Test Beam Studies for the ATLAS Tile Calorimeter Upgrade Readout Electronics

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Abstract. The ATLAS Tile Calorimeter will need to upgrade the readout electronics for the High-Luminosity LHC era. In order to test the new electronics, they were implemented in a module that was then exposed to test beams of muons, electrons and hadrons of different energies and incident angles. The data collected was analysed to test the response of the prototype. The results show good agreement with the expected response and confirm the good performance of the new electronics for the TileCal upgrade.

1. Introduction
The Tile Calorimeter (TileCal) [1] is the hadronic calorimeter of the central part of the ATLAS (A Toroidal LHC ApparatuS) detector [2]. Located in the CERN accelerator complex in Geneva (Switzerland), the ATLAS detector is one of the experiments of the Large Hadron Collider (LHC) [3]. Consisting of a 27-kilometer ring and with a design center-of-mass energy of $\sqrt{s} = 14$ TeV, the LHC is the biggest hadron collider in the world. An upgrade to the LHC is planned to increase its luminosity from the nominal $10^{34}$ cm$^{-2}$ s$^{-1}$ to about 5 to 7 times larger in what is referred to as the High-Luminosity LHC (HL-LHC), expected to be fully operational in 2026.

The upgrade of the LHC will present significant challenges for the experiments, which will have to upgrade consequently some of their components. The Tile Calorimeter, specifically, will upgrade the readout electronics to cope with the increased rate and pileup. In order to test the new electronics, test beam studies were performed on a spare module equipped with the full new readout electronics using electron, muon and hadron beams at the Super Proton Synchrotron (SPS) at CERN. The results confirm the good performance of the upgrade prototype.

An overview of the ATLAS detector and the Tile Calorimeter is given in section 2. The main aspects of the upgrade for the readout electronics of TileCal are summarized in section 3. The setup used for the test beam is described in section 4, and the results with different particle beams are presented in section 5.

2. The ATLAS detector and the Tile Calorimeter
The ATLAS detector is a multipurpose particle detector located at the LHC. It consists of several layers of concentric subdetectors around the beam, which have different functions in the particle detection, identification and measurement. The closest to the interaction point is

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the inner detector, which detects the trajectories of charged particles, and is embedded in a solenoidal magnetic field. Outside of it, the Electromagnetic Calorimeter is designed to detect, measure and contain electromagnetic showers. It uses liquid argon as active material and lead as absorber. The next layer is formed by the hadronic calorimeter, which is composed of three main parts: The central part $|\eta| < 1.8$ is covered by the Tile Calorimeter, while the Hadronic End-cap Calorimeter covers the region $1.8 < |\eta| < 3.1$ and the Forward Calorimeter (FCal) extends up to $|\eta| < 4.9$. The hadronic calorimeter system is designed to contain and measure hadronic showers. Both the HEC and FCal use liquid argon as active material, while TileCal uses plastic scintillators. Finally, the Muon Spectrometer constitutes the outermost layer of the ATLAS calorimeter, immersed in a toroidal magnetic field and designed to identify and measure high-$p_T$ muons. A trigger system is used to select and store only events potentially useful for physics analysis, since the rate of data collected in the detector would be otherwise non-manageable.

![Figure 1. Overview of the ATLAS calorimeter system [4].](image)

The Tile Calorimeter layout is shown in figure 1. It is divided into four partitions, two in the long barrel in the central part ($|\eta| < 0.9$) and two extended barrels on the sides. It is made of plastic scintillating tiles and iron plates. Each of the barrels is subdivided into 64 modules in the azimuthal direction ($\phi$). A scheme of one of these modules is shown in figure 2. The light produced in the scintillating tiles is collected by optic fibers and delivered to photomultipliers (PMTs).

The modules are organised in cells as shown in figure 3, where each cell is read out by two PMTs, except for the E-cells, located in the crack regions, which are read by only one PMT.

3. The ATLAS Tile Calorimeter readout electronics upgrade

The increase of luminosity of the LHC will result in a corresponding increase of particle fluxes through the ATLAS subdetectors, which will face a higher radiation and will require a more efficient trigger and data acquisition systems. Most of the TileCal components will not be replaced, like the scintillator tiles, the PMTs, the absorbers and the fibers. However, the readout system will undergo significant changes.

