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Calibration of the Tile Hadronic Calorimeter of ATLAS at LHC

Djamel BOUMEDIENE, on behalf of the ATLAS collaboration
CNRS/IN2P3/LPC Université Blaise Pascal, 24 avenue des landais, 63171 AUBIERE

E-mail: `djamel.boumediene@cern.ch`

Abstract.
The Tile Calorimeter (TileCal) is the central section of the hadronic calorimeter of the ATLAS experiment. The TileCal provides important information for reconstruction of hadrons, jets, hadronic decays of tau leptons and missing transverse energy. This sampling calorimeter uses iron plates as absorber and scintillating tiles as active medium. The light produced by the passage of charged particles is transmitted by means of wavelength shifting fibers to photomultiplier tubes (PMTs). The TileCal readout is segmented into about 5000 cells (longitudinally and transversally), each of them being read by two PMTs. A brief description of the individual calibration systems (Cs radioactive source, laser, charge injection, minimum bias) is provided. Their combination allows to calibrate each part of the data acquisition chain (optical part, photomultiplier, readout electronics) and to monitor its stability to better than 1%. The procedure for setting and preserving the electromagnetic energy scale during Run 1 data taking is discussed. The issues of linearity and stability of the response, as well as the timing adjustment are also shown.

1. Introduction

The TileCal Calorimeter of ATLAS [1] has three key elements: the scintillators, the photomultiplier tubes (PMTs) and the read-out electronics [2, 3]. The light is produced in scintillating tiles and converted into electric currents by the PMTs.Their signal is shaped and amplified with two gains. The sampling and the digitization is realised by ADCs. During collisions, if an event is selected by the trigger system, the digitized signals are collected and processed by a Read-Out Driver. In parallel to this, integrators measure the integrated current from the PMTs.

The reconstructed energy of each channel, $E(\mathrm{GeV})$, is derived from the raw response, $A(\mathrm{ADC})$, as follows:

$$E(\mathrm{GeV}) = A(\mathrm{ADC}) \cdot C_{ADC\rightarrow \mathrm{pC}} \cdot C_{\mathrm{pC}\rightarrow \mathrm{GeV}} \cdot C_{Cesium} \cdot C_{Laser}$$

This relation is established for each TileCal channel. The factors can evolve in time because of unstability of PMTs high-voltage, PMTs stress induced by high light flux or optics aging. The calibration systems are used to monitor the stability of these elements and provide per channel calibration.

While $C_{\mathrm{pC}\rightarrow \mathrm{GeV}}$ was fixed during dedicated test beam campaigns, the remaining calibration constants are provided by individual systems:

- spaced by weeks or months, calibrations of Tile optic components with movable Cesium radioactive gamma source;
- frequent calibrations of phototube gains with custom Laser calibration system;
- daily to weekly calibrations of digital gains and linearities with charge injection system (CIS) integrated on module front-ends;
- monitoring of beam conditions and Tile optics with the so-called integrator system (minimum bias).

The calibration tools follow different and partially overlapping read-out paths allowing for easier identification of potential failure and for crosschecks.

2. Calibration Systems of TileCal

2.1. The Cesium Calibration

The Cesium calibration system [4] is based on three movable radioactive sources using hydraulic control. The ^{137}Cs γ-sources move inside the calorimeter body. The channel response to the energy deposits is used to equalize the response of all the cells and maintain global response of the calorimeter at the electromagnetic scale.

Deviation of measured Cesium signals from expected values, corrected for the Cesium decay curve (-2.3%/year), are interpreted as gain variations and translated into calibration constants (C_{Cesium}).

The Cesium calibration is performed taking into account the presence of magnetic field produced by the ATLAS Toroid and Solenoid. It tests the optical chain and the photomultipliers, with a precision better then 3 per 1000, including the scintillators aging effect.

During this calibration, the Integrator is used to record the PMT responses making the Cesium measurement insensitive to what can effect the readout used for collision data. It has to be completed by a dedicated system, the CIS. On another hand, the frequency of the Cesium calibration can be insufficient to track fast drifts of the PMT responses. For prompt calibration, the Laser system is used between two Cesium scans.

2.2. The Laser Calibration

The gain of each PMT is measured using a Laser calibration system [5] that sends a controlled amount of light in the photocathode of each PMT in the absence of collisions. Both high and low gain regimes of TileCal read-out are monitored using two different light amplitudes. Deviations of any channel response with respect to its nominal response (at the time of the latest Cesium calibration) lead to a calibration constant: C_{Laser}.

The typical precision on the gain variation is better than 0.5% per channel when 10,000 Laser pulses are used. The Laser measurements are used for fast monitoring of TileCal and to correct the gain of some specific channels.

