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# Scintillating sampling ECAL technology for the LHCb PicoCal

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A R T I C L E I N F O

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A B S T R A C T

The aim of the LHCb Upgrade II is to operate at a luminosity of up to $1.5 \times 10^{34}$ $cm^2s^{-1}$ to collect a data set of 300 $fb^{-1}$. The required substantial modifications of the current LHCb electromagnetic calorimeter due to high radiation doses in the central region and increased particle densities are referred to as PicoCal. Modification of the ECAL already during Long Shutdown 3 (LS3) will reduce the occupancy and mitigate substantial ageing effects in the central region after Run 3. Several scintillating sampling ECAL technologies are currently being investigated in an ongoing R&D campaign: Spaghetti Calorimeter (SpaCal) with garnet scintillating crystals and tungsten absorber, SpaCal with scintillating plastic fibres and tungsten or lead absorber, and Shashlik with polystyrene tiles, lead absorber and fast WLS-fibres. Timing capabilities with tens of picoseconds precision and increased granularity with denser absorber in the central region are needed for pile-up mitigation. Time resolutions of better than 20 ps at high energy were observed in test beam measurements of SpaCal and Shashlik prototype modules.

## 1. Introduction

The LHCb experiment is a forward spectrometer ($2 < \eta < 5$) optimized for heavy-flavour physics measurements at the Large Hadron Collider (LHC) at CERN [1]. The main purpose of Upgrade I of the LHCb detector is to collect 50 $fb^{-1}$ by the end of Run 4. The changes were mostly on the side of readout electronics to allow the experiment to collect data based on the software trigger. The Upgrade II is aimed to make the detector able to operate at a much higher instantaneous luminosity to obtain 300 $fb^{-1}$ of integrated luminosity by the end of Run 6 to fully exploit the flavour-physics opportunities of the HL-LHC [2]. The expected integrated and instantaneous luminosity as a function of year is presented in Fig. 1.

Running with the increased luminosity will imply a significant change in the hardware part, particularly the electromagnetic calorimeter (ECAL), to still have a performance comparable to Run 3. This could be achieved by utilizing timing information of the shower, employing denser and more radiation-tolerant materials (with a smaller Moliere radius), and enhancing granularity in the central region.

In the meantime, significant light yield degradation of the innermost Shashlik modules is anticipated already by the end of Run 4, which will increase the constant term of ECAL energy resolution in the inner region to as much as 6%. Given the short duration of CERN Long Shutdown 4 (LS4), the initial steps towards ECAL Upgrade II must be undertaken during LS3. The baseline plan is to implement the ECAL upgrade in two phases.

The first phase — ECAL enhancement during LS3 with an approved TDR [3] includes re-arranging modules from the present square regions in granularity to the rhombic shape (Fig. 2), introducing two new subregions with improved granularity using spaghetti-type modules (SpaCal): tungsten absorber with $20 \times 20$ $mm^2$ cell size and lead-based absorber with $30 \times 30$ $mm^2$ cell size. Both SpaCal modules are equipped with polystyrene scintillating fibres. The list of types of modules for the LS3 configuration is summarized in the Table 1.

The second phase - ECAL Upgrade II (Picocal) during LS4 foresees: equipping tungsten SpaCal modules with radiation hard crystal fibres, replacing significant part of 1-cell Shashlik modules with 4-cell modules and replacing WLS-fibres with faster option (e.g. YS4, 1.4 ns decay time), introducing double-sided readout to have improved timing information, and installing new readout electronics suitable for the time measurements. The baseline layout configuration of the PicoCal is presented in Fig. 3 and is summarized in Table 2. Note that each cell is supposed to be read by two photomultipliers, thus the total number of channels in the baseline configuration is 30 976.

