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The LHCb Calorimeter System: Design, Performance and Upgrade

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The LHCb detector

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Main subdetectors:

- Vertex Locator (VeLo): a silicon strip detector surrounding the IP
- warm magnet, ~ 4 Tm;
- tracker stations (inner: silicon; outer: straw)
- two RICH detectors
- ***electromagnetic calorimeter with preshower***
- ***hadron calorimeter***
- muon identification system

The LHCb Calorimetry System

- solid angle coverage
300x250 mrad
- distance from IP: ~12.5 m
- four subdetectors:
SPD, PS, ECAL, HCAL
- based on scint./WLS
technique, light readout
with PMT
- provides:
 - L0 trigger on high p_T $e^\pm$, π^0 , γ , hadron
 - precise energy measurement of $e^\pm$ and γ
 - particle identification: $e^\pm/\gamma$ /hadron;
contributes to Muon ID (HCAL).

PS / SPD

Preshower detector: two planes of scintillator tiles, with 1.5 cm thick lead plane between them. Size and segmentation: matches ECAL.

The scintillator tiles are 15 mm thick. The light is captured and re-emitted by WLS fiber (3.5 loops) glued in a deep groove machined at the surface of the tile. Light readout: multi-anode PMT.

The scintillation light is captured by WLS fibers glued into the tiles, and transported via clear fibers to 64-channel HAMAMATSU multi-anode PMT R7600-00-M64MOD.

Both PS and SPD are equipped with LED monitoring system

HV setting: uniform, ~ 700 - 800 V

The light yield of all 12032 cells measured on cosmics at production: $\sim 25 \pm 12$ ph.el. / MIP

Shashlik technology

- 4 mm thick scintillator tiles and 2 mm thick lead plates, $\sim 25 X_0$ ($1.1 \lambda_I$); Moliere radius ~ 36 mm;
- modules $121.2 \times 121.2 \text{ mm}^2$, 66 Pb +67 scintillator tiles;
- Segmentation: 3 zones $\rightarrow$ 3 module types, Inner (9 cells per module), Middle (4), Outer (1). Total of 3312 modules, 6016 cells, $(7.7 \times 6.3) \text{ m}^2$, ~ 100 tons.
- Light readout: PMT R-7899-20, HAMAMATSU. HV supply: individual Cockcroft-Walton circuit at each PMT.

Average performance figures from beam test (there is slight difference between zones):

Light yield: $\sim 3000 \text{ ph.el. / GeV}$

Energy resolution: $\frac{\sigma_E}{E} = \frac{(8 \div 10)\%}{\sqrt{E(\text{GeV})}} \oplus 0.9\%$

HCAL

HCAL module: self-supporting structure containing either 16 outer or 8 outer + 32 inner cells. HCAL consists of 52 modules, 9.5 tons each.

- Tilecal technology (originally developed for ATLAS).
- The volume ratio Scint:Fe $\sim 3:16$.
- Instrumented depth: 1.2 m, 6 tile rows, $\sim 5.6\lambda_i$
- Outer cells: 26x26 cm², Inner : 13x13 cm² (half tiles)
- Total of 1488 cells, 2x26 modules, 500 tons
- Scintillator, fibers, PMTs, LED system: similar to ECAL
- built-in ¹³⁷Cs calibration system

Performance from the beam test:

- energy resolution $\frac{\sigma}{E} = \frac{(69 \pm 5)\%}{\sqrt{E}} \oplus (9 \pm 2)\%$
- light yield 105 ± 10 ph.el. / GeV

The LHCb trigger: Run II

➤ Hardware Level-0 trigger

- SPD multiplicity ← CALORIMETRY
- search for a highest E_T object:
 - $E_T (e^\pm/\gamma) > 2.7 \text{ GeV}$ ← CALORIMETRY
 - $E_T (\text{hadr.}) > 3.6 \text{ GeV}$ ← CALORIMETRY
 - $p_T (\mu) > 1.4 \text{ GeV}/c$ ← MUON ID system
- up to 1 MHz output, adjustable thresholds

➤ Software High Level Trigger (HLT)

- ~26000 CPU cores

➤ Storage rate: 12.5 kHz

LOCALO: 60% of the L0 bandwidth

Calibration and monitoring

CALO calibration

more details: see talk of D. Pereima, this conference

The SPD is calibrated on data, via threshold scan with charged tracks. The nominal efficiency is ~95% (threshold ~0.7 MIP).

