Study of Individual Tiles Aging using Cesium Scans

ADRIÁN BERROCAL GUARDIA

ON BEHALF OF THE ATLAS COLLABORATION

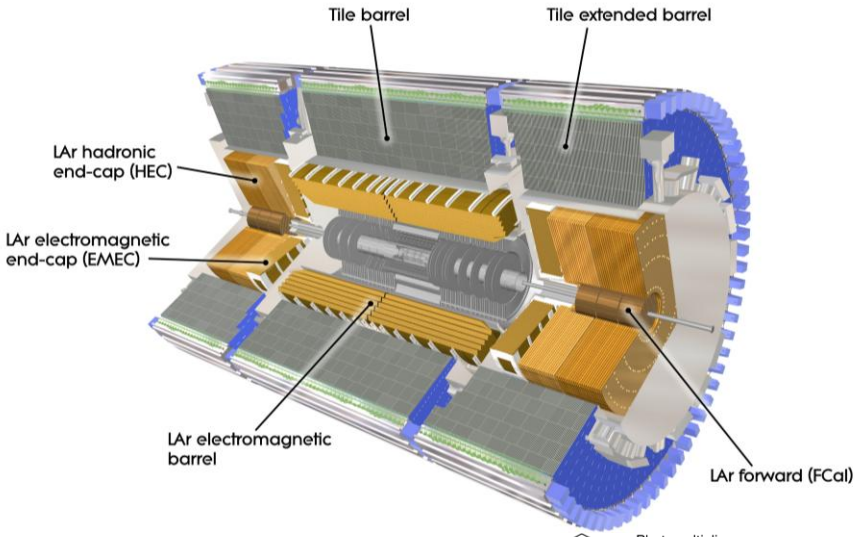
Introduction

ATLAS Tile Calorimeter

Tile Calorimeter (TileCal) is the central **hadronic calorimeter** of the ATLAS detector at LHC. It provides:

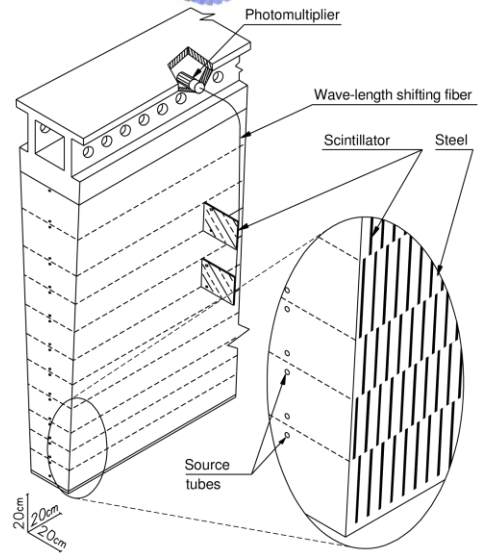
- Information for **reconstruction of hadronic jets,** τ-leptons and **missing transverse energy**.
- Inputs for **L1 trigger** and **muon identification**.

It is divided into **4 parts**: 2 halves of central barrel and 2 extended endcaps.



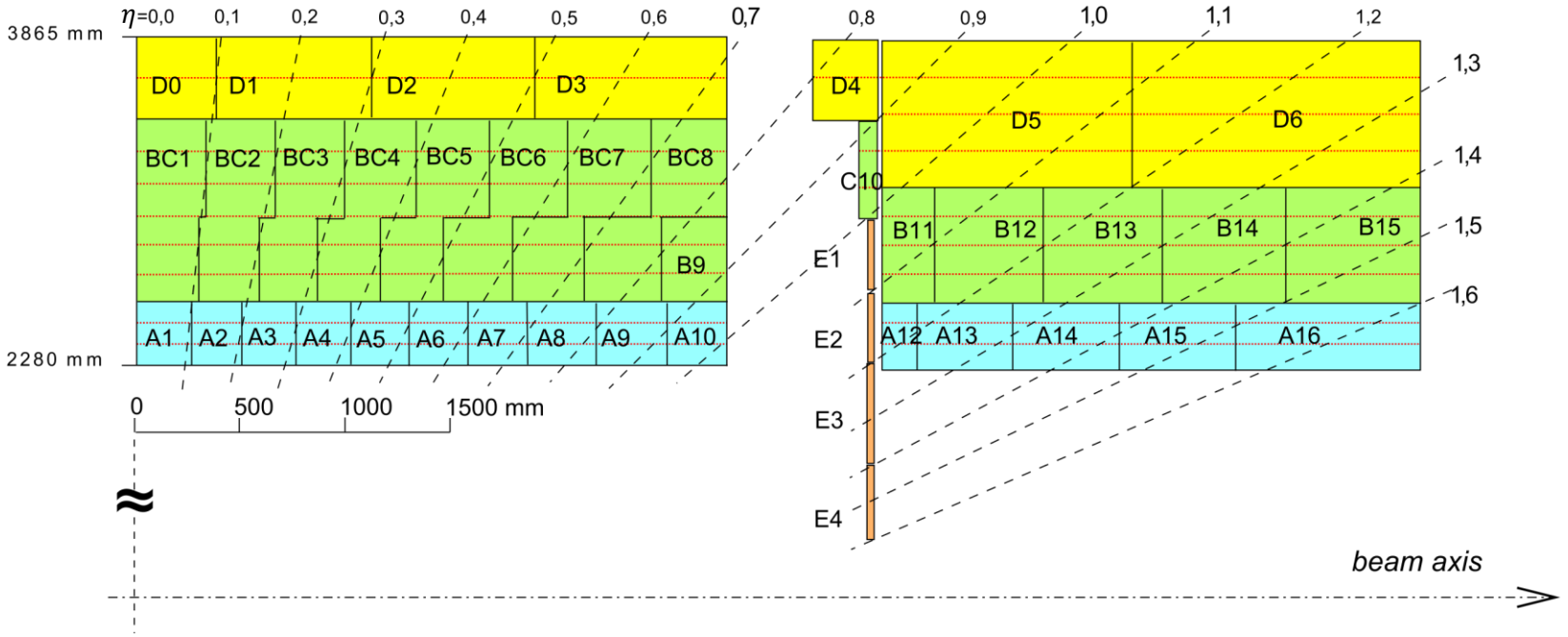
Each partition has **64** wedge shaped **modules** ($\Delta\phi = 0.1$ segmentation):

- The modules are made of **11 rows of plastic scintillating tiles** (active medium) with **steel** (absorber medium) in between.
- Each tile is connected to **two wavelength shifting (WLS) fibres** that transport light to two different **photomultiplier tubes (PMT)**.



Flow of the Particle Signal

- The **tiles** produce **light** when an **ionising particle** passes through, and it is **transmitted to PMTs** via the fibres.
- The fibres are **grouped in radial layers (A, BC/C, D and E) of cells**, so that fibres from a cell are read by the **same PMT**. **Each cell** is formed for several **radial rows of tiles**.
- The signal from PMTs is **read and processed** by **electronics**.
- The **electric signal** is **proportional to the energy** deposited in the cell and depends on response of the **optical components** and the **electronics**.



Schematic showing the TileCal cell mapping.

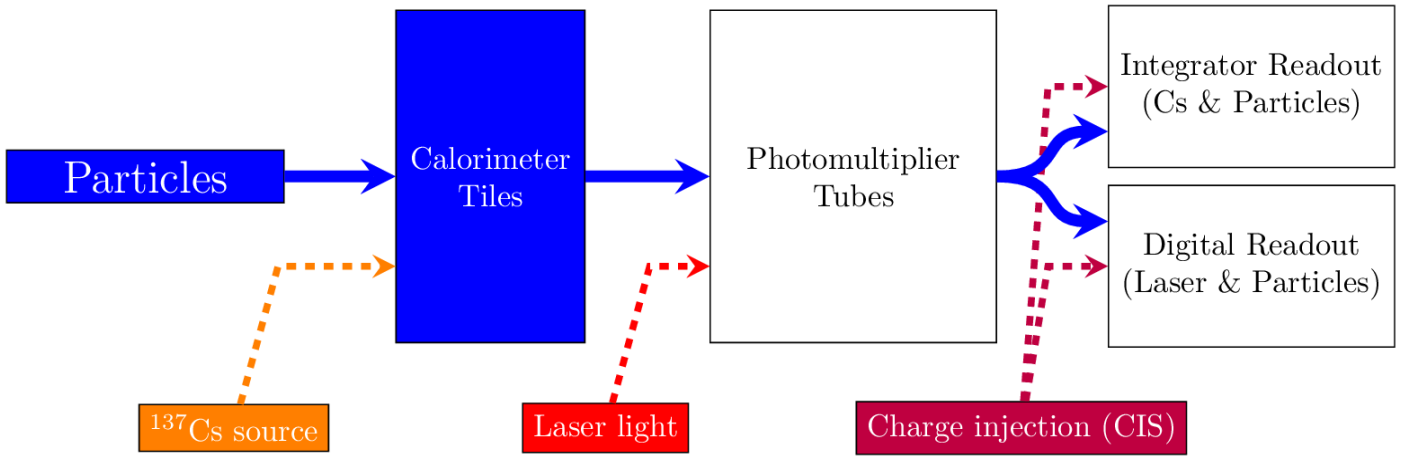
Calibration Systems

- **Three calibration systems** monitor the **response of the TileCal** components.
- They are used to determine the **relation** between **electric signal** and produced **current from the PMT** and to compensate the **variations in the response**.

