Calibration System of the ATLAS Tile Calorimeter and its Upgrade for HL-LHC

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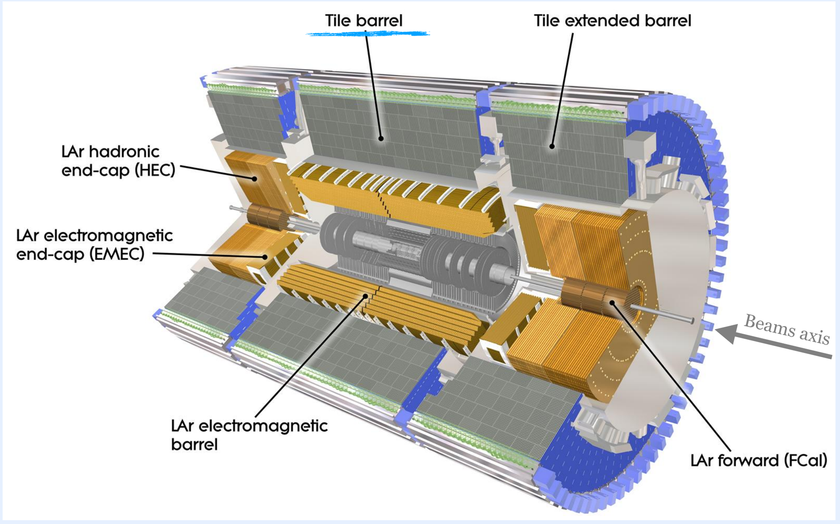
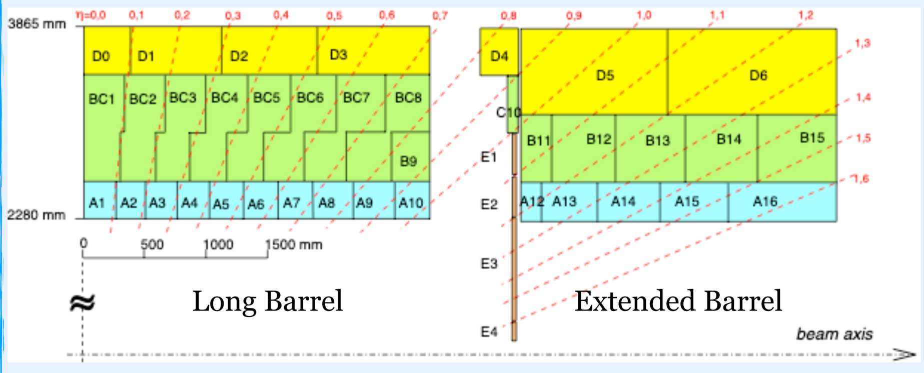
ATLAS Tile Calorimeter (TileCal)

TileCal is the central section of the hadronic calorimeter of the ATLAS experiment. It provides inputs for reconstruction of hadrons, jets and missing transverse energy. It is a sampling calorimeter made up of steel plates and plastic scintillating tiles. Tiles are coupled to optical fibers and read-out by photomultiplier tubes (PMT). The grouping of fibers defines the cells, which are organized in 3 longitudinal layers:



ATLAS inner detector and calorimeters.



TileCal pseudo projective cell layout.

- 1 Long Barrel ($|\eta| < 1.0$);
- 2 Extended Barrels ($0.8 < |\eta| < 1.7$), each composed of 64 modules in Φ, for about 7λ depth.

Dynamic range per cell: 10 MeV - 2 TeV.

Design jets resolution: $\sigma_E/E_{\text{jet}} \simeq 50\,\%/\sqrt{E\,[\text{GeV}]} \oplus 3\,\%$