During 2011–2012, a few hundred of channels required a Laser calibration, most of these gain drifts were induced by luminosity effects.

Laser pulses are also sent during empty bunch crossings of the LHC, with a frequency of 1 Hz, and the timing of TileCal response is measured and used for channel per channel time calibration.

2.3. The Charge Injection System (CIS)

The CIS simulates physics signals in TileCal channels by injecting a known charge into the ADC and measuring the electronic response, as described in [6]. It provides then a quantitative relationship between the analogic physical signals from the Tile Calorimeter photomultiplier tubes and the electronic response of TileCal read-out channels and corrects for non-linearity in the analog signal processing. A set of CIS calibration constants ($C_{\mathrm{ADC}\rightarrow\mathrm{pC}}$) are regularly produced and applied to TileCal data.

The precision on the CIS calibration constant is about 0.7% for each channel.

2.4. The Minimum Bias integration

High energy proton-proton collisions are dominated by soft parton interactions, so-called Minimum Bias (MB) events. The response of the TileCal to signals induced by the MB interactions scale with instantaneous luminosity [7]. It can be used to measure the luminosity delivred to ATLAS and to monitor the stability of the channels and to provide an independent cross-check of the Cesium calibration.

The PMT currents are integrated over a time window of 10 ms. The MB data are continuously recorded during proton-proton collisions.

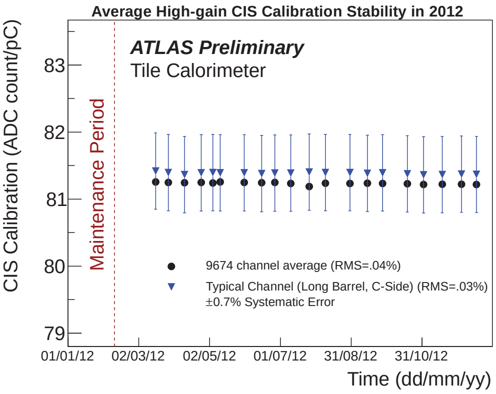

Figure 1. Time stability of the average high-gain readout calibration constants from February 2012 to December 2012 for 19421 ADC channels. The calibrations are measured in-situ with the Charge Injection System (CIS). The RMS values printed in the legend represent a measure of the fluctuations present in calibrations.

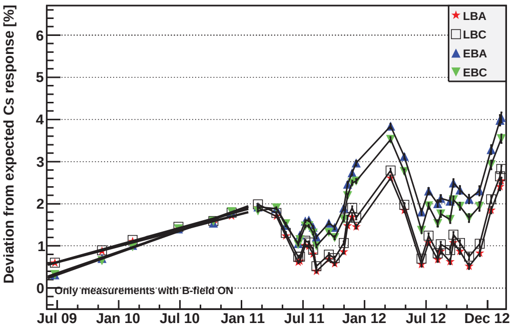

Figure 2. Deviation of TileCal response to Cesium sources per partition, in the inner radial layer (A layer), from 2009 to 2012.

3. Calibration and gain stability of TileCal

The four TileCal calibration systems were operated during Run 1 of LHC. Their performances, measurements and diagnostics are presented in the following sections. In addition to this, the High Voltage and the temperature are monitored in order to target possible unstable channels in the calibration process.

3.1. High Voltage and Temperature monitoring

High Voltage is monitored channel by channel while temperature is recorded in a representative sample of 2.5% of the total PMT number. Stability monitoring of the PMT high voltage with respect to its reference value, averaging over all PMTs for two running periods of nine months in 2011 and three months in 2012 shows a typical variation of 0.4V leading to a gain variation lower than 5 per 1000. The identification of channels with unstable High Voltages is used to target them in the calibration process. The stability of temperature averaging over all modules

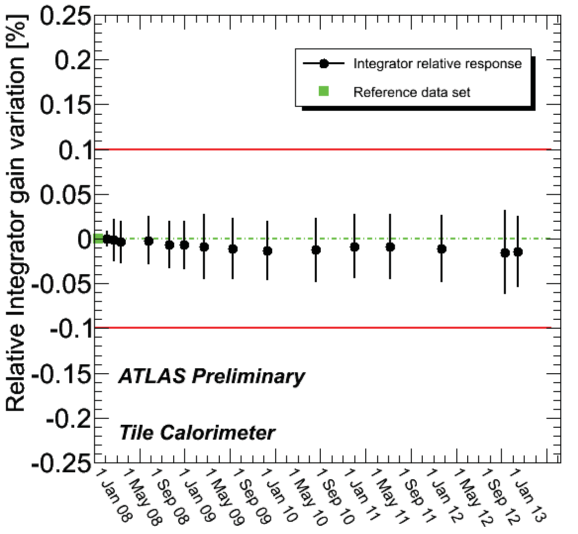

Figure 3. Comparison of channel responses, from 2008 to 2013, with respect to a reference sample taken in 2008. The error bars represent the standard deviation from the mean of the relative variation (precision per channel).

