EPJ Web of Conferences **320**, 00060 (2025) https://doi.org/10.1051/epjconf/202532000060
CALOR 2024

Study of the time and energy resolution of an ultracompact sampling calorimeter (RADiCAL) module at EM shower maximum over the energy range 25 ≤ E ≤ 150 GeV using scintillation and wavelength shifting technology

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Abstract. The RADiCAL Collaboration is conducting R&D on precision-timing electromagnetic (EM) calorimetry to address the challenges expected in future collider experiments under conditions of high luminosity and/or high irradiation such as those expected at the FCC-ee and FCC-hh colliding beam facilities. Under development are sampling calorimeter structures known as RADiCAL modules, based on scintillation and wavelength-shifting (WLS) technologies, and read out by SiPM photosensors. The module in the test described here consists of alternating layers of very dense tungsten (W) absorber and scintillating crystal (LYSO:Ce) plates, assembled to a depth of 25 radiation lengths (X_0). The scintillation signals produced by the EM showers in the region of EM shower maximum (shower max) are transmitted to SiPM located at the upstream and downstream ends of the module via quartz capillaries which penetrate the full length of the module and which contain either organic DSB1 WLS filaments or ceramic LuAG:Ce WLS filaments positioned within the region of shower max, where the shower energy deposition is greatest. The remaining volume within the capillaries, upstream and downstream of the WLS filaments, is filled and fused with quartz rod to form solid quartz waveguides. Preliminary results are presented of the timing resolution of the RADiCAL module over the energy range 25 GeV ≤ E ≤ 150 GeV using both types of wavelength shifters. The studies were conducted using electron beam in the H2 beamline at CERN, Geneva, Switzerland.

1 Introduction

The R&D objectives of the RADiCAL Collaboration are focused on the development of precision electromagnetic (EM) calorimetry, based primarily on optical techniques, for future applications at FCC-ee, FCC-hh [1-5], 10 TeV pCM, muon collider, as well as fixed target and forward direction, small-angle experiments. The effort is consistent with the Priority Research Directions (PRD) for calorimetry listed in the US Department of Energy Basic Research Needs (BRN) workshop for HEP Instrumentation [6], and RADiCAL is a participant in ECFA DRD6 [7] and CPAD RDC9 programs [8-11]. Through the development of fast, radiation-hard scintillators, wavelength shifters, and optical transmission elements, performance goals include producing modular structures capable of achieving: an EM energy resolution of $\sigma_E/E = 10\%/\sqrt{E} \oplus 0.3/E \oplus 0.7\%$; a timing resolution of $\sigma_t \leq 20$ ps at high energy; and EM shower centroid position localization to within a few mm. Measurements of the radiation tolerance of various fluorescent and photo-sensing elements along with initial measurements of the energy resolution and timing resolution have been presented elsewhere and remain under active development and further study [12-14]. This paper presents initial results from a beam test of a RADiCAL module for timing resolution over a range of electron beam energies: 25 GeV ≤ E ≤ 150 GeV. And an extensive discussion of this work may also be found in reference [15].

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2 RADiCAL Modular Structure and Characteristics

For these studies the RADiCAL module, shown schematically in Figs. 1-2 below, is a shashlik-style module of overall dimensions 14 x 14 x 135 mm^3 that consists of a layered structure of 29 LYSO:Ce crystal plates of 1.5 mm thickness interleaved with 28 Tungsten (W) plates of 2.5 mm thickness and assembled to a depth of 25 X_0 and corresponding to an absorption length of 0.9 λ.

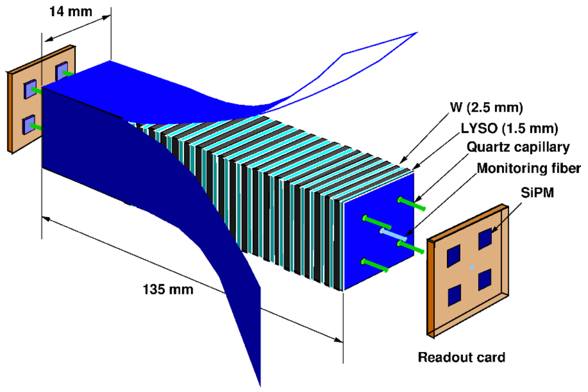


Fig. 1. A schematic of a RADiCAL module for ultra-compact EM calorimetry based upon interleaved layers of W and LYSO:Ce crystal in a shashlik-like structure and read out via specialized WLS quartz capillary elements which penetrate through the module to SiPM photosensors, positioned at both ends of the module. In this schematic, the beam enters the module from the upper left. The cross-sectional dimensions of the module are set by the Moliere radius of the structure.

Thin Tyvek sheets were inserted between successive LYSO:Ce and W layers to act as reflective spacers to avoid optical absorption between LYSO:Ce and W surfaces. Overall, the structure had a radiation length X_0 ~ 5.4 mm and a Moliere radius R_M ~ 13.7 mm. Holes were drilled through all of the tiles to facilitate the penetration of quartz capillaries through the layered structure, each capillary containing wavelength shifter (WLS) filaments positioned strategically in the region of EM shower max, as shown in Fig. 2, to facilitate energy and timing measurement. SiPM photosensors were mounted on front-end electronic cards located at both upstream and downstream ends of the module to detect the optical signals from the capillaries. The capillaries contained either DSB1 organic plastic WLS filaments [16] or LuAG:Ce ceramic filaments of 15 mm length, positioned within the region of shower max, where the shower energy deposition is greatest, and filled and fused with quartz rod elsewhere.

