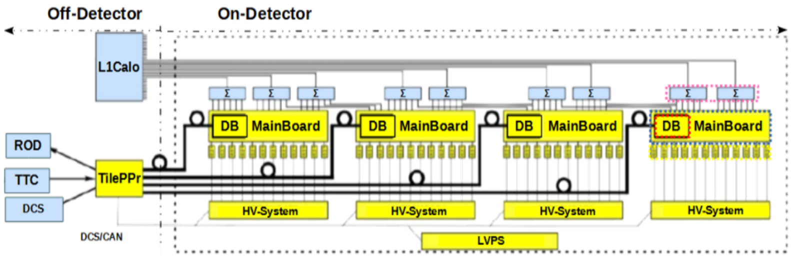

Figure 1: Block diagram of the Demonstrator read-out chain (yellow) interfacing with TileCal legacy electronics (blue) [1].

1. Introduction

The upgraded version of the LHC accelerator, HL-LHC [1], is expected to have a peak luminosity which represents a five-fold increase past the initial designed luminosity value. A Toroidal LHC ApparatuS (ATLAS) is a general purpose detector designed to explore proton-proton collisions and heavy ion collisions. The increase in integrated luminosity will correspond to an average of 200 simultaneous proton-proton interactions per bunch crossing. The ATLAS TileCal which covers the central region of the ATLAS experiment is a sampling calorimeter using iron as the absorber and plastic scintillator as the active material and divided longitudinally into three cylindrical barrels. The partition scheme of the barrels consists of two central long barrel segments (LBA, LBC) and shorter extended barrel segments (EBA, EBC) at each end. Each partition is comprised of 64 wedge-shaped segment modules.

The light from two sides of a TileCal cell is collected by wavelength shifting fibers and transported to the core element of the two photo-multiplier tubes (PMTs), the photo-multiplier being used for converting the incoming photons into an electrical signal [1]. Close to 10 000 PMTs are used in the TileCal where each PMT produces analogue signals that are shaped, conditioned and amplified into two gains, before being digitized every 25 ns. The full set of data generated in the detector is expected to be fully digitized for the HL-LHC and sent off-detector using the PreProcessors (PPr) for every bunch crossing before any selection is applied. The new design is expected to deliver better timing and energy resolution, with less sensitivity to out-of-time pileup. In order to evaluate the new readout architecture and the technology choices of the implementation, completely new on-detector and off-detector electronics are being developed, aiming to compensate for increased trigger rates and high-performance data acquisition. A hybrid demonstrator prototype coupled to a calorimeter module were tested in the Super Proton Synchrotron (SPS) accelerator complex. Data were collected with beams of muons, electrons and hadrons of various incident energies and impact angles. This was done to validate the calibration and to determine the performance of the upgraded electronics [1, 2].

2. Phase-II Upgrade readout chain and demonstrator system

The new architecture of the TileCal points to a full digital trigger system with high precision and granularity to improve event selection. Figure 1 diagram shows the readout chain for the

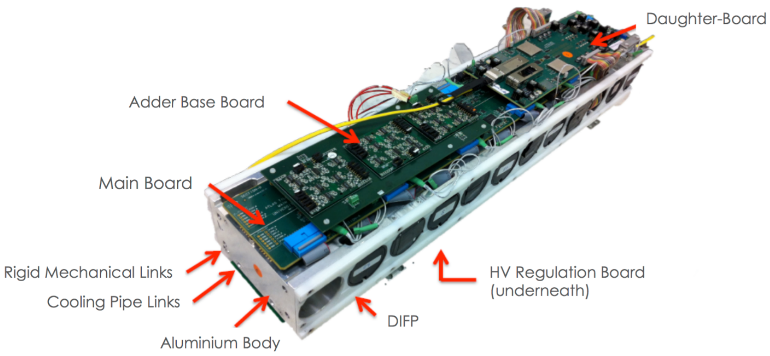

Figure 2: The TileCal Demonstrator mini-drawer for the HL-LHC. It incorporates the following mechanics aluminium body, Delrin Plate and cooling pipes, 12 PMTs, HV Regulation Board, a Main Board, a Daughter Board and the Adder Base Board, which are only required for analog triggering in the Demonstrator [2].

