The LHCb calorimeter performance and its expected radiation induced degradation

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LHCb: dedicated experiment to study rare effects in beauty (and charm) physics

LHCb detector - single-arm forward spectrometer 10-250 mrad (V), 10-300 mrad (H)

Three calorimeters PS, ECAL, HCAL and one threshold device SPD
arranged in the pseudo-projective geometry, variable granularity

Common principles:

- ❑ determination of the shower energy
 - ❑ scintillator tiles, Polystyrol + 2.5% PTP + 0.01% POPOP
 - ❑ shifting wavelength with optical fibers, Kuraray Y-11(250) MSJ
- ❑ R-O with PMT (Hamamatsu R7899-20 for ECAL and HCAL; 64 ch. MAMPT for SPD/PS), HV setting with Cockcroft-Walton bases
- ❑ monitoring stability of the R-O chain
 - ❑ use LED light injected during empty bunches
 - ❑ monitor LED stability with PIN diode wherever precision needed (ECAL, HCAL)
- ❑ pp-collisions every 25 ns
 - ❑ detector response within 25 ns
 - ❑ R-O within 25 ns
 - ❑ spill-over cancellation with FEE

Detector requirements

Purpose of the LHCb Calorimeter System Preshower (PS) and Scintillator Pad Detector (SPD):

- ❑ PID for LO electron and photon trigger
- ❑ electron, photon/pion separation by PS
- ❑ photon/MIP separation by SPD
- ❑ charged multiplicity veto by SPD

Electromagnetic Calorimeter (ECAL):

- ❑ E_T of electrons, photons and π^0 for LO trigger (e.g. $B \rightarrow J/\Psi K_s$, $B \rightarrow K^* \gamma$)
- ❑ reconstruction of π^0 and prompt γ offline
- ❑ particle ID

Hadron Calorimeter (HCAL):

- ❑ E_T of hadrons for LO trigger
- ❑ (e.g. $B \rightarrow \pi \pi$, $B \rightarrow D_s K$)
- ❑ particle ID

LO trigger $\rightarrow$ Calorimeters R-O every 25ns

Trigger

↓ 10 MHz

LO (hardware):

high p_T h , μ , $\mu\mu$, $e^\pm$, γ , π^0 alleys
(optionally: veto busy events)

Fully synchr. (40 MHz), 4 μ s latency

↓ 1 MHz

HLT (PC farm, full event)

HLT1: confirms LO candidate with tracker and VELO

HLT2: global event reconstruction, inclusive selections

↓ ~ 2 KHz

Electromagnetic calorimeter (ECAL)

- Shashlik technology, 6016 detector cells/R-O channels, grouped in 3312 modules
- Volume ratio Pb:Sc = 2:4 (mm), 25 X_0 , 1.1 λ depth
- Light yield: ~ 3000 ph.e./GeV

ECAL: module performance

Energy resolution, Design: $\frac{10\%}{\sqrt{E}} \oplus 1\%$

Measured: $\frac{(9.4 \pm 0.2)\%}{\sqrt{E}} \oplus (0.83 \pm 0.02)\% \oplus ((145 \pm 13) \text{ MeV})/E$

Lateral uniformity of response:

Lateral scan of ECAL module with
50 GeV e^- beam

Transverse scan with 80 GeV electrons

Spread over the module (Max.-to-Min.):

- $\pm 1.3\%$ for e-beam parallel to module axis
- $\pm 0.6\%$ for e-beam at 200 mrad

ECAL: lateral uniformity of response, simulation

MC modeling:

Light collection efficiency → ray tracer program
(refraction, reflection, attenuation...)

Scintillator thickness → measured

Convolution with particle energy deposition →
GEANT

Dead material of 0.2 mm thick steel
tape between modules compensated
with diffractive white edges

Data (points) vs. simulation (grey area)

ECAL: calibration strategy

All ECAL cells pre-calibrated with cosmic particles

	Inner	Middle	Outer
<Light yield> per cell, Nph.e./GeV	3100	3500	2600
MIP response, cell-to-cell variation, %	8%	5.3%	6.7%

MIP position, ADC channels

→ Cosmics pre-calibration
→ ~10%

→ Energy flow (every 6 months/after shutdowns)
→ ~5 %

→ π^0 & e reconstruction (every few days/weeks)
→ ~1%

→ Monitoring with LED stability every few minutes to follow *eventual* gain variation

Absolute calibration with resolved π^0

Bgrd shape from symmetric cells of the same events

Hadron calorimeter (HCAL)

- Two retractable halves each consisting of 26 modules stacked on a movable platform