Cesium system monitors all **optical components** (tiles, WLS, PMT) and the **electronics** on **monthly basis**.

Laser system monitors the **PMTs** and the **electronics** on **daily basis**.

Charge Injection system monitors the **electronics twice a week**.



The signal paths for each of the three calibration systems used by the TileCal.

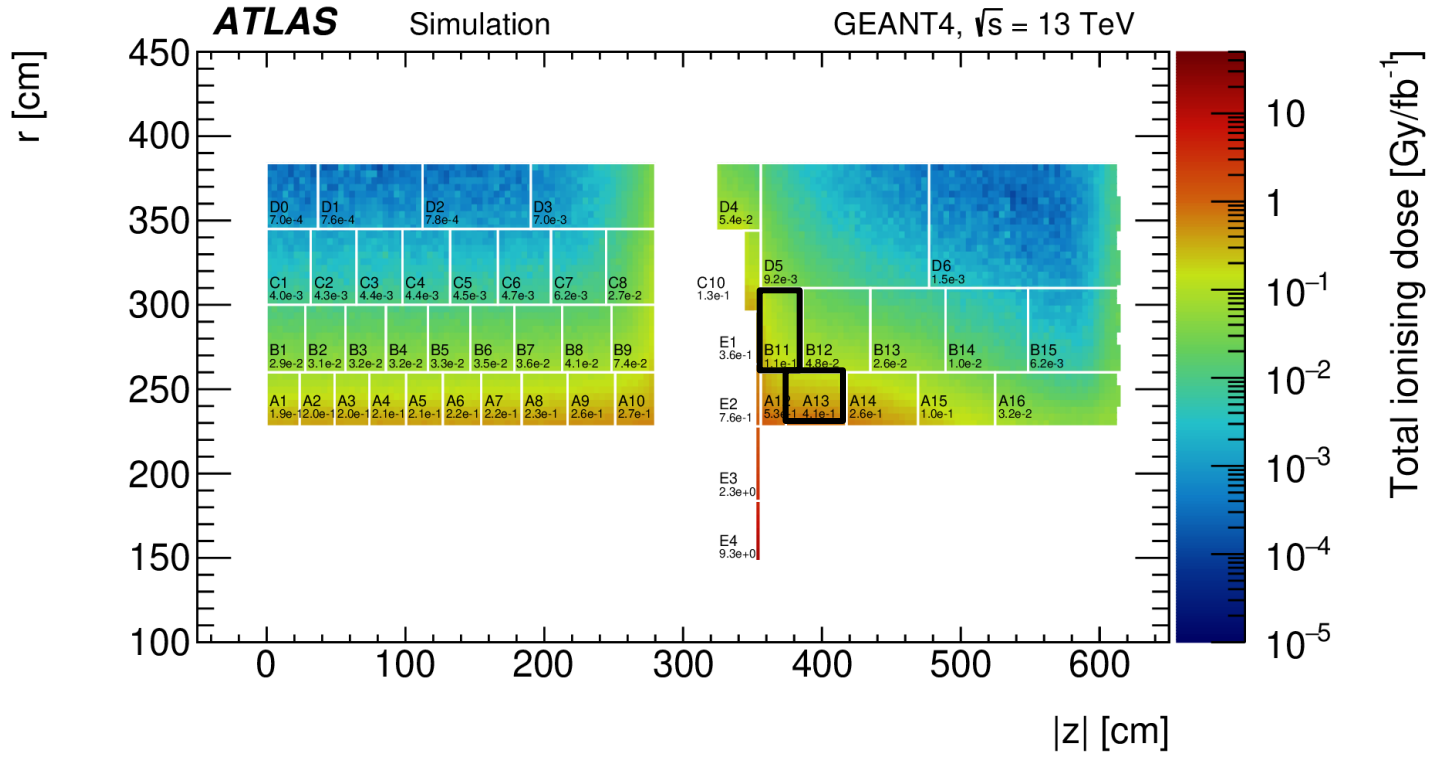
Radiation Environment

Optical components suffer **damage** due to the **energy** deposited by **ionising processes** per unit of mass of the material, which is called **total ionising dose** (TID).

The parts of the detector that are **closer to the interaction point** and/or are **less shielded** receive **more TID**.

Differences in the damage **between cells**, but also **between tiles**.

Possible **changes** in the **uniformity** of the **cell responses**.



Simulated TID obtained using 50000 inelastic proton-proton collisions at $\sqrt{s} = 13$ TeV and normalized to $\sigma_{inel.} = 78.42$ mb and $\mathcal{L}_{int} = 1$ fb^{-1}.

Motivation

- The damage in optical components affects their **energy-light conversion** (light yield output, I).
- This radiation will **significantly increase** in future data-taking periods, where an integrated luminosity of ~**4000fb^{-1}** is expected.
- We should **study** and try to **predict the performance** of TileCal.
- Two quantities, which can affect **jet energy resolution**, were studied:
  - The **average response** of the cells.
  - The **uniformity** of the cell responses.
- These studies can be found in the paper pre-print [1] (accepted by JINST).

Methodology

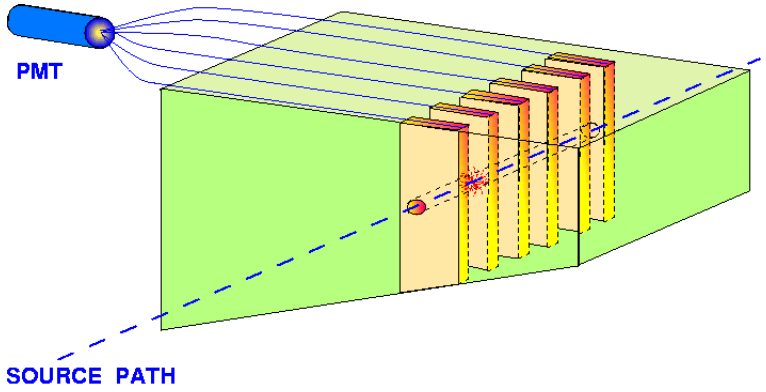
Cesium System

A 137-**cesium source** passes through **tubes inside the tiles**.

