The LHCb ECAL upgrade(s) and ongoing R&D

Outline:

- Limitations of current ECAL
- Requirements for Upgrades Ib and II
- Technological options and overview of ongoing R&D

→ See next talk by Loris on prototype results

On behalf of the SPACAL R&D group:

- Collaborating institutes
  - members of LHCb, RD18, CMS, …
  - CERN, IHEP, ITEP, MISiS, U Barcelona…
- Industrial partners
  - CRYTUR, FOMOS, Nanocom, …

(1st Miniworkshop with partners last week)

→ New groups most welcome!
The current LHCb Electromagnetic Calorimeter

Current LHCb ECAL:
- Large Shashlik array ~50 m² with 3312 modules and 6016 channels
- Modular wall-like structure of ~8 x 7 m², two halves open laterally within few minutes
- Three sections (Inner, Middle, Outer) of cell size 4x4, 6x6, 12x12 cm²
- $\sigma(E)/E \sim 10%/\sqrt{E} \oplus 1\%$

Energy resolution with electrons

\[
\frac{(9.4\pm0.2)\%}{\sqrt{E}} \oplus (0.83 \pm 0.02)\%
\]
ECAL Shashlik modules

Fibres with loops

Components:
- Germany
- Japan
- Russia
- ...

PMT and HV base

Components:
- Germany
- Japan
- Russia
- ...

3312 shashlik modules with 25 X0 Pb

Developed by Russia & CERN (TDR 2000)

Hamamatsu R7899-20

9 April 2019 4th Workshop on Upgrade II Amsterdam Andreas Schopper
Radiation environment at $L=2 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}$

- Radiation dose at shower maximum is ~2-2.5 kGy/fb$^{-1}$
- By now accumulated ~10 fb$^{-1}$ in run 1&2 $\rightarrow$ ~20-25 kGy
- Current Shashlik modules estimated to “survive” $\leq$ 40 kGy
- By LS3 ~32 inner modules to be replaced (~50-60 kGy)
- New modules to sustain much higher radiation doses up to ~1000 kGy (!)
LHCb ECAL Upgrade II

2020 - 2023: submit Technical Design Reports
- 2020/21: Framework TDR for Upgrade II including sub-detector “Consolidation” TDRs
- 2023/24: Sub-detector TDRs for Upgrade II

LS3 in 2024/25: Consolidation
- Replace modules around beam-pipe (~32 modules) compatible with L=2x10^{33} cm^{-2}s^{-1}

LS4 in 2030/31: LHCb Upgrade II
- Rebuilt ECAL in high occupancy “belt-region” compatible with luminosity up to L ≤ 2x10^{34} cm^{-2}s^{-1}
- Include timing information to mitigate multiple interactions/crossing
ECAL requirements for Upgrade II

Overall requirements:

✓ sustain radiation doses of up to ~1MGy and \( \leq 6 \cdot 10^{15} \text{ cm}^{-2} \) for 1MeV neq/cm\(^2\) at 300 fb\(^{-1}\)

✓ include a very fast component ~several 10\(^{th}\) ps for pile-up mitigation
  - into sampling modules or/and
  - with additional timing preshower

✓ keep good energy resolution of order \( \sigma(E)/E \sim 10\%/\sqrt{E} \oplus 1\% \)

✓ handle increased occupancy by improving spatial resolution in inner & middle region

✓ respect dimensional constraints of a module: 12 x 12 cm\(^2\) outer dimension

\(\text{(1MGy} = 100\text{Mrad})\)

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

ECAL 1MeV neq/cm\(^2\), Z=1260, 300 /fb

LHCb Preliminary

limit for Shashlik

\(\leq 4 \cdot 10^4 \text{ Gy}\)

does not exceed ~10\(^6\) Gy in centre

\(\leq 6 \cdot 10^{15} \text{ 1 MeV n eq./cm}^2\) in centre
ECAL requirements for Upgrade II

3 regions of ECAL

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

Matthias Karacson & Yuri Guz
ECAL requirements for Upgrade II

**inner region**

ECAL doses, Gy, 300 /fb

(@ EM shower max)

- **“hot” inner region:** ~$10^5$-$10^6$ Gy
- **“intermediate” inner region:** ~few$10^4$-$10^5$ Gy

Instrumented region but currently not R/O
Radiation resistance requirements to modules:

- in **“hot” inner region** need of very rad. hard modules sustaining up to $\sim 1000$ kGy
- in **“intermediate” inner region** need of modules sustaining between $\sim 50$ to $200$ kGy
- major(?) part of **middle region** and all of **outer region** compatible with current shashlik type modules resisting up to $\sim 40$ kGy

From radiation point of view: (not taking into account cell size requirements due to occupancy)