- Tile calorimeter
- Active area:
 $8.4 \times 6.8 \text{ m}^2$
- Instrumented depth: 120 cm
($5.6 \lambda_I$)
- Inner zone:
cells $131 \times 131 \text{ mm}^2$
- Outer zone:
cells $262 \times 262 \text{ mm}^2$
- 1488 cells/RO channels
- LED based monitoring system
- Built-in ^{137}Cs calibration system for *in situ* calibration

HCAL module

52 modules with longitudinal tiles

Fiber-tile contact length adjusted to compensate light attenuation difference

Scintillator tile
256 mm x 197 mm x 3 mm

HCAL module performance

Energy resolution

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

Light yield:
105 p.e./GeV

Angular dependence

~3% angular dependence at higher energies: shower not fully contained in $5.6 \lambda_I$

Timing spread

HV settings for physics:
correspond to
 $E_{\max} = 15 \text{ GeV}/\sin(\Theta)$
(trigger on E_T)

PM gains: 20k ... 350k
PM transit time ($\sim 1/\sqrt{\text{HV}}$)

+

Time of flight vary by $\sim 5 \text{ ns}$
Cable delay spread: $< 1 \text{ ns}$

Current measurement from
 Cs^{137} scan at each PMT

HCAL signal timing

A pulse shape study on 30 GeV electron beam for 6 different layers in depth of the HCAL: 25 ns pulse shaping

Signal variations due to detector depth and mirrors at fiber ends

HCAL: Cs^{137} source calibration

- ❑ QC/monitor with Cs^{137} source driven through each tile center.
- ❑ All modules measured with source before installation and in LHCb
- ❑ Requirement: tile response within $\pm 20\%$ of module average

Steel pipe
to drive
 Cs^{137} source
to a given cell

Measurements with Cs^{137} of all the tiles of one module

Amplitude variation:

(max-min)/average < 4%
over 2 months !

[PMT 13] Mean= 581 Fibr.RMS= 4.3% Perc= 20% Left-Top'

Independent calibrations with Cs source and 50 GeV π^- coincide within 2-3%

Correction from PIN diod

Scintillator Pad Detector (SPD) and PreShower (PS)

- Two layers of scintillator interspaced by 2.5 X0 lead
- Light transported via clear fibers to the MAPMT at the detector periphery

- Active area: 7.8m x 6.3 m
- Space constraint: 18cm in depth
- PS+SPD built from 16 super modules
- Segmentation matches ECAL cells
- Total of 12032 cells / R-O channels

Scintillator Pad Detector (SPD) and PreShower (PS)

PS / SPD modules

Scintillator + coiled fiber

15 mm thick tile with coiled WLS fiber
+ ~3m long clear fibers and interconnects

16 super modules for PS & SPD

Super
module
with
2 x 13
modules

Super
module
frame

All super-modules tested with cosmics
in horizontal position:

$\langle N \text{ p.e.} \rangle / \text{MIP}$ varies

from 19 p.e./MIP to 29 p.e./MIP
depending on the cell size

SPD and PS calibration and monitoring

SPD/PS monitoring: LED and particles

LED: each cell receives individual LED → detector stability, dead channels etc

Particles: 5 Hz online event reconstruction

The experiment is fully installed, commissioning well advanced ...

... no collisions yet → cosmons + too short experience with LHC protons.

Cosmic particles, the calorimeter tracking: example

→ PS efficiency 87 %

→ SPD efficiency as a function of threshold

9 σ above noise → 94%

0.5 MIP → 82%

1.5 MIP → 20%

Rare cosmic particle track fully contained in SPD

The calorimeter tracking: cosmics and first LHC particles

Cosmics triggered with ECAL/HCAL for the tracking detectors

Trigger with EM and H calorimeters with a high gain to see MIP

→ Tracks in large surface tracking detectors

LHC sector test: beam dumped on the injection line beam stopper, SPD triggered events (also LHC synchronization test trigger)

Calorimeter triggered event, 1M triggered cosmics collected

Readout of consecutive events → time alignment, optimizing signal vs. spill-over

Vertex Locator tracks

Time alignment with cosmics: signal time asymmetry with flight time corrections

Slope: -2.04
OffSet: **0.37 ns**
Sigma: 1.76

Slope: 2.49
OffSet: **0.71 ns**
Sigma: 1.52

	P	C	N
E	X	X	
H	X	X

Slope: -2.40
OffSet: **1.03 ns**
Sigma: 1.83

Slope: 1.58
OffSet: **2.00 ns**
Sigma: 1.84

	P	C	N
E		X	X
H		X	X

Alignment using
cosmics : ± 2 ns
few $\times 10^4$ evts : < 1 ns

Radiation conditions: expected annual dose in ECAL

1 LHCb year:
 10^7 s, $\int L dt = 2 \text{ fb}^{-1}$

Lateral

Longitudinal

□ Maximum expected dose rate: 0.03 rad/s

Irradiation of Sc tiles with p-beam

- ❑ Tiles: BASF-165,
40.2 x 40.2 mm²
- ❑ Irradiation: 1.8 GeV p-beam (ITEP)
- ❑ Total dose: 500 krad, 1000 krad
- ❑ Dose rate: ~28 rad/s

