The LHCb electromagnetic calorimeter

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Abstract. The design and construction characteristics of the Electromagnetic Calorimeter in the LHCb experiment are described. Current status of the subdetector is reported together with selected results of performance studies both with test beam and cosmic particles. Strategies for ECAL monitoring and calibration are discussed.

1. Introduction
The LHCb [1] detector is a forward single-arm spectrometer aimed at studies of CP-symmetry violation and rare decays of b-quark in the LHC collider environment. The tasks of Electromagnetic Calorimeter (ECAL) in this experiment are the following:

- to provide high transverse momentum electron, photon or π⁰ candidates to the LHCb trigger system [2] in order to pre-select b-containing events;
- to reconstruct precise kinematical parameters of neutral particles, for example to study B-meson decays containing prompt photon or neutral pion;
- to participate in the particle identification algorithms, particularly to ensure reliable e± / hadron separation.

ECAL performance should comply with the following list of specifications [3] dictated by LHCb operating environment and physical goals:

- an energy resolution \( \sigma_E/E(GeV) \) on the level of \( 10%\sqrt{E} \pm 1% \);
- a fast response time compatible with LHC bunch spacing 25 ns;
- a good reliability to operate for decades in a radiation hostile environment. Annual radiation dose can reach 2.5 kGy in the vicinity of the accelerator beam pipe (in the position of shower maximum);
- transverse segmentation should be small enough to separate significant fraction of γ-produced shower pairs from neutral pion decays and, at the general level, to minimize pile-up effects;
- for optimal detector and trigger performance the dynamic range should be adjusted according to the transverse energy (\( E_T \)) rule\(^2\) with an upper limit 10÷12 GeV;

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\(^2\) The exact formula is \( E_{\text{max}} = 7 + 10/\sin(\theta) \), where \( E_{\text{max}} \) is an upper limit of dynamic range in terms of deposited energies, \( \sin(\theta) = \sqrt{x^2 + y^2}/\sqrt{x^2 + y^2 + z^2} \) and \((x,y,z)\) are coordinates of the ECAL cell with respect to the interaction point.
Finally at the distance 12.5 m from the interaction point ECAL lateral size is chosen to be
7.8 m x 6.3 m, excluding $\theta_{x,y} < 30$ mrad central cut-out for the beam pipe.

2. Design overview

The general layout of the LHCb ECAL is sketched in figure 1. Subdetector itself is realized
as a rectangular wall constructed out of 3312 separate modules of square section. In purpose
of the maintenance the wall is split vertically in two halves; each of them covers right or left
hemisphere of ECAL acceptance and is positioned on independently retractable platform.

The ECAL is subdivided into three sections, Inner, Middle and Outer, comprising modules of
the same size but different granularities. Namely, modules of the Inner / Middle / Outer section
are subdivided into 9 / 4 / 1 readout cells or towers with transverse dimensions 4.04 x 4.04 / 6.06 x 6.06 / 12.12 x 12.12 cm$^2$
correspondingly.

ECAL media structure employs the shashlik technology [4], when interleaving scintillator-
absorber layers are pierced by optical fibers of light collection system. The light readout devices
are photomultipliers (PMs). Their output signals are digitized and processed at 40 MHz rate
by the dead-timeless Front-End electronics [5]. To control the behavior of the subdetector
performance Monitoring System is foreseen.

2.1. The construction of the module

Construction of ECAL module is illustrated in figure 2 with a module of the Inner section. The
sampling stack comprises 66 lead plates and 67 scintillator (Sc, BASF-165H polystyrene based
plastic doped with 2.5% p-terphenyl and 0.01% POPOP) planes, separated by thin (120$\mu$m)
TYVEC paper sheets. Scintillator plane is constituted out of 1, 4 or 9 optically decoupled tiles
thus ensuring required transverse segmentation of the module. Tile edges are chemically matted
in order to improve efficiency and lateral uniformity of the light collection as well as to prevent
tile-to-tile cross-talk.