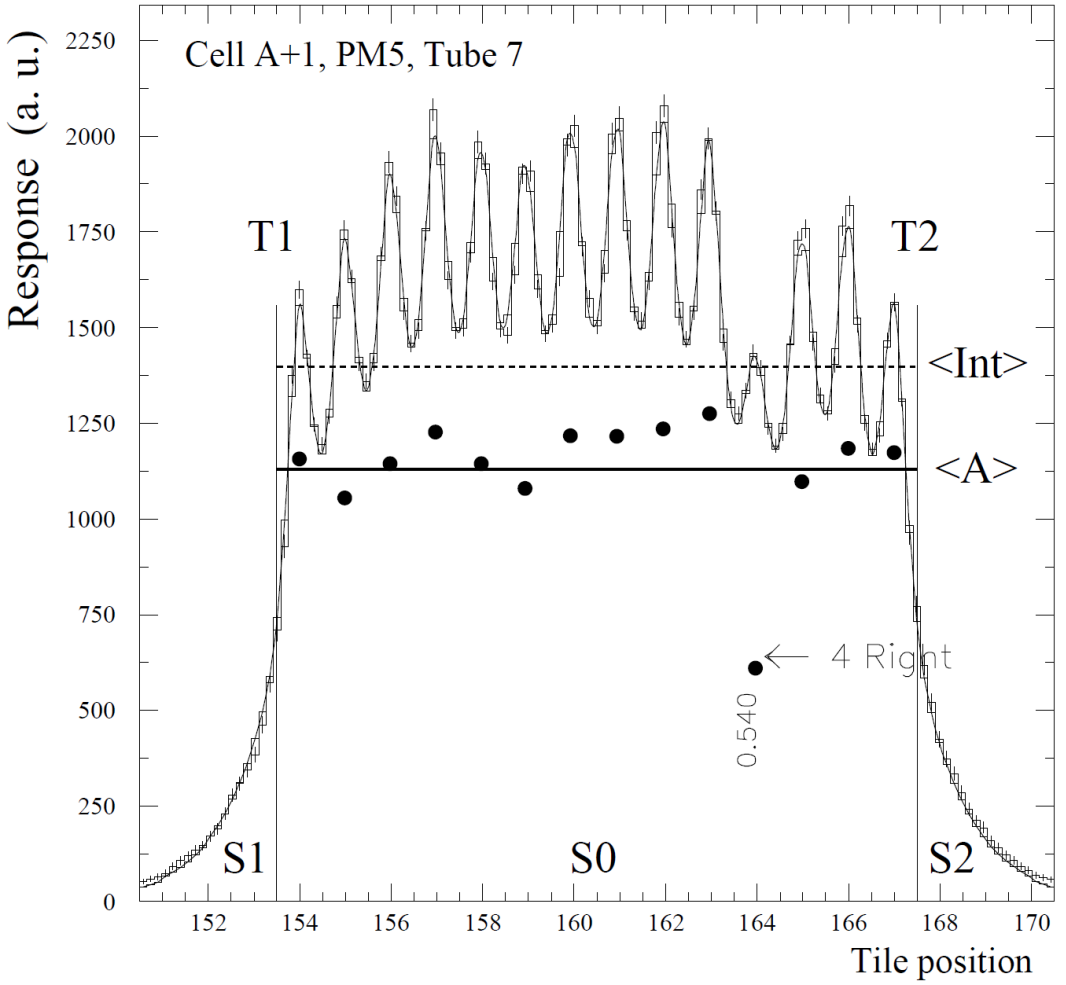
Their **response** is analysed via **two methods**:

Integral method: It **sums** all data points in signal regions S0, S1 and S2 and **divides by T2-T1** (<Int>).

Amplitude method: It performs a **fits** to obtain an **amplitude for each tile** (black dots).



Mechanical concept of the source calibration system.



An example of a tile row response sequence.

Amplitude Method

The response of **each tile** is described by two types of functions:

Gaussian: It represents the response of the **source** when it goes **through the tiles**.

Negative exponential: It represents the response of the **source** when it goes **through the steel**.

The **final response** is a **sum** of all these functions for the **tiles** that are connected to the **same PMT**. Hence, for a PMT with N_T tiles, the response is:

$$\sum_{n=0}^{N_T} A_n \left[g e^{-\frac{(x-x_0-n\cdot d+a)^2}{2\sigma^2}} + (1-g) e^{-\frac{|x-x_0-n\cdot d+a|}{\alpha}} \right]$$

From the fit, one obtains an **amplitude for each tile**, which is denoted by A_i for the i-th tile.

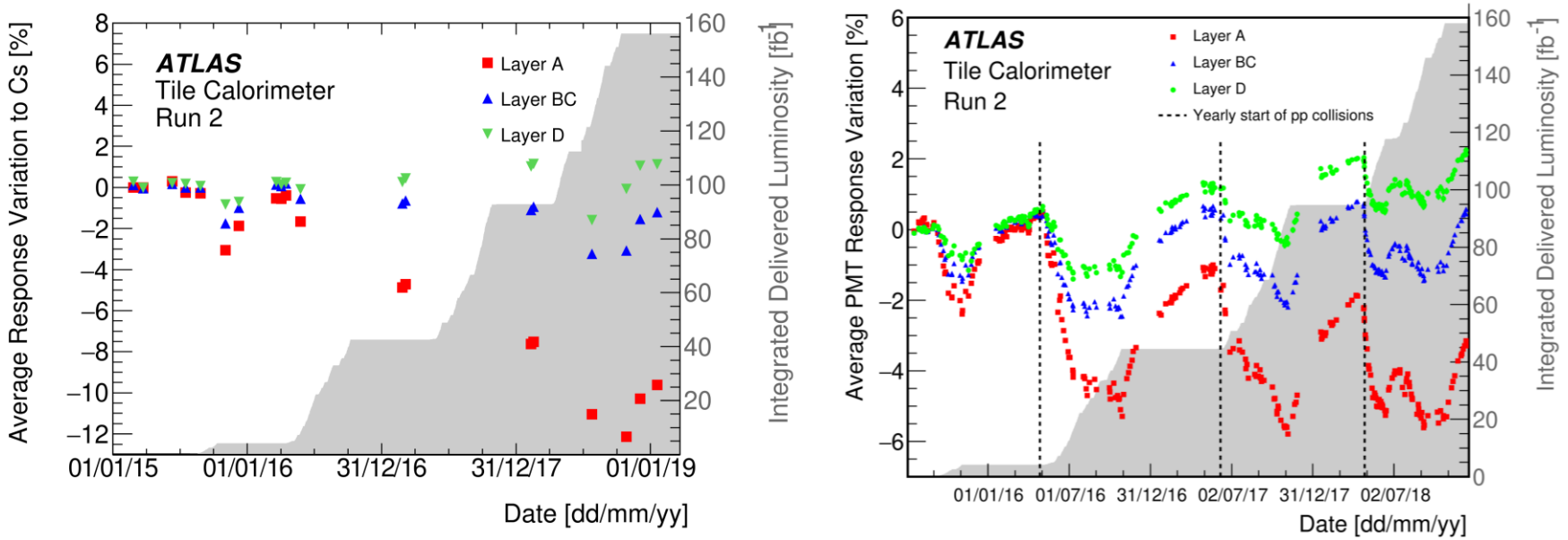
Methodology

From the fit, an A_i is obtained for **each tile** and two quantities are computed:

The **variation of the average of A_i** over all tiles of a row for a given **cell** to quantify the loss of **energy-light conversion.**

The **RMS of A_i divided by average** of all the tiles of a whole **cell** to quantify the **uniformity of its response**.

The response to the **Cs system** is compensated by the **PMT response variation**, measured by the **laser system**, to isolate the response **of the tiles and fibres.**



Variation of the response of several cell types from Cs (left) and laser (right) system.

