Calibration of the LHCb calorimetric system

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Instrumentation for Colliding Beam Physics

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Calorimeter system consists of:

- scintillator-pad detector (SPD);
- preshower detector (PS);
- electromagnetic calorimeter (ECAL);
- hadronic calorimeter (HCAL)

Main goals:

- to provide Level-0 (L0) trigger;
- particle identification and energy reconstruction

More details on design of the LHCb calorimeter system: talk of Yuri Guz
SPD/PS description:

- **Structure:**
  - Scintillator Pad – lead plane – Scintillator Pad;
- **Light collection and readout:**
  - WLS – fibers
  - 64-channel multi - anode PMT HAMAMATSU R7600

*Fig. 2: Photo of the SPD/PS modules*

inner 4×4 cm²  middle 6×6 cm²  outer 12×12 cm²

*Fig. 3: Photo of the SPD and PS*
ECAL description:

- performed in «shashlik» technology;
- subdivided into three zones: outer (1), middle (2) and inner (3);
- number of detection cells depending on zone

Energy resolution:

$$\frac{\sigma_E}{E} = \frac{(8.5 \div 9.5)\%}{\sqrt{E}} \oplus 0.8\%,$$

where $E$ – energy in GeV

Fig. 4: Photo of the ECAL modules for three sections

Fig. 5: Inner structure of the ECAL module
HCAL description:

- performed in the ATLAS TileCal technology;
- two symmetrical halves, system is subdivided into inner and outer zones;
- detection cells are subdivided into six sections in longitudinal direction

Energy resolution:

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

where \( E \) – energy in GeV

[2008 JINST 3 S08005]
Calorimeter system functionalities

**PS/SPD particle identification for L0 photon and electron trigger:**
- $e^-$, $\pi^0$, $\gamma$ separation by PS;
- $\gamma$/MIP separation by SPD;
- charged multiplicity by SPD

**ECAL:**
- high $E_T$ electrons, photons and $\pi^0$ for L0 trigger;
- reconstruction of $\pi^0$ and photons (+ PS);
- particle ID (+ PS)

**HCAL:**
- high $E_T$ hadrons;
- contributes to Muon ID;
- provides ~ 70% of L0 trigger output (500 kHz out of ~1 MHz)

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**Table 1: Coincidence of the calorimeter system**

<table>
<thead>
<tr>
<th>SPD</th>
<th>PS</th>
<th>ECAL</th>
<th>HCAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>1</td>
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<tr>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
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</tbody>
</table>
### Calorimeter system parameter summary

**Table 2: Selected parameters of calorimeter system**

<table>
<thead>
<tr>
<th>Sub-detector</th>
<th>SPD/PS</th>
<th>ECAL</th>
<th>HCAL</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Number of channels</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2×6016</td>
<td>6016</td>
<td>1488</td>
</tr>
<tr>
<td><strong>Lateral size</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>6.2×7.6 m²</td>
<td>6.3×7.8 m²</td>
<td>6.8×8.4 m²</td>
</tr>
<tr>
<td><strong>cell size in mm:</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- inner</td>
<td>SPD(PS): 39.66(39.84); 59.5(59.76); 119(119.5)</td>
<td>40.4; 60.6; 121.2</td>
<td>131.3; (no middle section); 262.6</td>
</tr>
<tr>
<td>- middle</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- outer</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Longitudinal depth</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>180 mm – 2.5X₀ – 0.1 λᵢ</td>
<td>835 mm - 25X₀ – 1.1 λᵢ</td>
<td>1655 mm - 5.6 λᵢ</td>
</tr>
<tr>
<td><strong>Light yield</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>~ 20 ph.el./MIP</td>
<td>~ 3000 ph.el./GeV</td>
<td>~ 105 ph.el./GeV</td>
</tr>
<tr>
<td><strong>Basic requirement</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Average light yield ~ 20 ph.el./MIP</td>
<td>(8.5 ± 9.5)% / √E + 0.8%</td>
<td>(69 ± 5)% / √E + (9 ± 2)%</td>
</tr>
<tr>
<td><strong>Dynamic range</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0-100 MIPs – 1 bit (SPD) 10 bits (PS)</td>
<td>E_{max} = 10 + 7·sin Θ</td>
<td>E_{max} = 30 / sin Θ</td>
</tr>
</tbody>
</table>

ECAL and HCAL dynamic range adjusted in each cell according to cells: \( \sin \Theta = \sqrt{x^2 + y^2} / \sqrt{x^2 + y^2 + z^2} \)
ECAL calibration strategy

Method:
- Initial calibration
- Energy flow method
- $\pi^0$ meson reconstruction

Accuracy:
- $\sim 10\%$
- $\sim 5\%$
- $\sim 2 - 2.5\%$

Periodicity:
- before LHC startup
- with the first data in 2010
- every month

Stability of PMT gains is monitored each 15 minutes by an LED system. Corrections are applied automatically.