Wavelength-shifting (WLS) fibers (KURARAY Y-11(250) MSJ, 1.2 mm diameter) of
the light collection system run parallel to the beam axis and penetrate the entire module body. In
order to improve the light collection efficiency and the lateral uniformity of the response, WLS
fibers form U-shape loops at the front side of the module, so each fiber traverses the module
twice. An additional clear fiber, penetrating each cell along the central axis, transports the light
pulses of the Monitoring System from the front to the rear side of the module. Fibers serving
the same cell are grouped together at the rear of the module; resulting bundle enters the PM

![Figure 1. ECAL layout (one quarter).](image1)

![Figure 2. Construction of the Inner module.](image2)
Table 1. Selected parameters of ECAL modules.

|                    | Inner  | Middle | Outer |
|--------------------|--------|--------|--------|
| # of fibers per module (WLS+clear) | 72+9   | 72+4   | 32+1   |
| Average light yield, photoelectrons per GeV | 3077   | 3516   | 2569   |
| Response on MIP, cell-to-cell variation, % | 8.0    | 5.3    | 6.7    |

compartment, where it is coupled with photomultiplier window via light mixer. At the front side the fiber loops are protected with a plastic cover, carrying an optical connector to inject the light of the Monitoring System. The entire module stack is held together by 100 $\mu$m stainless steel bands welded at the four sides of the module.

Effective depth of the module 42 cm is equivalent to 25 radiation lengths ($X_0$), the Moliere radius of ECAL media is 3.5 cm and the sampling ratio Pb:Sc is 2:4 (mm).

The energy resolution of the modules has been measured at the test beam at CERN [6]. Its value proved to be well within the design requirements, namely $\sigma_E/E(\text{GeV})$ is $(8.2 \pm 0.4)%/\sqrt{E} \oplus (0.87 \pm 0.07)\%$ and $(9.4 \pm 0.2)%/\sqrt{E} \oplus (0.83 \pm 0.02)\%$ for the Inner and Outer modules correspondingly. A scan of module prototypes by means of 50 GeV electrons has shown that the non-uniformity of light collection over Sc tile is better than $\pm 1\%$. Cell-to-cell response on minimum ionizing particles (MIPs) varies within 8.0% over all modules accepted for the installation into the subdetector wall, as was measured during pre-installation data quality checks with the help of cosmic particles. The average light yield of the ECAL cell is found to be $\sim 3000$ p.e. per GeV of the deposited energy. More details can be found in table 1.

2.2. The timing of PM signals

ECAL employs HAMAMATSU produced R7899-20 photomultipliers as photodetectors. Each of them is coupled with an individual power supply based on Cockcroft-Walton voltage multiplier (C-W) [7]. The duration of a typical pulse of PM anode current exceeds LHC bunch spacing (see figure 3), therefore output chains of the C-W contain a clipping line for cancellation of the

Figure 3. Typical shape of PM anode current pulse.

Figure 4. PM output pulse after the clipping chain.
signal tail and thus for minimization of the contribution to the next event. After the clipping the pulse duration becomes compatible with 25 ns as it is illustrated in figure 4.

Two major factors contribute to the PM signal timing. The first one is the time of flight of the particle, which rises from the beam axis to the periphery of ECAL by $\sim 3$ ns as it shown in figure 5 by open triangles. The second factor originates from the large spread of PM gains depending on the coordinates of the cell with respect to the beam axis: from 1K to 20K from center to periphery to ensure the required dynamic range. As a consequence, the difference in signal collection time inside photomultiplier, which follows reverse square root dependence on high voltage supplied to it\(^3\), amounts on average to 4 ns (open circles in the same figure). These two factors work in opposite directions and therefore compensate each other to a certain extent. Resulting relative time of arrival of PM signal at the Front-End electronics input varies in the range of 2.5 ns (full squares).

2.3. Front-End electronics

The readout system of ECAL consists of 192 Front-End boards or FEBs, which reside in 14 crates on the top of the subdetector. Each FEB can read out up to 32 cells. Signal processing includes:

- integration of PM pulse by shaper integrator and posterior digitization by means of 12-bit 40 MHz two stage bipolar flash analog-to-digital converters (ADC) with dynamic range 80 pC. Fine synchronization of ADC gates and PM signal is done by programmable delay chips. Corresponding delay values (henceforth - FEB delays) can be varied in the 25 ns range with the step 1 ns. An example dependence of processed PM signal on FEB delay is shown in figure 6. The size of the top plateau, where the signal is processed in the optimal way, matches the expected dispersion in timing over all ECAL cells;
- pedestal subtraction. The value of the pedestal is estimated as the minimal reading over two preceding bunch-crossings (BX). Such mechanism allows suppressing low-frequency noise;

\(^3\) In its turn the gain of R7899-20 is related to the high voltage supplied as $G \sim HV^\alpha$ with $\alpha \sim 6$

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**Figure 5.** Relative contributions to PM signal timing: $\bigcirc$ - signal collection time, $\blacktriangledown$ - time of flight. $\blacksquare$ marks resulting relative delay.

