First years of running for the LHCb calorimeters

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Abstract. The design and construction characteristics of the LHCb calorimeter system are described. Strategies for monitoring and calibration during data taking are detailed in all aspects. Scintillating fibres, plastics and photomultipliers suffer from aging due to radiation damage or high currents; different methods which are used to calibrate the detectors and to recover the initial performances are presented. The performances achieved are illustrated in selected channels of interest for B physics.

1. Introduction
The LHCb detector [1] is a single arm spectrometer devoted to the study of CP violation and rare decays in B meson and hadron systems. Its calorimeter is divided in two, a Hadronic Calorimeter (HCAL) and an Electromagnetic Calorimeter which, in turn, splits into a Scintillator Pad Detector (SPD), a PreShower (PS) and the bulk of the Electromagnetic Calorimeter (ECAL) [2].

All four subdetectors work on the same principle: collect scintillation light produced by incoming particles, convert it to an electrical signal using photomultipliers and integrate it to obtain the energy measurement depending on the photo-electron statistics.

The PS-SPD system plays various roles in the detector operation. It provides particle identification for electrons and photons at the hardware trigger level (called L0 trigger). The PS is used for the electron, photon and pion separation while the SPD contributes with the photon-charged particle separation. To cut down too complex events, the SPD also provides a charged multiplicity veto. The ECAL measures the transverse energy of electrons, photons and \( \pi^0 \) for the L0 trigger, which is relevant in selecting \( B \)-decay channels such as \( B \to K^*e^+e^- \) or \( B \to K^*\gamma \). PS and ECAL are also used for the offline reconstruction of \( \pi^0 \) and prompt photons. HCAL gives the transverse energy of hadrons for the L0 trigger to select decay channels such as \( B \to \pi^0 s \) or \( B \to D_s K \). PS, ECAL and HCAL are used, of course, for particle identification.

The LHCb calorimeter system was installed between years 2004 and 2008. The commissioning took place between 2005 and 2009 using the built in monitoring tools, cosmic rays and injection tests splash events. The first trace of a cosmic ray was detected in January 2008 and the system was fully operational for the first collisions in November 2009.

This paper aims at giving an overview of the LHCb calorimeters, their structure, calibration strategies, the effects of aging after three years of operation and finally their performance illustrated through the results on one selected data channel, \( B \to X\gamma \). We devote one section to each of these points and we add some conclusions at the end.
2. Description of the LHCb Calorimeters

The four elements in the calorimeter system as found downstream from the interaction point are SPD, PS, ECAL and HCAL.

The SPD and PS are walls of scintillator pads with a wavelength shifting fiber (WLS) coil grooved inside for better light collection as seen on figure 1. They are separated by a 2.5 radiation length thick lead curtain. The SPD delivers a single bit depending on whether the crossing particle is charged or neutral and completes the PS tagging of the electromagnetic shower. The pad size is adjusted to three different values to achieve three zones with higher granularity around the beam-pipe The geometry is projective with respect to ECAL. Overall, SPD and PS have around 6000 cells each. The readout is made by multi-anode photomultipliers Hamamatsu 5900 M64.

![Figure 1. Scintillator pad with the WLS fiber coil grooved in and an LED for testing and calibration purposes.](image1)

![Figure 2. ECAL cells have a shashlik structure read out by photomultipliers.](image2)

LHCb ECAL cells have a shashlik structure (figure 2) with 4 mm-scintillator and 2 mm-lead layers equivalent to 25 radiation lengths. The readout is performed by Hamamatsu R7899-20 photomultipliers. The total number of cells is around 6000. As described for the SPD-PS system, three regions, inner, middle and outer have been defined according to the distance to the beam-pipe (figure 3). The energy resolution, as measured in test beam is [1]

$$\sigma(E)/E = 0.090 \pm 0.005/\sqrt{E} \pm 0.008;$$

where $E$ is the particle energy in GeV. The last term represents the contribution of the electronics noise.