Phase-II Upgrade where the demonstrator represents a fully functional Phase-II read-out prototype compatible with the current system (i.e. legacy system), as seen in Figure 2. The Demonstrator module provides energy measurements for every calorimeter cell as well as the analog trigger sums that are sent to the current Level-1 trigger. The Demonstrator is composed of a Superdrawer (SD) that partitions a legacy TileCal drawer into four Minidrawers, each servicing up to 12 PMT channels. The SD will continuously digitize two gains of up to 48 TileCal PMTs and send the digitized sampled data to the off-detector systems at 40 MHz. Calorimeter samples corresponding to each cell are simultaneously sent to the off detector electronics at 40 Mhz, using the new read-out architecture through optical links [1, 2].

The Off-detector electronics will be used to reset data in the pipeline buffers waiting for a trigger decision and, in parallel, providing the reconstructed data to the trigger system. The reconstructed information includes calibrated energy per cell or group of cells. After the trigger decision, the selected data will be transferred to the central ATLAS data acquisition system. The PreProcessor is the core element of the back-end system, providing communication with the front-end to transmit commands and to receive the digitized PMT data [1, 2]. Following the received trigger signal, the data are sent off-detector to be stored in pipelines, reconstructed and triggered-out by the TileCal PPr that receives legacy Timing Trigger and Control commands and triggers, Detector Control Systems commands, and sends the triggered data to a legacy read out driver.

3. Phase-II Demonstrator status and Testbeam results

A stack of three TileCal modules consisting of the updated front-end electronics has been exposed to the beams of the SPS at CERN. These modules were stacked on top of a scanning table that allows rotation at different angles with respect to the SPS H8 beamline. The SPS H8 beamline comprises of trigger scintillators in coincidence, Cherenkov counters for beam particle identification and wire chambers for measuring the lateral coordinates of the beam particles. The beams were produced by $E_{\text{beam}} = 400\,\text{GeV}$ protons from the SPS complex and delivering secondary and tertiary beams by placing beryllium and polyethylene in the path. These beams are expected to

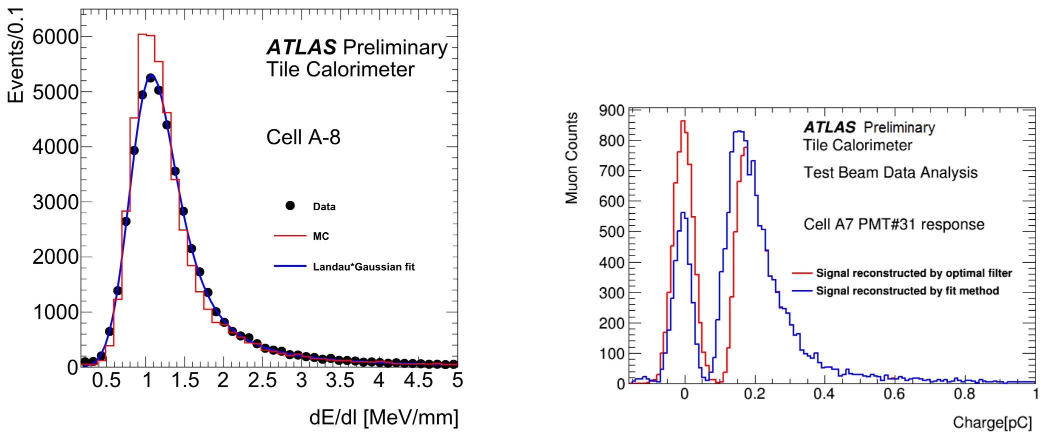

Figure 3: Distribution of the quantity dE/dl for the cell A-8 obtained using experimental (full points) and simulated muons (solid lines) at -90° hitting in the middle of Tile-row 2. The data are fitted with a Landau function convoluted with a Gaussian (blue curve). Results are given using September 2017 Testbeam data corresponding to both plots. Simulated results obtained using the Geant 4.10.1 [3–5] and the muon signal reconstructed using the fit method and Optimal Filter when 165 GeV muons are hitting the LBC of the Demonstrator, at - 90 ° (cell A7 PMT 31 reaction) (right) [3–5].