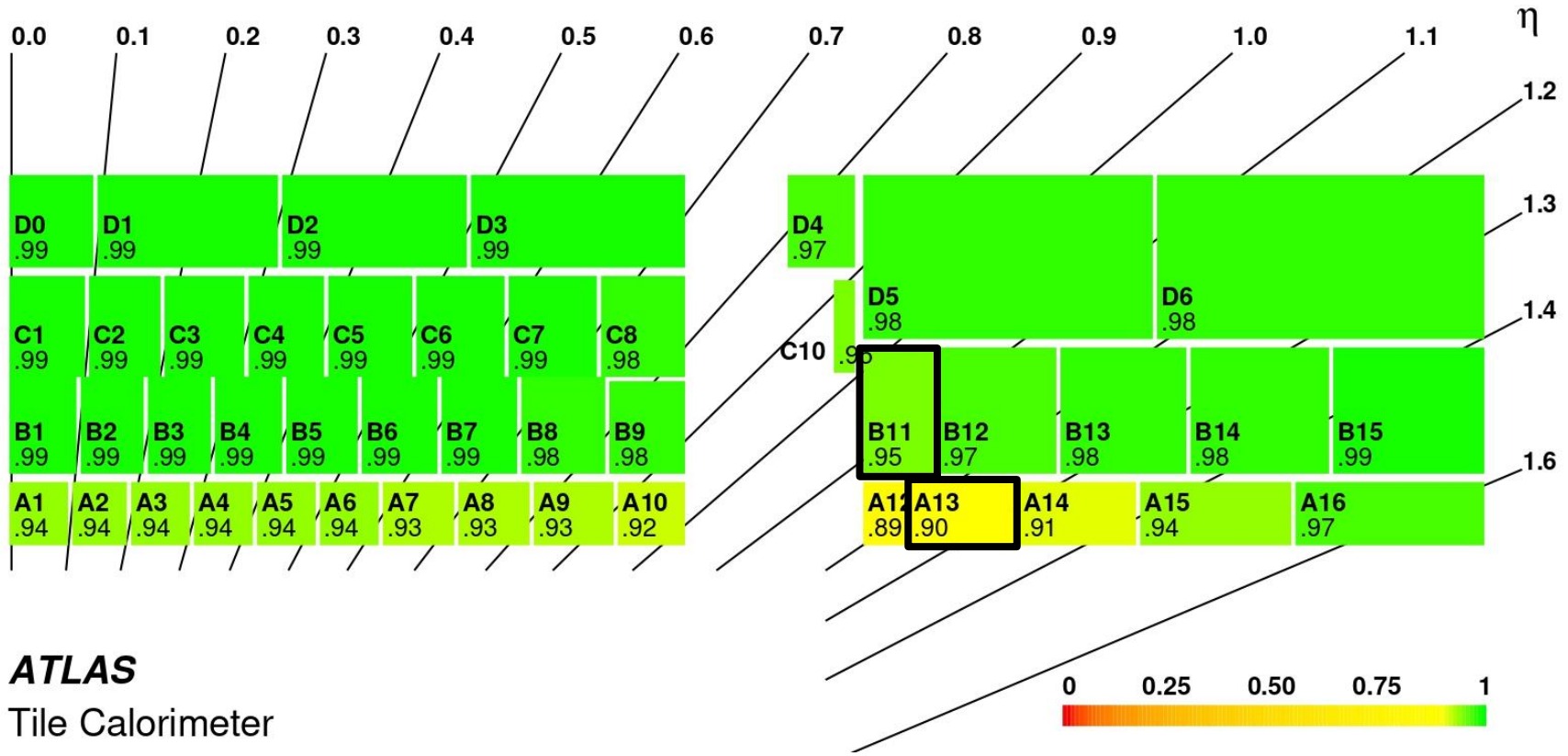
Results

Average Cell Response

Results of Average Cell Response

The average cell response is studied with the **integral method** with the variations of **<Int>** to quantify I/I_0, as the light response relative to the beginning of Run 2 (2015)

- At the **end of Run 2** (2018), **35% of the cells** have a degradation of ~**1%**.
- **A-cells**, with highest TID (10-85Gy), suffered degradations **up to 10%**.
- Degradation of **A13** and **B11** was **10%** and **5%**, respectively.



I/I_0 for TileCal cells at the end of Run 2, where total integrated luminosity was 160fb^{-1}.

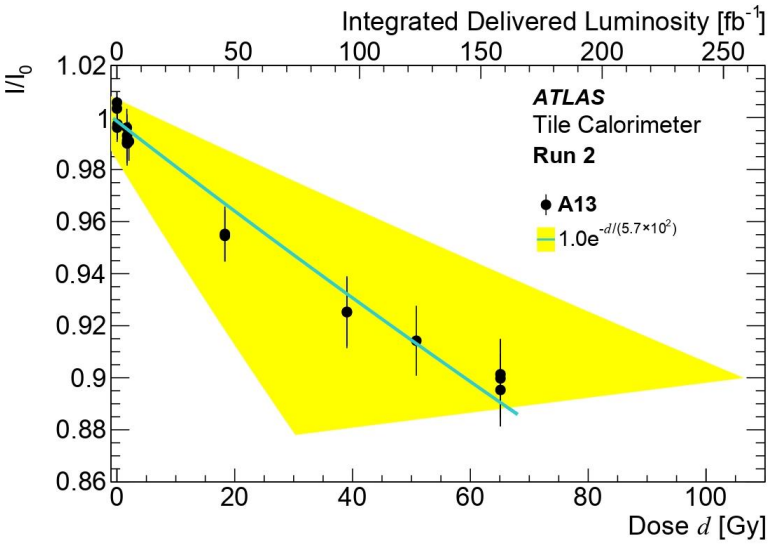
Dose Rate Effects

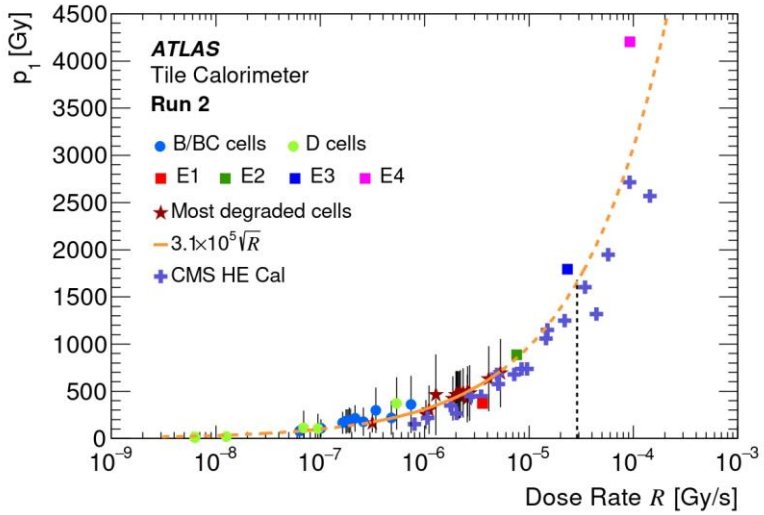
- **Light response** is expected to **decrease exponentially**:

$$I/I_0 = p_0 e^{-d/p_1}$$

- The results show that it also **depends on dose rate** (R), not only in TID. In particular, it is found that $\boldsymbol{p_1 = \alpha\sqrt{R}}$.

- TileCal **fitted** $\boldsymbol{I/I_0}$ to an **exponential** for the most exposed cells, e.g. A13 in right-top plot.
- Then, the **resulting** $\boldsymbol{p_1}$ was adjusted to $\boldsymbol{p_1 = \alpha\sqrt{R}}$ (right bottom plot).
- The fit results were **extrapolated** to lower and higher doses rates.
- The resulting model shows **good agreement** with the data from TileCal, and also with the results of CMS.



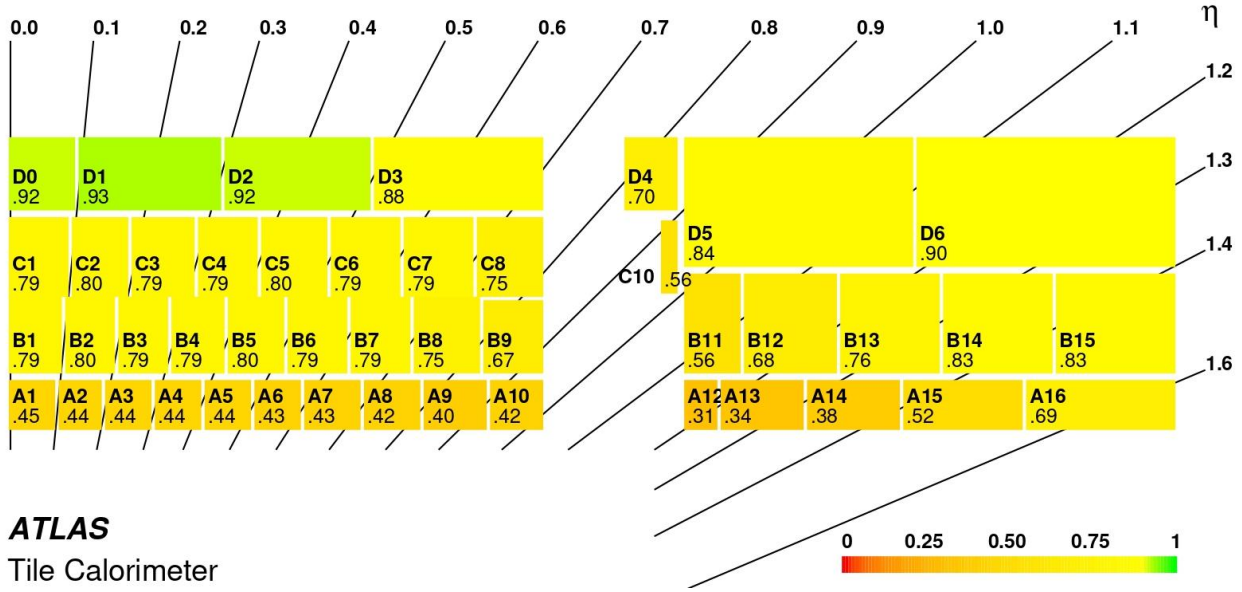


Extrapolations

The fits were used to **predict I/I_0** at the end of Run 4+5 of the HL-LHC (2041), where a total luminosity of 4000fb^{-1} is expected:

- Most of **A-cells**, with expected doses between 400-1000Gy, could have **degradations** up to **50%**.
- Most of **B-cells**, with doses between 30-125Gy, could have up to **25%**.
- Most of **D-cells** , with doses between 3-35Gy, are expected to be the least degraded, up to **10%.**

- Although 50% is large degradation, **this loss** can be **recovered** increasing the **voltage of PMTs** and changing the **calibration constants**.
- Studies using simulations with muons showed that with **50% degradation**, detection **efficiency** only **reduces 5%** (from 70%).



