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The LHCb PicoCal

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ABSTRACT

The aim of the LHCb Upgrade II is to operate at a luminosity of up to 1.5×10^{34} cm^{-2} s^{-1} to collect a data set of 300 fb^{-1}. The required substantial modifications of the LHCb electromagnetic calorimeter during Long Shutdown 4 (LS4) due to high radiation doses in the central region and increased particle densities are referred to as PicoCal. Several scintillating sampling ECAL technologies are currently being investigated in an ongoing R&D campaign in view of the PicoCal: Spaghetti Calorimeter (SpaCal) with garnet scintillating crystals and tungsten absorber, SpaCal with scintillating plastic fibers and lead absorber, and Shashlik with polystyrene tiles, lead absorber and fast WLS fibers. Timing capabilities with tens of picoseconds precision for neutral electromagnetic particles 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 prototype SpaCal and Shashlik modules.

1. The LHCb ECAL upgrade strategy

The LHCb electromagnetic calorimeter (ECAL) has to be modified to mitigate radiation damage after Run 3 and to meet the requirements of Run 5 [1,2]. By introducing the SpaCal technology in the inner regions and rebuilding the ECAL in a rhombic shape, the so-called "LS3 Enhancement", spanning between July 2026 and the end of 2029, will ensure the ECAL performance does not degrade due to radiation damage accumulated during Run 4. 32 new SpaCal modules with tungsten absorber (2 cm cell size) and 144 new SpaCal modules with lead absorber (3 cm cell size), both technologies equipped with radiation-tolerant plastic scintillating fibers, will replace the current Shashlik modules in the innermost and intermediate region, respectively.

With Upgrade II for Run 5 (datataking from 2036 to 2041), radiation-hard garnet scintillating crystals will be used in the SpaCal-W region instead, and all modules (including Shashlik) will have double-sided readout, as illustrated in Fig. 1, with precise timing information. The granularity of the innermost region with installed SpaCal-W modules will be improved by introducing 1.5 cm cells. Additionally, 272 new SpaCal-Pb modules with 4 cm cell size and around 900 refurbished 4-cell Shashlik modules (6 cm cell size) will be added to the outer regions, as shown in Fig. 2. Furthermore, to improve the timing capabilities of Shashlik modules, the current wavelength shifting (WLS) fibers will be replaced with faster ones.

2. Design optimization of SpaCal modules

Several SpaCal and Shashlik prototypes were evaluated during test beam campaigns at DESY II and SPS North Area, as later discussed in Section 3. The recent SpaCal prototypes include many novel technologies, such as 3D-printed tungsten absorber, garnet scintillating crystals with accelerated decay time, lead absorber produced by low-pressure casting integrating stainless steel capillary tubes, fast PMTs, and radiation-hard hollow light guides. Extensive R&D has been performed and remains ongoing to optimize the detector performance.

2.1. Hollow light guide optimization studies

An example of such optimizations is the response uniformity study. A test bench, shown in Fig. 3, was assembled at CERN to measure the uniformity of light collection efficiency of hollow light guides. Complementary irradiation studies of reflective materials at PS-IRRAD confirmed that the Enhanced Specular Reflector Film (ESR), the current best reflective material for hollow light guides thanks to its low price, ease of handling, and high reflectivity, showed no degradation after irradiation up to 300 kGy. In the hollow light guides, a reflective layer placed inside a (typically plastic) frame enables light transport such that photons travel through the air instead of bulk material. If the performance of the reflective layer is not compromised by radiation, as is true for ESR (up to at least 300 kGy), such light guides are

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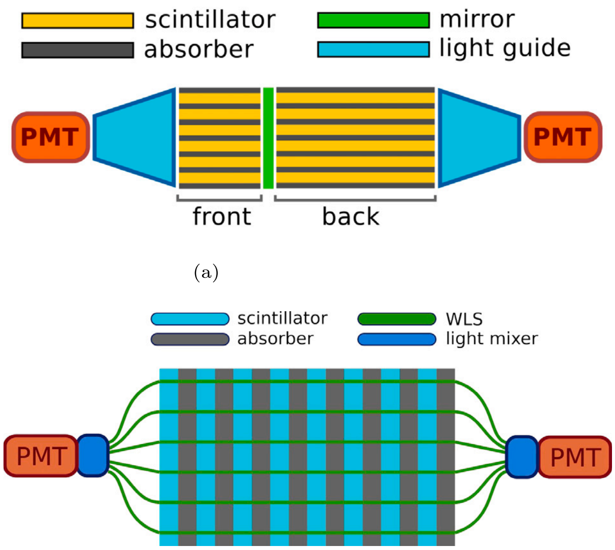