- need $\leq 32$ modules for extreme conditions (up to $\sim 1$MGy)
- need another $\sim 150$ new modules with “moderate” radiation requirements (up to $\sim 200$kGy)
- can “reshuffle” inner-type modules (176 modules with $4 \times 4 \text{cm}^2$ cells) to middle region
- can “re-shuffle” middle-type modules (448 modules with $6 \times 6 \text{cm}^2$ cells) to outer region
- 2688 modules out of a total of 3312 modules are of outer-type with $12 \times 12 \text{cm}^2$ cells

From physics and reconstruction point of view: (→ talk by Zehua and Yasmine)

- 5D ECAL requirements ($E, x, y, z, t$) to be determined from physics performance studies for:
  - “hottest” and “intermediate” inner region to define $E$-resol., cell size, Moliere radius…
  - middle and outer region to optimize “re-shuffling strategy”
  - note: no need anymore of square regions (no L0) → better match to irradiation map
ECAL requirements for Upgrade II

- 32 modules around beam-pipe can be replaced without dismantling of complete structure (special mechanics to lift columns)
- Replacing and re-shuffling modules within “the belt” will require **dismantling of a major part of the calorimeter wall**

Special mechanics to lift columns for replacing modules around beam-pipe
Possible options for new ECAL modules

- **Homogeneous crystal calorimeter (with longitudinal segmentation?):**
  - Fast and **radiation hard crystal** with high light yield

- **Sampling calorimeter:**
  - **Converter material:** Lead, Tungsten or various alloys (with typical $R_M \sim 1-2\text{cm}$)
  - **Radiation hard crystal:** as scintillating medium with high light yield and fast response
  - **Fast timing component:** of ~few $10^{\text{th}}$ ps in scintillating crystal for pile-up mitigation
  - **Radiation hard photodetector:** with high efficiency in the required spectral range
  - For Shashlik: **Radiation hard light-guide/fibre** to transport light

**Generic R&D is ongoing in collaboration with experts on crystals & absorbers:**
- performance studies of sampling calorimeters (energy & timing resolution)
- radiation hard and fast scintillators of garnet type (i.e. YAG and GAGG)
- absorber materials from tungsten alloys with Cu and Pb
- radiation hardness of GaAs photodiodes with epitaxial technology
- determination of specifications for fast readout electronics
Performance studies of sampling calorimeters
Possible options for new ECAL modules

Pros and cons of different options:

**Homogeneous Crystal:**
- Requires long crystal of ~40cm to contain 25 $X_0$
- “given” Moliere Radius
- Very good homogeneity
- Potentially very good E-resolution (<10%)
- Large volume of crystal → high cost

**Shashlik type module:**
- Can be made very compact ~15-20cm
- Moliere Radius “tunable”
- No rad. hard WLS fibers (yet) to transport light!
- Challenging optimization to reach $\sigma(E)/E \leq 10%/\sqrt{E}$
- Some cost optimization possible

**Spaghetti type module:**
- Can be made very compact ~15-20cm
- Fibers scintillate AND transport light!
- Moliere Radius “tunable”
- Challenging optimization to reach $\sigma(E)/E \leq 10%/\sqrt{E}$
- Some cost optimization possible

**Sampling Technologies**
Performance optimization of sampling calorimeters

Advantage of sampling calorimeters:

- sampling fraction (ratio of active to inactive material) can be optimized
  - define fiber dimension (cross section)
  - define fiber-to-fiber distance and fiber layout
- tunable radiation length ($X_0$) and shower width ($R_M$)
  - $R_M$ should be of same order than cell size
  - $X_0$ should be as small as possible (short module = short fibers)

Ongoing R&D:

- for inner region $\rightarrow$ SPACAL R&D: (no need of rad hard wavelength-shifting fibers)
  - fiber size and
  - fiber-to-fiber distance and fiber layout
  - crystal to absorber ratio
  - longitudinal segmentation
  - minimization of module length ($X_0$)
  - optimization of Moliere radius ($R_M$) and cell size
  - optimization of timing response
- for middle and outer region $\rightarrow$ Shashlik R&D
  - performance of timing response ($\rightarrow$ see talk by Loris)
Performance optimization of SPACAL

Simulation studies ongoing on dependence of energy resolution on:
✓ fiber dimension
✓ fiber-to-fiber distance
➢ Current prototype 1x1 mm² fibers with 1.8 mm pitch

Simulation studies will start on detailed fiber layout with:
➢ shifted fiber rows vs. aligned fiber rows
➢ possibility of inclined fibers?