## 2. New technologies for the ECAL inner region

The new modules for the innermost region of the ECAL are going to be built using a SpaCal structure — a matrix of scintillating fibres installed into dedicated holes in the passive absorber. To keep the constant term of the energy resolution at a level of 1%, scintillating

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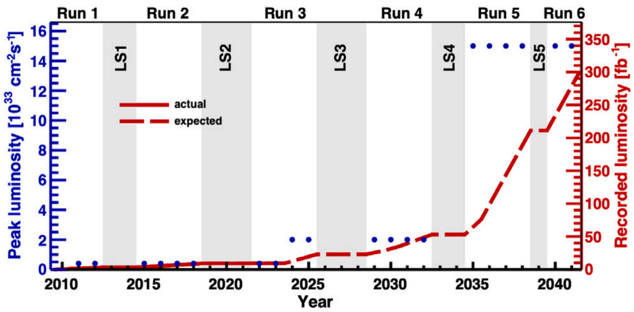


**Fig. 1.** LHCb expected integrated and instantaneous luminosity by year.

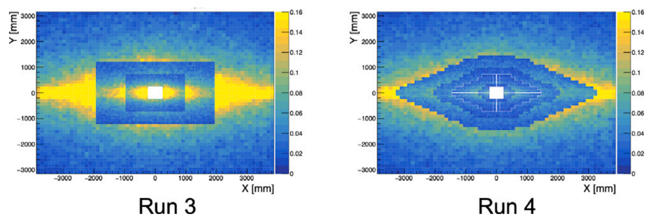


**Fig. 2.** Average occupancy during Run 3 (present layout) and during Run 4 with the new layout planned for after the LS3.

**Table 1**
Cell size, technology, number of modules and number of cells per region planned for the Run 4 configuration.

| Region | Cell size [mm$^2$] | Type | #Modules | #Cells |
|---|---|---|---|---|
| 1 | 15 × 15 | W-Poly | 32 | 1152 |
| 2 | 30 × 30 | Pb-Poly | 144 | 2304 |
| 3 | 40 × 40 | Shashlik | 176 | 1584 |
| 4 | 60 × 60 | Shashlik | 448 | 1792 |
| 5 | 120 × 120 | Shashlik | 2512 | 2512 |
| | | Total | 3312 | 9344 |

fibres must be small enough, and the modules must be inclined by 3 degrees in both XZ and YZ planes. The inner region is going to be equipped with two SpaCal technologies: tungsten-absorber in the very central area and a lead-based absorber in the intermediate area between tungsten-based SpaCal and Shashlik.

## 3. Additive technology for the tungsten absorber

A single block (Fig. 4 right) is made of a tungsten structure with outer dimensions of $121.2 \times 121.2 \times 50$ mm$^3$ and contains a matrix of square holes with a cross-section of $1.2 \times 1.2$ mm$^2$ each. One calorimeter module is an assembly of three such blocks, ensuring a total depth of 25 $X_0$.

The R&D campaign started with EOS (Germany) from a single-cell prototype and was concluded with a full-size single module. All prototypes are presented in Fig. 4 (left). The full-size tungsten SpaCal module comprises the three absorber blocks. It has been assembled with polystyrene $1 \times 1$ mm$^2$ square SCSF-78 fibres (photo during the assembly is shown in Fig. 4 right) and tested with the extracted electron beam at DESY and CERN SPS.

Now LaserAdd (China) is tuning technology for mass production. To characterize the prototype a dedicated single-cell prototype with external dimensions $15 \times 15 \times 40$ mm$^3$ and a $9 \times 9$ set of holes has been cut with a diamond wire saw. The surface has been prepared following a dedicated grinding and polishing procedure. The examination was carried out with a Zeiss AXIO Imager Z2.m optical microscope and revealed the built structure composed of a checkerboard structure with finer contouring layers and some defects like microcracks, pores and decohesion of the contouring layer, shown in Fig. 5.

**Table 2**
Cell size, technology, number of modules and number of cells per region planned for the Run 5 configuration (ECAL Upgrade 2).

| Region | Cell size [mm$^2$] | Type | #Modules | #Cells |
|---|---|---|---|---|
| 1 | 15 × 15 | W-GAGG | 40 | 2 560 |
| 2 | 30 × 30 | Pb-Poly | 136 | 2 176 |
| 3 | 40 × 40 | Shashlik | 448 | 4 032 |
| 4 | 60 × 60 | Shashlik | 1344 | 5 376 |
| 5 | 120 × 120 | Shashlik | 1344 | 1 344 |
| | | Total | 3312 | 15 488 |