The PS signal is digitized by 10-bit ADC. The inter-calibration of cells is based on the position of the signal from charged track.

The ECAL fine calibration on data is based on the π^0 peak position.

Up to now, was performed offline.

Starting from 2017, the plan is to do it ~ once per month online (special data stream).

HCAL: the main tool is embedded ^{137}Cs calibration system, calibration out of data taking.

LED monitoring

- ❑ Each CALO subdetector is equipped with a LED calibration system.
- ❑ The HCAL and ECAL monitoring systems have similar design
 - ✓ LED flash magnitudes are monitored by PIN photodiodes
- ❑ For HCAL and (since 2015) ECAL: “active” monitoring
 - *to enable it for ECAL, we had to replace LED light distribution fibers to quartz ones, because of radiation*
 - The goal is to improve L0 operation stability
 - HV corrections are calculated from deviation of average LED amplitudes from reference
 - from 2016 – in automatic regime (HV correction at the end of each fill)
 - This compensates for the ECAL/HCAL PMT gain drift
 - for ECAL it also partially compensates for the radiation degradation of light yield

LED monitoring: ECAL in 2016

Active monitoring: HV correction after each LHC fill

More stable detector response: stabilizes L0 rate, facilitates offline calibration.

Performance

Photon reconstruction, e/h separation

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e/h separation: momentum dependence of efficiency and mis-ID rate for different $\Delta \log \mathcal{L}^{\text{CALO}}(e-h)$

On average: 5% misID rate for 90% efficiency

Ageing effects

Radiation environment @ CALO

(M. Karacson, PhD thesis)

Dose map @ ECAL front, corresponding to the 2012 FLUKA simulation (2.21 fb^{-1} , $E_{\text{CM}} = 8 \text{ TeV}$)

For $E_{\text{CM}} = 8 \text{ TeV} \rightarrow 14 \text{ TeV}$: factor of ~ 1.7 for same integrated luminosity
 For the position of EM shower maximum in ECAL: factor of ~ 2 wrt ECAL front.

Dose profiles at the depth of EM shower max.
 Rapid decrease with $|x|$.

Dose profiles along z at different x positions.
 HCAL front: ~ 0.3 of ECAL front (*the CW HV generators are operational till 10-15 kGy*)
 HCAL back: 0.03 of ECAL front

ECAL radiation hardness

Irradiation of Inner modules in the LHC tunnel

Two ECAL modules were installed in 2009 in the LHC tunnel upstream of the LHCb interaction point, close to the beam pipe.

The dose is measured at the module surface

Sizeable uncertainty ($\sim x1.5 - x2$) in obtaining the dose inside the module

The module may be considered operational till $\sim 3-4$ Mrad at shower maximum:

- $10...13 \text{ fb}^{-1}$ @ 14 TeV for the innermost cells (32 cm from the beam)
- $25...30 \text{ fb}^{-1}$ @ 14 TeV at 48 cm
- ...

HCAL radiation degradation

The HCAL radiation degradation can be evaluated *in situ* from the ^{137}Cs calibration data.

The hadronic shower maximum lays within the tile row 0 (ECAL is $\sim 1.2 \lambda_1$); the dose in the row 5 is much less.

The light yield degradation in a tile row $\#i$ is approximately: $R_i = (A_i / A_5) / (A_i / A_5)_{Lumi=0}$

PMT ageing

Significant DC anode current in HCAL and ECAL PMTs occurs during LHC operation

HCAL: up to 100 C/year

ECAL: up to 30 C/year

Compensated by gradually increasing HV

The dynode system ageing was tested in the lab:

LHCb CALO Upgrade(s)

*For the overview of LHCb upgrades:
see talk of M. Williams, this conference*

The LHCb trigger: Upgrade

With the present trigger organization, 1 MHz L0 limit saturates the physics processes yield with increasing luminosity (especially L0Hadron).