Extrapolation for I/I_0 with dose rate effects and luminosity 4000fb^{-1}.

Uniformity of Cell Response

Uniformity in Cell A13

The plot on the right contains the results of the **amplitude method** for **A13**.

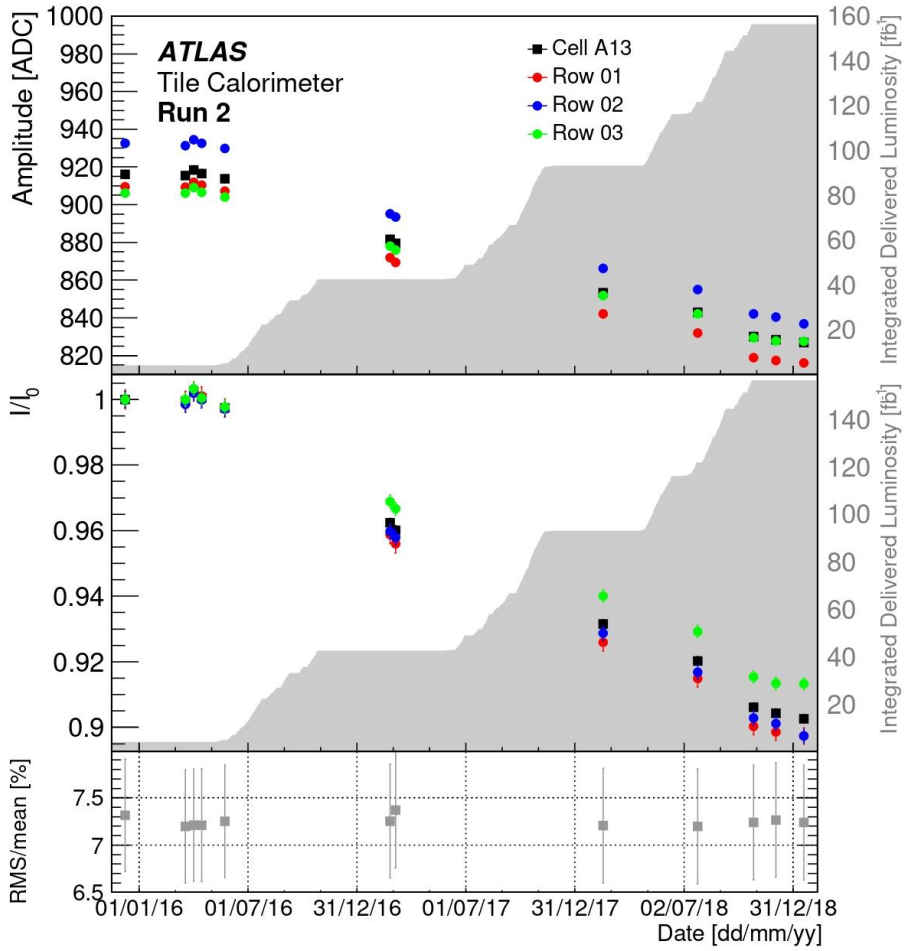
It shows that I/I_0 for **cell** response **decreases up to ~10%,** which is compatible with the integral method.

Row 1 and 2 have a **greater decrease** in I/I_0 than row 3, because **row 3** is **more shielded** and has **less TID**.

Row 3 had the **smallest amplitude initially**.

RMS is nearly **constant**, because amplitude of **row 3 crosses** the one of **row 1.**

Eventually, row 3 should cross also row 2 and **RMS could increase** in the future.



Amplitude, I/I_0 and RMS of cell A13 vs time.

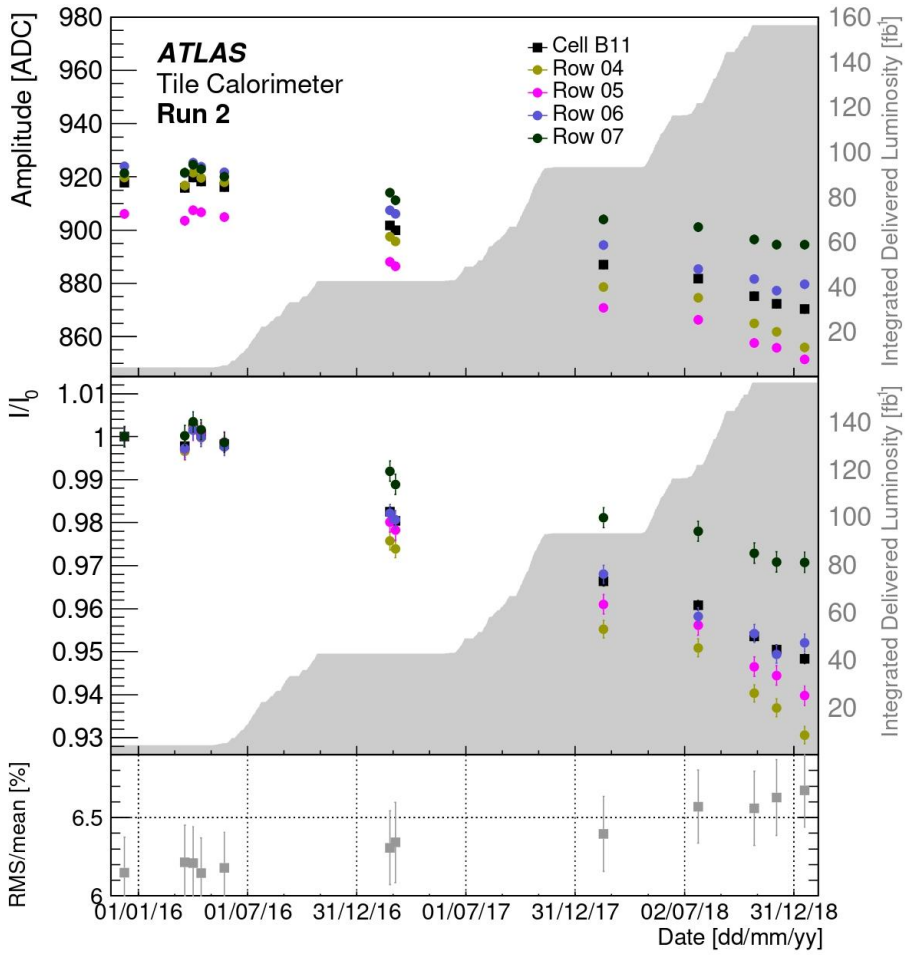
Uniformity in Cell B11

I/I_0 for **B11 decreases up to ~5%,** which is also compatible with the integral method.

Similar to A13, the **decrease in I/I_0** is **smaller** for higher **rows** which are **more shielded** and has **less TID**.

In B11, the **higher rows** have **larger amplitudes initially** than the lower ones.