→ LY was measured at ~20 positions of ⁹⁰Sr source over the tile surface, and then averaged

LY normalization:

$$\frac{LY(\text{Dose}=D, t=t_2) / LY^{\text{ref}}(\text{Dose}=0, t=t_2)}{LY(\text{Dose}=0, t=t_1) / LY^{\text{ref}}(\text{Dose}=0, t=t_1)}$$

where *ref* - reference module.

Degradation at the level of annealing plateau:

→ ~12% for D = 0.5 Mrad

→ ~20% for D = 1.0 Mrad

Y11 fibers irradiation with p-beam

- ❑ Fibers: Y11(250)MSJ
- ❑ Irradiation: 1.8 GeV p-beam (ITEP)
- ❑ Total dose: 500 krad, 1000 krad
- ❑ Dose rate: ~28 rad/s

Light attenuation fit with $LY = B e^{-x/T}$,
where x - distance from tile to the PM.

Normalization:

$$\frac{X(\text{Dose}=D, t=t_2) / X^{\text{ref}}(\text{Dose}=0, t=t_2)}{X(\text{Dose}=0, t=t_1) / X^{\text{ref}}(\text{Dose}=0, t=t_1)}$$

where *ref* - reference set.

Degradation at the level of annealing plateau
for the dose of 1 Mrad:

→ ~12% for B coeff., ~25% for T coeff.

Annealing "brightness" curve

Annealing "transparency" curve

Results from irradiation at LIL : Sc tiles

❑ Irradiation particles:

500 MeV e-beam (LIL)

❑ Total dose (@ shower max.): 5 Mrad

❑ Dose rate: 10 rad/s

❑ Artificial stack:

20 × (1.5mm Pb + 20mm Sc)

+ fibers (no loops), clear edge

cf LHCb stack:

66 × (2mm Pb + 4mm Sc)

+ fiber loops

→ Longitudinal scan with Sr90 source of irradiated Sc + reference fibers

PSM-115 + 2.5% p-terphenyl + 0.01% POPOP

→ Sc LY: $B_{Sci} = B_{Sci}^0 \cdot e^{-\frac{D}{D_S}}$

Results from irradiation at LIL : WLS fibers

BCF-91A(DC)

Y11-200(MS)

→ Longitudinal scan with Sr90 source of reference Sc + irradiated fibers

→ Attenuation length: $\lambda_{Fib} = \lambda_{Fib}^0 \cdot e^{-\frac{D}{D_F}}$

Results from irradiation at LIL: projection to 10 years of LHCb

→ From measured components degradation + expected dose profile (EM type damage only)

Sc + Y11-200(MS)

□ Measure dose map over the calorimeter surface

→ a set of passive monitors installed

□ Replaceable innermost modules:

- ❑ LHCb upgrade after ~5 years of running at $L = 2 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$
- ❑ **Upgraded detector:**
 - Operation at L up to $2 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$ with multiple interactions / BX,
collect 100 fb⁻¹
 - Maintain at least the original performance for LHCb
 - Improved trigger efficiency for hadronic modes
 - Goal: precision physics for selected channels (UT and CPV, FCNC)
 - Main challenge: LO trigger output rate
 - Perform whole trigger in the CPU farm
 - **Calorimeter related demands:**
 - Modified FEE
 - **Radiation resistance of the inner ECAL**
 - sacrifice physics using inner ECAL
 - or
 - other technology (e.g. PANDA like PWO crystals)
 - Increased pileup → particularly dangerous for π^0 modes

ECAL module radiation resistance in the LHCb realistic conditions

Use the LHCb environment

→ Realistic dose rate
 $\sim 0.05 \text{ rad/s}$

→ Realistic irradiation
particles decomposition

→ Realistic LHC timing

→ Online performance
vs. dose monitoring:
longitudinal scan with
radioactive source &
active dose monitors

Projection of the ECAL module radiation resistance to the upgraded LHCb

→ Irradiation with $D_1 \sim 3 \text{ Mrad}$ and $D_2 \sim 7 \text{ Mrad}$ in 12/2009 at IHEP

- ❑ The LHCb calorimeter is optimally designed to meet trigger and physics requirements
- ❑ The system is ready for data taking
- ❑ Understanding of the calorimeter for upgraded LHCb is ongoing