(a)

(b)

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

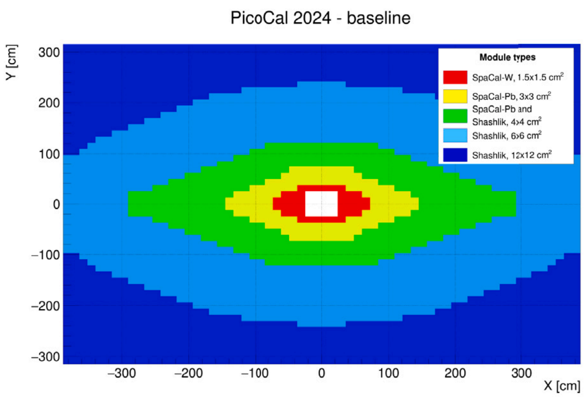


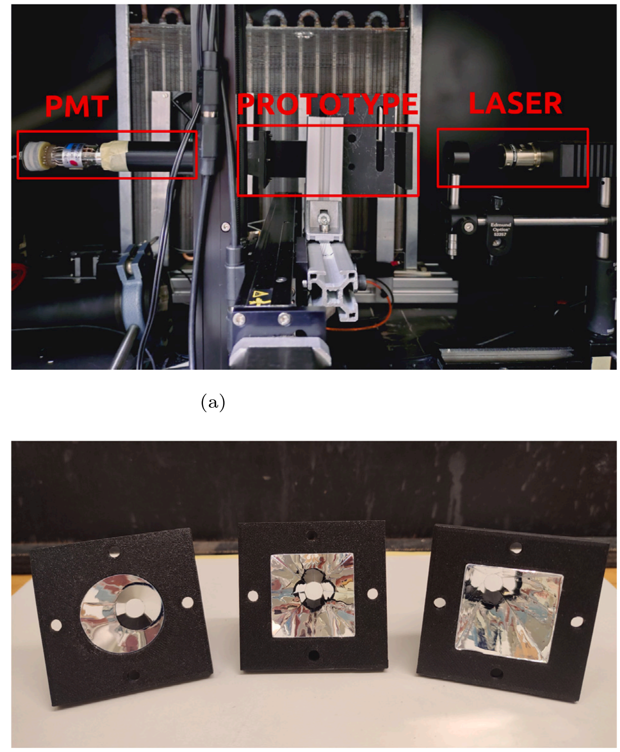
Fig. 2. ECAL regions, technologies and cell sizes of the LHCb PicoCal.

intrinsically radiation-hard. The key conclusions of the hollow light guide optimization studies are threefold:

1. Response uniformity is better for light guides where the ratio between the readout and entrance area is closer to one. This result is a direct consequence of the Liouville's theorem applied to the light transport.
2. Longer light guides improve uniformity thanks to better light mixing and a higher acceptance angle for photons entering and propagating inside the light guide.
3. Creating a bundle of fibers allows more favorable light guide geometries leading to improved uniformity and increased total light collection efficiency.

2.2. Module-size SpaCal prototypes

Two of the recent SpaCal prototypes are particularly noteworthy: (1) the module-size SpaCal prototype with a tungsten absorber and plastic scintillating fibers, (2) the module-size SpaCal prototype with a lead absorber and plastic scintillating fibers. Both feature single-sided readout, intended for Run 4 following the LS3 enhancement. The production of absorber with small holes into which the fibers have to be



(a)

(b)