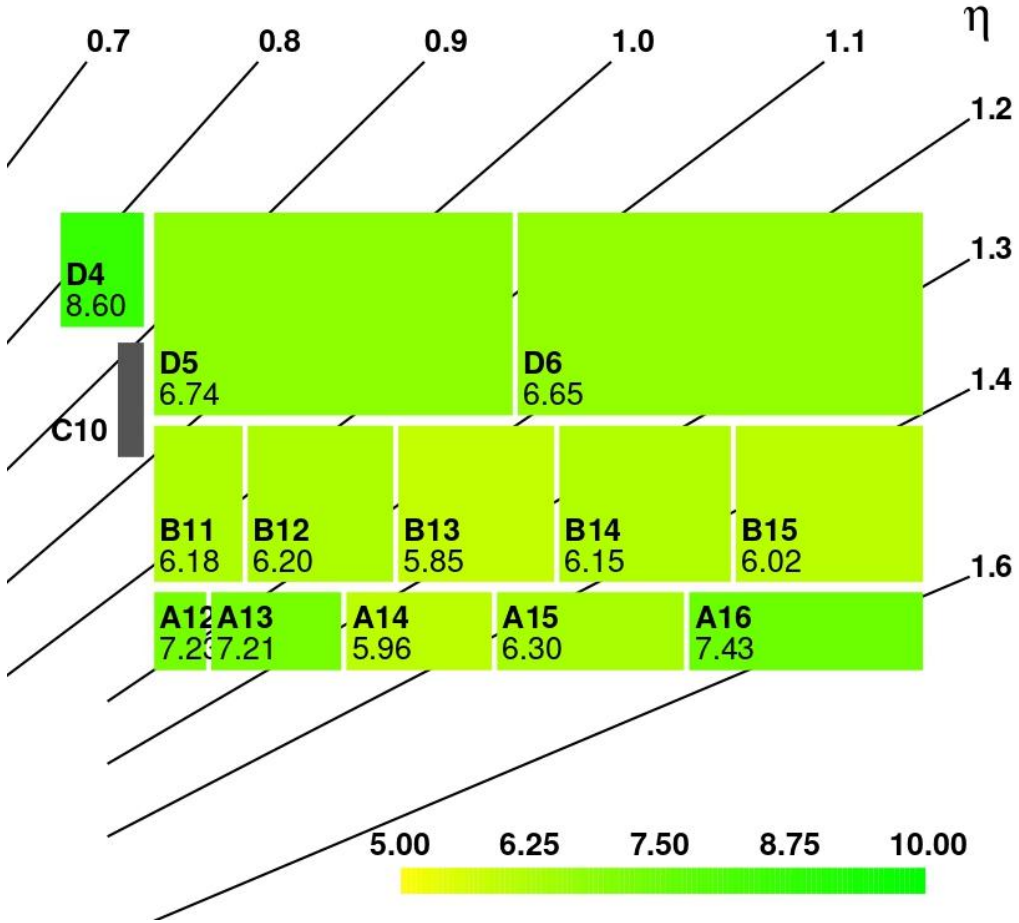
Uniformity of the cell response gets **worse** and **RMS increases** in B11.

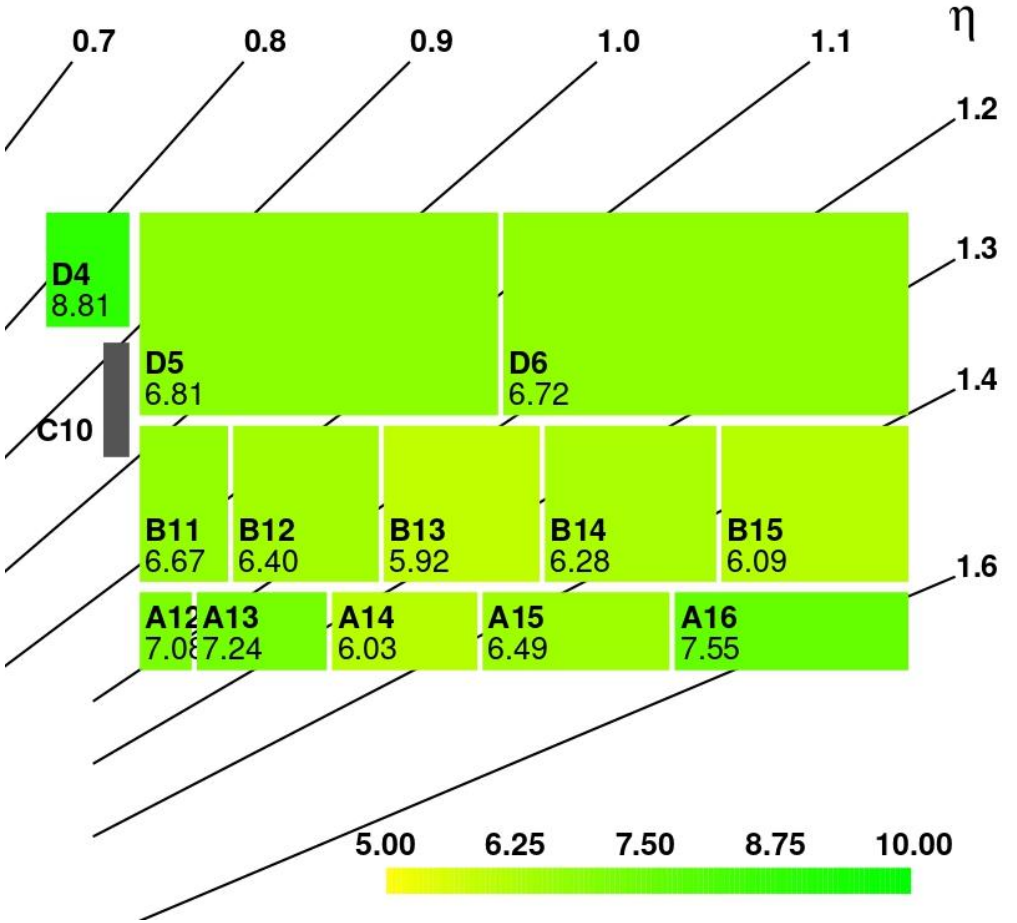


Amplitude, I/I_0 and RMS of cell B11 vs time.

RMS Map

Uniformity decreases in most of the cells, but **not drastically**.





RMS of the cells of EBA in 11/11/2015 (left) and in 19/01/2019 (right).

Unformity at the End of Run 2

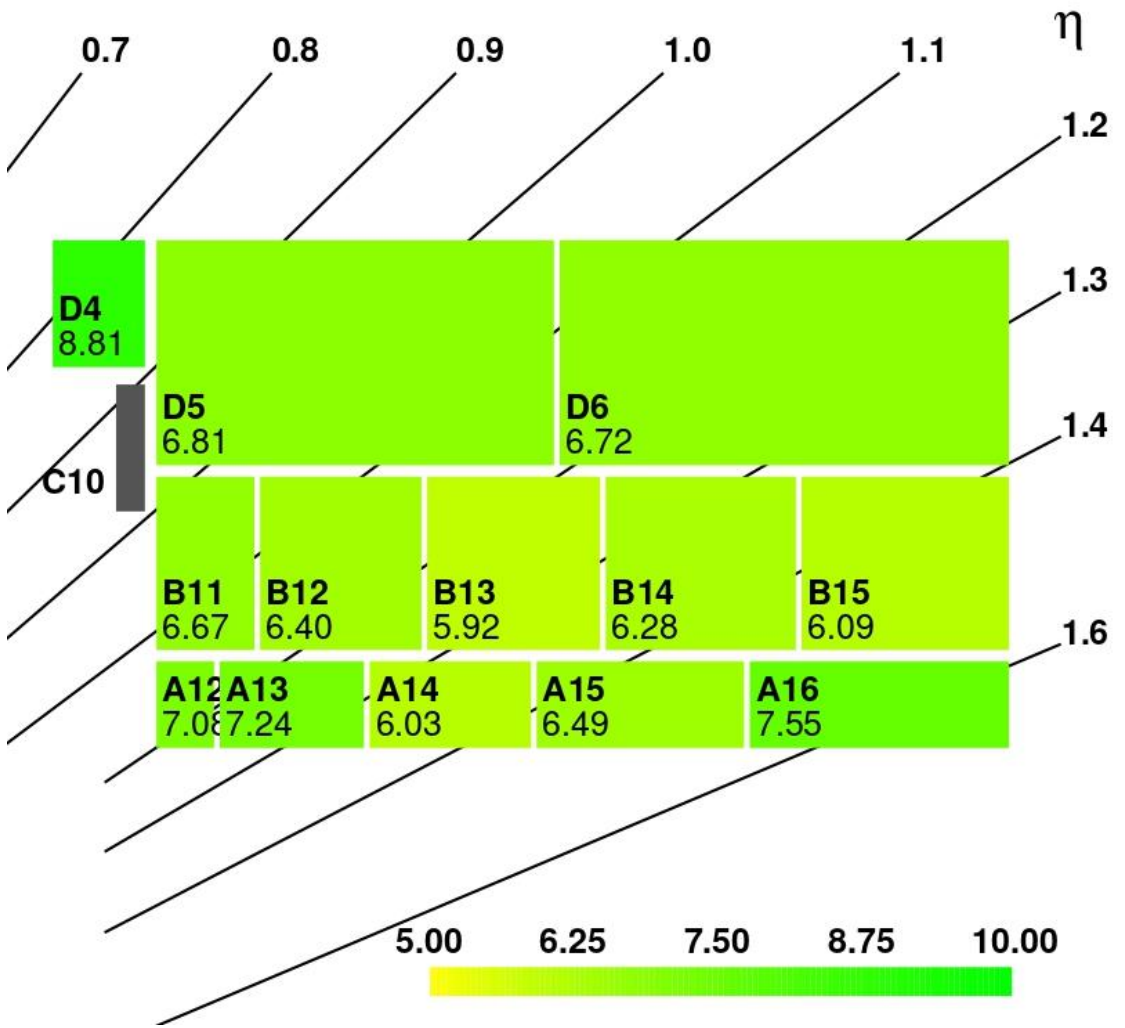
In **other cells**, the **initial conditions** of the amplitudes **prevented an increase** in RMS, like in A13.

