The Phase 2 Upgrade of the LHCb Calorimeter system.

Yu. Guz (IHEP Protvino) on behalf of the LHCb collaboration
The LHCb experiment

A single arm forward spectrometer at LHC.

Flavor physics, CP violation, hadron spectroscopy.
Yu. Guz

The LHCb Calorimetry System of Run I and Run II

- 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 $p_T e^\pm, \pi^0, \gamma, \text{hadron}$
  - precise energy measurement of $e^\pm$ and $\gamma$
  - particle identification: $e^\pm/\gamma$/hadron; contributes to Muon ID (HCAL).
The LHCb ECAL

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

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

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

Shashlik technology

• 4 mm thick scintillator tiles and 2 mm thick lead plates, $\sim 25 X_0 (1.1 \lambda I)$; Moliere radius $\sim 36$ mm;

• modules 121.2 x 121.2 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 x 6.3) m$^2$, $\sim 100$ tons.

• Light readout: PMT R-7899-20, HAMAMATSU. HV supply: individual Cockcroft-Walton circuit at each PMT.
LHCb Upgrade 1

Luminosity: $4 \cdot 10^{32} \rightarrow 2 \cdot 10^{33} \text{cm}^{-2}\text{s}^{-1}$

Detector upgrade to 40 MHz readout
LHCb CALO Upgrade – phase 1 (ongoing)

Luminosity $2 \cdot 10^{33} \text{ cm}^{-2}\text{s}^{-1}$ (~5.5 $pp$ interactions per event):
- **PS and SPD are removed**: no need for particle ID in L0
- **no change in the present ECAL and HCAL**

For Run 3:
- the frontend electronics is being replaced to new one, compatible with the new DAQ & Trigger
- The PMT gain will be reduced by factor of ~5, to reduce PMT degradation
  - PMT linearity: OK within required dynamic range
- to compensate, the FE gain will be increased x5
  - new low noise ASIC (ICECAL)
- detector maintenance will follow radiation degradation of detector components:
  - regular replacement of degraded parts (PMTs / Cockcroft-Walton HV boards)
  - LS3: replacement of ECAL Inner modules
LHCb – the long term roadmap

 Upgrade 2:
 - luminosity up to $2 \cdot 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ (~55 pp interactions per event)
 - ~300 fb$^{-1}$ will be collected
LHCb – the long term roadmap

ECAL in LS3 (2025-2027):
- replace modules around the beam pipe (~32 modules), to improve performance for Run 4

ECAL in LS4 (2031-2032):
- rebuild ECAL for maximum performance at \( L = 2 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1} \)
- include time measurements to disentangle multiple interactions in a bunch crossing.
LHCb ECAL Upgrade II – conditions and requirements

LHCb Preliminary

ECAL doses @ EM shower max, Gy, 300 /fb

Limit for Shashlik
~ $4 \times 10^4$ Gy

up to ~1 MGy in the centre

LHCb Preliminary

ECAL 1MeV neq/cm², Z=1260, 300 /fb

up to $6 \times 10^{15}$ 1MeV neq/cm² in the centre
LHCb ECAL Upgrade II – conditions and requirements

• need at least three areas with different granularities (maybe more)
  • two or three different technologies (e.g., for 0-20 krad, 20-200 krad, >200 krad)
  • the Central area should sustain radiation doses of up to ~ 1 MGY and neutron fluences of up to $6 \cdot 10^{15}$ 1MeV neq/cm$^2$
    • scintillating garnet crystals
• The Outer area: Shashlik is a viable option
• The Middle area – not defined yet (e.g., PWO?)

• requirements for the whole calorimeter:
  • fine granularity, which is required to handle increased occupancy
    • Molière radius should match the granularity (~1 cm at the centre $\rightarrow$ dense absorber!)
  • good energy resolution, $\sigma(E) \sim 10\% / \sqrt{E} \oplus 1\%$
  • ability to measure time with few*10ps precision – for pile-up mitigation. The options are:
    • use intrinsic time resolution of the calorimeter modules
    • add a dedicated timing layer
Homogeneous Crystal:
- requires long crystals to contain 25 $X_0$
- “fixed” Moliere Radius
- very good homogeneity $\rightarrow$ good energy resolution
- requires good radiation hardness (low rad-induced attenuation over the whole length)
  - can be mitigated by longitudinal segmentation

Shashlik type module:
- can be made very compact ~15cm
- “tunable” Molière radius
- more relaxed requirements to the scintillator rad. hardness (no att. over the cell size)
  - but no rad. hard WLS fibers (yet) to transport light!