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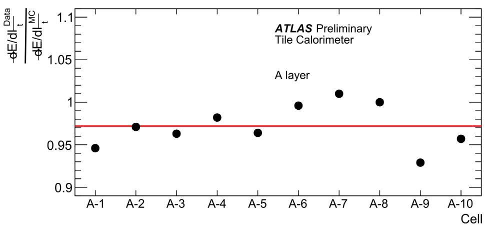

Figure 4: Ratios of the truncated means of the distributions of the energy deposited in the A layer cells per unit of path length obtained using -90°; experimental and simulated muon data are shown as a function of the cell number. The horizontal line corresponds to the mean value of the determinations. Results are given using September 2017 Testbeam data. Simulated results were obtained using the Geant 4.10.1 [3, 5].

be for the most part made out of pions, protons, electrons, muons, as well as kaons [3]. Presented are a few results showing the response of the various particles with different beam energies and incident angles. Results obtained using experimental data are compared to simulations obtained utilizing the GEANT4 toolkit [4]. The ATLAS software framework (Athena) is used to reconstruct the raw data stored in the Event Builder as well as the Front-End LInk eXchange (FELIX) to energy and time per cell. This operation is performed online for some events for monitoring. The muon matter interaction has been studied and thoroughly understood. In Figure 3 (left) we see the TileCal response to high energy muons follow a Landau type distribution with characteristically long tails at increasing high energies.

The peak value of the signal divided by the muon path length, displays a significant residual dependence on the path length. Instead, the mean value of the measured muon energy loss spectrum truncated at 97.5% of the total number of entries. The truncated mean was preferred

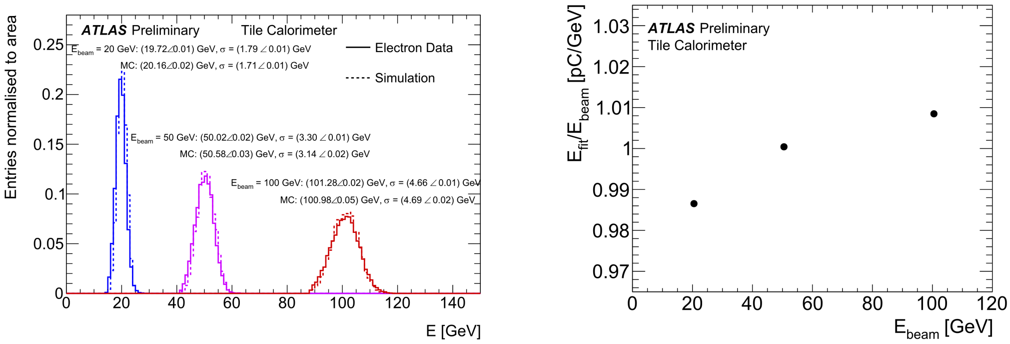

Figure 5: Distributions of the total energy deposited in the calorimeter obtained using electrons beams of 20, 50 and 100 GeV incident in the cell A-4 of the middle layer of the stack at 20 °. The solid (dashed) distribution corresponds to experimental (simulated) data (left). Simulated results were obtained using the Geant 4.10.1 [5] and ratios E_{fit}/E_{beam} obtained using electrons beams of 20, 50 and 100 GeV incident in the cell A-4 of the Demonstrator module at 20 °. Results are given from the September 2017 Testbeam data (right) [3, 5].