![Figure 3. Three regions have been defined to improve the granularity close to the beam-pipe.](image3)

![Figure 4. HCAL cells have a tile structure read out by photomultipliers.](image4)

The HCAL has a tile structure. The same photomultiplier as in ECAL, namely Hamamatsu R7899-20, is used for the read out. It overall has 1500 cells divided in two regions, inner and
outer, corresponding to the distance to the beam-pipe. The energy resolution follows [1]:

\[ \sigma(E)/E = (0.69 \pm 0.05)/\sqrt{E} \oplus (0.09 \pm 0.02), \]

where \( E \) is the deposited energy in GeV.

The common approach to process the photomultiplier signal is first to make an analog integration of the signal, then sample and finally digitalize it to send it through the trigger and data paths. The physical construction of the calorimeters and the detector frequency cause the signal to spill over more than one clock cycle. Two solutions are adopted to face this problem. ECAL and HCAL electronics performs a clipping of the signal prior to integration so that it fully fits in one clock cycle. The readout is performed by an analog chip hosted in the so called front end boards located in crates on top of the calorimeters. PS and SPD, in turn, subtract a fraction of the signal measured in the previous clock cycle to solve the spill over problem. For this a dual channel integration system is built in an analog chip. Since the readout uses 64 channel multi-anode photomultipliers (MA-PMT), small boards, called very front end boards, located close to the detector, host the MA-PMT and the associated signal processing electronics. The conditioned analog signal of the PS and the SPD bit are sent to front end boards in the crates on top of the detector. Further details can be found in reference [1] for the general structure of the calorimeters and in reference [3] for the strategy of the detector time alignment.

High Voltage (HV) is provided for the four subsystems by full custom Cockroft-Walton voltage multipliers. PS and SPD share a common design for their 64 channel MAPMTs just as ECAL and HCAL do for their R7899-20. Besides, PS and SPD MAPMT bases are full custom ones, involving active elements to provide the last PMT dynodes with the necessary current to keep the response in the linear regime.

Detectors include built in LED systems for monitoring the detector stability. ECAL and HCAL share a common system [1]. LED’s are pulsed simultaneously and their signal is monitored by a pin diode. The driver is designed to control time and temperature stability. It provides a small pulse duration with low dispersion of amplitude. The pulse rate is adjustable as well as the amount of light in order to emulate electromagnetic particles in full physics region. The gain control allows an accuracy better than 1%. The LED system runs in empty bunches to monitor the detector.

3. Calibration tools and methods

Each part of the calorimeter system follows a different strategy for calibration.

The SPD-PS system looks at the tracks pointing to the SPD-PS cells and extrapolates their trajectory. In the case of the SPD, tracks should correspond to positive signals: the efficiency is defined as the fraction of tracks effectively leaving signal on the SPD [4]. Efficiencies show to be around 90%. In the PS case, the MIP signal is fitted and adjusted to a given number of ADC counts.

The calibration approach for ECAL relies on fitting the \( \pi^0 \) mass from two photon signals, using the mass distribution fit method [5]. This is an iterative procedure which consists in selecting \( 3 \times 3 \) clusters corresponding to photon signals and fix the seed, corresponding to the central cell. For each cell, we compute the di-photon invariant mass and then we fit the \( \pi^0 \) mass distribution. We correct the calibration of every seed cell and restart the procedure until we obtain stable calibration coefficients. The first fit of the \( \pi^0 \) mass was obtained in November 2009 from the first collisions by setting a uniform ADC count value per transverse energy unit. The result was a mass fit \( M_{\pi^0} = 133 \pm 3 \) MeV with a width \( \sigma = 11 \pm 4 \). Figure 5 shows the effect of the calibration algorithm on the \( \pi^0 \) mass fit: the final width is of the order of 6%.

