Studies of the response of the ATLAS Tile Calorimeter to beams of particles at the CERN test beams facility

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ATLAS Tile Calorimeter – Introduction

- Measures energies of hadrons, jets, $\tau$-leptons and contributes to the $E^\text{miss}_T$ reconstruction
- 4 partitions: EBC, LBC, LBA, EBA
  - LBC and LBA form Long barrel (LB) → coverage: $|\eta| < 1.0$
  - EBC and EBA form Extended barrel (EB) → coverage: $0.8 < |\eta| < 1.7$
- Each partition has 64 modules → to achieve full azimuthal coverage around the beam axis
  - One module hosts up to 48 photomultiplier tubes (PMTs)
- Sampling calorimeter built from plastic scintillator tiles and steel absorber plates
- A particle traversing the detector generates light in the scintillators, which is collected on both sides of the tile and further transported to the PMTs by wavelength shifting (WLS) fibres
- Around 10,000 readout channels
The readout cell geometry is given by a group of WLS fibres from individual tiles coupled to PMTs.

Usually, a cell is read out by two PMTs, with each corresponding to a single channel.

The cell energy is then reconstructed as the sum of energies measured by two channels.

The radial segmentation divides the module into three layers – A, BC (B in the EB), D.

Layers comprise of cells with different dimensions.

Dimensions of A and BC cells are $\Delta \eta \times \Delta \phi = 0.1 \times 0.1$.

Dimensions of D cells are $\Delta \eta \times \Delta \phi = 0.2 \times 0.1$. 
TileCal Phase II Upgrade

Complete replacement of on-detector and off-detector readout electronics for the High Luminosity LHC

- To be compatible with full digital TDAQ (analogue system will be replaced) and all information from the TileCal cells will be sent to the trigger system at 40 MHz
- Radiation and time ageing (will be 20x higher than legacy)
- Redundancy in data links and power distribution → Improvement in the system reliability

Top: current system (legacy). Bottom: upgraded system

- Shaping is done in the front-end board located in the PMT base, digitisation on the Mainboard, high-speed communications on the Daughterboard. The off-detector PPr processes and streams data to the DAQ system and trigger processors through the TDAQi module.
Demonstrator project and plans

- Evaluation of the new readout schema and trigger system interfaces
- Showed a good performance and calibration during several test beam campaigns (TB)
- **A Demonstrator module was inserted into the ATLAS Detector in July 2019**
  - Fully integrated in the current system
  - Stable performance, low noise, good signals from calibration runs
  - Will operate in ATLAS during the Long Shutdown 2 and possibly Run 3
- Readout architecture for HL-LHC keeping backward compatibility with the legacy system
  - New 3-in-1 cards (FENICS): Provide analogue trigger signals to the current ATLAS trigger system
  - Physics and calibration data readout through the legacy Read Out Drivers (RODs) and the Front End Link Exchange (FELIX)
Demonstrator module

One module is composed of 4 mini-drawers (48 PMTs)
Each mini-drawer has 2 independent read out sections for redundant cell readout

- 12 PMTs + 12 front-end boards reading out 6 TileCal cells
- 1 x MainBoard: provides low voltage and controls to the 3-in-1 cards, digitises their signals, and routes the data to the link DaughterBoard
- 1 x DaughterBoard: handles all high-speed communication with the back-end electronics preprocessor (PPr)
- 1 x High Voltage regulation board
- 1 x Adder base board + 3 adder cards: trigger analogue signals
- 1 x Low Voltage Power Supply (LVPS): low voltage power distribution
Test beam setup

- Located at the Super Proton Synchrotron (SPS) North Area – H8 beam facility
- Three detector modules equipped with legacy and upgraded electronics
  - **LBC65** with the Upgraded 3-in-1 cards → DEMONSTRATOR module
  - **LBA65** equipped with FATALIC (alternative to the 3-in-1 front-end option)
  - **M0 C** and **EBC65** – Legacy SD
  - **M0 A** equipped with Multi-Anode (MA) PMTs
Beam Line

Beams produced by extracting 400 GeV protons from the SPS

- Primary target (beryllium) → secondary beams with energies from 10 to 350 GeV
- Secondary target (polyethylene + lead absorber) → tertiary beams

Beam line elements:

- **3 Cherenkov counters** – Ch1, Ch2 and Ch3
  - Separate $p/K/\pi/e$ for beam energy < 50 GeV
- **2 trigger scintillators** – S1 and S2
  - Used in coincidence to trigger the data acquisition and provide the trigger timing
- **2 wire chambers** – BC1 and BC2
  - Monitor the transverse beam profile
Scatter plot of the Ch1/Ch3 signals (left/right) vs. the energy measured in the calorimeter in the case of 18 GeV particle beams
Test beam results with:

- **Muons**
  - The high-energy muons available at the H8 beam-line traverse the entire TileCal modules for any angle of incidence, so we are able to **study of the module response** in great detail through their entire volume.
  - The dominant energy loss process is the **ionisation** and the energy lost is essentially **proportional to the muon track path length**.
  - Muons deposit approximately 300-600 MeV in TileCal cells.
  - Muon data allows us to **verify the new electronics performance by checking the equalisation of the cell response**.