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to the full one because it is less affected by rare high energy loss processes. The response of the detector has been studied determining the ratio between the energy deposited in a calorimeter cell (dE) and the track path-length in the cell (dl) using 165 GeV muons at an incident angle of -90° [1]. Figure 3 (right) shows the amplitude reconstructed using both the optimal filter and fit methods which give identical results for good signals above noise thresholds. The peak at zero represents the noise events reconstructed without iterations whereas the peak above zero effectively selects events which have some signal above the noise threshold. The behavior for the small signals is due to different noise thresholds where 5 ADC counts in Optimal filter and 3.2 ADC counts in fit method. The ratio of experimental and simulated dE/dl values was defined for each calorimeter cell. In Figure 4 the Data/MC ratio for all of the A-cells are displayed. The horizontal red line corresponds to the mean value of the determination where layer A reached a uniformity of 1% and a maximum offset of 4% was observed. Figure 5 (left) the responses of E_{beam} = 20, 50, and 100 GeV electron beams incident on the center of cell A-4 at 20 degrees were measured. For a given beam energy the experimental and the simulated shapes are very similar proving the purity of the selected experimental electron samples. The solid (dashed) distribution corresponds to experimental (simulated) data. The linearity of the calorimeter response to electrons was checked in the range of 20-100 GeV as seen in Figure 5 (right).

The hadron response was extracted using a Gaussian fitted within the range ± 2σ around peak value (Figure 6) (left). The width of the distributions is defined as a standard deviation of the fit function. The low energy peak is due to muons coming from kaon decays. Figure 6 (right) shows the measured energy response as function of the beam energy. The agreement with the simulated results obtained using the Geant 4.10.1 improves with increase of the beam energy. The agreement Data/MC is better than 5% for measured response and better than 12% for measured width [5].

[1]The angle of incidence particularly 90 ° alludes to the test beam when incident on the side of a module in which the cell numbers are the smallest and the angle of incidence of 90° which refers to the side in which the cell numbers are the largest

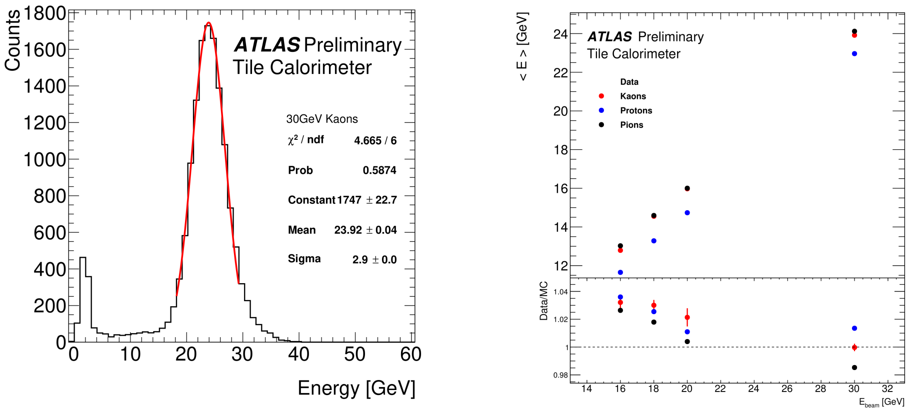

Figure 6: Distribution of the measured energy for 30 GeV kaons. The Gaussian function fit, performed in the range ±2 centred on the peak value is shown (left). The low energy peak is due to muons [3] and Kaon/Proton/Pion energy extracted and filled for multiple beam energies (right) [5]. Results are given using September 2017 Testbeam data corresponding to both plots.

4. Conclusion

Several Testbeam campaigns took place between 2015 and 2017 with three detector modules at the SPS accelerator complex. The results obtained using muons, electrons and hadrons are in agreement with the calibration settings obtained using the TileCal Phase-II Upgrade electronics that are being evaluated which have resulted in overall good performance of the new electronics, and agreement with simulated data and calibration. The tests on the Demonstrator were successful and the Demonstrator proves the good performance of the electronics to be used in HL-LHC. Research and development is ongoing for the TileCal Phase-II upgrades and more tests are being planned in 2022. Demonstrator upgrade prototypes have been produced and tested with beam while maintaining backwards compatibility, with the Demonstator having already been inserted inside ATLAS.

References

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