Fig. 8: Distribution of $\pi^0$-meson invariant mass
ECAL $\pi^0$ invariant mass calibration

The fine absolute calibration method uses reconstructed $\pi^0$ meson invariant mass:
- allows to achieve the accuracy of calibration of 2%

**Step 1:** photon reconstruction by the standard experiment algorithms

- Central (seed) cells of the cluster
- Energy deposition in preshower detector
- Out of the shower outside the cluster
- Moliere radius 3.5 cm

**Reconstructed photon energy:**

$$E_{\gamma}^{\text{rec}} = E_{\text{prs}} \times \beta + (E_{\text{seed}} + \sum_{i \neq \text{seed}} E_i') \times \alpha$$

- seed cell is defined as maximum energy cell in the cluster;
- at low energy deposition in the preshower detector the reconstructed photon energy is substantially defined by the energy of the seed cell

**Fig. 9:** Energy deposition in the cluster cells
ECAL $\pi^0$ invariant mass calibration

**Step 2:** selection of photon pairs, which form $\pi^0$-candidate

$$M^2_{\pi^0} = 2E_1E_2(1 - \cos \theta_{\gamma\gamma})$$

- Photons energies
- Opening angle between photons

**Step 3:** select photon pairs, for which the cell is the central cell of the cluster

**Step 4:** determination of the shift of $\pi^0$-meson mass from the nominal value in the given cell

For all ECAL cells

Program modules in Python language

Algorithm in C++ language

**Fig. 10:** Distribution of $\pi^0$-meson invariant mass
ECAL $\pi^0$ invariant mass calibration

**Step 5:** estimation of the calibration coefficient:

$$
\lambda = 1.0 - \frac{\delta M_{\pi^0}}{M_{\pi^0}}
$$

**Step 6:** «primary» iterations

To correct for the fact that not all photon energy is deposited in the central cell of the cluster.

**Step 7:** «secondary» iterations

To account for the fact, that after applying calibration coefficients the cluster positions may change. After the third "secondary" iteration the values of majority of the coefficients vary by no more than 1%

**Fig. 11:** Dependences of $\pi^0$ invariant mass (a) and mass resolution (b) on the number of iterations.

- **π$^0$-meson invariant mass**
- **Mass resolution of π$^0$-meson**

$$
\lambda = \lambda_1 \times \lambda_2 \times ... \times \lambda_N
$$

$N$ – number of iterations, required to achieve convergence.

Program modules in Python language

Algorithm in C++ language
HCAL calibration is performed with $^{137}$Cs source:

- similar to the ATLAS TileCal system
- two ~ 10 mCi $^{137}$Cs sources used (1 per each detector half);

Features:

- allows to measure the response of every scintillating tile;
- absolute normalization ~10% (the accuracy of the source activity measurements)

During data taking LED monitoring system is used to control HCAL response

Fig. 12: Sketch of hydraulic system (a), PMT anode current as a function of run time (b)
Each module has a ~ 27 m embedded six-fold pipe. The pipe passes through the centers of each tile row. All modules are connected together.

- between calibrations the source is housed inside lead container (so-called garage), the hydraulic pipe system is integrated into it;
- the source is driven by a pump, a system of valves determines the direction of water flow;
- average source speed ~ 30 cm/sec;
- calibration data taking is performed for both capsule movement directions
The precision of the $^{137}$Cs calibration was studied at the 50 GeV $\pi^-$ beam in 2003 at SPS X7. Independent calibrations coincide within 2-3%. The ratio of sensitivities to $^{137}$Cs $\gamma$ - radiation to hadrons and scintillator light yield was measured:

$$\kappa_{Cs} = 41.07(20.88) \left[ \frac{nA/mCi}{pC/GeV} \right]$$ - ratio of the sensitivities to $^{137}$Cs and hadronic shower for outer (inner) cells

$$P_h = 105 \pm 5 \left[ \frac{\text{ph. el.}}{\text{GeV}} \right]$$ - scintillator light yield

[Fig. 15: The distribution of the ratio $S_{Cs}/S_\pi$ for inner (a) and outer (b) cells]
HCAL $^{137}$Cs calibration data

Calibration data from 14.09.2016: measured PMT anode currents, illustrates the nominal calibration

Fig. 16: Calibration results (map of average PMT anode currents)
The effective regulation curves can be obtained from several sequential $^{137}\text{Cs}$ runs at different PMT HV settings. Multipass calibration is carried out once a year. A PMT regulation curve could be parameterized in the form:

$$G^{\text{eff}} = G_0^{\text{eff}} \cdot HV^\alpha$$

$G^{\text{eff}}$ - determined under assumption that the light yield of the cell is $\sim$100 ph.el/GeV

The main goal is to obtain PMT regulation curve parameters, $G_0$ and $\alpha$, at the HV range around the expected working point ($\pm$20%). The $\alpha$ parameter is then used to calculate HV corrections.

Fig. 17: Typical view of the PMT regulation curve

Fig. 18: Multipass calibration results: distributions of $G_0$ (a) and $\alpha$ (b) parameters of regulation curve
HCAL ageing monitoring

$^{137}$Cs calibration system allows to measure the response $A_i$ of every individual scintillating tile row $i$. Therefore degradation of relative light yield $A_i/A_5$ is measured with respect to a reference $^{137}$Cs run at zero luminosity:

$$ R_i = \left( \frac{A_i}{A_5} \right) / \left( \frac{A_i^{\text{ref}}}{A_5^{\text{ref}}} \right), \quad A_i^{\text{ref}} \quad \text{and} \quad A_5^{\text{ref}} \quad \text{reference amplitudes, from the } ^{137}\text{Cs scan of 29.03.2011} $$

Fig. 19: Light yield degradation; average over 44 central cells
Conclusion

**ECAL:**
- Calibration based on reconstruction of the $\pi^0$ meson invariant mass is carried out on a monthly basis;
- Allowed to achieve a calibration accuracy of 2 - 2.5%

**HCAL:**
- The cesium calibration system is regularly used for the HCAL calibration starting from the beginning of the LHCb operation in 2008;
- This method provides very detailed information about the calorimeter and allows to measure the response of every individual scintillating tile and the average characteristics of entire cell

The presented methods allow to achieve fast and accurate calibration of ECAL and HCAL. Calorimeter system is in excellent condition and always ready for work
Thank you for attention!