PROCEEDINGS OF SCIENCE

The LHCb PicoCal

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The High-Luminosity LHC era will enable the LHCb experiment to record an unprecedented dataset of up to 300 fb^{-1}, operating at instantaneous luminosities approaching 1.5×10^{34} cm^{-2} s^{-1}. Under such conditions, the electromagnetic calorimeter (ECAL) must withstand MGy-level radiation in its central region, cope with significantly higher occupancy, and maintain excellent energy and time resolution performance. The "PicoCal" concept, proposed for Upgrade II, combines high-density absorbers, radiation-hard scintillators, and timing capabilities at the level of $O(10\text{ ps})$ to mitigate pile-up effects. Several technology options are being investigated, including spaghetti calorimeter (SpaCal) modules with tungsten or lead absorbers coupled to plastic or garnet scintillating fibers, and upgraded Shashlik modules with faster wavelength-shifting fibers. A key material development is the use of ultra-fast, radiation-tolerant GAGG:Ce crystals, grown via the Czochralski method and optimized through high-level Mg/Ce co-doping. These crystals aim to achieve effective decay times below 10 ns and can withstand up to 1 MGy of radiation, enabling both fine granularity and precision timing in the most demanding innermost ECAL regions. Test-beam studies have confirmed that the proposed configurations can meet the target energy resolution ($\sim 10\%/\sqrt{E} \oplus 1\%$) and achieve timing precision below 20 ps at high energies. The combined detector and materials R&D ensures readiness for high-luminosity operation with enhanced spatial, temporal, and radiation performance.

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*Speaker

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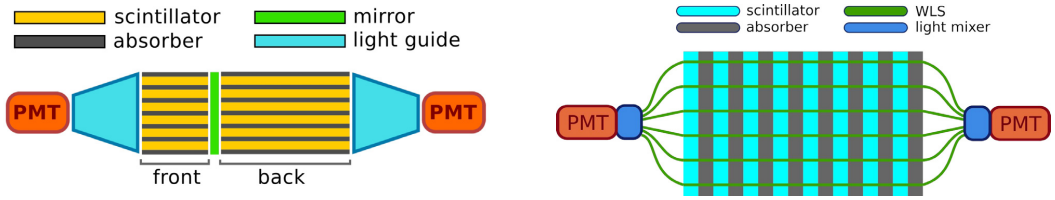
1. The LHCb ECAL upgrade strategy

The LHCb electromagnetic calorimeter (ECAL) upgrade is divided in two main phases. During the LS3 enhancement (2026–2029)[1], the innermost and intermediate Shashlik modules will be replaced by SpaCal units: 32 tungsten-absorber modules with 2×2 cm^2 cells for the central high-dose region, and 144 lead-absorber modules with 3×3 cm^2 cells for the surrounding areas. These employ radiation-tolerant plastic scintillating fibers and a new rhombic geometry to mitigate accumulated damage while preserving calorimetric resolution.

In Upgrade II (Run 5, 2036–2041)[2–4], the most exposed SpaCal-W region will transition from plastic fibers to GAGG:Ce crystal fibers, selected for their high light yield, fast decay time, and proven radiation hardness. These fibers will be manufactured from large-diameter ingots ($\geq \Phi 50 \times 110$ mm) grown with optimized composition—balancing Mg/Ce co-doping and Ga/Al ratios—to accelerate scintillation decay while suppressing slow components and minimizing light-yield loss. Radiation testing campaigns will validate their stability up to 1 MGy under gamma and charged particle exposure.

For Upgrade II, all ECAL modules will adopt double-sided readout to enable precise time-of-flight reconstruction and mitigate shower timing jitter, as illustrated in Fig.1. The innermost granularity will increase by making use of 1.5×1.5 cm^2 cells, with the addition of 272 lead-absorber SpaCal modules (4×4 cm^2 cells) and 900 refurbished Shashlik modules (6×6 cm^2 cells) in the outer region. Shashlik units will receive faster WLS fibers, improving timing from ~40 ps to $\leq$20 ps at 100 GeV.