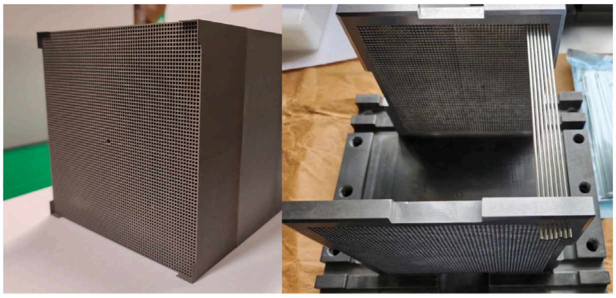
Fig. 3. 3(a) Test bench to measure the uniformity of light collection efficiency of hollow light guides. 3(b) Examples of single-cell hollow light guides coated with ESR inside. The round shape is adapted to read out a cell with bundled fibers, which are usually grouped into either an octagon or a circle.

inserted without being damaged was one of the R&D challenges. It turns out that the 3D printing of tungsten absorber is not only convenient for prototyping but is also suitable for large-scale productions. A successful R&D campaign was done with industrial partners and module-size (12.1×12.1 cm^2) absorber pieces, shown in Fig. 4(a), were used to assemble the above-mentioned SpaCal-W prototype. The fibers used in this prototype were 1 mm square SCSF-78 single-cladded plastic scintillating fibers from Kuraray, which were glued and polished with a diamond mill on both ends.

The R&D on the lead absorber presented similar challenges. A new production technique was investigated, where before the casting, several thousand stainless-steel capillary tubes were inserted and aligned with a pair of steel masks, as shown in Fig. 4(b). The capillary tubes are kept inside the lead after the casting, as it was simulated that they do not introduce significant changes in the shower development. The SpaCal-Pb prototype was assembled with 3 such module-size absorber pieces and 1.5 mm diameter round 3HF plastic scintillating fibers from Kuraray, which were bundled, to improve response uniformity, as discussed in chapter 2.1. 15 out of 16 cells had multi-cladded fibers and the remaining one single-cladded fibers. The polishing procedure was similar as previously mentioned.

3. Test beam results with SpaCal and Shashlik prototypes

The test beam setup, as described in [1,3], with additional tracking information provided by 3 planes of delay wire chambers (DWCs) and time reference by a pair of microchannel plate PMTs (MCP-PMTs), allows measuring both the energy and time resolution. For the energy measurements, the signals are integrated over a 400 ns gate using 3 LeCroy 1182 ADC modules. For the timing measurements, the waveforms are digitized using the DRS4-based V1742 CAEN digitizer with 5 Gs/s and 500 MHz bandwidth, with a custom calibration.



(a) (b)

Fig. 4. 4(a) Four aligned 3D-printed tungsten absorber pieces. 4(b) A few out of several thousand stainless steel capillary tubes aligned with a pair of steel masks inside the mold before the casting.

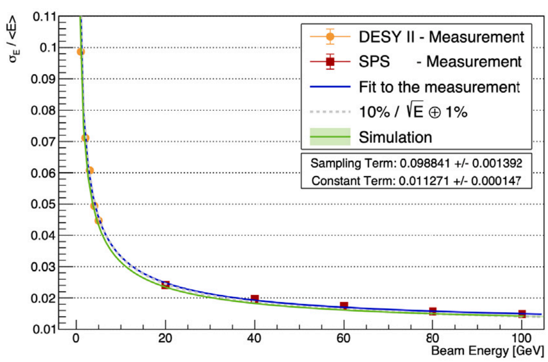


Fig. 5. Energy resolution of the tungsten/polystyrene SpaCal prototype measured at 3°+3° in single-sided readout and equipped with Hamamatsu R14755U-100 coupled via a hollow light guide. Figure taken from [1].

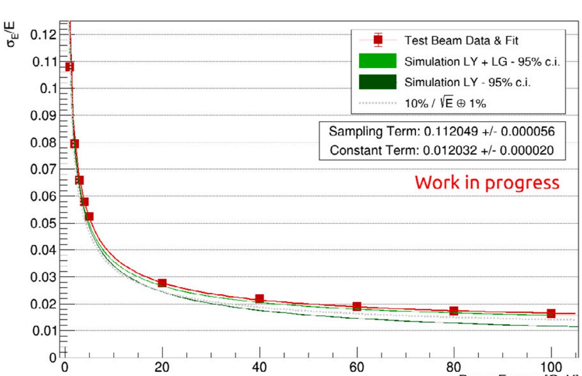


Fig. 6. Energy resolution of the lead/polystyrene SpaCal prototype measured at 3°+3° in single-sided readout and equipped with Hamamatsu R11187 coupled via a hollow light guide.