**Figure 6.** PM response to LED as function of relative ADC gate delay. PM gain setting is 1K.
• storage of the readings in memory, and, in parallel, conversion of them into the 8-bit values, re-calibrated to the transverse energies. These values are used in the trigger part of the Front-End board.

Trigger part of the FEB considers all 2x2 cells combinations (i.e. trivial clusters) and for each event selects a cluster candidate with the highest $E_T$ to be sent to level-zero trigger [8]. The exchange by readings for border cells, necessary for cluster reconstruction, is done via backplanes of the crates. Each board also evaluates the full sum over all input channels useful for selection of energetic neutral pion candidates for the trigger.

Finally, if the event is accepted for further processing, the FEB formats corresponding data block and sends it to the DAQ.

2.4. Monitoring System

The general structure of LHCb ECAL Monitoring system is illustrated in figure 7. It employs super-bright red Light Emitting Diodes (LEDs) LUR3333H. One LED serves a group of readout cells: 16 in case of Middle/Outer and 9 in case of Inner section. LEDs reside beneath/on the top of the subdetector in several monitoring boxes, their light is delivered to modules front surface by means of long clear fibers. The fibers, transporting the light of the same LED, are grouped in a separated bundle, covered by protective opaque coat. The length of such bundles varies from 2 to 8 m introducing an additional dispersion into the timing of the LED signals up to 36 ns. To compensate this effect a controllable delay is foreseen for an individual LED fire pulse. The intensity of an individual LED is also adjustable and allows covering the substantial part of ECAL dynamic range.

The major tasks of the Monitoring System are to check the readout chain serviceability and to trace its stability (mostly dominated by the stability of PM gains). In order to fulfill it one should eliminate the effects, coming from the possible instability of the monitoring devices themselves or prove that these effects are negligible. To that purpose the stability of LEDs is monitored by means of silicon PIN photodiodes S1223-01 (HAMAMATSU) having negligible temperature variation coefficient. The PINs reside in the same monitoring boxes as the LEDs; the light between them is transported via short clear fibers, escaping each bundle. One PIN serves a group of two or four LEDs, its response is readout by FEBs of the same type as for PMs.

![Figure 7. General structure of the ECAL Monitoring System.](image-url)
An example of the compensation procedure for possible LED instability is shown in figure 8. The LED magnitude was decreased in several steps down to 70% level with respect to the reference intensity to emulate the drift (X-axis, relative change in LED magnitude $\delta$). The original PM readings (open circles) were corrected by the factor obtained from the PIN (full squares). It was found that the accuracy of such procedure $Q$ is better than 1% up to 30% change in LED magnitude, as is shown in figure 9. Here the accuracy is estimated as $Q = (k_{PIN} \times I_{PM} - I_{PM}^{ref}) / I_{PM}^{ref}$, where $k_{PIN}$ is the correction coefficient, $I_{PM}$ - PM readings at the current LED intensity and $I_{PM}^{ref}$ are PM readings at reference LED intensity.

3. Monitoring and calibration of the subdetector response

Three basic conditions have to be met to ensure normal ECAL operation:

(i) good timing of subdetector response on the level of individual cells;
(ii) periodical fine absolute calibration of the cell response;
(iii) monitoring of cell response in-between of absolute calibration runs. In case of a significant change the necessary correction factors for calibration constants will be provided according to the change of the response to the LEDs regarding also the information provided by the PIN system (so-called relative calibration).

3.1. Adjustment of subdetector timing

LHCb physical events. The first goal is to perform the synchronization of ECAL readings with the LHC accelerator cycle in the way which ensures optimal processing of individual PM output pulse by readout ADCs. As it was shown in section 2.2, for the events under discussion the timing at uniform FEB delay settings is rather good; their remaining fine tuning, also allowing for possible additional spread introduced by the cabling, will be performed in situ when the accelerator starts to deliver interactions.

Monitoring (LED) events. As soon as the set of optimal FEB delays is fixed by the foregoing, the timing of the Monitoring System can be adjusted. To that purpose a tuning of individual LED fire pulse arrival times will be performed in the way which guarantees the appearance of all PM/PIN responses on LEDs flash synchronously with the same bunch-crossing and, preferably, with an optimal integration of the signals.