In the **most shielded** cells, like D6, **TID** is **smaller** and **more uniformly distributed**.

Uniformity decreases in most of the cells, but **not drastically**.

Studies showed that **non-uniformity** at the **level of 10%** affects the **jet resolution** by ~**1%**

All the cells have **RMS<10%**, but the situation can get **worse in future**.



Conclusions

Conclusions

- Results show that TileCal maintains **a good performance after Run 2** (160fb^{-1}), and should be able to **keep working** under the **high luminosity** (4000fb^{-1}) runs.
- At the end of Run 2, **cell average response** has decreased **less than 1%**, except for **A-cells** where decrease is **up to 10%.**
- The results seem to **confirm the dose rate effects** that CMS found**.**
- **Extrapolations** show that **degradation** could reach levels of **50%** with the **future high luminosity,** but this degradation **can be compensated**.
- **Uniformity** of the cell response **decreased** due to **differences** in the received **TID** and **dose rate** conditions between tiles.
- The decrease was **not drastic** owing to the **initial conditions in many A-cells.**
- At the **end of Run 2**, RMS is **lower than 10%**, so TileCal measurements have **not been affected** by the loss of uniformity in the cell response.
- These studies can be found in the paper pre-print (accepted by JINST): https://arxiv.org/pdf/2412.15944

Thank you for your attention!

References

- J. Abdallah et al. *Study of the Radiation Hardness of the ATLAS Tile Calorimeter Optical Instrumentation with Run 2 data*. arXiv. https://doi.org/10.48550/arXiv.2412.15944
- ATLAS Collaboration, *ATLAS Tile Calorimeter: Technical Design Report*, ATLAS-TDR-3; CERN-LHCC-96-042, 1996, url: https://cds.cern.ch/record/331062.
- ATLAS Collaboration, *Readiness of the ATLAS Tile Calorimeter for LHC collisions*, Eur. Phys. J. C 70 (2010) 1193, arXiv: 1007.5423 [hep-ex].
- ATLAS Collaboration, *Operation and performance of the ATLAS Tile Calorimeter in Run 1*, Eur. Phys. J. C 78 (2018) 987, arXiv: 1806.02129 [hep-ex].
- ATLAS Collaboration, *Operation and performance of the ATLAS tile calorimeter in LHC Run 2*, (2024), arXiv: 2401.16034 [hep-ex].
- C. Zorn, *A pedestrian's guide to radiation damage in plastic scintillators*, Nuclear Physics B Proc. Suppl. 32 (1993) 377, issn: 0920-5632.
- J. Abdallah et al., *Mechanical construction and installation of the ATLAS tile calorimeter*, JINST 8 (2013) T11001.
- J. Abdallah et al., *The optical instrumentation of the ATLAS Tile Calorimeter*, JINST 8 (2013) P01005.
- G. Blanchot et al., *The Cesium Source Calibration and Monitoring System of the ATLAS Tile Calorimeter: Design, Construction and Results*, JINST 15 (2020) P03017, arXiv: 2002.12800 [physics.ins-det].
- M. N. Agaras et al., *Laser calibration of the ATLAS Tile Calorimeter during LHC Run 2*, JINST 18 (2023) P06023, arXiv: 2303.00121 [physics.ins-det].
- V. Khachatryan et al., *Dose rate effects in the radiation damage of the plastic scintillators of the CMS hadron endcap calorimeter*, JINST 11 (2016) T10004, [Erratum: JINST 14, E08001 (2019)], arXiv: 1608.07267 [physics.ins-det].

Back-Up

Introduction

Methodology

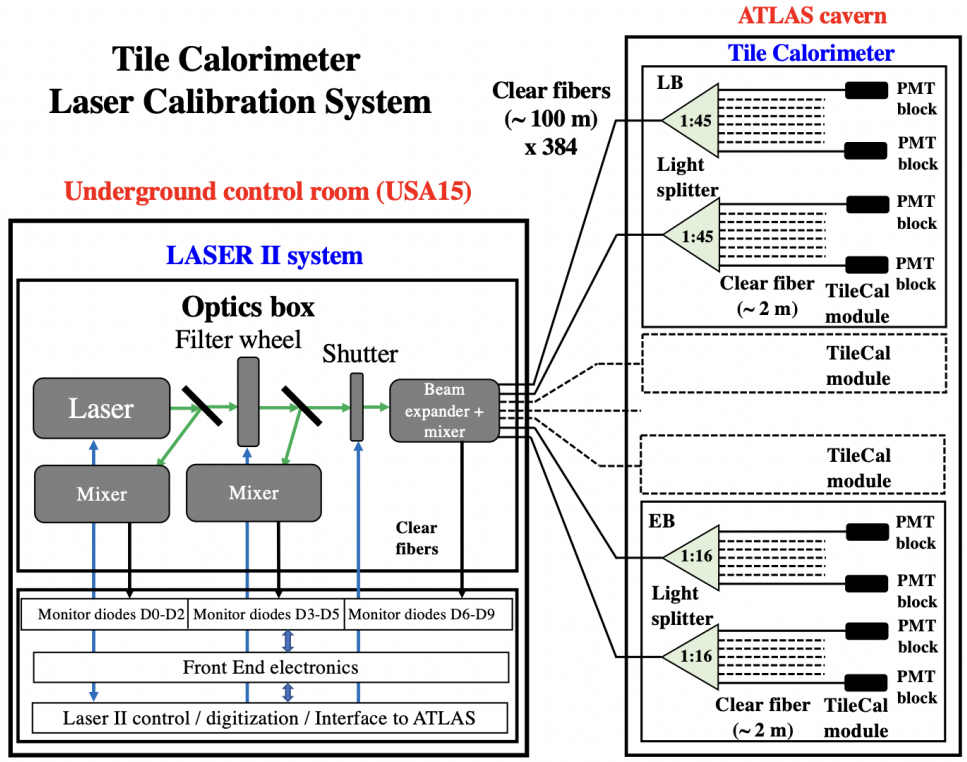
Laser System

Laser source with **532nm pulses** are transmitted in 10ns intervals to the **PMTs** to evaluate their response and the one of the **electronics**.

Pulses are sent **twice a week**, but also **between collisions** to calibrate timing.

PMTs response show a up-down pattern:

- During **collisions**, response **decreases** due to radiation.
- During **long stops**, response **increases** due to recover.



Schematics of the laset system.

Amplitude Method

- The response is fitted to:

$$\sum_{n=0}^{N_T} A_n \left[g e^{-\frac{(x-x_0-n\cdot d+a)^2}{2\sigma^2}} + (1-g) e^{-\frac{|x-x_0-n\cdot d+a|}{\alpha}} \right]$$

- The **function** is a sum of gaussian and exponential functions:
  - The **exponentials** describe the attenuation of the radiation when the source goes through the **steel**.
  - The **gaussians** describe the radiation when the source goes through the **tiles**.
- For each tile there is a gaussian and an exponential centred in the centre of the tile.