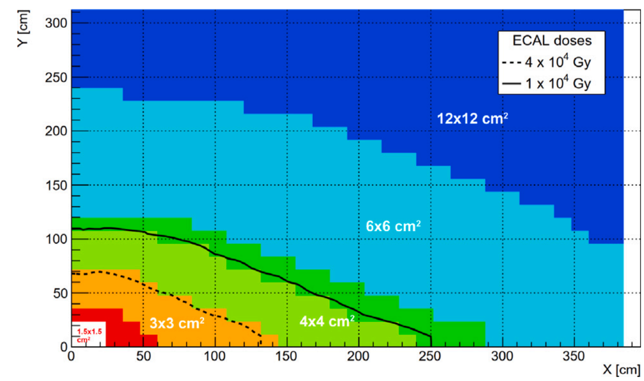


**Fig. 3.** Layout of the LHCb ECAL Upgrade 2 (one quadrant). Different colours represent different regions in granularity and sampling technology used. Red and Orange — SpaCal regions with tungsten-Crystals and Lead-Polystyrene. Green, Cyan and Blue — Shashlik modules with different granularity.

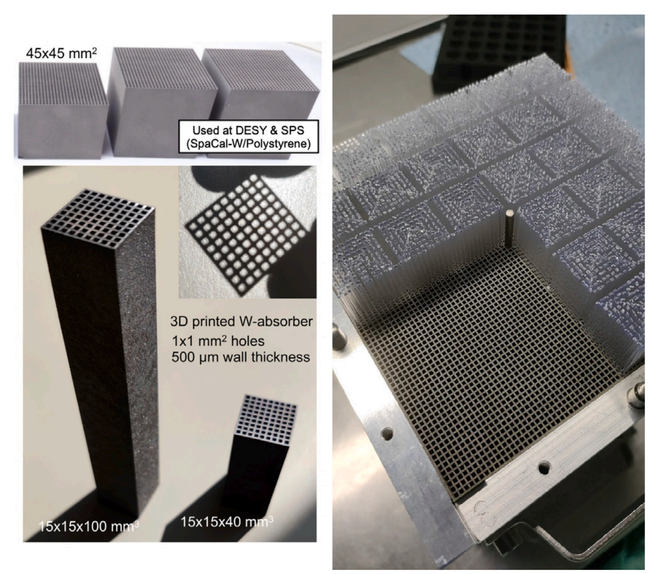


**Fig. 4.** Photos of the tungsten absorber R&D at various steps. Left — photos of the single prototypes. Right — one full-size module during the assembly.

## 4. Cast lead-based absorber

Traditional absorber for the spaghetti-type modules is produced by using rolled grooved lead sheets. The possibility of modifying SpaCal modules after assembly, e.g. extracting/exchanging fibres, might give a certain advantage in case of radiation damage of the scintillating fibres. The dedicated technology development for the casting lead-based absorber has been initiated in NUST MISIS (Russia) [4–6] and currently is ongoing with ICM/MTH (Germany).

The absorber part is comprised of a lead-based block with dimensions of $121.2 \times 121.2 \times 300$ mm$^3$ and a $56 \times 56$ matrix of capillary tubes.

