Calibration system of the LHCb hadronic calorimeter

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Abstract. The Hadron Calorimeter of LHCb (HCAL) is one of the four sub-detectors of the experiment calorimetric system, which also includes: Scintillator Pad Detector (SPD), Pre-Shower Detector (PS), and electromagnetic (ECAL) calorimeter. The main purpose of HCAL is to provide data for Level-0 trigger for selection events with high transverse energy hadrons. It is important to have a precise and reliable calibration system which produces result immediately after the calibration run. LHCb HCAL is equipped with a calibration system based on $^{137}$Cs radioactive source embedded into the calorimeter structure. It allows to obtain absolute calibration with good precision and monitor technical condition of the detector.

1. Introduction
Hadronic calorimeter of LHCb is a sampling device made out of steel and scintillating tiles, as absorber and active material respectively, arranged along the collider beam direction [1]. Its structure is similar to ATLAS TileCal [2]. The thickness of HCAL is about 5.6 $\lambda_I$ (nuclear interaction length). The light readout system is based on wavelength shifting (WLS) fibers running along the edges of the scintillator tiles. Providing Level-0 trigger imposes the following design requirements to HCAL:

- high radiation tolerance (expected dose rate in the centre is 100 krad/year);
- ability to measure the particles transverse momentum at 40 MHz bunch crossing rate;
- moderate energy resolution is sufficient for triggering purposes;
- limited longitudinal space (HCAL is located between ECAL and the muon system);

In the LHCb Run II HCAL provides more than 50% of Level-0 trigger decisions.

2. HCAL overview
The HCAL consists of two independent halves, each containing 26 modules stacked on movable platform. Its total weight is about 500 ton. The lateral dimensions of the sensitive area are $X = 8.4$ m width, $Y = 6.8$ m height; the distance between the HCAL front face and the interaction point is $Z = 13.33$ m. Its instrumented depth is 1.22 m, it has no longitudinal segmentation. The HCAL is subdivided into two zones, inner and outer, with square cells of size 131.3 $\times$ 131.3 mm$^2$ in the inner zone and 262.6 $\times$ 262.6 mm$^2$ in the outer zone. The two central modules of each half are 26 cm shorter than others, forming an opening to let the LHC beam pipe to run through.
In total HCAL contains 1488 cells (608 outer + 880 inner). A view of the HCAL detector assembly and a single module is shown in figure 1.

Each module consists of a self-supporting steel absorber structure (see figure 2) with optical elements, such as scintillator tiles and WLS fibers embedded into it. Total weight of one module is about 9.5 tons. Absorber structure is periodic, made from laminated steel plates of only six various dimensions that are connected together. One period is composed of two 1232 mm long and 6 mm thick master plates interlaced by six 4 mm thick spacer plates. The scintillator tiles are placed between the spacers. Identical periods are repeated 216 times in each module. In the longitudinal direction the structure forms six 202 mm sections (rows) with alternating order of steel and scintillator plates. It was shown in [3] that, although the chosen depth does not provide full shower absorption, it is sufficient for the Level-0 trigger requirements.

3. Light collection and system readout

The calorimeter active elements include 3 mm thick scintillating tiles (polystyrene + 1.75 % paraterphenyl + 0.05 % POPOP) and 1.2 mm diameter WLS fibers (Kuraray Y-11(250) MSJ) running along the tile edges at both sides of the module. During assembly each fiber is fed inside the TYVEK® envelope at the edges of the tile. Each fiber collects the light over three tiles in total. In the outer zone the tiles transverse size is 256 × 197 mm², while in the inner zone, in order to achieve better segmentation, the tiles are cut into two halves with size 127 × 197 mm².
The transverse segmentation is achieved by proper grouping of fibers into bundles. Each fiber collects the light from tiles of three rows; in the outer zone the light from each tile is read by two fibers, the inner zone tiles are read out by one fiber.

The WLS fiber attenuation length is 3.5 m. To obtain a more uniform response along the fiber and improve the light collection uniformity, the front end of each fiber was cut and coated by pure aluminum mirror with typical reflectivity of 85%. For long-term stability the mirror was protected with a MgF$_2$ coating. The mirror allows to increase an effective attenuation length in the fiber from 3.2 – 3.6 to 4.9 – 5.3 m.