From technical point of view the time alignment will be performed by recording and further analysis of detector readings in several consecutive BX around the one under interest (so-called time-alignment events).
3.2. Monitoring during data taking

LEDs will be fired in the midst of the group of several consecutive not-filled bunches with the frequency 50±100 Hz (pre-scaled accelerator cycle). At the same time one LED over group served by the same PIN will be flashed at most. LED events will be read out and redirected to the calibration farm of few PCs (see figure 10), where dedicated software code will process them and produce spectra for individual cells containing pedestal and LED distributions as well as some summary histograms. Periodically spectra from all farm nodes will be retrieved via network to the analysis node, where the following sets of resulting parameters will be extracted:

- a list of malfunctioning cells;
- LED / pedestal distribution positions and widths;
- PM gain correction factors if any.

These sets will be stored in the database to be used afterwards in the offline analysis as well as to prepare new configuration sets for DAQ and Trigger system. In case of emergency alarms and warnings will be sent to the Experiment Control System.

3.3. Calibration algorithms

The dispersion in modules characteristics is less than 8% for all cells, the individual photomultiplier parameters are provided by the manufacturer, the reproducibility of PM gain setting over all C-W is on the level of 1.5% and the dispersion in ADC sensitivity values is better than 5%. All these conditions give a hope that trivial physical signal (like $\pi^0$ peak) will be seen in ECAL as soon as LHC starts to deliver interactions. Nevertheless, to be on the safe side, additional methods of rough but fast calibration are now considered, allowing to achieve calibration accuracy 10±15%\(^4\). These methods are based on such parameters as energy flow, occupancies, etc., but the details of their implementation strongly depend on LHC / LHCb start-up scenario (beam energy, magnetic field presence, etc). More detailed discussion of these methods can be found elsewhere [9].

Calibration with $\pi^0\rightarrow\gamma\gamma$ decays. Neutral pions should be copiously produced in LHC environment and the noticeable part of their decays will be resolved by ECAL as two clusters.

\(^4\) Initial level, which allows seeing the $\pi^0$ signal

Figure 10. Monitoring with LEDs during data taking.

Figure 11. ○ - MIP position in terms of ADC counts. ■ - the factor to rescale ADC counts into MeVs of deposited energy.
Therefore \( \pi^0 \) peak should be clearly seen in di-cluster invariant mass distribution as well as good signal-to-background ratio can be achieved using minimal set of cuts. The major obstacle for the method is 2.5 \( X_0 \)-thick lead converter in the front of ECAL between Scintillator Pad and Preshower (PS) detectors. Therefore ECAL cannot be calibrated in standalone mode: at least PS data have to be used either for full reconstruction of shower energy or for selection of decay photons which did not interact in the lead wall. Despite the fact that the last option means significant statistics loss, calibration with the help of neutral pion decay photons is considered as good starting point for the beginning of LHC operation.

Calibration with MIPs. The equivalent energy deposition of the MIP in ECAL cell is 0.33 GeV (on condition of full containment). This value is small and, for the majority of ECAL cells, ADC precision is too coarse to provide a reasonable accuracy of the calibration. The average response to a MIP in terms of ADC counts (see figure 11, open circles) changes from 3 counts in the inner up to 40 counts in the very periphery of the Outer section. Therefore the best precision which could be achieved is 3% and, while PM gains are kept at nominal values, the MIP-based method might be somewhat useful to calibrate the very periphery of the Outer section.

Calibration with electrons. The major benefit of the calibration with a help of energy-to-momentum ratio for electrons is the high accuracy of the method (up to 0.5% according to simulations). However it requires precise information from tracker system and a pure sample of \( e^+/e^- \) candidates. Therefore this method is planned to be used later on, when the tracker chain of LHCb becomes fully operational.

4. Current ECAL status
At present time all ECAL sub-components are installed in the experimental hall and commissioned. Current activities cover the following set of tasks:

- study the behavior of ECAL as whole system;
- development and debugging of software for monitoring, time alignment, calibration;
- participation in general LHCb commissioning on cosmic particles. ECAL is involved in combined CAILO trigger, which requires a coincidence between ECAL and hadron calorimeter. To have MIP response as far from the pedestal as possible, ECAL PM gains are set to 300K;

In general ECAL is now ready to receive fist interactions.

Acknowledgments
Author is mostly grateful to Yu. Gilitskiy, D. Golubkov, V. Egorychev, I. Korolko and M. N. Minard for their comments and useful discussion. Author also would like to thank CALOR08 organizers for their hospitality during the conference.

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