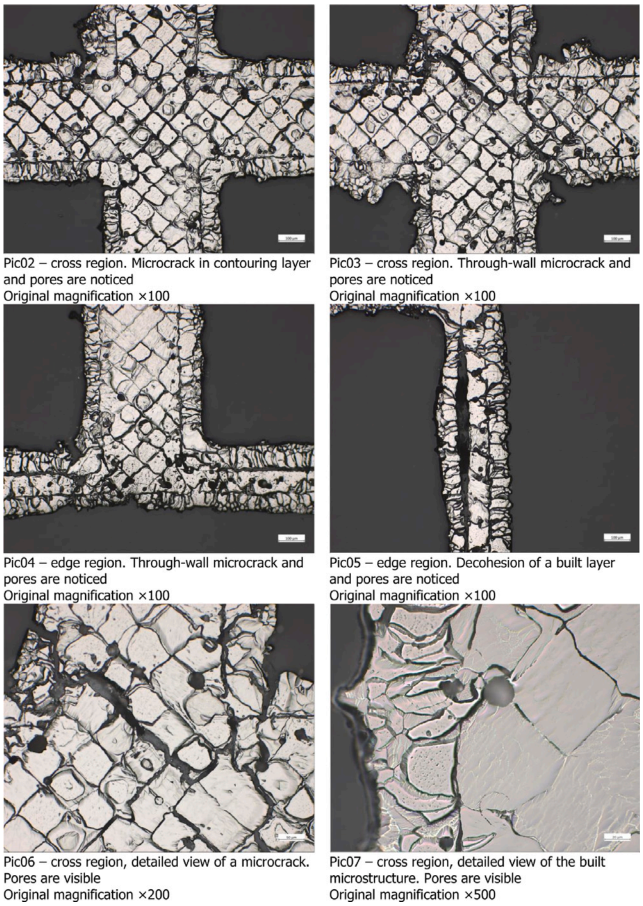


**Fig. 5.** Micrographs of the 3D-printed tungsten absorber prototype obtained using Zeiss AXIO Imager Z2.m optical microscope.

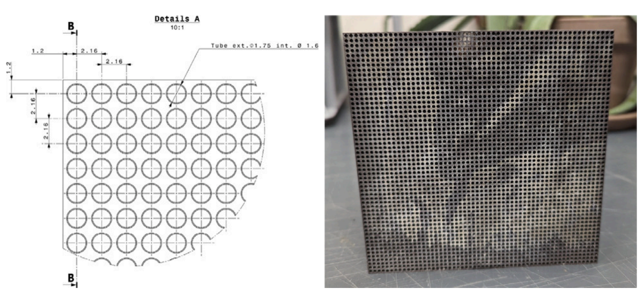


**Fig. 6.** Schematic view (left) and photo (right) of the cast lead-based absorber. Dimensions of the single object are $121.1 \times 121.1 \times 100$ mm$^3$ with the 56 × 56 matrix of $\oslash 1.6$ mm holes ensured by stainless steel capillary tubes.

The inner diameter of the tubes is 1.6 mm and the outer diameter is 1.75 mm (wall thickness of 75 um). Capillary tubes are used to accommodate $\oslash 1.5$ mm scintillating fibres. The volume between the tubes is filled with lead-based alloy to ensure the Moliere radius of the final module at 30 mm.

The schematic view of the absorber part and the photo of the newly produced prototype are shown in Fig. 6. Assembly and first beam tests of the module are planned for summer 2024.

A low-pressure casting technique is used to produce the prototype of 100 mm length. The single module is composed of three absorber units.

The mould assembly with 3136 tubes/unit remains the most time-consuming step in the production. An alternative technology based on a calcium babbitt alloy and dedicated casting tooling without capillary

