Current status and performance of the LHCb electromagnetic and hadron calorimeters

Irina Machikhiliyan for the LHCb calorimeter group
Laboratoire d’Annecy-le-Vieux de Physique des Particules (LAPP), 9 Chemin de Bellevue,
F-74941 Annecy-le-Vieux Cedex, France
E-mail: Irina.Machikhiliyan@cern.ch

Abstract.
As a part of the calorimeter system of the LHCb experiment both the Electromagnetic Calorimeter (ECAL) and the Hadron Calorimeter (HCAL) play a key role in the LHCb trigger system providing it with energetic electron, photon and hadron candidates. The article discusses the designs of both calorimeters and reports their present performance as it was obtained from the analysis of early data collected in the spring of 2010.

1. Introduction
LHCb [1] is one of six experiments operating at Large Hadron Collider (LHC) at CERN. Its physics program is focused on b-physics; in particular it covers such topics as the studies of CP-violation and the indirect searches of new physics via rare B-decays. Experimental set-up is the single arm spectrometer which includes the vertex detector, the tracking system supplemented with dipole magnet, two RICH detectors, the calorimeter system and several layers of muon chambers. LHCb trigger system should be able to reduce the events rate from original 40 MHz down to 2 kHz in the stage of data storage. The selection scheme adopts two-level structure. On the first step (Zero Level Trigger or L0) the fast hardware triggering is performed on events containing secondary particles of high transverse momenta which is the indication of b-events. On the second step (High Level Trigger) the selection is refined further by dedicated software which analyzes partially reconstructed data.

One of major purposes of the LHCb calorimeter system [2] is to provide fast (within 4 μs) L0 trigger on events containing energetic $e^+/e^-$, photon, $\pi^0$ or hadron. The main detectors of this system are the Electromagnetic Calorimeter and the Hadron Calorimeter supplemented by the preceding Scintillator Pad Detector (SPD) and Preshower Detector (PS). SPD and PS are two single layers of scintillator tiles separated by lead sheet 2.5 \(X_0\) in depth. They are vital for the discriminating between photons, electrons and hadrons in the stage of L0 decision; detailed discussion of their design can be found elsewhere [2]. Apart from being involved in the trigger ECAL is also used for the precise reconstruction of the kinematical parameters of neutral particles and for the identification of electrons and positrons. HCAL on the contrary does not play any significant role in offline analysis since is not able to ensure the full containment of energetic hadronic showers on account of the insufficient depth. Therefore it is only employed in L0 where it is expected to provide up to 70% of triggers. Both ECAL and HCAL are the subjects of the present article which discusses their design, describes the procedures used for
time-alignment, calibration and monitoring as well as presents current performance of both calorimeters.

2. Design overview

In many aspects designs of ECAL and HCAL are similar. The detector bodies are rectangular walls with solid angle coverage 300×250 mrad excluding central 30 mrad cut-out for the LHC beam pipe. The calorimeter media is the interleaving structure of absorber plates and scintillator tiles readout by WLS fibers. LHCb ECAL is the calorimeter of shashlik type: layers of lead and scintillator, orientated perpendicularly to the beam direction, are pierced by optical fibers. HCAL design is similar to the one of ATLAS TileCal [3]: plates of iron and scintillator are arranged parallel to the beam axis and the light is collected from the top and the bottom tile edges. WLS fibers from square areas are reunited in bundles forming readout cells; cell size increases from the center of detectors to their periphery (see figure 1). In general ECAL comprises three sections - Inner, Middle and Outer - of different transverse segmentation. In case of HCAL the subdivision into two sections - Inner and Outer - is enough.

