ATLAS Tile Calorimeter performance for single particles in beam tests

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Abstract. The modules of the ATLAS Tile hadronic calorimeter underwent extensive tests in the test beams at CERN. Studies were carried out with electrons, muons and hadrons ranging in energy from 10 GeV to 350 GeV. The Tilecal calibration systems and energy reconstruction algorithms were also studied in great details, the associated systematics has been evaluated. The updated calibration scheme led to improved linearity and uniformity of the response.

Electrons and muons were used to set and understand the electromagnetic (EM) scale and the uniformity of the calorimeter. The pion response shows the expected behaviour with energy. The performance of the real Tile calorimeter modules to pions in terms of linearity and resolution corresponds well to that of earlier Tilecal prototype modules, after accounting for the different lengths and segmentations of the calorimeters. The experimental results are also compared to MC simulation samples.

1. Introduction
The ATLAS experiment at the CERN Large Hadron Collider (LHC) is designed for precise measurements and fundamental discoveries in proton-proton collisions at the center-of-mass energy of 14 TeV. Calorimeters represent an indispensable part of the ATLAS detector system. The electromagnetic lead/liquid argon (LAr) calorimeter followed by the hadronic Tile calorimeter cover the central region of the ATLAS detector, other LAr based calorimeters span across the forward regions [1].

The Tile Calorimeter (Tilecal) is a hadron iron/plastic scintillator calorimeter. It consists of three cylinders – one central barrel (LB) and two extended barrels (EB) on its sides. Every cylinder is composed of 64 modules, each covering the azimuthal angle of $2\pi/64 \approx 0.1$ [2].

Tilecal modules are made of alternating layers of iron plates and scintillating tiles. The tiles are placed parallel to the incoming particles and radially staggered in depth. A schematic drawing is given in Fig. 1. The scintillating tiles are read-out by wave-length shifting (WLS) fibers on both sides of the module. These fibers deliver the light to photo-multipliers located in the outer iron structure that also houses the front-end electronics. Each cell is readout by 2 PMTs.

The calorimeter modules are segmented into three radial compartments. These compartments are further subdivided into cells of the dimension $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$ ($0.2 \times 0.1$ in the third radial compartment).
Figure 1. Mechanical structure of a TileCal module, showing the slots in the iron for scintillating tiles and the method of light collection by WLS fibers to PMTs. Radially, tiles are organized in eleven rows (tilerows) of different size.

1.1. Tilecal beam tests
The final Tilecal modules have been extensively tested with electron, muon and hadron beams, ranging in momentum from 10 to 350 GeV/c. Altogether, 11% of all modules were exposed to SPS beams in H8 beam-line at CERN during the years 2000 – 2003.

The modules under tests were placed on the scanning table, that could be positioned at various \( \eta, \phi \) and \( z \) with respect to the incoming particle beams. A typical setup is drawn in Fig. 2. The stack consisted of the very first barrel module (so-called module 0) in the bottom, one LB module in the middle and either two EB modules or another LB module in the top.

The main goals of this testing program were to set and measure the energy-to-charge conversion factor, to explore the uniformity of the response and to determine the calorimeter performance at projective pseudorapidities.

In order to address these goals, data were taken in various configurations:

- Electrons impinging at the angle of 20° measured from the \( \eta = 0 \) direction were used to determine the EM scale as well as the uniformity of the cells in first radial compartment.
- Muons entering at ±90° were used to address the uniformity of the modules over all cells. Electron data were taken in this configuration too in order to determine the uniformity of the cells on the module edges. Beams impinging at ±90° were also used for special studies, e.g. hadron shower profiles [3], light-yield measurement etc.
- Runs at projective pseudorapidities were used to assess the detector performance in the “ATLAS”-like configuration. The attention was focused on the pion linearity and resolution, however the performance to electrons and muons was also explored.

