The LHCb Hadron Calorimeter

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Abstract. The Hadron Calorimeter of LHCb is a sampling iron-scintillator calorimeter of 5.6 \lambda_t thickness with structure arranged along the collider beam direction. The light readout is performed with WLS fibers running along the scintillator tile edges. The fast front end electronics allows to digitize events at 40 MHz without dead time. The self-calibration system based on $^{137}$Cs radioactive source embedded into the calorimeter structure allows to obtain absolute calibration with precision of about 2\%. It is also equipped with a LED monitoring system, which allows to follow the PMT response variations during physics data taking.

1. Introduction
The Hadron Calorimeter of LHCb is a part of the experiment’s calorimetric system [1, 2] intended to provide the Level-0 trigger on presence of high transverse momentum hadrons, which is a signature of $B$-event. This imposes the following design requirements:

- it should be able to measure the particle’s transverse momentum at 40 MHz bunch crossing rate;
- its elements should be radiation tolerant, the expected dose rate in the central area is $\sim$50 krad/year;
- moderate energy resolution is sufficient for triggering purposes.

HCAL is supposed to provide $\sim$70\% of Level-0 trigger output.

2. HCAL description
2.1. Structure and layout
The detailed description of the calorimeter system is given in [3]. For the LHCb HCAL the iron-scintillator sampling structure arranged parallel to the collider beam direction have been chosen. Such structure, first proposed in [4], was implemented in ATLAS TileCal [5]. The LHCb HCAL design [6] follows the same idea; the differences in structure and main parameters are caused by different design requirements and detector geometry.

The HCAL is placed at 13.33 m from the interaction point and has lateral dimensions of 8.4×6.8 m$^2$. Its instrumented depth is 122 cm, it has no longitudinal segmentation. The general view of HCAL is shown in Figure 1. It consists of two symmetrical halves, each of which is assembled out of 26 stacked horizontal modules and placed on a separate movable platform. Laterally it is segmented into cells of two sizes, 262×262 and 131×131 mm$^2$ in the outer and inner sections, respectively. The two central modules of each half are 26 cm shorter than others,
forming a hole which lets the beam pipe pass through. In total HCAL contains 1488 cells, 608 outer and 880 inner.

One module is 262 mm high, it consists of self-supporting steel absorber structure and optical elements, scintillator plates and WLS fibers, embedded into it. The weight of one module is about 9.5 ton.

The absorber structure is periodical (Figure 2), one period is composed of two 1232 mm long, 6 mm thick master plates interlaced by six 4 mm thick spacer plates. The scintillator tiles are placed between spacers. This structure is repeated 208 times in each module. In longitudinal direction it presents six 202 mm rows with interchanging order of steel spacers and scintillator tiles. It was shown in [7] that, although the chosen depth does not provide full shower containment, it is sufficient for the trigger operation.

2.2. Light collection and readout

The active elements of the calorimeter are 3 mm thick scintillator tiles (Polystyrene + 1.75% Paraterphenyl + 0.05% POPOP). The tiles are wrapped by TYVEK®, in order to improve the light collection. In the outer section the tiles are 256×197 mm², while in the inner section, in order to arrange finer segmentation, the tiles are cut into two halves 127×197 mm².

The light readout is performed by WLS fibers (Ø1.2 mm Kuraray Y-11(250)MSJ) running along the tile edges at both sides of the module. In order to have optical contact between tile and fiber, the fiber is passed inside the TYVEK envelope.

The transverse segmentation is achieved by proper grouping of fibers into bundles. Each fiber collects light from tiles of three rows; the light from each full size tile in the outer section is read out by 2 fibers, the half size tiles in the inner section — by one fiber.

The WLS fibers’ light attenuation length is about 3.6 m. In order to improve the light collection and longitudinal uniformity of response, one end of each fiber was cut by diamond mill and coated by aluminum, forming a mirror with reflectivity of about 85%. For long term
Further improvement of the HCAL longitudinal uniformity was achieved by introducing artificial attenuation of light in the tile rows close to the photomultipliers. This was done simply by tuning the length of the optical contact between fiber and tile. Namely, the lengths of the optical contact were set to 197, 194, 189, 181, 169 and 149 mm for tile rows 1–6, respectively; the maximum light attenuation of ~24% is applied in the row 6, which is closest to PMTs.

The photomultiplier used in the LHCb HCAL is HAMAMATSU R7899-20. This version of R7899 photomultiplier, specially designed for LHCb, differs from the basic version by its enhanced stability of gain with respect to variations of anode current. The High Voltage is supplied to each photomultiplier by an individually regulated Cocroft-Walton (CW) circuit installed on the photomultiplier [8]. The CW bases are therefore made of radiation hard components. The control voltages for CW bases are produced by DAC boards installed outside the radiation area. These boards communicate with the Experiment Control System via SPECS bus [9].