SPACAL type module:
- can be made very compact ~15cm
- “tunable” Molière radius
- fibers scintillate AND transports light! $\rightarrow$ potentially high photoelectron yield
- worsening energy resolution @ small angles
- radiation hardness requirements are similar to homogeneous crystal, mitigated by
  - compact length
  - longitudinal segmentation

- started R&D on SPACAL type module, together with Crystal Clear Collaboration
## Radiation hard scintillating crystals

<table>
<thead>
<tr>
<th></th>
<th>$Y_3Al_5O_{12}$:Ce (YAG)*</th>
<th>$Lu_3Al_5O_{12}$: Ce (LuAG)*</th>
<th>$Gd_3Al_2Ga_3O_{12}$: Ce (GAGG)**</th>
<th>$Lu_2SiO_5$:Ce (LSO)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Density (g/cm$^3$)</strong></td>
<td>4.57</td>
<td>6.73</td>
<td>6.63</td>
<td>7.4</td>
</tr>
<tr>
<td><strong>$X_0$ (cm)</strong></td>
<td>3.5 cm</td>
<td>1.3</td>
<td>1.19</td>
<td>1.1</td>
</tr>
<tr>
<td><strong>Refraction index</strong></td>
<td>1.83</td>
<td>1.84</td>
<td>1.85</td>
<td>1.82</td>
</tr>
<tr>
<td><strong>$\Lambda$ max (nm)</strong></td>
<td>550</td>
<td>535</td>
<td>520</td>
<td>420</td>
</tr>
<tr>
<td><strong>LY @ RT (ph/MeV)</strong></td>
<td>35000</td>
<td>25000</td>
<td>50000</td>
<td>30000</td>
</tr>
<tr>
<td><strong>Decay time (ns)</strong></td>
<td>70 + slow component</td>
<td>70 + slow component</td>
<td>60 + slow component</td>
<td>40</td>
</tr>
<tr>
<td><strong>Rise time (ps)</strong></td>
<td>1590-137</td>
<td>923-230</td>
<td>497-92</td>
<td>59</td>
</tr>
</tbody>
</table>

rise time: S. Gundacker, NIM A 891 (2018) 42-52
Crystal production

Grown by Czochralski method

GAGG:Ce, FOMOS (RU)

Square (1x1 mm²) fibers are produced by cutting and polishing

YAG:Ce, Crytur (CZ)
GAGG: radiation hardness

Sample irradiation, 24 GeV protons
$3.1 \times 10^{15} \text{ p/cm}^2 (0.91 \text{ Mgy})$

Fiber irradiation, 24 GeV protons
$3.4 \times 10^{15} \text{ p/cm}^2 (1.02 \text{ Mgy})$

$\kappa = \frac{1}{d} \ln \frac{I_{\text{before}}}{I_{\text{after}}} = 3.6 \text{ m}^{-1}$ at 520 nm

( significatively better than LYSO)

before irradiation: $L_{\text{ATT}}=101.5 \text{ cm}$

after irradiation: $L_{\text{ATT}}=33.6 \text{ cm}$

$\Rightarrow$ OK for 10 cm length after 1 MGy!
timing properties: decay time

It is important to minimize spill-over by minimizing pulse length (25 ns LHC bunch spacing) co-doping with Mg, Ti, ... reduces decay time and fraction of “long” exponential.

* Note the R&D on the GAGG and GYAGG material (M. Korzhik, this conference; exhibition of FOMOS Materials (Moscow)).
The rise time is important for the precision of timing measurements. Co-doping with Mg also improves the rise time.
Absorber for the central area

- Should be more dense than Lead: hence Tungsten based
- should have a rather complicated shape to place crystal fibers

For the material, the options are pure W, W-Cu or W-Pb alloys
- pure W is very hard and brittle, difficult for machining
- W-Cu alloy is available on market, with good mechanical properties
- W-Pb alloy is preferable (smaller $X_0$ for same $R_M$), but is not commercially available

The R&D on absorber technologies is ongoing (MISIS, Moscow). Several technologies are considered: Selective Laser Melting, Chemical Vapor Deposition, Metal Injection Molding etc.
Prototype studies
The Phase 2 Upgrade of the LHCb Calorimeter system