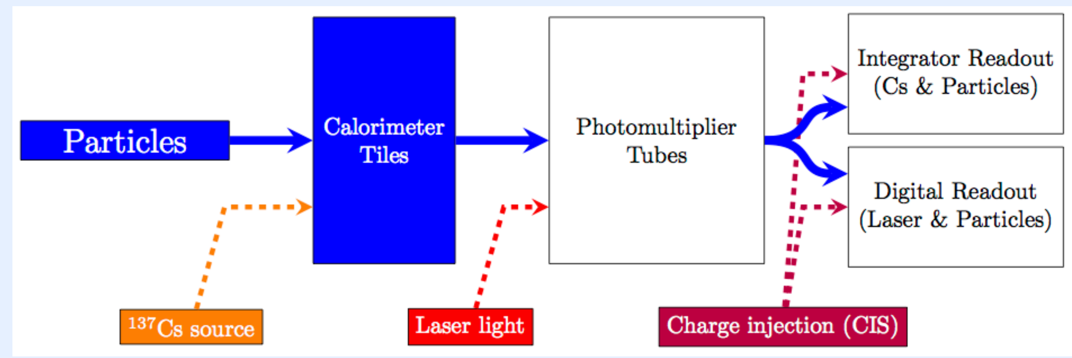
TileCal Energy Calibration

A percent-level calibration of each cell is required to maintain the calorimeter excellent performance. TileCal response is calibrated using 4 systems (*charge injection* (CIS), *Cesium source, laser light, minimum bias* (MB) *signal*) to monitor all parts of the readout chain[1]. The reconstructed energy is given by

$$E_{\text{PMT}}\,[\text{GeV}] = \text{A}\,[\text{ADC}] \cdot \text{C}_{\text{ADC}\to\text{pC}} \cdot \text{C}_{\text{pC}\to\text{GeV}} \cdot \text{C}_{\text{Cs}} \cdot \text{C}_{\text{Laser}} \cdot \text{C}_{\text{MB}}$$

where the correction factors come from:

- Charge Injection system ($\text{C}_{\text{ADC}\to\text{pC}}$), used to monitor the electronics stability;
- $\text{C}_{\text{pC}\to\text{GeV}}$ determined by measuring the modules response to dedicated $e^{\pm}$ test beams;
- Cesium system (C_{Cs}), used to monitor and to equalize individual cells response to the known source;



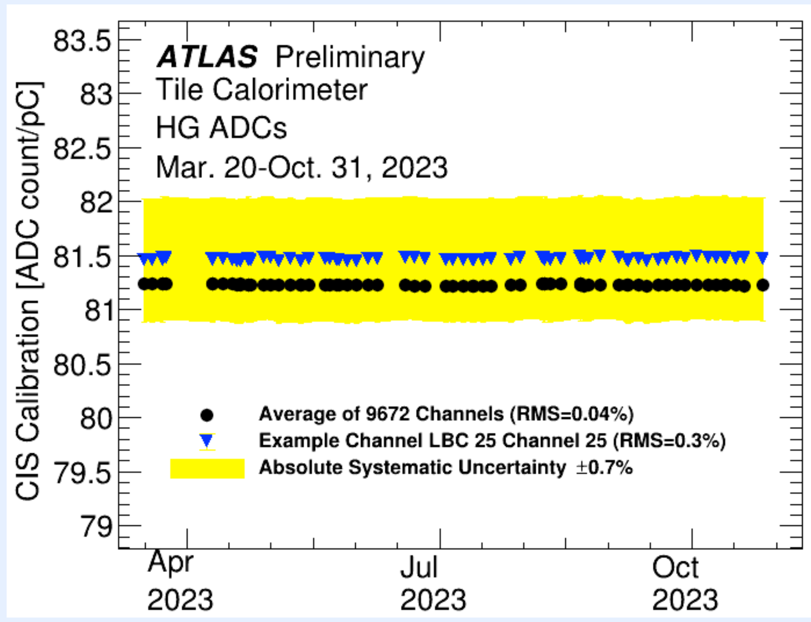
Signal paths for TileCal calibration systems.

- Laser system (C_{Laser}), used to monitor PMT signal stability and timing;
- Charge integration readout of MB events (C_{MB}) used to monitor full optical chain.

Charge Injection system

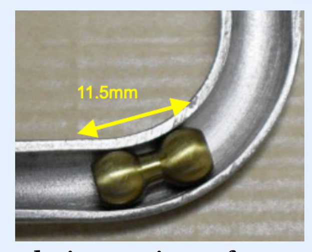
The CIS calibrates the response of the front-end electronics injecting well defined charges in the high- and low-gain ADCs for each PMT signal. The full combined analog range covers the full range of energies expected during regular running of the LHC.

- Determines the amplitude (ADC counts) to charge (pC) conversion factors.
- Used also to calibrate the analogue L1 trigger system.
- Precision is 0.7%, very good stability over time.



High-gain ADC coefficients stability in 2023.