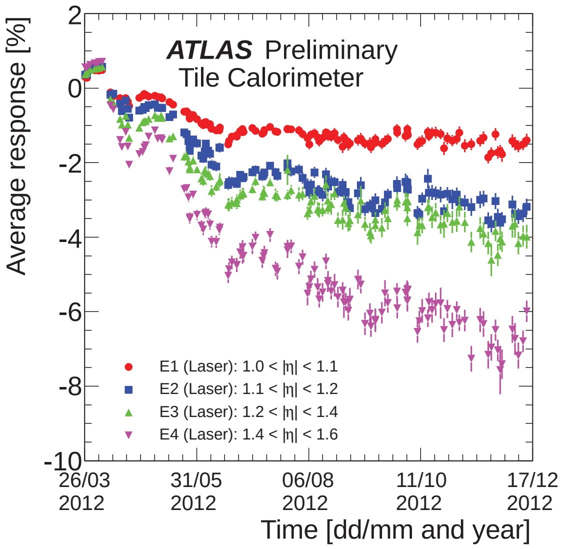

Figure 4. Gain variation measured by the Laser for the special cells E1 to E4. The measurement is shown as a function of time in 2012. A mean over modules is performed. Error bars are the uncertainty on the mean value.

during the same periods as for the HV monitoring analysis shows a typical variation of 0.2 °C. This small variation allows for no correction in the PMT gain since the gain dependence on the temperature is -0.2%/°C.

3.2. Readout stability and calibration

The mean of CIS calibration data for February 2012 was compared to the mean of CIS calibration data for December 2012. The RMS variation is approximately 0.1%. Channels with variation greater than 1.0% were targeted for recalibration. This in-situ calibration was applied to all collision data collected in LHC Run 1. The average read-out calibration constants, as provided by Charge Injection System over all LHC Run 1 and for all ADC channels, show a typical stability in time of 0.02% as illustrated on Figure 1 [8].

3.3. Global gain stability and calibration

An average up-drift of about 0.8% per year was measured by the Cesium calibration in 2009–2010. This up-drift effect is compensated by an opposit effect in 2011 and 2012. Since LHC reached a high luminosity regime, a sizable down-drift is seen when beam is on while the response recovers slowly when beam is off, *i.e.* during LHC technical stops, and during heavy ion collisions which have a low luminosity. The biggest down-drift is in the innermost part of the calorimeter - in A cells where up to -8%/year was observed in August 2011, while in the D cells of the barrel partition, down-drift is negligible. The deviation in the A TileCal layer is shown on Figures 2 [8].

Using the integrator system, the relative variation of the gains is obtained by comparing the response of 9389 channels (95% of all TileCal channels) measured at different dates, with the ones measured in January 2008. These measurements are shown on Figure 3 [8]. The stability of individual channels is better than 0.05% while the average stability is better than 0.01%.

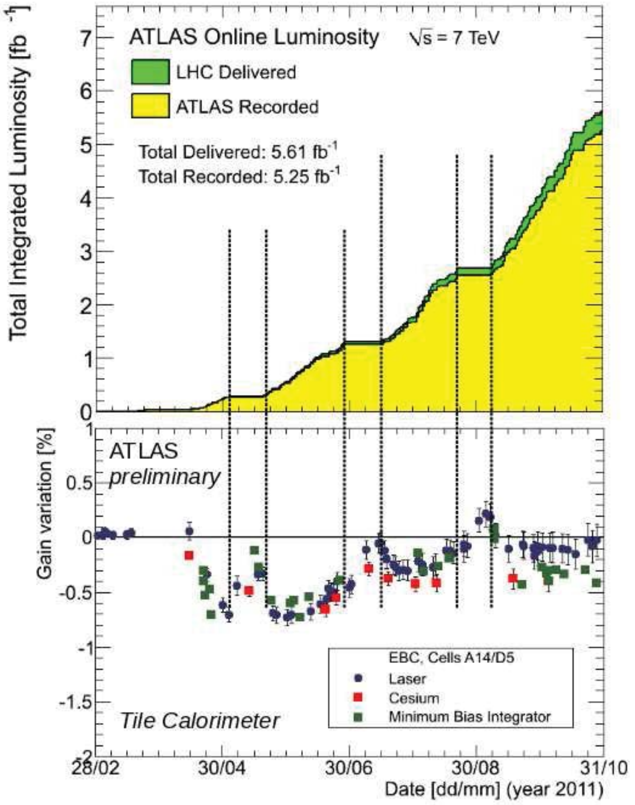

Figure 5. Gain variation measured by the Cesium, Laser and Integrator systems, averaged over one cell type (A14) in 2011, compared to LHC integrated luminosity (upper plot). Periods with no collisions are delimited by vertical dotted lines.