2. Tilecal calibration systems
The Tilecal design includes four calibration and monitoring systems:

- Cesium (Cs) source system, that monitors the scintillators and PMTs responses
- minimum bias system for precise in-situ monitoring and (relative) luminosity measurement
- laser system, that monitors the PMT and front-end electronics
• charge injection system (CIS) to calibrate the front-end electronics

While Cs-source and minimum bias systems share the slow integrator readout (samples with approx. 100 Hz frequency), laser, CIS and physics data are readout through pulsed electronics chain that samples every 25 ns [4].

The Cs-source system and CIS are crucial for setting up the EM scale of the modules in the beam tests, therefore their main features are highlighted below.

2.1. Cesium source system
The Cs-source system is designed to measure the quality of the optical response of each calorimeter cell. Using this system, the response of every cell is equalized prior to the particle data taking. The $^{137}\text{Cs}$ radioactive source is passing at normal incidence through holes in every tile and absorber plate of the calorimeter, as indicated in Fig. 1.

Since the Cs-source movement through the calorimeter is very well controlled, one can reconstruct amplitudes of the individual tile responses (see Fig. 3). The gain of the cell is then determined as the average amplitude over all tiles in that cell.

2.2. Charge injection system
The pulse readout electronics for each PMT contains two analog scales, referred to as high- and low-gain. Both are digitized with 10-bit ADC. This bi-gain system allows to measure energies up to 1.6 TeV/cell, while it is still sensitive to small signals e.g. from muons.

CIS is designed to inject well-defined charge into both scales and to provide the respective conversion factors. Dedicated studies showed that a non-linearity up to 2% occurs in the low-gain due to the high-gain analog circuit saturation (see Fig. 4). The measured dependence is used offline for correcting data acquired via the pulsed electronics chain.

The uncertainty associated with the ADC performance and the calibration constant determination has also been evaluated [5]. It is below 0.7% for single particle response over the full energy range. The impact on jet energy measurement will be even smaller, since much more channels will be involved.

3. Data analysis
3.1. Event selection
The beams in are usually a mixture of electrons, muons and hadrons. In order to measure the response to a given particle type, a careful event selection has to be performed. Two kinds of selection criteria were combined – the beam and particle separation cuts.

The beam cuts require a MIP-like signal in upstream beam scintillators to avoid upstream showering and/or double particle events. The angular spread and impact point, measured by two x-y wire chambers, was also restricted in order to avoid halo particles that potentially have incorrect beam energy.

Particle selection criteria:

• Muons, that leave only small signal in the calorimeter, are selected by a cut on the total energy. The muon wall also assisted in the detection of high-energy muons that pass through the whole calorimeter.

• The electron/pion separation relies on the difference in size between the compact EM showers and rather large hadron showers. The average density is used for this purpose:

$$A_D = \frac{1}{N_{\text{cell}}} \sum_{i=1}^{N_{\text{cell}}} \frac{E_i}{V_i}$$  (1)
Figure 3. The Cs-source signal measured in one PMT as a function of the source position. The signal (middle curve) is obtained by subtracting the leakage estimate (bottom curve) from raw data (top curve). The individual tile amplitudes (full circles) are obtained by fitting the signal by a sum of pulse shape functions for individual tiles.

Figure 4. The non-linearity in low-gain as mapped with CIS. Horizontal axis indicate the true injected charge, the vertical axis shows relative difference between the measured and true charge.

Figure 5. Example of electron/pion separation for $E_{\text{beam}} = 20$ GeV. The average density defined by Eq. (1) is used as a baseline, the Cerenkov counter signal is used to improve the selection. The two lines denote the applied cuts, the bottom left region corresponds to pions selected for further analysis.

where $E_i$, $V_i$ denote the energy and volume of the $i$-th cell. For beam energies $E_{\text{beam}} \leq 20$ GeV, the threshold Cerenkov counter is used to further improve the separation. An example is shown in Fig. 5.

- Apart from muons, electrons and pions, the positive-charged beams also contain a considerable fraction of protons. The pion:proton share is energy dependent and ranges approximately from 3:1 at 50 GeV up to 1:4 at 180 GeV. The threshold Cerenkov counter with appropriate settings is used for pion/proton separation.