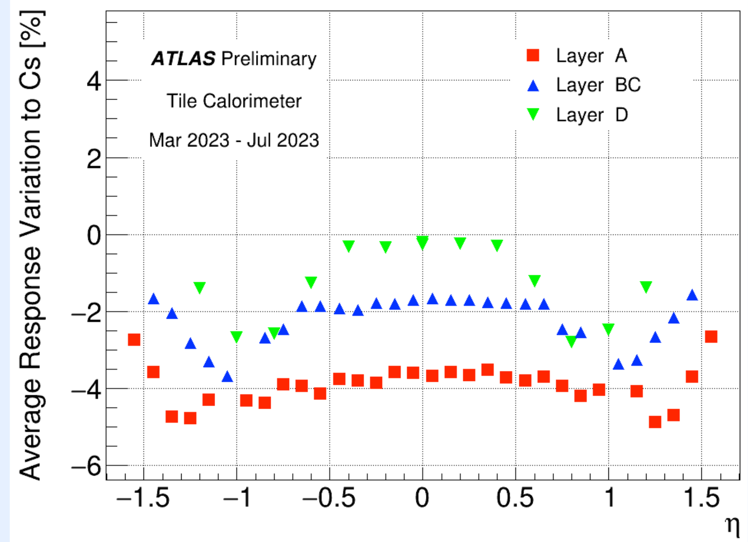
Cesium system



^{137}Cs capsule in section of transport pipe.

Three ^{137}Cs radioactive sources (one for each TileCal barrel) are monthly circulated inside the tiles through dedicated hydraulic circuits. The source emits 0.662 MeV γs that generate scintillation light in each tile, allowing the calibration of the entire optical chain (optic fibers, PMTs, active tiles) and monitoring the detector response over time.

- The precision in a typical cell is ~ 0.3%, up to ~ 0.5% for cells on the extreme sides of the barrels.
- Larger response variations in time are observed for cells closer to the beam line.

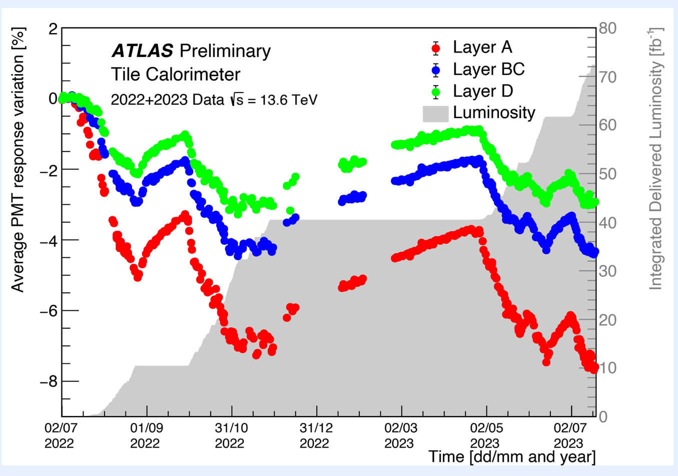


Average response variation of TileCal cells to the Cs source.