The light collected over each cell is readout by photomultiplier (PM). The typical duration of the PM anode pulse is compatible with LHC bunch spacing 25 ns and the trailing edge of the pulse extends partially outside the 25 ns time slot. This small tail is canceled in the first stage of the signal processing by means of the dedicated clipping circuit embedded in the PM power supply. The shaped pulse is transmitted then to the input connector of Front-End Board (FEB) for further treatment which includes integration, digitization by means of analog-to-

| Table 1. Selected parameters of ECAL and HCAL. $\sin(\theta) = \sqrt{(x^2 + y^2)/(x^2 + y^2 + z^2)}$, where (x,y,z) are coordinates of the center of the detector cell; $N_{p.e.}$ is the number of photoelectrons. |
|-----------------|--------|-----------------|-----------------|--------|-----------------|-----------------|
|                 | Inner  |     Middle      |     Outer       | Inner  |     Middle      |     Outer       |
| Cell size, cm   | 4.04   |   6.06          |  12.12          | 13.1   |   26.2          |     |
| # of cells      | 1536   |   1792          |  2688           | 880    |   608           |     |
| Lateral size, m×m | 1.9×1.5 | 3.9×2.4          | 7.8×6.3         | 4.2×3.7 | 8.4×6.8       |     |
| Distance to the interaction point, m | 12.5   |                 | 13.3            |       |                 |     |
| Depth           | 25 $X_0$, 1.1 $\lambda_I$ |       |  5.6 $\lambda_I$ |       |                 |     |
| Upper limit of dynamic range, GeV | $7+10/\sin(\theta)$ |       | 15/$\sin(\theta)$ |       |                 |     |
| Energy resolution, % (E is in GeV) | $(8 \div 10)/\sqrt{E \oplus 0.9}$ |       | $69/\sqrt{E \oplus 9}$ |       |                 |     |
| Average light yield, $N_{p.e.}/$GeV | 3077   |   3516          |  2569           | 105    |                 |     |
digital converter (ADC) and the following subtraction of the ADC pedestal. Each FEB is also equipped with delay chips for precise (1 ns accuracy) adjustment of the relative timing of the ADC clock and the integrated PM signal in order to compensate for different PM signal arrival times (see next section). One FEB is able to process data from 32 calorimeter cells thus hosting 32 readout channels. ADC readings are stored in the pipeline deep enough to keep the data for the latency of L0 decision. In parallel they are used by the trigger part of the FEB which locates trivial cluster candidate with highest transverse energy in the detector region served by given board. A list of such clusters serves as an input for the L0 trigger level.

To monitor the functionality of the readout chain described above and the stability of its characteristics both ECAL and HCAL are equipped with monitoring systems on the basis of light emitting diodes (LEDs). Each photomultiplier is illuminated by light flashes of fixed intensity, so the value of average PM response can be used to follow up the behaviour of each readout channel (mostly defined by the stability of the PM gain). In order to eliminate the effects, coming from possible variations of the intensity of LED flash, LEDs themselves are monitored by means of very stable silicon PIN photodiodes.

Selected parameters of both calorimeters are presented in table 1.

3. Time-alignment
For both ECAL and HCAL the time of the arrival of PM signal at the FEB input depends on the cell position. The main contribution comes from two factors: the typical particle time-of-flight increasing from the center of detector to its periphery and the different signal collection time inside photomultiplier decreasing with the distance from the beam axis. In total the spread of timing over all detector cells is on the level of 4–5 ns. In order to ensure the fine mutual synchronization of readout channels of each detector and also the correct time alignment of different detectors with respect to the accelerator cycle, LHCb data acquisition system offers special Time-Alignment Events which can contain up to ±3 consecutive time slots of 25 ns around the one under interest. If the timing is optimal the signal fraction registered in the time slots adjacent to the central one is minimal. In the particular case of ECAL and HCAL the asymmetry-like variable \( R = (E_{\text{cent}} - E_{\text{next}})/(E_{\text{cent}} + E_{\text{next}}) \) is used to estimate the size of the misalignment in time \( \delta t \) in each readout channel, where \( E_{\text{cent}} \) and \( E_{\text{next}} \) are average energy depositions in the central time slot and the next one after it respectively. It was shown that \( R \sim \delta t \) if (i) the timing is already not very far from the optimal one and (ii) the measurement of \( R \) is done on the condition that an artificial shift of timing of about 12.5 ns is introduced in the readout system. It allows calculating \( \delta t \) directly from one measurement avoiding multi-step time scan in 25 ns range. This method was used for the fine adjustment of the timing for both ECAL and HCAL at the end of 2009 when LHC delivered first collisions. After the procedure was completed a small time scan in few ns range was performed in order to verify the optimal sampling of the PM integrated signals. The same exercise was also repeated in the spring of 2010 as soon as LHC resumed its operation after long technical stop. It was shown that for the vast majority of ECAL and HCAL cells the timing was set with the precision ±1 ns.