3.2. Corrections applied to raw data
In all the analyses, the raw calorimeter data are corrected for dead channels. The energy is recovered by considering twice the signal from the second PMT reading the same cell in case the first PMT is malfunctioning.

The possible impact of the electron/pion separation procedure on the total pion response was also carefully studied. Since the event selection is based on the shower shapes, the pion events
Figure 6. The muon response summed up over the whole LB module length in the 90° configuration. Mean value of muon signal truncated at 97.5% of the total number of entries (TM97.5) was adopted as the definition of the calorimeter response. Results are averaged over 5 LB modules for every tilerow, the error bars represent the corresponding RMS spreads. Vertical dotted lines indicate the individual radial compartments in the LB module.

with high EM content tend to be classified as electrons. This may lead to underestimation of the total pion response. The possible bias has been studied with MC and also with nominal pion beams, that contain only negligible fraction of electrons (as opposed to nominal electron beams, where the electron:pion ratio typically ranges from 1:1.5 to 2:1 depending on the energy and the exact beam settings). It was found that the above mentioned electron/hadron separation procedure causes an underestimation of the total pion response by less than 0.4% in electron runs, nevertheless we correct for this effect. The impact on the pion energy resolution was found negligible.

The real beam energy is calculated for every run using the data of the bending magnet and collimator settings in the beam-line. As a result, the real beam energies are slightly different for nominal pion and electron beams. The calculation also takes into account the synchrotron radiation of electrons, therefore electrons have lower energy than pions even in the same nominal electron beam.

Other two corrections are described in more detail in the following Sections 3.2.1, 3.2.2.

3.2.1. Particle/Cs correction. High-energy muons entering the calorimeter modules at ±90° are used to study the uniformity of the individual cell response and to ensure that the EM scale is kept along all cells.

To check the EM scale in individual tilerows, the muon signal was summed up over the whole tilerow (i.e. approximately 6 m in LB and 3 m in EB modules). An example for LB modules is shown in Fig. 6, after the gains of all PMTs were equalized with Cs. The signal is clearly underestimated in the second and third radial compartment. This effect is due to trapezoidal shape of the tiles. The signal in a tile increases along the radial direction from the edge at lower radius to that at higher radius (approximately by ∼ 1%/cm). Since Cs pipes run through the tiles close to their upper edge, the Cs signal is bigger than that induced by particles passing through the center of the tile, which in turn well represents the average signal over the tile surface.

The same result was obtained with electrons entering the tile-centers in 90° configuration and was further confirmed by special 137Cs and 90Sr source measurements.

This effect is corrected for by applying weights in individual radial compartments\(^1\). The weight in the first radial compartment is set to one, in order to preserve the EM scale as

\(^1\) The individual tilerow corrections cannot be applied for beams entering at projective pseudorapidities, since every PMT collects the signal from several tilerows in the given cell.
Table 1. The weights to correct for the particle/Cs difference, averaged over several analyzed modules. Statistical errors are shown as well.

| Compartment | Barrel | Extended barrel |
|-------------|--------|-----------------|
| 1           | 1.000  | 1.000           |
| 2           | 1.025 ± 0.002 | 1.009 ± 0.005 |
| 3           | 1.088 ± 0.005 | 1.055 ± 0.003 |

determined with electrons at 20°. The weights in the second and the third radial compartment are evaluated as the ratio of the mean muon responses in the respective tilerows.

The pattern observed in the EB modules is very similar to that shown in Fig. 6 for LB modules, nevertheless the weights differ due to different radial segmentation. Whereas the second and third radial compartment in LB modules is composed of six and two tilerows respectively, four tilerows constitute both second and third radial compartment in EB modules. The weights are averaged over all modules analyzed. Their values are listed in table 1.

3.2.2. Corrections for calorimeter length

The pion response is corrected for the longitudinal leakage, that has been measured in the 90° configuration [3], see Fig. 7. The results presented in Section 3.3.2 are rescaled for an infinitely long calorimeter. This approach also enables a simple comparison to beam-tests results of earlier prototype Tilecal modules [2], that were radially longer – 9.30 λ at 20°, while final modules are 7.84 λ long at the same impact angle.