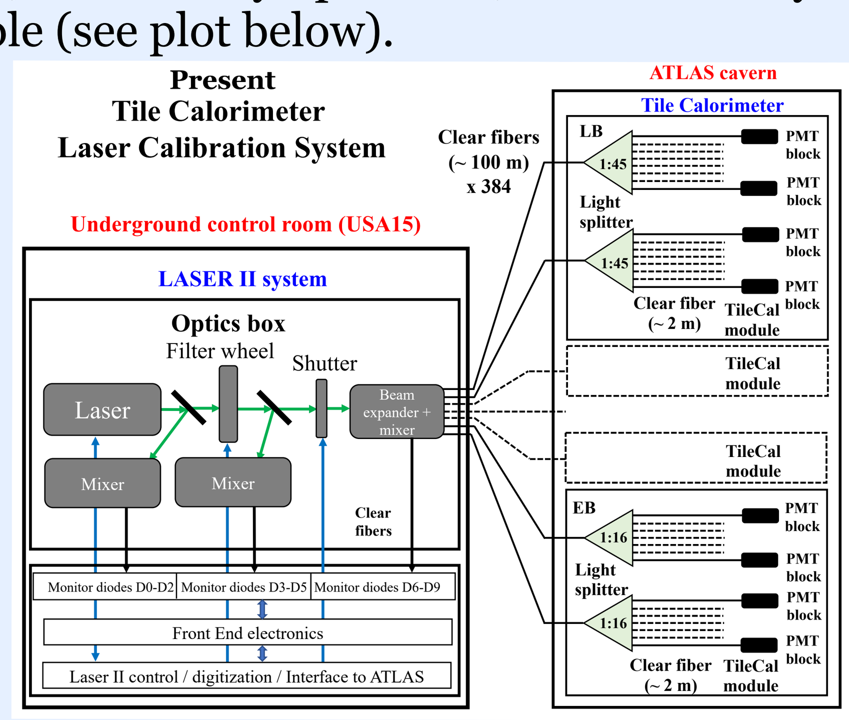
Laser system

TileCal exploits a laser source (532 nm, 10 ns pulse) to calibrate its 9852 PMTs[2]. The laser system is composed by an optics box with the laser source, its readout, control and interface with ATLAS and a fiber light distribution system to each individual TileCal module. Signals are collected in dedicated runs every 2-3 days to monitor the gain and stability of each PMT. Precision of the system is at the level of 0.5%.

- Periods of down-drifts (during *pp* collisions) followed by up-drifts (due to recovery in periods of technical stops) are clearly visible (see plot below).
- During ATLAS physics runs laser pulses are also sent in the LHC empty bunches of the beam to calibrate the calorimeter timing.



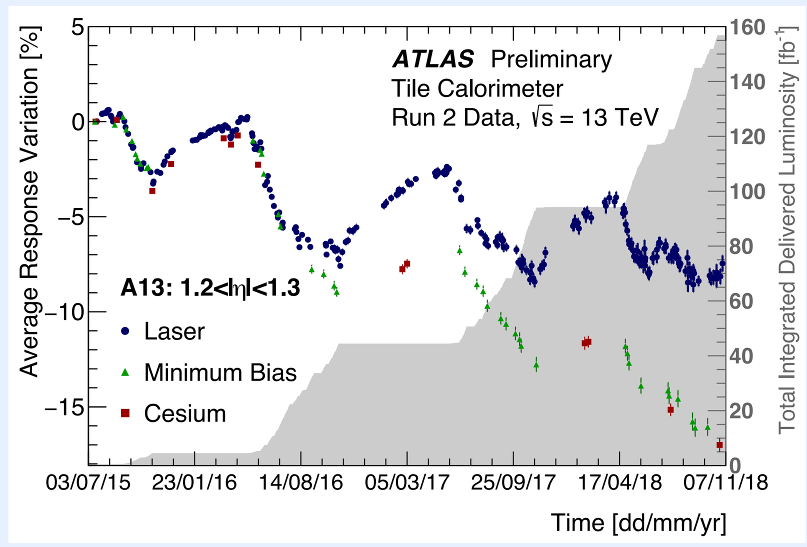
Relative PMT response variation evolution in 2023.



Minimum Bias system

High energy *pp* collisions are dominated by soft parton interactions (MB).

- The integrator readout measures integrated PMT signals over a time ~10 ms and monitors the full optical chain.
- Measured currents depend linearly on the luminosity and they provides an independent measurement of the ATLAS interaction rate.
- At the end of Run 2, the maximum response loss in E4 (E3) special cells was ~ 40% (~ 27%), therefore E3 and E4 scintillators were replaced by new ones after Run2.



Average response to laser, Cesium, and Minimum Bias for the cell A13.

Upgrade for High Luminosity LHC

In preparation for HL-LHC phase, a complete replacement of TileCal on- and off-detector electronics is foreseen[3] (see David Calvet poster).

The TileCal calibration procedures and global architecture will stay the same. However the individual systems will get updated due to the aging of the present components and to be compliant with the new Atlas TDAQ and DCS systems.