The front-end electronics will be replaced with a new system [4] that will provide fully digital trigger data at 40MHz (instead of the current rate of 100kHz) with higher reliability and precision. The new electronic readout system is shown in figure 4.
4. Test Beam setup

In order to test the performance of the new electronics, a prototype (also referred to as “demonstrator”) was exposed to test beams of different particles, energies and incident angles [4]. The data used for the studies presented in this document were collected in September 2017 with the layout schemed in figure 5. Simulated samples were obtained using the GEANT4 toolkit [5] and PYTHIA 8 [6]. Three Cherenkov counters are placed in the beam line for particle identification. Two scintillators are also present in the beam line, used in coincidence to trigger the data recording, together with two beam chambers that measure the beam position.

Three modules were located on the scanning table, which is able to move and rotate at any desired angle, and exposed to the test beam, one of them (demonstrator) including all the new electronics for the TileCal upgrade. The data for the analyses shown were collected with the demonstrator module, which is calibrated at the electromagnetic (EM) scale.
5. Test Beam results

5.1. Results with muons

Muons are expected to lose energy mostly through ionisation as they cross the calorimeter. The high-energy muons used for the studies travel all the way through the module, and the energy lost in the process is essentially proportional to the path length.

Data were collected with a muon beam of 165 GeV/c incident on the module at 90 degrees, in the middle of each of the Tile rows shown in figure 2. The events used for the analysis are required to have a total deposited energy between 700 and 15000 MeV.

The response of the demonstrator to muons was studied in terms of the deposited energy over the path length \( \langle dE/dl \rangle \), and studies were performed independently for each cell. As it can be seen in figure 6, the deposited energy follows a Landau distribution.

![Figure 6. Muon energy deposited over path length for cell A8 in data (full black points) and simulation (red line). A fit to a Landau function convoluted with a Gaussian is also shown (blue line) [4].](image)

The muon response for the different cells, \( \langle dE/dl \rangle \), is calculated as the truncated mean of the 97.5% distributions of \( dE/dl \). The results shown in figure 7 include the response to muons in all cells and shows the ratio of the data over simulation,

\[
R = \frac{\langle dE/dl \rangle_{\text{Data}}}{\langle dE/dl \rangle_{\text{MC}}}. \tag{1}
\]

In this way, most non-linearities arising from the truncated mean calculation are avoided. In the figure, it can be seen that the maximum offset of the data/MC ratio is of about 6%, and the mean values of the different layers are consistent.

5.2. Results with electrons

Electron data were collected with beams of 20, 50 and 100 GeV/c particles incident at the center of cell A4 at an angle of \( \theta = 20 \) degrees. Electrons are expected to deposit all their energy in the calorimeter, such that \( \langle E \rangle / E_{\text{beam}} \sim 1 \), where \( \langle E \rangle \) is the mean energy deposited.

For the electron analysis, a more sophisticated selection is needed in order to identify a clean electron sample. Two variables are defined for this purpose, \( C_{\text{long}} \) and \( C_{\text{tot}} \) [7]. The variable \( C_{\text{long}} \) gives a measure of the longitudinal profile of the shower and its depth. It is defined as the ratio of energy deposited in the first two layers of the module and the total beam energy

\[
C_{\text{long}} = \frac{2}{\sum_{i=1}^{2} \sum_{j=1}^{3} \frac{E_{ij}}{E_{\text{beam}}}}, \tag{2}
\]

where \( j \) runs on three contiguous cells of layer \( i \) centered around the beam, and \( E_{ij} \) is the energy deposited in a certain cell.
The variable $C_{\text{tot}}$ measures the transverse profile and the spread of the shower

$$C_{\text{tot}} = \frac{1}{\sum_c E_c^\alpha} \sqrt{\frac{1}{N_{\text{cell}}} \sum_c \left( E_c^\alpha - \frac{1}{N_{\text{cell}}} \sum_c E_c^\alpha \right)^2}.$$  \hspace{1cm} (3)

Here $E_c$ is the energy deposited in a given cell, and $N_{\text{cell}} = 9$ is the number of cells considered. The exponent $\alpha = 0.6$ was determined from simulation to maximize separation between the electron and the hadron samples. These variables are used together to select a clean electron sample, as it can be seen in figure 8. The cuts on $C_{\text{long}}$ and $C_{\text{tot}}$ applied are different depending on the energy of the beam. For a beam of 100 GeV/c, events with $C_{\text{long}} > 0.88$ and $C_{\text{tot}} > 6.5$ are selected. For a low-energy beam (20 GeV/c), $C_{\text{long}} > 0.75$ and $C_{\text{tot}} > 2.1$ is used, and an additional requirement on the Cherenkov counters Ch1 and Ch3 to have a signal of at least 500 ADC counts is applied.