- **Electrons**
The muon response has been studied determining the ratio between the energy deposited in a calorimeter cell \((dE)\) and the track path-length in the cell \((dl)\).

The energy is obtained as the sum of the reconstructed energy in the each PMT of a cell.

To define the muon response we used a truncated mean, \(\langle dE/dl \rangle_t\) → preferred as it is less affected by rare high energy loss processes wrt the full mean.

The blue curve is a fit of Landau function, convoluted with a Gaussian, to the data.

Cuts used to purify the muon beam:

- BeamChamber cuts: selecting correct region for response
- Cut on the total energy \(E_{\text{tot}} < \sim 16\) GeV: to reject other particles in the beam
- At least one PMT with high signal \((E > \sim 0.06\) GeV): to reject false trigger muons
Muons: $dE/dl$ vs. cell

Furthermore, we measured the uniformity of the cells response in one layer.

The ratio of the experimental and simulated truncated means was defined for each calorimeter cell:

$$R = \frac{\langle dE/dl \rangle_t^{\text{Data}}}{\langle dE/dl \rangle_t^{\text{MC}}}$$

The red horizontal lines - the mean values of $dE/dl$ for each layer.

The data show a layer uniformity at 1% and a maximum offset of 4%.

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Test beam results with:

- **Muons**

- **Electrons**
  - Used to determine the electromagnetic scale
    - We measure signals of beam particles at known energies and calculate the average charge-to-energy conversion factor in pC/GeV
  - Used to verify the linearity of the response vs. energy
Electrons: Identification (I)

Particle beams at H8 beam facility are a mixture of electrons, hadrons and muons

- **To reject muons** we require the total measured energy to be $E_{\text{tot}} > 5 \text{ GeV}$

- **To separate electrons/hadrons** we used two shower profile criteria, namely $C_{\text{long}}$ and $C_{\text{tot}}$, which exploit the difference of electromagnetic and hadronic showers profiles in the calorimeter

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

- $C_{\text{long}}$ represents the fraction of energy deposited in the first two longitudinal layers
  - $j$ runs over 3 adjacent cells of the layer $i$ centred around the beam
  - $E_{ij}$ is the energy measured in a cell

\[
C_{\text{tot}} = \frac{1}{\sum_{c} E_{c}^{\alpha}} \left( \frac{1}{N_{\text{cell}}} \sum_{c} \left( E_{c}^{\alpha} - \frac{1}{N_{\text{cell}}} \sum_{c} E_{c}^{\alpha} \right) \right)^{2},
\]

- $C_{\text{tot}}$ measures the spread of the energy deposited in the calorimeter cells
  - $E_{c}$ is the energy cell $c$
  - $N_{\text{cell}} = 9$ stands for the total number of cells considered
  - exponent $\alpha = 0.6$ was tuned using a MC simulation to achieve max $e$/had separation
Electrons: Identification (II)

- Variables $C_{\text{long}}$ and $C_{\text{tot}}$ are used for electron/hadron separation
  - Example in the plot 50 GeV beam hitting on the A4 cell
  - The region on the right/top corresponds to electrons, the other to hadrons

- The cut on $C_{\text{long}}$ ($C_{\text{tot}}$) depends on the beam energy
  - ranges from 0.75 (2.1) at 20 GeV to 0.88 (6.5) at 100 GeV
Electrons: Data vs. MC comparison

- Distributions of the total energy deposited in the calorimeter in case of electrons beams of 20, 50 and 100 GeV incident in the cell A4 are shown.