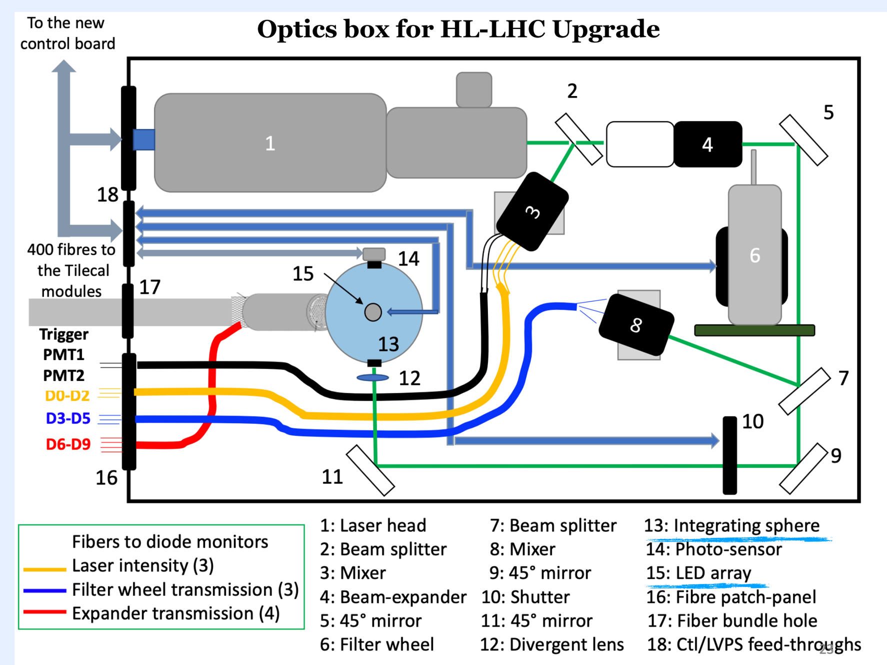
- The CIS calibration will be handled by the FENICS board (Front-End board for the New Infrastructure with Calibration and signal Shaping).
- The Cesium electronics will be replaced and a new hydraulic circuit will be upgraded to improve the system robustness.
- The laser calibration system will undergo an upgrade of the control electronics with the new card ILANA that will interface with trigger and DAQ.

The optical path will be upgraded (see next frame).

New optics of the Laser calibration system

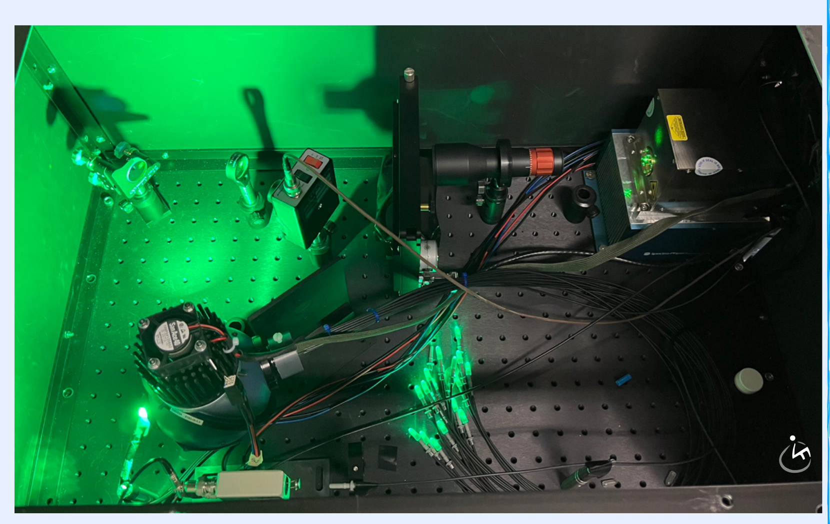
During the analysis of Run2 data it was observed that the PMT response to fixed intensity laser pulses may vary as a function of the average current induced by MB events.

- To mimic the actual regime during collisions, an adjustable DC light component is superimposed to laser pulses.
- A 4-port integrating sphere (Newport 819D IS 3.3) will replace the beam expander in the optic box. It will allow to mix laser pulsed light and DC LED matrix light to provide pile-up current to the PMTs.



Preliminary results

- We successfully verified that the LED matrix (from HTDS) can provide enough DC light to generate up to ~10 μA PMT anode current after the full optical line (including 100 m long clear fiber) ⇒ that is what we expect for the most exposed cells during HL-LHC operations.
- During 3 hours of data taking, it was observed that:
  - integrating sphere temperature is stable (~ 120 °C) and below the operating limit (300 °C);
  - integrating sphere reflectivity is stable within 1%.
- More time stability measurements are currently in progress both in Pisa and at CERN.



New optical line under test at CERN.

Thanks to the TileCal ATLAS group.

[1] *Operation and performance of the ATLAS tile calorimeter in LHC Run 2*, ATLAS Collaboration, arXiv:2401.16034 (2024)
[2] *Laser calibration of the ATLAS Tile Calorimeter during LHC Run 2*, M.N. Agaras et al., 2023 JINST 18 P06023 (2023)
[3] *Technical Design Report for the Phase-II Upgrade of the ATLAS Tile Calorimeter*, ATLAS Collaboration, CERN-LHCC-2017-019 (2017)