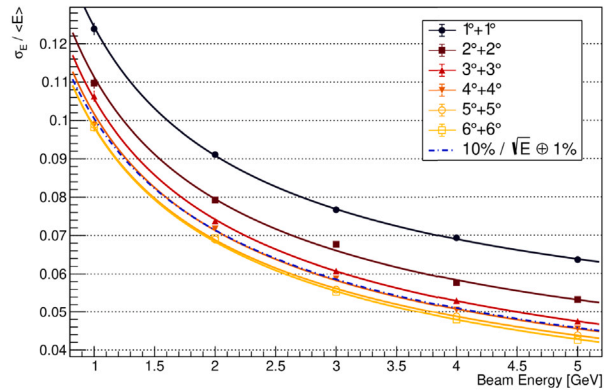


Fig. 7. Energy resolution of the tungsten/garnet-crystal SpaCal prototype measured at 3°+3° in double-sided readout and equipped with Hamamatsu R12421 coupled via a PMMA light guide in dry contact, i.e. without optical grease or glue.
Source: Figure taken from [3].

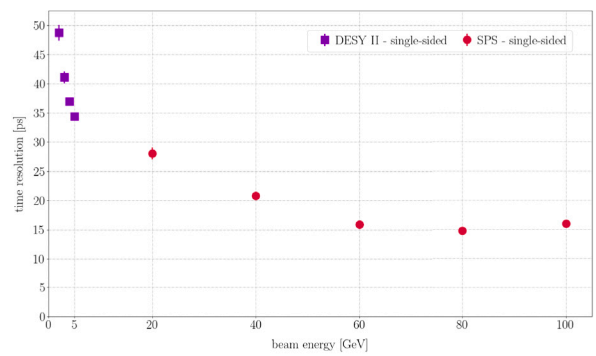


Fig. 8. Time resolution of the tungsten/polystyrene SpaCal prototype measured at 3°+3° in single-sided readout and equipped with Hamamatsu R7600U-M4 coupled via a hollow light guide. Figure taken from [1].

3.1. Energy resolution

One of the requirements for the ECAL is to maintain a target energy resolution of around 10% sampling and 1% constant term throughout its operation [1,2]. The measured energy resolution in test beams is shown for SpaCal prototypes with plastic scintillating fibers and tungsten or lead absorber in Figs. 5 and 6, respectively. Both prototypes have a single-sided readout and the results are in a good agreement with Monte-Carlo simulations. Similarly, a plot is shown for a SpaCal prototype with tungsten absorber, garnet scintillating crystals and double-sided readout in Fig. 7.

3.2. Time resolution

The results for the time resolution are shown for SpaCal prototypes with plastic scintillating fibers in Figs. 8 and 9, for SpaCal prototype with garnet scintillating crystals in Fig. 10, and for Shashlik prototypes in Fig. 11, where all technologies demonstrate better than 20 ps precision at higher beam energies. For Shashlik, worth highlighting is the improvement in time resolution, from 40 ps to below 20 ps at 100 GeV, achieved by replacing WLS fibers with faster ones and equipping the prototypes with faster PMTs. The WLS fibers of the current Shashlik modules (Y11) have a decay time of 7.0 ns, compared to faster options such as YS2 and YS4, with 1.1 ns and 3.0 ns decay times, respectively. True for both SpaCal and Shashlik, the double-sided readout brings improvements in time resolution over the single-sided readout thanks to a possible correction of the time jitter from shower fluctuation, achievable by combining time stamps obtained by the front and back sections.

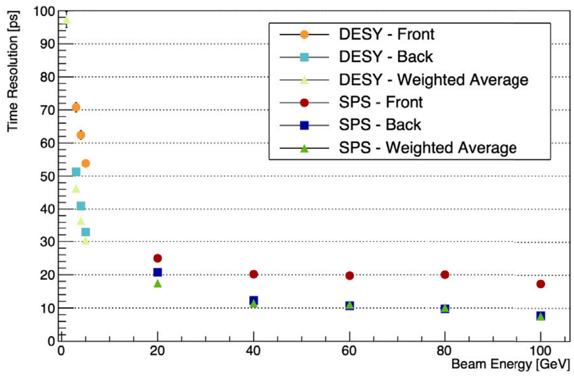


Fig. 9. Time resolution of the lead/polystyrene SpaCal prototype measured at 3°+3° in double-sided readout and equipped with Hamamatsu R7600U-20 in direct contact. Figure taken from [1].