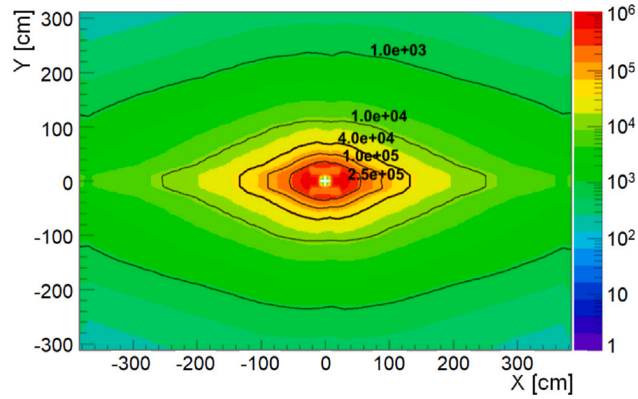


**Fig. 7.** Expected integrated radiation dose in the ECAL at the end of Run5.

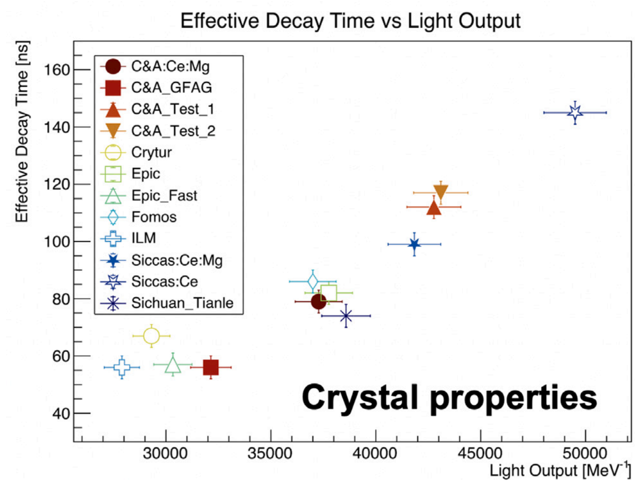


**Fig. 8.** Effective decay time vs. light output of the GAGG scintillating crystals.

tubes is in parallel development to further reduce the cost of the absorber unit.

## 5. R&D on the garnet scintillating crystals

The Upgrade Phase II implies that the calorimeter must be capable of sustaining integrated radiation doses of up to 1 MGy in the innermost modules (Fig. 7). The 40 kGy boundary is the limit for the Shashlik technology [7].

Among the crystal candidates, garnet crystals, in particular GAGG, appear to be the most promising choice. Measurements of the scintillation characteristics show light yields in the range between 27 900 and 49 500 photons/MeV, and effective scintillation decay times of about 50 ns and 70 ns [8] respectively. There is a correlation between light output and the effective decay time of the GAGG crystals doped with Cerium and Magnesium, shown in Fig. 8. An ongoing R&D with the various producers, both in the EU and China is aimed to develop fast (below 10 ns decay time) radiation hard GAGG crystals.

## 6. Modification of the Shashlik modules

The current Shashlik modules used for the ECAL are already well-optimized for time resolution. The change of the Lead/Scintillator ratio (e.g. to reduce the fluctuation of the shower maximum position) gives no additional improvement in the time resolution. Further improvements can be achieved by replacing the wavelength-shifting fibres from the present Kuraray Y11 (decay time 6.9 ns) with faster

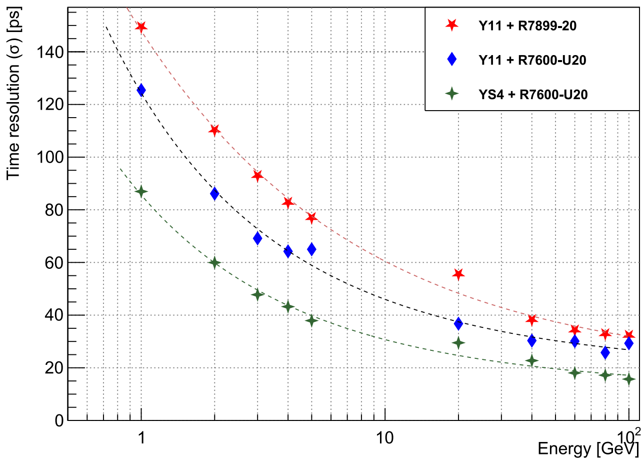


**Fig. 9.** LHCb outer Shashlik module time resolution as a function of incident electron energy for the present configuration, with Y11 WLS-fibres and R7899-20 photomultiplier and modified versions with fast YS4 WLS-fibres and R7600-U20 photomultiplier.

options, e.g. YS4 (decay time 1.1 ns) and by using photomultipliers with reduced transit time spread. Several spare outer modules have been modified and tested using an extracted electron beam. Fig. 9 shows the time resolution of a single-cell outer module with single-sided readout as a function of the incoming electron energy for the three options: current configuration (Y11 WLS-fibres and R7899-20 photomultiplier) and two modified configurations: Y11 WLS-fibres and new photomultiplier (R7600-U20) and new WLS-fibres YS4 and new photomultiplier (R7600-U20).

## 7. Summary

The upcoming replacement of the innermost 176 modules within the LHCb ECAL during LS3 is essential to mitigate radiation damage. The proposed solution involves adopting SpaCal technology, which includes tungsten and lead absorbers, to meet the specific requirements for this region. The subsequent Upgrade II during LS4 will introduce advanced timing capabilities at the tens of picosecond level and increased radiation hardness.

Tungsten additive technology and specialized lead casting techniques have been developed and are ready for implementation during LS3. There is ongoing R&D focused on producing radiation-hard crystals with effective decay time below 10 ns.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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