The photodetector which is used in the LHCb HCAL is a HAMAMATSU® R7899-20 photomultiplier (PMT). This version of the R7899 PMT was specially designed for LHCb. The main difference from the basic version is enhanced stability of gain with respect to variations of anode current. The PMTs specifications are as follows:

- ultra violet glass (185 – 650 nm);
- PDE 15% at 520 nm;
- pulse linearity: within ±2%;
- dark current < 2.5 nA;
- max average current: 100 µA;
- rate effect: < 1% at I > 10 nA.

The high voltage power supply is based on the Cocroft – Walton (CW) voltage multiplier circuits. Each PMT is equipped with individual power supply [4]. The CW bases are made of radiation hard components. The control voltages for CW bases are produced by DAC (Digital to Analog Converter) boards installed outside the detector sensitive area.

4. $^{137}$Cs calibration system

Based on the requirements of the HCAL, its calibration system is able to control the whole optical path (scintillator, WLS fibers, PMT). For this propose a stainless steel pipe of 8 mm diameter and 1 mm thick wall is fed through the centers of each of the six tile rows of the calorimeter cell. This pipe is used to guide a movable capsule with radioactive $\gamma$ source $^{137}$Cs with ~ 10 mCi activity. This method allows to measure the response of every individual scintillating tile.

The source capsule moves with the flow of liquid inside the steel pipe by a hydraulical system. The source movement system design is similar to that of the ATLAS TileCal [2], however in case of LHCb HCAL pure distilled water is used as moving medium. The length of pipe system is ~ 27 m per module. Each half of HCAL has the pipes of its modules connected together and equipped with its own $^{137}$Cs source and a hydraulic drive system.

A sketch view of one hydraulic system is shown in figure 3. The capsule with the source is driven by a pump; the direction of water flow is determined by a system of valves. Between calibration operations the source is housed in a lead container (garage) with 5 cm thick walls. During the calibration run average velocity of the capsule is about 30 cm/sec, the source passes sequentially through all the 26 modules. Data taking is carried out for both capsule directions (F - forward and R - reverse), then the capsule returns back to the garage.

During calibration procedure the source induces a DC current of up to 100 nA in the PMTs, that is integrated and measured by a dedicated electronic circuit. Measurements are repeated every ~ 1.5 ms and recorded for further analysis. A typical picture for one of the PMTs response functions is shown in figure 4. The calibration procedure includes a fit with a sum of empirically obtained tile response functions $I(t)$ with different amplitudes $C_i$ placed at equal time intervals $\Delta t$:

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

where $N$ is the number of tiles in this row read out by one PMT and $C_i$ are coefficients representing response of each tile.
5. Cesium calibration analysis software

Regular cesium calibration runs are necessary to provide required accuracy of energy reconstruction in HCAL and Level-0 trigger operation. In addition, the long time of operation of the detector, with considerable radiation load, makes it necessary to follow-up (monitor) calorimeter performance with changing beam intensity and integrated recorded luminosity (aging effect). To simplify the calibration procedure, a GUI application for visualization and calculation of calibration parameter is developed.

The software development is carried out in C++ under Linux OS used on the LHCb online cluster. The software is a standalone package depending on CERN ROOT v6 libraries [5] and the specific libraries used for communication with ORACLE® database where the HCAL calibration parameters are stored. The program interface is a 2D map of HCAL with $X$ and $Y$ axes corresponding to geometrical coordinates of calorimeter cells and $Z$ axis shows the value of the chosen visualized parameter. The main menu of the program is shown in figure 5. Some features of the software are:

- visualization of all calibration parameters as 2D map and 1D distributions;
- history plots of calibration values over time;
- light yield reduction over six cell rows as a function of delivered luminosity (aging plots).
  For example, light yield degradation plot, average over 20 central cells is shown in figure 6;
- calculation of new PMTs high voltages and gains, uploading calibration results to the LHCb database.

Figure 3. Sketch view of the HCAL hydraulic system.

Figure 4. Dependence of PMT anode current calibration run time. Each peak corresponds to one scintillator tile.

Figure 5. Main view of the GUI with a 2D HCAL view and the menu.

Figure 6. Relative light yield in five first rows as a function of the integrated luminosity.
6. Conclusion
The described $^{137}$Cs calibration system is the main tool for calibration of the LHCb hadronic calorimeter. It is routinely used for the HCAL calibration starting from the beginning of the LHCb operation in 2008. A GUI application has been developed for calibration data visualization and analysis. The latest version of the program is made available on LHCb online cluster and was successfully used to perform HCAL calibration. In future the software capabilities will be expanded to processing the «raw» data directly from the GUI.

References
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