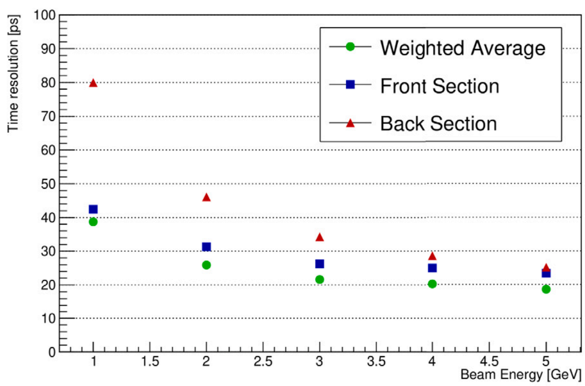


Fig. 10. Time resolution of the tungsten/garnet-crystal SpaCal prototype measured at 3°+3° in double-sided readout and equipped with Hamamatsu R7600U-20 in direct contact.
Source: Figure taken from [3].

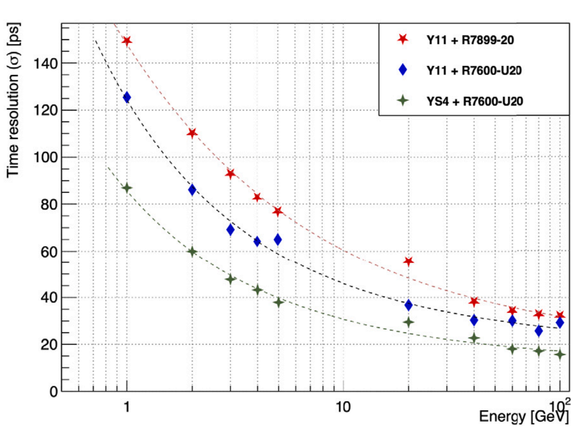


Fig. 11. Time resolution of Shashlik prototypes with different WLS fibers. All of the prototypes have single-sided readout and are equipped with either Hamamatsu R7899-20 (the current ECAL PMT) or Hamamatsu R7600U-20.
Source: Figure taken from [1].

4. Conclusions

An upgrade of the LHCb ECAL is planned to mitigate radiation damage after Run 3 and meet the requirements of Run 5. The LS3 Enhancement, scheduled from mid-2026 to late 2029, will introduce SpaCal technology in the inner regions, replacing existing Shashlik modules. For Run 5, the LHCb PicoCal will incorporate radiation-hard garnet scintillating crystals in the SpaCal-W region instead of the plastic scintillating fibers and adopt a double-sided readout with precise timing information in the full calorimeter.

To optimize the SpaCal module design, extensive R&D is ongoing, including tungsten absorber production with 3D printing, scintillation material development, and optimization studies of hollow light guides. Laboratory measurements showed that optimizing light guide geometry by making the light guides longer and decreasing the ratio between the entrance and readout area can improve response uniformity, which would otherwise worsen the constant term of energy resolution.

Prototypes of SpaCal modules with tungsten and lead absorbers have been developed and tested. The module-size tungsten prototype uses 3D-printed absorber, while the lead prototype was assembled with lead absorber incorporating stainless-steel capillary tubes. Both prototypes were equipped with plastic scintillating fibers and took data in single-sided readout.

Test beam campaigns at DESY II and the SPS North Area studied the performance of SpaCal and Shashlik prototypes. Measurements confirmed that the energy resolution of SpaCal prototypes aligns well with Monte Carlo simulations, achieving around 10% sampling and 1% constant term. Time resolution measurements show that all technologies reach sub-20 ps precision at high energies. For Shashlik, replacing the current wavelength-shifting fibers with faster ones and equipping the prototypes with faster PMTs significantly improved timing resolution. In both technologies, double-sided readout improved timing precision with respect to the single-sided readout.

These developments ensure that the upgraded ECAL will meet performance requirements for high-precision measurements in future LHCb runs, with improved radiation tolerance, introduced timing capabilities, and finer granularity.

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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