The energy resolution scales with the calorimeter length too. In order to compare the energy resolution for pions between the final and prototype calorimeter modules (see Section 3.3.2), the results from prototype modules were rescaled for the length of final modules. The measurements performed in 90° configuration were used to determine the scaling factor, see Fig. 8.

3.3. Results

The results reported in this paper come from recently re-calibrated data acquired during the beam test periods 2002 – 2003.
3.3.1. Electromagnetic scale  The EM scale is measured with electron beams. As the calorimeter response to electrons slightly depends on the impact angle (due to sampling fraction frequency that also changes with incident angle), the EM scale is determined at a fixed angle in all modules. The angle of 20° was chosen for this purpose; it corresponds to pseudorapidity $\eta = 0.35$.

Electrons at the incidence angle of 20° were shot into all cells of the first radial compartment, entering the cell-center. The mean response measured over all such cells in all tested modules determines the EM scale factor, see Fig. 9. The uniformity of the response is fully explained by the tile-to-tile response variation (see also Fig. 3) as has been demonstrated by MC simulations.

3.3.2. Response to pions  The important parameters of a hadronic calorimeter are the response linearity and the associated energy resolution to incoming hadrons.

The pion response is shown in Fig. 10 relative to the beam energy of incident pions, after all corrections mentioned in Section 3.2 have been applied. The results demonstrate that Tilecal is a non-compensated calorimeter, the pion response is well described by the parameterization proposed by Fabjan [6] with $e/h = 1.36$ [7]. MC results (Geant4.8.3 using QGSP and Bertincascades models) match well the experimental data.

The energy resolution for pions is shown in Fig. 11. The data were fitted by the standard energy resolution formula

$$\frac{\sigma}{E} = \frac{A}{\sqrt{E_{\text{beam}}}} \oplus C$$

The fit results in $A = (52.7 \pm 0.9)\%$, $C = (5.7 \pm 0.2)\%$. The results are in reasonable agreement with MC simulations (same version as for linearity studies).

Defined as Gaussian mean fitted on the signal spectrum in the range from $-2\sigma$ to $+2\sigma$ around this Gaussian mean value.
Earlier prototype data results\textsuperscript{3} have been rescaled to the final Tilecal module length (see Section 3.2.2). A fair agreement is observed between the prototype and final Tilecal modules, as can also be appreciated from Fig. 11.

4. Conclusions

A big effort has been invested into understanding many details of the Tile calorimeter calibration and its performance for particles.

The calibration systems have been investigated in great details. The procedure to reconstruct the Cs-signal and to determine the gain of a cell has been improved as well as our understanding of the pulsed electronics calibration.

The EM scale was measured with electrons and the charge-to-energy conversion factor has been determined. The cell-to-cell uniformity as observed with electrons at 20° incidence has been explained by the variation in individual tile responses.

Muons provide a tool to check the EM scale in all cells of the calorimeter. The analysis of muon response resulted in additional particle/Cs correction that restores the EM scale in second and third radial compartment.

The response to pions has been carefully studied. The pion linearity curve, after correcting for all known effects, scales logarithmically with beam energy as expected. The results with final modules are compatible with recent MC simulations and also similar to results from earlier prototype modules. The energy resolution for pions corresponds well to that of prototype modules. It is also well reproduced by MC simulations.

The experience at the beam tests should allow to calibrate all Tilecal channels at the EM scale with a precision of 1 – 2%.

References

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\textsuperscript{4} Anderson K et al 2005 \textit{Nucl. Instr. and Meth. A} \textbf{551} p 469

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\textsuperscript{6} Fabjan C W Ludlam T 1982 \textit{Ann. Rev. Nucl. Part. Sci.} \textbf{32} p 335

\textsuperscript{7} Akhmedaliev S et al 2000 \textit{Nucl. Instr. and Meth. A} \textbf{449} p 461

\textsuperscript{3} It should be noted that the energy resolution parameters $A, C$ quoted for prototype modules in Ref. [2] are better due to longer calorimeter. Moreover, the linear sum was used in the fit instead of the quadrature sum in formula (2).