2.3. HCAL parameters from beam tests

The HCAL prototype beam test measurements [7, 10] are summarized in Figure 3. Its energy resolution is

$$\frac{\sigma_E}{E} = \frac{(69 \pm 5)\%}{\sqrt{E}} \oplus (9 \pm 2)\%,$$

the average light yield with HAMAMATSU R7899-20 is 105 photoelectrons per GeV.

2.4. Front end electronics

For the HCAL usage within the LHCb Level-0 trigger, it is essential that the signal duration is less than the time between two consecutive bunch crossings, 25 ns. The decay time of Kuraray Y-11 fiber $\tau_D = 7$ ns [11] leads to a longer signal; the clipping circuit shown in Figure 4 is used for shaping. The delay line of ~6 ns necessary for this circuit is made of 1.15 m long 50 Ohm coaxial cable, which is used also to supply the signal to the integrator board of the $^{137}$Cs calibration system, which measures average PM current. The elements of the clipping circuit are also placed on the integrator board.

The signals from photomultipliers are processed by specially designed Front End Boards (FEB) [12, 13]. At the first stage the signal is digitized by dedicated dead timeless ADC. The
principles of operation of the input circuit of such ADC are shown in Figure 5. The input signal is split into two parts, one of which is delayed by 25 ns. The delayed part is then subtracted from the direct one, and the difference is integrated, so that the output of the analog chip at any moment of time represents the integral of the input signal in preceding 25 ns. The output signal is then digitized by the 40 MHz 12-bit flash ADC (AD9042). The sensitivity of Front End Board is $20 \text{ fC/ADC count}$.

After digitization Front End Boards perform pedestal subtraction. The pedestal value is calculated as a minimum of the two preceding ADC measurements. The pedestal subtraction eliminates also the low frequency noise which is present at the output of the integrator.

The information for the Level-0 trigger decision is also prepared in FEBs. It consists in detection 2x2 clusters with total energy deposition such that the corresponding transverse energy ($E_T$) exceeds certain limit. For that, the ADC value in each cell is multiplied by an individual calibration factor, such that the result is proportional to $E_T$.

In order to facilitate the calculation of the transverse energy in Front End Boards, the high voltages in the photomultipliers are supposed to be set such that the corresponding cell sensitivity (signal amplitude per unit energy deposition) is proportional to $\sin \Theta$. Namely, with 5 GeV trigger threshold, the PMTs’ HV will be set as $E_{\text{max}} = 15 \text{ GeV}/\sin \Theta$, where $E_{\text{max}}$ is energy corresponding to maximum ADC count.

3. LED monitoring system

During physics data taking, the gain of the HCAL PMTs is supposed to be continuously monitored by LEDs [10]. Significant variations of gain will be recorded into the run conditions database and used in the offline analysis. The LEDs will be flashed during the series of empty LHC bunches foreseen for detector calibrations. For the HCAL monitoring, fast blue LEDs (WU-14-750BC) are used. The light of a LED installed in a HCAL module is distributed to all
cells of this module through 2.4 m long clear fibers (Ø1.2 mm Kuraray CLEAR-PSMS40J). The flash intensity is set by control voltage supplied to the LED driver board. As the LED flash intensity itself can vary with time because of e.g. temperature variations, it is monitored by a PIN photodiode (Hamamatsu S1223-01) installed on the LED driver board next to the LED. Each HCAL module is equipped with two independent LED-PIN assemblies.

Results of a 108 hours long stability test made during the HCAL commissioning are shown in Figure 6. One can see that the LED flash intensity, according to the measurement with the PIN photodiode, is very stable (within 0.1%). In the same time, the PM signal amplitude shows slow drift by ~1.5%.

During the HCAL production and commissioning, the LED monitoring system was intensively used as a quality control and time alignment tool.

4. $^{137}$Cs calibration system

The LHCb HCAL is situated in the downstream part of LHCB, behind the Electromagnetic Calorimeter, so it is difficult to calibrate it on physics events. HCAL will be calibrated using the ~10 mCi radioactive source $^{137}$Cs moving through every cell. This method provides very detailed information about the calorimeter, it allows to measure the response of every individual scintillating tile.

The source integrated into the dumb-bell shaped aluminum capsule moves with flow of liquid inside the stainless steel pipes embedded into every HCAL module. The calibration system based on hydraulical movement of source was originally developed for the ATLAS TileCal [14]. The liquid used as moving medium in our case is pure demineralized water. Each HCAL module has an embedded pipe with inner diameter of 6 mm and wall thickness of 1 mm. The pipe is six-fold, it passes through the centres of each of the six tile rows. Its length is ~27 m (26 m in central modules). The pipes of all 26 modules of each HCAL half are connected together. Each half is then equipped with its own $^{137}$Cs source and a hydraulic system for moving it.