- For a given beam energy the experimental and the simulated shapes are in good agreement proving the purity of the selected experimental electron samples.
The linearity of the calorimeter response to electrons was checked using electron beams with energies of 20, 50 and 100 GeV incident in the cell A4.
Summary

▶ High Luminosity upgrade of the LHC plans to increase the instantaneous luminosity by a factor of 5-10
  ▶ Electronics will have to withstand a much higher radiation dose as well as an increased demand for data throughput
  ▶ Upgraded electronics will be installed during the LS 3 (2025 – mid-2027)

▶ Seven test beam campaigns during 2015 and 2018
  ▶ Three TileCal modules equipped with the updated front-end electronics were exposed to the SPS beams at CERN
  ▶ All prototypes extensively tested and showed a good performance

▶ Physics results obtained from the TB data confirm good performance of the new electronics
  ▶ These results are in agreement with those obtained using the old electronics

▶ Demonstrator module was inserted in the ATLAS (end of July 2019)
  ▶ Fully integrated in the current system
  ▶ Showing good performance
  ▶ Will operate during LS2 and possibly Run 3
BONUS SLIDES
Electrons: Sampling fraction variation

- Due to the compactness of electromagnetic showers, the electron response varies with the periodicity of the sampling fraction and thus depends on the coordinate of the impact point along the $x$-axis of the front face of the calorimeter.

- The variation is described by a periodic function

$$E_{\text{raw}}(X) = p_0 \left[ 1 + p_1 \sin \left( \frac{2\pi X}{p_2} + p_3 \right) \right]$$

- $p_0$ – mean energy ($E_{\text{fit}}$)
- $p_1$ – relative amplitude of the oscillation
- $p_2$ – period thickness as seen by the beam
- $p_3$ – phase

- 20 GeV electron beam incident in the cell A4

![Graph showing energy vs. X impact parameter]
Separation using topological analysis

- Cherenkov counters not properly tuned → e/had separation was based entirely on topological analysis
- Definition of two discriminating variables $C_{\text{tot}}$ & $C_{\text{long}}$

\[
C_{\text{long}} = \sum_{i=1}^{2} \sum_{j=1}^{3} \frac{E_{ij}}{E_{\text{beam}}} \quad \text{Selected cells (except D-cells)}
\]
\[
C_{\text{tot}} = \frac{1}{\sum_{c} E_{c}} \sum_{c} \left( E_{c}^\alpha - \frac{\sum E_{c}^\alpha / N_{\text{cell}}}{N_{\text{cell}}} \right)^2 \quad \text{Selected cells (N_{\text{cell}} = 24, 3x3 towers in $\eta \times \phi$)}
\]

- Simultaneous cuts on $C_{\text{tot}}$ and $C_{\text{long}}$ define "rectangular" topological regions in C space (2D)

- Separation using topological analysis seems to work quite well

$\alpha = 0.6 \ (10, 20, 50 \text{ GeV})$

$\alpha = 0.38 \ (100 \text{ GeV})$

Stergios Kazakos

Tile TB Data Analysis meeting at Tile week | 12-06-19

→ slide from Stergios Kazakos’ talk at Tile Calorimeter week
Front-end boards: Upgraded 3in1 cards
- PMT pulse shaping
- Shaper with bi-gain output: $2 \times \text{LG} + 1 \times \text{HG}$
- Improved noise and linearity
- Improved calibration circuitry
- Final version: FENICS cards tested during the last testbeam (November 2018)

MainBoard
- Digitize analog signals coming from 12 FEBs
- Routes the digitized data from the ADCs to the DaughterBoards
- Digital control of the FEBs
- HG and LG, 12-bit samples @40 Msps
- TID, NIEL, SEE tests performed

→ slide from Fernando Carrio Argos’ talk at 7th Beam Telescopes and Test Beams Workshop
High-speed link with the back-end electronics
- Data collection and transmission
- Clock and command distribution
- Data link redundancy

Daughterboard version 4
- 2 × Xilinx Kintex 7 FPGAs
- 2 × QSFP modules (~40 Gbps each)
- 2 × GigaBit Transceiver (GBT) chips

New version 5 being qualified
TID tests with ~ 9 MeV electron beam
SEE and SEL tests done with 58 MeV and 226 MeV proton beam
- Soft error rate is low → Triple redundancy
- No destructive effects observed

→ slide from Fernando Carrio Argos’ talk at 7th Beam Telescopes and Test Beams Workshop
TilePreprocessor Demonstrator

First element of the back-end electronics
- Data processing and handling from detector
- Clock distribution towards the modules
- Detector Control System data distribution
- Interfaces up to 4 mini-drawers (one module) through the Daughter Boards → 160 Gbps!

Fully functional prototype
- Xilinx Virtex 7, Kintex 7, 4 QSFPs
- Double mid-size AMC (μTCA / ATCA carrier)
- 1/8th of the full-size PreProcessor for HL-LHC

Used during the testbeam campaigns to validate the new readout electronics
- Keeps backward compatibility with the legacy system: TTC system, RODs
- Triggered events are transmitted to FELIX system

→ slide from Fernando Carrio Argos’ talk at 7th Beam Telescopes and Test Beams Workshop