Prototypes 2018

Present ECAL module
- shashlik, Pb:Sc = 1:2 (vol)
- 25X₀ = 40cm; Rₘ = 36mm

“Short” shashlik module
- Pb:Sc = 1:1 (vol)
- 25X₀ = 27cm; Rₘ = 27mm
  (produced in Protvino, 2017)

PMTs

PMTs 3x3

Cu-W alloy, 14.9 g/cm²
- 20 cm long module to reach 25 X₀

Longitudinal segmentation: 10+10 cm
- 9 cells of 2 x 2 cm² with MR~1.5 cm
- 1 cell of GAGG, 4 cells of YAG, 4 cells of SCSF78 (KURARAY)
beam test 2018

- Energy resolution for SPACAL prototype
- Time resolution for SPACAL and Shashlik

**Time reference:** two beam counters based on MCP PMTs$^*$
(<20 ps resolution)

**Electronics:**
- LeCroy 1182 ADC for energy measurements
- CAEN DT5742 (5 GS/s, 12 bit) digitizer for time measurements

DWC = Delay Wire Chamber

(*$^*$) The MCP PMTs were kindly provided by Alexander and Mikhail Barnyakov, BINP, Novosibirsk
Yu. Guz

The Phase 2 Upgrade of the LHCb Calorimeter system

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**Time resolution in SPACAL, front section**

<table>
<thead>
<tr>
<th>E, GeV</th>
<th>PMT HV</th>
<th>σ(t), ps</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>630 V</td>
<td>85</td>
</tr>
<tr>
<td>20</td>
<td>730 V</td>
<td>78</td>
</tr>
</tbody>
</table>

**Present ECAL module (Shashlik) + present PMT (R7899-20)**

<table>
<thead>
<tr>
<th>E, GeV</th>
<th>PMT HV</th>
<th>σ(t), ps</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>800 V</td>
<td>69</td>
</tr>
<tr>
<td>30</td>
<td>800 V</td>
<td>56</td>
</tr>
<tr>
<td>30</td>
<td>750 V</td>
<td>57</td>
</tr>
</tbody>
</table>

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**SPACAL energy resolution**

$\sigma(E)/E = 2.9\%$

(3.1% from GEANT4 simulation)

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**Beam tilt:**

$\theta_x = 3^\circ$, $\theta_y = 3^\circ$. 

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more details in:

DOI: 10.1109/TNS.2020.2975570
Prototypes 2019

Longitudinally split versions of SPACAL and Shashlik (at 7X0 ~ shower max) improves time resolution; also, creates a natural place for the separate timing layer.

Absorber: Crytur (CZ)  
pure W; electroerosion cutting of 0.5mm plates

Scintillator:  
YAG:Ce (Crytur), 6 cells  
GAGG:Ce (FOMOS), 3 cells

Shashlik prototypes  
(several versions)
Beam test 2019 (DESY)

e+ beam, energies 1-5 GeV
Basically same setup as in 2018

Shashlik with split WLS

Better than the existing modules with standard readout:
70 ps resolution is achieved at 5 GeV (same as @20 GeV for the standard version)

Nearest plan: try new KURARAY WLS fibers YS-2
(much faster luminescence decay time than Y11)
→ expect improvement in the time resolution

dependence of the energy resolution on incident angle
(in agreement with GEANT4 simulation).
Stochastic term within 10-13%, which is in the right ballpark.

The analysis is ongoing.

(Time resolution measurements for the SPACAL prototype failed, to be redone in May 2020).
(~50 ps @ 5 GeV expected from simulation)
Conclusions

• At present, LHCb is undergoing a major first upgrade. A second upgrade is foreseen in ~2030.

• The electromagnetic calorimeter needs some consolidation of the inner region by LHC LS3 (2025-2027) compatible with the running conditions after Upgrade II, which requires R&D on radiation hard ECAL modules.

• In Long Shutdown 4 (LS4) a major upgrade of the ECAL will be required to cope with the increased luminosity, the harsh radiation and pile-up conditions, by replacing a significant part of the modules with new technologies.

• Generic R&D and prototyping has started to develop radiation hard sampling ECAL modules of SPACAL type, as well as studies of intrinsic time resolution of ECAL modules.