(a) SpaCal **(b)** Shashlik

Figure 1: Schematics of (a) SpaCal and (b) Shashlik in double-sided readout.

By integrating detector geometry optimization with advanced GAGG:Ce crystal development, as shown in Fig.2, the upgraded ECAL will combine fine spatial resolution, $\mathcal{O}(10$ ps) timing, and robust radiation tolerance—ensuring that LHCb can fully exploit the HL-LHC luminosity.

2. SpaCal-W Module Design and Key Technical Challenges

The sampling calorimeter modules with tungsten–plastic or garnet scintillating fibers are designed for the high-radiation innermost region of the LHCb ECAL. Each module measures 12×12 cm^2 and consists of 36 or 64 individual cells of 2×2 cm^2 or 1.5×1.5 cm^2. The absorber is manufactured using additive manufacturing techniques(3D printing) to produce thin-walled tungsten structures with 0.24 mm thickness, as shown in Fig. 3, enabling fine granularity while minimizing dead material.

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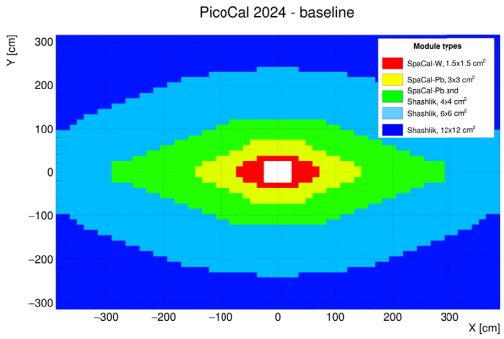

Figure 2: ECAL regions, technologies and cell sizes of the LHCb PicoCal.

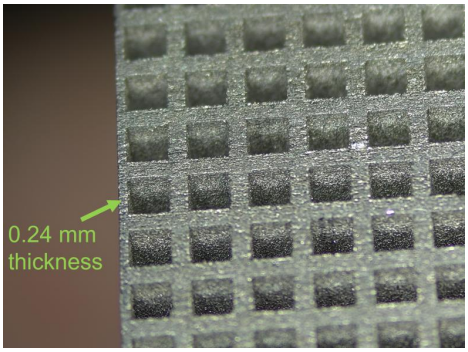

Figure 3: Absorber of the SpaCal-W module.

A key mechanical challenge is ensuring sufficient structural integrity during handling and operational stresses. Thin tungsten walls are prone to local deformation, particularly at junctions between the four absorber segments that form a module. Finite element analysis has been used to predict stress distribution, guiding the design of temporary fixtures and clamps to prevent mechanical damage during assembly.

Optical performance is determined by the arrangement and quality of the 1×1 mm^2 plastic or garnet scintillating fibers, which are embedded in longitudinal channels of absorbers, as shown in Fig. 4. Fiber bending radii and surface cleanliness have a direct impact on light transmission, making precise routing essential. Dedicated assembly procedures ensure fibers remain in place without microbending losses, while polished fiber ends reduce losses in coupling to photodetectors. Segment-to-segment alignment must be maintained within ± 0.2 mm to preserve shower containment and minimize channel-to-channel response variations.

3. GAGG:Ce Scintillator Development and Radiation Performance Optimization

For Upgrade II[2–4], the most radiation-exposed SpaCal-W modules will transition from plastic scintillating fibers to garnet-based scintillating fibers produced from GAGG:Ce crystals. The target performance includes a decay time below 10 ns, a light yield comparable to or exceeding plastic scintillators, and stability under radiation doses up to 1 MGy.