Fitting Function

- Function:

$$\sum_{n=1}^{N_T} A_n \left[g e^{-\frac{(x-x_0-n\cdot d+a)^2}{2\sigma^2}} + (1-g) e^{-\frac{|x-x_0-n\cdot d+a|}{\alpha}} \right]$$

where:

- N_T: Number of fitted tiles.
- A_n: Amplitude of the response of the n-th tile.
- g: Fraction of the responds that corresponds to the tile. Meanwhile $(1-g)$ is the fraction that corresponds to the attenuated response from the steel.
- σ: Standard deviation of the gaussian of the tile response which should be close to the tile thickness ($\sim$3mm).
- d: Distance between tiles.
- x_0: Position of the first tile.
- a: This parameter shifts the position of the tiles to consider the variations of velocity of the caesium sources.
- α: Attenuation constant of the steel.

Corrections

- A set of **corrections** are applied to the data to consider different effects:
  - **Pedestal subtraction**: The PMTs have a non-zero response when there is no signal which is known as pedestal. This pedestal is calculated from the average of data when the source is outside of the cells and subtracted from the data.
  - **τ-Correction**: The integrator response function disturbs the input signal a bit. This effect is compensated shifting the response with a term proportional to its derivative.
  - **Energy leakage**: 22% of energy is deposited in the next outermost row (leakage). Hence, the data of the PMTs are a sum of two responses, expect for the outermost row of a cell. For the outermost row, the leakage is deposited to the next cell. In order to consider the leakage:
    - The program fits first the outermost row whose leakage is in the response of a different cell.
    - Then, in the fitting of the next innermost row, the program adds the response of the previously fitted row reducing the amplitudes by a tabulated factor.
    - This procedure is repeated until all rows are fitted.

τ-Correction

- The integrator response function disturbs the input signal a bit.
- τ-correction intends to compensate for that with the expression:

$$A_i = A_i + \delta \cdot (A_i - A_{i-1})$$

where A_i is the response in i-th trigger number and δ is a corrective factor.

- In the past they found that the best value of δ is $\delta = 0.7 \pm 0.1$

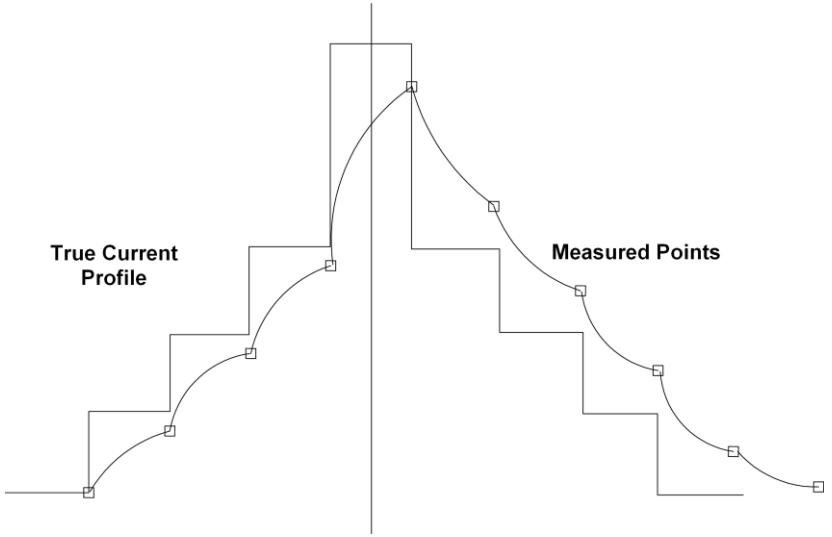


Illustration of the shift caused for the RC integrator circuit.

22% Energy leakage

- **22% of energy** is deposited in the next **outermost row** (leakage).
- The leaked energy in the outermost row of a cell goes to the next cell, so there is not issue.
- For the other rows, the energy leaks to a row in the **same cell**, so the response is a **sum of two rows**.

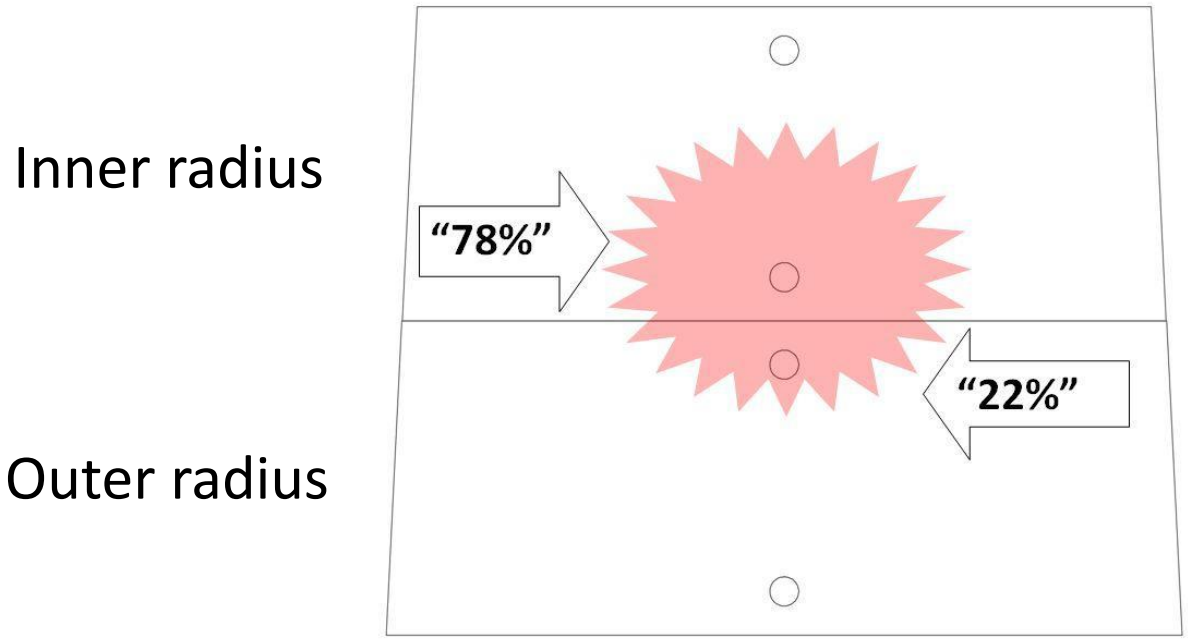


Illustration of the energy leakage to the next outermost row.

22% Energy leakage

- The leakage is considered fitting data to:

$$\sum_{n=0}^{24} A_n^{(i)} \left[g_{78} e^{-\frac{\left(x - x_0^{(i)} - n \cdot d^{(i)}\right)^2}{2\sigma_{78}^2}} + (1 - g_{78}) e^{-\frac{\left|x - x_0^{(i)} - n \cdot d^{(i)}\right|}{\alpha_{78}}} \right]$$

$$+ \sum_{n=0}^{24} R_{leak} \cdot A_{24-n}^{(i+1)} \left[g_{22} e^{-\frac{\left(x - x_0^{(i)} - \mathrm{d}^{(i)}/2 - n \cdot d^{(i+1)}\right)^2}{2\sigma_{22}^2}} + (1 - g_{22}) e^{-\frac{\left|x - x_0^{(i)} - \mathrm{d}^{(i)}/2 - n \cdot d^{(i+1)}\right|}{\alpha_{22}}} \right]$$

where superindex (i) indicates that the parameters corresponds to the i-th row enumerated from innermost to outermost. The 78 and 22 subindices are explained in the following slides.

22% Energy leakage

- Notes about (i+1)- th row:
  - Its parameters are fixed and they come from its fitting.
  - The position of its first tile ($x_0^{(i+1)}$) is the same as the i-th row plus a displacement, which is half a period ($d^{(i)}/2$).
  - Its profile is reversed because consecutive rows in Cell A13 are scanned in opposite direction.
  - Its amplitudes are multiplied by factor (R_{leak}) which is also a tabulated value.
- Notes about g, σ and α:
  - Their tabulated values are different if the row corresponds to the main response (subindex 78) or to the leakage (subindex 22).
  - The reasons are:
    - The zone of scintillating light changes, because the source is outside tile.
    - There is additional 30 mm of absorber due to the displacement in tiles.
    - Angular distribution of the gammas rays is different.

Other Corrections

- **Pedestal** subtraction.
- Correction of **noisy points**:
  - Each response is compared to the average of the previous and following measured responses.
  - If the response is 25% below or over the average, this response is replaced by the average.
  - The correction is used to remove too noisy responses.
  - In the results we present in the following slides, there is no response where this correction was necessary.
- Compensation for the **loss of radioactivity** of the cesium sources.