4. Stability of detector response
The monitoring of ECAL and HCAL responses is performed online in parallel with data taking. LEDs flash with the frequency of about 50 Hz synchronously with one of accelerator empty buckets which are not filled with protons. The stability of ECAL and HCAL was studied using data collected during the period from 6 April to 19 July 2010. For each data sample the deviation of response on LED in each cell \( i \) from its value averaged over all data sets was calculated:

\[
\Delta_i = (A_i - \overline{A_i})/\overline{A_i}
\]

Figure 2 represents the value of \( \Delta_i \) averaged over all operational detector cells (>99% of all cells) as function of time. It is seen that the average stability of the response of both ECAL and HCAL is well within 2 %. 

3
5. Calibration of ECAL

The calibration of ECAL was performed in three consecutive steps. During detector commissioning gains of photomultipliers were pre-calibrated with the help of LEDs. With the first LHC collisions the calibration of ECAL was improved using energy flow method. Finally the fine calibration of the detector was done using $\pi^0 \rightarrow \gamma\gamma$ decays.

**Pre-calibration of PM gains.** Major factors defining the accuracy of the initial adjustment of the ECAL energy scale were:

(i) the cell-to-cell variation of light yield value $Y$. Average values of $Y$ for each ECAL section were measured with the help of cosmic particles and on the test beam (see table 1). These studies showed also that the r.m.s. of the distribution of $Y$-values is on the level of 8%;

(ii) the dispersion in the sensitivity $s_{ADC}$ of readout ADCs. Permissible variation for $s_{ADC}$ value was set to $\pm 5\%$ limit; only ADCs fulfilling this requirement were allowed to be used in FEBs;

(iii) the dispersion in the quantum efficiency of PM photocathodes. Related values of green sensitivity index $q_{gr}$ were provided by the manufacturer for each PM individually;

(iv) the precision of the adjustment of PM gains.

To minimize the influence of the last factor all photomultipliers were pre-calibrated in situ with the help of the monitoring system. The PM gain $G$ was calculated as $G = K \times (\sigma^2_{LED} - \sigma^2_{ped})/(A_{LED} - A_{ped})$, where $A_{LED}/A_{ped}$ - positions of Gaussian peaks associated with PM response on LED / ADC pedestal, $\sigma_{LED}/\sigma_{ped}$ - widths of these peaks and $K$ - known parameter defined by hardware properties. The formula is valid on the condition that the main contribution to the width of LED peak comes from photo statistics, i.e. $\sigma_{LED} \sim \sqrt{N_{p.e.}}$, where $N_{p.e.}$ is the number of photoelectrons emitted from PM photocathode. To fulfill this requirement the LED spectra for the measurement of $G$ were collected in the reference point at LED flash intensity as low as possible. In order to fit small PM signals into ADC dynamic range the high voltages (HV) supplied to PMs were significantly increased. To cover the nominal range of ECAL gains the relative dependence $G(HV)$ with respect to the reference point was also measured for each PM following the relative change of PM response with HV at fixed LED flash intensity. The outcome of the procedure described above was the set of regulation curves $G(HV)$, one per each detector channel. The statistical error of the measurement was $3\div4\%$ and the accuracy of the method itself was found to be within $8\%$.

Finally individual regulation curves, individual $q_{gr}$ values as well as average values of $Y$ and $s_{ADC}$ were used to produce initial HV settings for all ECAL PMs. The overall average accuracy of initial channel-to-channel inter-calibration was estimated to be within $13\%$. Such precision was sufficient to observe the peak corresponding to decay $\pi^0 \rightarrow \gamma\gamma$ immediately after first collisions were delivered by LHC.