The distribution of the total energy deposited follows a gaussian distribution. This is shown in figure 9. The agreement between data and simulation illustrates that the electron selection is very efficient. The electron response is determined by fitting the total energy deposited as a function of the impact point in the X axis (along the beam axis in the ATLAS detector and in figure 3) to a periodic function of the form

$$E(X) = p_0 \left[ 1 + p_1 \sin \left( \frac{2\pi X}{p_2} \right) \right],$$  \hspace{1cm} (4)

where $p_0$, $p_1$ and $p_2$ are parameters of the function. The periodicity is due to the periodical structure of the tiles in the module. The parameter $p_0$ is the mean energy around which the oscillations occur, named $E_{\text{fit}}$ as well. The electron response is obtained by comparing this parameter to the beam energy. The result is shown in figure 10, where the ratio of $E_{\text{fit}}$ to the beam energy is displayed as a function of the beam energy. The results show that the total deposited energy calculated from the fit is within 2% of the beam energy. This can be taken as an estimate of the precision on the EM scale calibration performed before the start of the data taking.
5.3. Results with hadrons

The demonstrator was exposed to hadron beams of 16, 18, 20 and 30 GeV/c incident in cell A3 with a projective angle. The particle identification is done using the cherenkov counters located upstream the beam line. Figure 11 shows the scatter plots of each of the counters versus total energy deposited for a beam of 18 GeV/c. The requirements used for the selection of protons, kaons and pions is shown in the figures. First, the pions and electrons (kaons and protons) are selected by requiring Ch1 and Ch3 signals to be larger (lower) than 400 and 420 ADC counts, respectively. The two plots on the right show Ch2 vs total energy after applying a selection on Ch1 and Ch3. An extra requirement on Ch2 < 460 ADC is applied for protons, Ch2 > 460 ADC for kaons, or Ch2 > 3900 ADC for pions.

The determination of the response for hadron signals is done with a gaussian fit, with a reduced range of 2σ around the peak. As it can be seen in figure 12, the total energy distribution shows a secondary peak at low energy due to muons resulting from pion and kaon decays on fly. With the reduced range, the fit to the gaussian does not take into account this and the fit to the kaon energy is more accurate.

The results of the gaussian mean and σ are shown in figures 13 and 14. The response to protons is lower than to pions and kaons, as expected. The agreement between data and simulation increases with high energies. As shown in figure 14, the energy resolution of the demonstrator is better for protons than kaons and pions.
Figure 11. Signal in Ch1 and Ch3 counters (left) and Ch2 (right) for a 18 GeV/c hadron beam versus total energy. On the plots on the right a selection for electron/pion (top) or proton/kaon (bottom) has already been applied on the Ch1 and Ch3 signals. The particle identification of the clusters is shown in the figures, as well as the criteria used for their selection [4].

Figure 12. Distribution of total energy for a 30 GeV/c beam with kaon selection applied. The secondary peak on the left is due to muons from kaon decay. The gaussian fit is performed within 2\(\sigma\) of the main peak [4].
6. Conclusions

The ATLAS TileCal readout system will be upgraded for the HL-LHC era. The new components were exposed to test beam to study the response of the calorimeter to different particles. Studies performed with beams of 165 GeV/c muons incident at 90 degrees prove the uniformity of the calorimeter response, and the expected linearity of the muon deposited energy with the path length is observed. The electron analysis was performed with data of 20, 50 and 100 GeV/c electron beams incident at 20deg on cell A4. Good agreement between data and simulation was found, and the energy deposited in the demonstrator was within 2% of the beam energy. Hadron data collected for 16, 18, 20 and 30 GeV/c beams were analysed, showing good agreement with simulation, and the expected higher response to kaons and pions with respect to protons.

These results confirm the good performance of the new electronics for the Tile Calorimeter upgrade, and good agreement between calibrated and simulated data.

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