One particular case in TileCal are the Gap and Crack cells. They are located between long and extended barrel and named E1, E2, E3 and E4. They are characterized by a larger exposure to the irradiation and by the large amount of light they produce and that is thus read by the associated PMTs. E3 and E4 being located outside TileCal modules, at smaller radius, they are not monitored by the Cesium system. Their gains are equalized once per year using muons from collisions and by the Laser system for fast drifts. Figure 4 [8] shows the measured gain variation. It reaches -8% in the E4 cells after one year of collisions in 2012.

As shown on Figure 5 [8], the down-drift periods coincide with the periods of data taken with high instantaneous luminosity, while the up-drifts coincide with the technical stops (no collisions). The maximum variation is below 1% over all 2011 data taking period with an integrated luminosity of $5.6\ \text{fb}^{-1}$.

Such a luminosity induced drift is confirmed by the Laser system. It mostly affects cells at inner radius, that are the cells with higher current, as shown on Figure 6 [8] on a full TileCal map where the drift is clearly observed a few weeks after the first collisions of 2012. A comparison of the drifts observed by TileCal monitoring systems is also given on Figure 5 [8] for one typical cell. Their compatibility indicates that the gain variation is dominated by the PMTs gain variation.

4. Conclusion

The calibration systems of Tile Calorimeter were successfully operated during Run 1 of the LHC. Their performances were established. It was shown that these systems can be used in conjunction to monitor and correct fine unstabilities affecting the channels gain like PMT drifts induced by high instantaneous luminosity or to identify the small fraction of pathological channels.

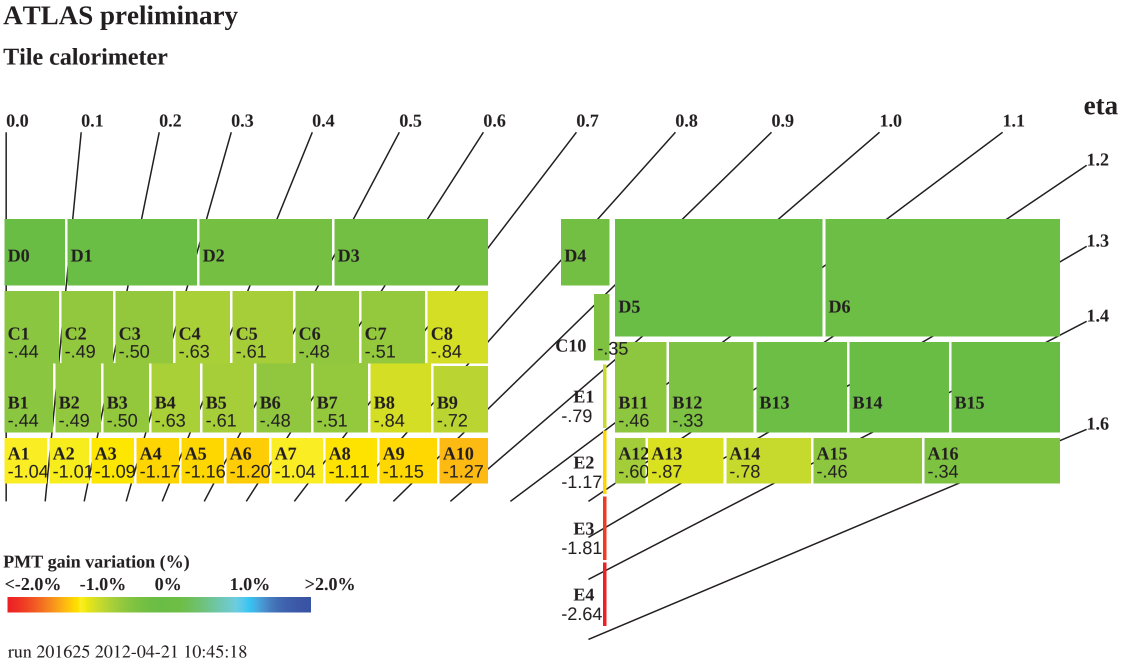

Figure 6. The mean gain variation of the 10000 channels is computed cell by cell as a function of η and radius, between the 19 March 2012 and the 21 April 2012 with the Laser system. The mean values are averaged over total azimuthal coverage of the detector.

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