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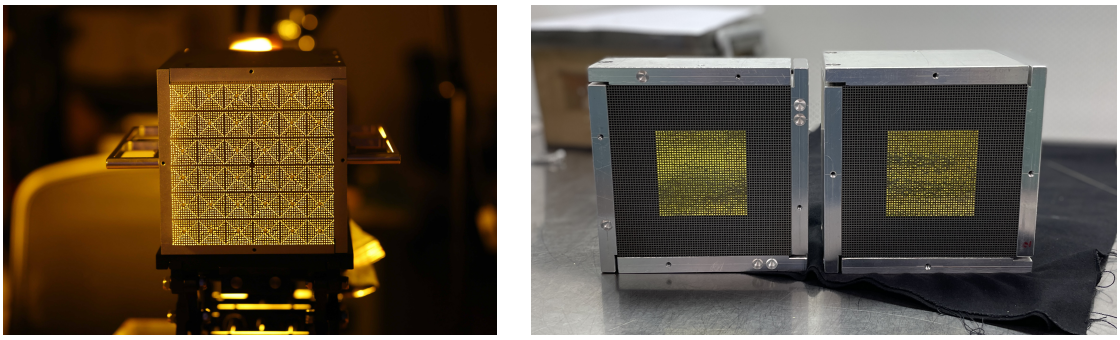

(a) plastic **(b)** garnet

Figure 4: Insertion of (a) plastic or (b) garnet scintillating fibers into the absorber.

Large-volume crystals (diameter ≥ 50 mm, length ≥ 110 mm) are grown using the Czochralski method, with composition tuning to optimize performance. Co-doping with Mg and Ce has been demonstrated to suppress slow scintillation components, while adjusting the Ga/Al ratio further reduces afterglow and improves radiation hardness. The crystal drawing process must preserve optical clarity and uniformity along the fiber length, as defects can introduce scattering and timing jitter.

Extensive characterization includes measuring the scintillation decay profile and light yield. To quantify the overall decay behavior in a single parameter, the effective decay time ($\tau_{d,eff}$) is defined as

$$\frac{1}{\tau_{d,\text{eff}}} \equiv \sum_{i=1}^{N} \frac{\rho_i}{\tau_{d,i}}, \tag{1}$$

where ρ_i and $\tau_{d,i}$ is the relative abundance and decay time of the ith component. As shown in Fig. 5, the correlation between the effective decay time and light yield is monitored to select crystals that balance fast decay time with sufficient light output(≥ 4000 ph./MeV). The energy and time resolution were measured under an electron test beam, with the results presented in Fig. 6. These results guide iterative improvements in crystal ingot growth and machining techniques to ensure long-term stability in the HL-LHC environment.

To address the challenge posed by scintillation decay times exceeding 40 ns, novel GAGG compositions have been developed that not only quench scintillation effectively but also accelerate decay time. Although normally light yield is smaller with faster decay time, our focus on maintaining both competitive time and energy resolution remains unchanged. Through R&D efforts, large-size and homogeneous Czochralski ingots with fast decay time have been successfully produced. A W-GAGG prototype was assembled, which has the integration of R&D advances, including both modified SIPAT(CETC Chip Technology Group Co., Ltd, China) GAGG with 20 ns effective decay time, and 3D-printed absorber. It has been characterized in the testbeam, and the results are shown in Fig. 6a and Fig. 6b.

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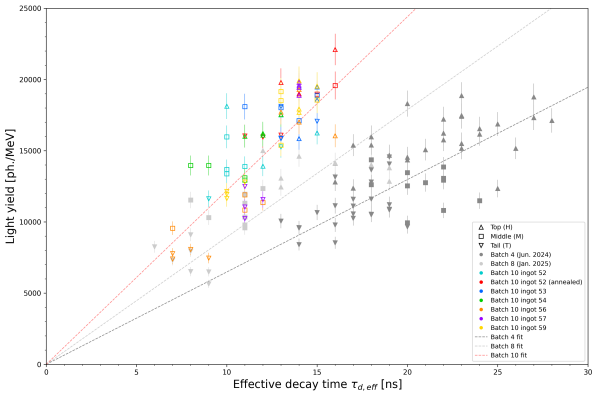

Figure 5: Measurement results of light yield and effective decay time for GAGG crystals from different batches. Upper triangle, square, and lower triangle respectively represent different positions from the GAGG ingot. The $\tau_{\mathrm{d,eff}}$ is measured with X-ray, and the light yield is measured with ^{137}Cs.