Fiber layout has draw-back on manufacturing technique of absorber!
Performance optimization of SPACAL

Optimization of longitudinal segmentation:
- reconstruction of overlapping showers
- needs detailed simulation

γ, e±  
overlapping showers in 1st segment

γ, e±  
shower separation in 1st segment

1/2 1/2  
present prototype

1/3 2/3  
asymmetric segmentation might be better for overlapping shower separation
→ next prototype

For illustration only!
R&D on radiation hard and fast scintillation crystals
Properties of Garnet:Ce doped crystals

<table>
<thead>
<tr>
<th></th>
<th>( \text{Y}_3\text{Al}<em>5\text{O}</em>{12}:\text{Ce} ) (YAG)*</th>
<th>( \text{Lu}_3\text{Al}<em>5\text{O}</em>{12}:\text{Ce} ) (LuAG)*</th>
<th>( \text{Gd}_3\text{Al}_2\text{Ga}<em>3\text{O}</em>{12}:\text{Ce} ) (GAGG)**</th>
<th>( \text{Lu}_2\text{SiO}_5:\text{Ce} ) (LSO)</th>
</tr>
</thead>
<tbody>
<tr>
<td>density (g/cm(^3))</td>
<td>4.57</td>
<td>6.73</td>
<td>6.63</td>
<td>7.4</td>
</tr>
<tr>
<td>( X_0 ) (cm)</td>
<td>3.5 cm</td>
<td>1.3</td>
<td>1.59</td>
<td>1.1</td>
</tr>
<tr>
<td>Refraction index</td>
<td>1.83</td>
<td>1.84</td>
<td>1.85</td>
<td>1.82</td>
</tr>
<tr>
<td>( \Lambda_{\text{max}} ) (nm)</td>
<td>550</td>
<td>535</td>
<td>520</td>
<td>420</td>
</tr>
<tr>
<td>( \text{LY} ) @ RT (ph/MeV)</td>
<td>35000</td>
<td>25000</td>
<td>50000</td>
<td>30000</td>
</tr>
<tr>
<td>decay time (ns)</td>
<td>70 + slow component</td>
<td>70 + slow component</td>
<td>60 + slow component</td>
<td>40</td>
</tr>
<tr>
<td>rise time (ps)</td>
<td>?</td>
<td>?</td>
<td>?</td>
<td>?</td>
</tr>
</tbody>
</table>

Key requirements:
- radiation hardness up to 1MGy (light yield, attenuation length…)
- good timing properties for both, the decay time component (spill-over, 25ns) and the rise time (pile-up mitigation, ~several 10\(^{th}\) of ps)
R&D on radiation hardness of Garnet crystals

R&D on radiation hard garnet crystals:

- GAGG:Ce,Mg

1 cm thick sample
- before irradiation
- after irradiation to 910 kGy

Ingot GAGG crystal

Irradiation by Yuri Guz
M. Lucchini et al. NIM a 816 (2016) 176-183

Cutting 1mm x 1mm, 10cm long GAGG fiber from ingot

- GAGG crystals resist to radiation of ~1 MGy (100 Mrad)
- Can be cut to 1x1 mm² fibers with max length of ~10 cm

YAG:Ce - sample #2948

tested up to ~100 kGy

Irradiation by CERN RD18 (CCC) group

Samples of GAGG crystals irradiated at CERN
R&D on optical performance of GAGG fibers

- 500 GAGG fibers of 1mm x 1mm x 10 cm produced by FOMOS
- Quality Assurance (QA) of fibers at CERN and in Moscow
- Developed portable QA setup, easy and fast to use

- two measurements:
  - effective attenuation length
  - relative fiber light yield

- Preproduction samples measured:
  - $L = 104.2 \pm 3.7$ cm
  - $L = 101.5 \pm 3.3$ cm

- fibers have an excellent effective attenuation length of ~ 1m
R&D on timing properties of Garnet crystals

**Decay time properties: \( t_d \)**

- **GAGG:Ce**
  \( t_d: 101\text{ns}, 319\text{ns} \)

- **GAGG:Ce:Mg**
  \( t_d: 51\text{ns}, 196\text{ns} \)

- **GAGG:Ce:Mg with improved co-doping**
  \( t_d: 36\text{ns}, 125\text{ns} \)

- **Kamada et al., O-14-3 at SCINT2015**
- **M. Lucchini et al., NIM A Volume 816 (2016), pp 176–183**

- ✓ minimize **spill-over** by minimizing pulse length
- ✓ the decay time can be parametrized by two components
- ✓ a shorter decay time and strong decrease of the slow component can be achieved by proper choice of Ce and Mg co-doping

- ➤ achieved already \( t_d \) in the right ballpark, optimization ongoing
R&D on timing properties of Garnet crystals

**Rise time properties: $t_s$**

- **GAGG:Ce**
  - $t_{\text{rise}} = 1757\text{ps}$

- **GAGG:Ce, Mg**
  - $t_{\text{rise}} = 53\text{ps}$

- Mitigate pile-up by minimizing rise time
- The rise time can be parametrized by a single component
- A fast rise time and strong decrease of slow component can be achieved by proper choice of Mg co-doping