Solution for LHCb Upgrade:

- No Level-0 trigger any more!
- Event selection will be based of full event reconstruction

All the Front End electronics should work at 40 MHz. The electronics has to be rebuilt for most subdetectors.

Upgrade I.

Step in luminosity to $2 \cdot 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$

LHCb CALO Upgrade Phase 1

- **Present ECAL and HCAL will be kept**
- **PS and SPD will be removed:** for particle ID in HLT the tracker information will be used
- **The ECAL and HCAL Frontend electronics will be rebuilt**
- The ECAL and HCAL PMT gain will be reduced by factor of 5, to reduce PMT degradation
 - PMT linearity: OK within required dynamic range
- to compensate, increase x5 the FE preamplifier gain
 - low noise frontend ASIC (ICECAL)
- detector maintenance should follow radiation degradation of detector components:
 - regular replacement of PMTs / CW bases of ECAL
 - HCAL degradation in the centre will not affect the LHCb performance
 - replace damaged ECAL Inner modules at LS3 (~2025)

LHCb CALO Upgrade: FEB

main features:

- number of channels: 32
- input impedance: $50\ \Omega$
- integration time: 25 ns
- sensitivity: 4 fC / ADC count
- dynamic range: 12 bit
- dynamic pedestal subtraction
- timing: individual per channel
- non-linearity: $<1\%$
- spill-over: $<1\%$
- cross-talk: $<0.5\%$

CALO FEB prototype

LHCb CALO Upgrade Phase 1b and 2

CERN-LHCC-2017-003

Phase 1(b) Upgrade (~2025, LS3):
consolidation and enhancement.

LHCb will continue running at $L=2 \cdot 10^{33} \text{cm}^{-2}\text{s}^{-1}$,
to reach $\sim 50 \text{fb}^{-1}$.

By LS3 HCAL will not be necessary any more
(no hardware E_{hadron}^T selection)
and will be dismantled, in favor of additional muon filter.

ECAL: at $L=2 \cdot 10^{33} \text{cm}^{-2}\text{s}^{-1}$, occupancy is too high not only in the centre

- instead of replacing only very central modules, it is suggested to enhance granularity by replacing all modules in the horizontal band
- high granularity $\rightarrow$ small Moliere radius $\rightarrow$ W based modules in the centre

LHCb CALO Upgrade Phase 1b and 2

CERN-LHCC-2017-003

Phase 2 (~2030):

the goal is a detector which is able to
take data at $L=2 \cdot 10^{34} \text{cm}^{-2}\text{s}^{-1}$,
Integrated luminosity $\sim 300 \text{fb}^{-1}$

ECAL: migration to new technology

- sampling calorimetry
- high granularity $\rightarrow$ W based
- timing layer (measure time at ~ 20 ps precision, to distinguish between primary vertices)
 - either 4D Si planes embedded to ECAL modules, or a separate subdetector

First new modules can be installed in the ECAL
centre during the Phase I(b) Upgrade (LS3)

Conclusions

- The Calorimetry system of LHCb is running successfully in 2010-2016, demonstrating very good detector performance.
- Upgrade for higher luminosity ($2 \cdot 10^{33} \text{cm}^{-2} \text{s}^{-1}$) is foreseen during LHC LS2.
- The Calorimetry system will be subject to the following modifications:
 - The Preshower, SPD and lead converter will be removed
 - All the Front End electronics of HCAL and ECAL will be rebuilt.
 - The gain of all the PMTs will be reduced by factor of 5, with corresponding increase of sensitivity of input amplifiers of Front End Boards
- Further LHCb upgrades, Phase 1(b) and 2, are now under consideration, for LHC LS3 and LS4. The final goal is to have a detector running at $L = 2 \cdot 10^{34} \text{cm}^{-2} \text{s}^{-1}$.
 - HCAL will be removed
 - ECAL will be rebuilt using a new technology.

Thank you!

backup

The LHCb operation

LHCb Cumulative Integrated Recorded Luminosity in pp, 2010-2016

luminosity leveling

LHCb is running at a constant luminosity lower than ATLAS and CMS ($3.3 \cdot 10^{32} \text{ cm}^{-2}\text{s}^{-1}$ in 2016) using luminosity leveling technique.

HCAL ageing

Determined from the ^{137}Cs calibration data