Another available method to monitor and correct the calibration of ECAL cells is through electron \( E/p \). Electrons are identified by estimating the momentum of the extrapolated of tracks
4. Aging

The effects of the aging of the detector have been observed from different perspectives. We may look for instance to the impact on the L0 trigger by computing the ratios between the trigger rate on hadron channels and on muon-dimuon channels in which a 5% decrease was observed in 80 pb$^{-1}$ in 2011. The ratio between the electron/photon L0 trigger rate and the muon-dimuon channels decreased a 20% in 1.2 fb$^{-1}$.
In the case of HCAL, aging can be seen on LED response. We have shown that aging affects both the detector and the photomultiplier. We define the PMT sensitivity variation as the PMT gain variation reduced to the gain at the beginning of the run (March 2011) HV, calculated from the calibration coefficients. Figure 9 shows how the PMTs of the cells closer to the beam-pipe, so with higher occupancies, have a gain loss. This gain loss is compatible with the cumulated charge gain loss measured in the laboratory. Besides, scintillator rows in the tile get affected depending on their depth as shown by figure 10 for the central cells, where the light yield is measured with respect to the delivered luminosity for different rows. First rows, where the hadronic shower is maximum, degrade faster.

Figure 9. "PMT sensitivity variation" for each HCAL channel.

To compensate for the detector aging, we follow a two-fold strategy. From the measurements given by the $^{137}$Cs source, followed up by the LED monitoring we compute the correct modification of the PMT gain and so, the corresponding new high voltage. To keep the gain variation moderate, we may also modify the calibration coefficients of the HCAL cells.

If the offline accounting for the HCAL ageing would be found necessary, one can use the $E/p$ based calibration on hadron tracks. The $E/p$ calibration gives absolute scale and calibrates the whole signal chain, accounting also for the spread of electronics sensitivities. Figure 11 shows the correlation of ratio of $E/p$-based calibration coefficients for fill ranges 1883-1901 and 1997-2007 (around 5 weeks in between) and LED amplitude change for the same period. This validates the use of the LED corrections at least for short time scale.

ECAL aging effects can be seen from the variation on the $\pi^0$ mass peak fit for calibration over time (figure 12). To solve this problem, we proceed by calibrating ECAL at two levels. First, we apply the fine calibration of each ECAL cell using $\pi^0$ mass fit and adjusting its mass on a short period of data taking. Then, on top of fine-calibrated coefficients, data trending coefficients are applied. Since $\pi^0$ statistics is not high enough to follow closely the changes, we use the photon conversion and look at the $E/p$ calibration technique.

So far, no relevant aging effect has been observed neither on PS nor on SPD.

5. A sketch of physics results
To illustrate the performance of the LHCb calorimeter systems, we focus onto a result related to decays $B_d^0 \to K^{*0}\gamma$ and $B_s \to \Phi\gamma$, which are particularly sensitive to the ECAL calibration [6]. Reference [7] updates the results of reference [6] to 1 fb$^{-1}$ of pp collisions at a centre of mass energy of $\sqrt{s} = 7$ TeV. The ratio of branching fractions of $B_d \to K^{*}\gamma$ and $B_s \to \Phi\gamma$ decays has been measured to be
Figure 11. Ratio between $E/p$-based calibration coefficients in a 5 week time period and the corresponding ratio of the LED corrections for the same period.

Figure 12. Observed $\pi^0$ mass variation on ECAL due to aging.

$$\frac{B(B_d \to K^*\gamma)}{B(B_s \to \Phi\gamma)} = 1.23 \pm 0.06{\text{stat}} \pm 0.04{\text{syst}} \pm 0.10(f_s/f_d)$$  \hspace{1cm} (1)

in good agreement with the theoretical prediction of $1.0 \pm 0.2$ [8].

Using $B(B_d \to K^*\gamma) = (4.33 \pm 0.15) \times 10^{-5}$ [9], one obtains

$$B(B_s \to \Phi\gamma) = (3.5 \pm 0.4) \times 10^{-5}$$  \hspace{1cm} (2)

(statistical and systematic errors combined), which agrees with the previous experimental value. This is the most precise measurement of the $B(B_s \to \Phi\gamma)$ branching fraction to date.

6. Conclusions
The LHCb calorimeter system are fully functional and deliver precise measurements which contribute to accurate physics results. Aging has been observed in the hadronic and electromagnetic calorimeters. Aging effects are compensated by modifying the photomultiplier gains and the calibration coefficients so that physics results are not affected.

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