- Achieved already $t_s$ of 53ps, optimization ongoing

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*S. Gundacker et al, NIMA A 891 (2018) 42–52*

R&D on absorber materials with tungsten alloys (Cu, Pb)
R&D on absorber materials

- Tune radiation length ($X_0$) and shower width ($M_R$)
  - $M_R$ should be of same order than cell size
  - $X_0$ should be as small as possible (short module = short fibers)

<table>
<thead>
<tr>
<th></th>
<th>W</th>
<th>Pb</th>
<th>Cu</th>
<th>GAGG</th>
<th>YAG</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density [g/cm³]</td>
<td>19.3</td>
<td>11.4</td>
<td>8.96</td>
<td>6.7</td>
<td>4.6</td>
</tr>
<tr>
<td>$X_0$ [cm]</td>
<td>0.35</td>
<td>0.56</td>
<td>1.44</td>
<td>1.59</td>
<td>3.53</td>
</tr>
<tr>
<td>$M_R$ [cm]</td>
<td>0.93</td>
<td>1.60</td>
<td>1.57</td>
<td>2.10</td>
<td>2.76</td>
</tr>
</tbody>
</table>

- Pure tungsten has very small Moliere radius and small radiation length but problematic mechanical properties (brittle)
  - Cannot be machined and therefore strongly limits possible absorber shapes
- Cu-W (25%-75%) alloy is available on the market with good mechanical properties
  - Small Moliere Radius but relatively large radiation length (long module)
- Pb-W alloy allows for same Moliere radius as Cu-W but with smaller radiation length
  - Shorter module → shorter fibers!

However:

lead-tungsten alloys have never been produced!
→ have started R&D on Pb-W alloys
**R&D on different alloys for absorber**

- **SPACAL prototype (CERN)**
  - 25% Cu – 75% W converter with 1.2 mm machined square holes

- **Cu-W absorber plate**
  - machined grooves to host fibers

- **First Pb-W test sample (MISiS)**
  - Monolithic block of Pb-W composite including 1x1 mm² scintillation fibers

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<table>
<thead>
<tr>
<th>Technology</th>
<th>Infiltration</th>
<th>Powder metallurgy</th>
<th>Squeeze casting</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rolling</td>
<td>?</td>
<td>☒</td>
<td>✓</td>
</tr>
<tr>
<td>Forming (forging)</td>
<td>?</td>
<td>?</td>
<td>✓</td>
</tr>
<tr>
<td>Machining</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

**Ongoing activity:**
- R&D on reducing Pb content in Pb-W alloy
- Developing cost effective manufacturing techniques of absorber!
Current SPACAL prototype:

- Cu-W alloy with density of 14.9 g/cm$^2$
- 20 cm long module to reach 25 $X_0$
- Longitudinal segmentation: 10 cm + 10 cm
- 9 cells of 2 x 2 cm$^2$ with $M_R \sim 1.5$ cm
- 1 cell of GAGG (FOMOS)
- 4 cells of YAG (CRYTUR)
- 4 cells of SCSF78 (KURURAY)

New prototype under discussion:

- Pb-W alloy (or pure W) with modified geometry (fiber layout)
- With reduced length (~15 cm)
- Longitudinal segmentation: 5 cm + 10 cm
- Cell size of 2 x 2 cm$^2$ or 1.5 x 1.5 cm$^2$
- Equip all cells with GAGG and YAG

- Study energy resolution and timing properties as function of alloy, crystal, geometry, cell size, segmentation, …
Upgrade II requires R&D on new rad hard ECAL modules for inner region

Ongoing R&D to develop a SPACAL type sampling calorimeter with:

- very good energy resolution of $\sigma(E)/E \sim 10%/\sqrt{E} \oplus 1%$
- good spatial granularity with varying cell sizes (1.5x1.5 cm$^2$, 2x2 cm$^2$, etc.)
- segmentation in depth with readout on both sides (note: segmentation could be 1/3, 2/3 or 1/4, 3/4 etc. and could possibly consist of different materials)
- respecting the given modularity of a module with size 12x12 cm$^2$
- scintillators sustaining radiation doses up to 1 MGy and up to a few $10^{15}$ 1 MeV neq/cm$^2$
- scintillators that have fast rise time ($10^{th}$ of ps) and short decay time (~25 ns)
- absorber material that consists of a very dense (~17 kg/dm$^3$) alloy allowing to “tune” the Moliere Radius (X,Y dim.) and the radiation length (Z dim.)
- absorber that fulfills the mechanical specifications to host 1x1 mm$^2$ fibers

Need to pursue physics and reconstruction studies to define 5D ECAL requirements ($E$, $x$, $y$, $z$, $t$) in inner and middle ECAL region
Many thanks to the organizers for hosting us in such an inspiring location!