4. Test beam results with SpaCal-W prototypes

The test beams are conducted at facilities such as DESY and CERN SPS. Properties of W-GAGG prototype, including energy resolution, linearity, time resolution, and spatial uniformity are measured. The test beam setup is described in article [2]. Timing performance of setup is evaluated, and the reference time is obtained using a pair of microchannel plate PMTs (MCP-PMTs) to extract intrinsic calorimeter resolution, with the goal of achieving ≤20 ps at high energy. Test results are compared to Monte Carlo simulations, enabling iterative design improvements in absorber geometry, fiber routing, readout electronics etc. The peformance of W-Polystyrene prototype is discribed in article [2] and meets the targets. Below are the performances of W-GAGG prototype.

4.1 Energy resolution

To perform the measurement of the energy resolution, the W-GAGG prototype is equipped with the Hamamatsu R7600U-M4 PMT coupled via a hollow light guide. The energy resolution is modeled using the function:

$$\frac{\sigma_E}{E} = \frac{a}{\sqrt{E}} \oplus b. \tag{2}$$

Results are presented in Fig. 6a, where a sampling term a of 10.6% and a constant term b of 2% are observed, which are extremely close to the target of $10\%/\sqrt{E} \oplus 1\%$. This degradation of performance is partially attributed to crystal inhomogeneity and optical coupling imperfections of light guides (LGs), as the initial measurements were conducted with a non-optimal configuration.

4.2 Time resolution

To evaluate the timing performance, the W-GAGG is coupled to various types of PMT. As shown in Fig. 6b, the time resolution for energies above 20 GeV is better than 20 ps when using the Hamamatsu R9880U PMT. Further improvement is expected with R&D for LGs and PMT.

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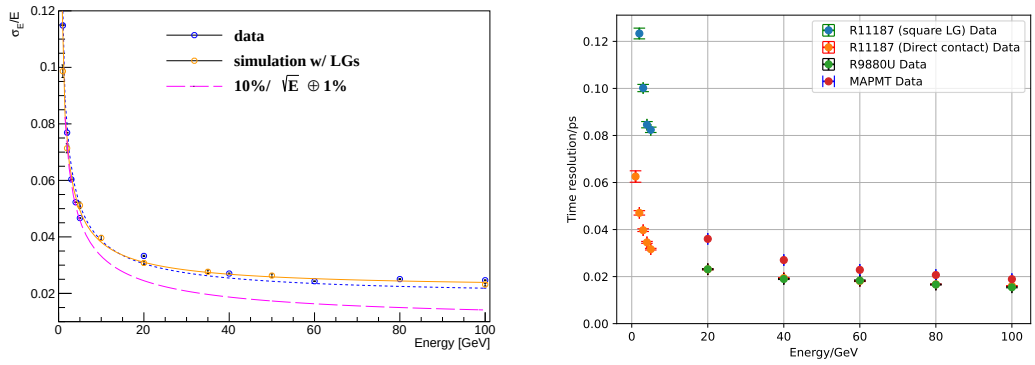

(a) energy resolution **(b)** time resolution

Figure 6: (a) Energy resolution and (b) time resolution of the tungsten/garnet-crystal SpaCal prototype measured at 3° + 3° in double-sided readout.

5. Conclusions

The LHCb ECAL upgrade program integrates advanced detector design, innovative materials, and precision assembly techniques to meet the stringent demands of high-luminosity operation. The SpaCal-W modules, with their fine granularity and thin-wall tungsten absorbers, provide the mechanical robustness and spatial resolution needed in the most challenging radiation environment of the detector. The parallel development of ultra-fast, radiation-hard GAGG:Ce scintillators ensures that the innermost calorimeter region will maintain both excellent time and energy resolution over the full operational lifetime.

By coupling material innovation with detector engineering, this program not only secures the performance of the LHCb ECAL for the HL-LHC era but also establishes technical capabilities that can be applied to other high-energy physics experiments. The resulting system will enable precision measurements in electromagnetic channels, expanding the physics reach of LHCb in the coming decades.

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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