**Calibration with energy flow.** Energy flow method allows improving cell-to-cell inter-calibration up to $4\%$ level on the basis of relatively small statistics (few millions of minimum...
bias events). Its basic idea is the smoothing of the map of transverse energy depositions over detector surface. For each cell correction factor is produced with respect to the mean deposit over eight neighboring cells. The method does not require any information from other sub-detectors and uses only the raw energy deposits in detector cells, i.e. it does not depend on Monte Carlo (MC) based parameters employed in the reconstruction software. All these advantages make the method very profitable in the early stage of detector operation. However it does not provide absolute calibration so for the normalization the positions of the net peaks associated with decays $\pi^0 \rightarrow \gamma\gamma$ and $\eta \rightarrow \gamma\gamma$ were used. Figure 3(a) and figure 3(b) show the maps of ECAL cluster occupancies before and after energy flow calibration respectively. The resulting smoothing is clearly seen. Corresponding improvement of the net $\pi^0$ peak relative width was from 9.1% to 7.5% while $\eta$ peak width decreased from 6.1% to 5.4%.

**Calibration with neutral pions.** The fine calibration of ECAL with $\pi^0$ decays is now in progress. This is an iterative procedure which uses a set of the invariant mass distributions for combinations of two photon candidates. Such distributions are constructed for each detector cell in order to detect the $\pi^0$ peak. The shift of its position with respect to the 135 MeV/c$^2$ is used to correct the adjustment of energy scale of given cell. The required amount of statistics is rather high: for the most peripheral cells it numbers up to 250 millions of interactions.

The specific of LHCb ECAL is that it can not be calibrated by $\pi^0$ method in standalone mode since the measured parameters of particles are constructs based on the energy depositions and

**Figure 3.** ECAL cluster occupancy: (a) before (b) after energy flow calibration

**Figure 4.** Particle signals reconstructed with the participation of the ECAL: (a) $\pi^0/\eta \rightarrow \gamma\gamma$ (b) $\eta/\omega \rightarrow \pi^+\pi^-\pi^0$ (c) $\eta' \rightarrow \phi\phi(\pi^+\pi^-)\gamma$ (d) $D^0 \rightarrow K^-\pi^+\pi^0$ (e) $J/\Psi \rightarrow e^+e^-$
the coordinates of impact points both in PS and ECAL detectors. Also in case of photons both SPD and tracking system are used to suppress conversions in front of the calorimeter system. PS is now calibrated with the precision better than 5% [4]. Also various weighting and correction factors employed in the reconstruction software have been verified and tuned on the first data. With regard to all these improvements the first cycles of π0 calibration were performed recently. The accuracy of ECAL calibration which is presently achieved is on the level of 2÷2.5%.

As the demonstration of present ECAL performance figure 4 shows signals reconstructed with the participation of ECAL for the following particles: π0, η, ω and η′ in various decay modes as well as D0 and J/Ψ. For π0 → γγ and η → γγ decays where the resolution is defined mostly by ECAL performance the relative widths of the peaks are 7.1% and 3.4% respectively.

6. Calibration of HCAL

The HCAL calibration is performed on the regular basis with the help of embedded cesium radioactive source calibration system originally developed for ATLAS TileCal. Two ∼10 mCi 137Cs sources (one per each detector half) are driven by hydraulic system so they traverse each scintillator tile. The PM response is measured with the help of dedicated system of current integrators. Relation factors between the value of PM anode current and the measured particle energy are known from test beam studies, which showed also that this method allows achieving cell-to-cell inter-calibration level 2÷3%. Such precision is more than enough to fulfill all HCAL objectives in the LHCb experiment. The source calibration was also cross-checked with energy flow method which proved that HCAL is currently inter-calibrated with the accuracy better than 4%. As concerns the adjustment of absolute energy scale, its precision is defined mostly by the uncertainty in the values of source activities which are known with the accuracy of about 10%. In order to verify the global normalization the basic physics signals are used such as the position of hadron peak on the distribution of ratios of energy E deposited in HCAL to the particle momentum p measured by the tracking system. Examples of E/p distributions for HCAL Inner and Outer section are shown in figure 5(a) and figure 5(b) respectively (full circles). Open circles represent E/p distributions for MC events. The difference between simulations and data does not exceed 3%.

Acknowledgments

Author is mostly grateful to M. N. Minard and P. Perret for their comments and useful discussion. Author would also like to thank CALOR2010 organizers for their hospitality.

References

[1] Alves A et al 2008 Journal of Instrumentation 3 S08005
[2] LHCb Collaboration 2000 LHCb technical design report: calorimeters Preprint CERN/LHCC/2000-0036
[3] Aad G et al 2008 Journal of Instrumentation 3 S08003
[4] Niess V These proceedings