A sketch view of one of the two hydraulic systems is shown in Figure 7. The source is driven by a pump; a system of valves determines the direction of water flow. Between calibration runs the source is housed in the container with 5 cm thick lead walls (called garage) which is inserted into the capsule pathway on top of the HCAL half. During the run the source passes sequentially through all 26 modules, with a speed of 20-30 cm/sec, then passes the same way in reverse direction and returns back to the garage.
During the run, the anode current of photomultipliers is being measured every 3 ms and recorded to disk for the offline analysis. A typical picture of dependence of PMT anode current on time during the passage of the source through the 13 tiles of one tile row read out by this PMT is shown in Figure 8. The superimposed curve is a fit by a weighted sum of (empirically obtained) tile response functions placed at equal time intervals $\Delta t$:

$$I(t) = \sum_{i=1}^{N} c_i \cdot f(t - t_0 - i\Delta t),$$

where $N$ is the number of tiles in this row read out by the PMT and $c_i$ is a set of coefficients representing the response of each tile.

The $^{137}$Cs calibration system was used as a quality control tool during the HCAL modules production. After the assembly the Cs run was performed in each module, aiming in the debugging of its optical system. Namely, it was required that the response of each tile should not deviate by more than 20% from the average over all tiles read out by this PMT. In case of finding defective optical elements, they were replaced and test repeated. The final result for one of the PMTs is shown in Figure 9. The resulting optical uniformity can be characterized by the average RMS of responses of tiles in groups read out by the same PMT which equals to 4.7%; their distribution is shown in Figure 10.

The precision of the $^{137}$Cs calibration was studied at the beam tests [10]. Total of 47 outer and 30 inner cells were independently calibrated with $^{137}$Cs and with 50 GeV $\pi^-$ beam. The average ratio of sensitivities to the $^{137}$Cs and to hadron showers was measured:

$$\frac{S_{Cs}}{S_h} = 41.07 \pm 20.88 \frac{\text{nA/mCi}}{\text{pC/GeV}}$$

for outer (inner) cells, respectively. The RMS of its distribution over tested cells, which represents the precision of the $^{137}$Cs calibration, was 2 (3)% of average.
The anode currents of PMTs are measured by sensitive integrating amplifiers, whose outputs are then multiplexed and digitized by a 12 bit ADC. The amplifiers have integration time of 1.5 ms and four selectable measurement ranges: 0.3, 1.5, 9 and 50 $\mu$A. The current measurements are read out through the SPECS bus independently on the main DAQ. Mechanically, the amplifiers and multiplexers are placed on 188 8-channel integrator boards, housing also the components of signal clipping circuitry. These boards are installed at the rear surface of HCAL, nearby the PMTs. They are read out by four control boxes, containing the ADC and SPECS interface. The control boxes are placed outside the radiation area.

The maximum anode currents in the HCAL PMTs during calibration at "nominal" HV settings, $E_{\text{max}} = 15$ GeV/$\sin \Theta$, are expected to vary in the range of 40–1200 nA, depending on the cell position. However the system for measuring currents will be used not only for the HCAL calibration: the anode currents of the PMTs will be continuously monitored during the physics data taking. The monitoring of the HCAL anode currents will give independent information on the relative luminosity and dose rates. The Monte-Carlo predictions for the anode currents in the HCAL PMTs corresponding to the "nominal" HV settings and "nominal" luminosity, $L = 2 \cdot 10^{32}$ $cm^{-2}s^{-1}$, are shown in Figure 11. One can see that currents up to several tens of $\mu$A are expected in the central area of the detector. Therefore the two most sensitive measurement ranges of integrator boards, 0.3 and 1.5 $\mu$A, are intended for the $^{137}$Cs calibration, while during data taking all the four ranges will be used.

5. Conclusion
The LHCb HCAL is an iron-scintillator sampling device with structure arranged parallel to the beam direction. The light is read out by WLS fibers to PMT. Its performance is adequate for providing Level-0 trigger for high-$E_T$ hadrons. It is equipped with $^{137}$Cs calibration system and LED monitoring system.

At present (July 2008) the HCAL is installed in the LHCb experimental area and is fully operational. Currently it is under intensive tests with LEDs; it is also used to provide trigger on cosmic events for LHCb. The first $^{137}$Cs calibration run is scheduled for mid-July.

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Figure 11. MC predictions for anode currents in HCAL PMTs at luminosity of $2 \cdot 10^{32} \text{cm}^{-2} \text{s}^{-1}$ and HV settings corresponding to $E_{T}^{\text{max}} = 15 \text{GeV}$

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