What makes the shower max region special, is that the shower particle density is greatest there (see Fig. 3) and the shower transverse profile is not given by the Moliere Radius, but rather is far more compact and more appropriately described by the radiation length as shown in Fig. 4. The figure shows a GEANT4 simulation of an EM shower of E = 50 GeV in the RADiCAL module and indicating that a shower centered on the module is fully contained transversely at that region.

The signals from the eight SiPM, four each on the upstream and downstream front-end cards were amplified at low gain for local energy measurement and differentially amplified at high gain for timing measurement. The waveforms were digitized using CAEN DT5742 digitizers. Sample low-gain and high gain signals from the SiPM are shown in Figs. 5 and 6. The energy of the EM signals measured at shower max are determined from the amplitude of the low gain signals.

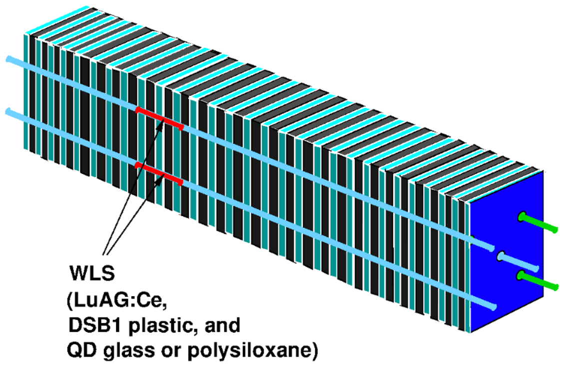


Fig. 2. Schematic of the locations of the WLS capillaries, with the WLS filaments positioned in the region of EM Shower Max.

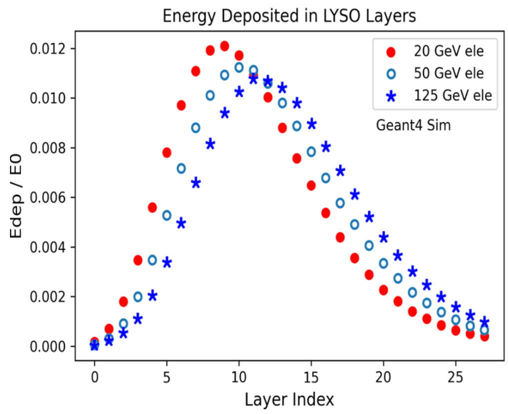


Fig. 3. GEANT4 simulation of energy deposition in successive LYSO:Ce scintillation tiles as a function of electron beam energy. The largest signals are seen in the EM shower max region.

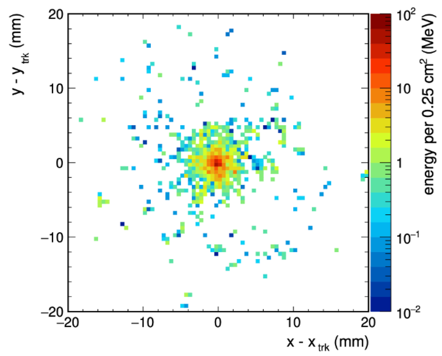


Fig. 4. GEANT4 simulation of transverse distribution of energy deposition in the region of EM shower max for a 50 GeV electron shower, indicating full containment of the shower at that location in the RADiCAL module whose cross section is 14 x 14 mm^2.

The beam position at the location of the module was recorded using a CERN beam chamber with submillimeter precision and, when combined with the amplitude of the low-gain light signals from specific capillaries, provides a "CT Scan" of the cross section of the module, an example of which is shown in Fig. 7. The locations of the holes in the scintillation tiles for the penetration of the WLS capillaries are clearly seen.

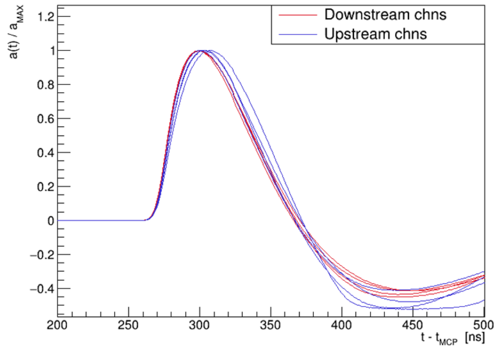


Fig. 5. Low-gain signals from the SiPM of the RADiCAL module utilized for local energy and position measurement.

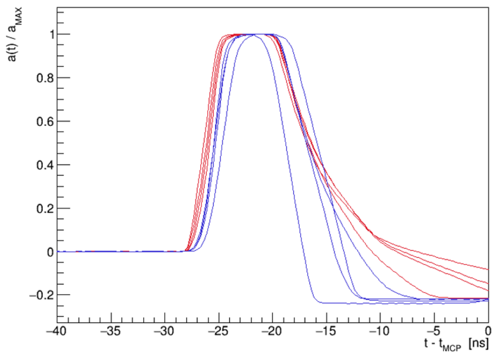


Fig. 6. Differential high-gain signals from the SiPM of the RADiCAL module utilized for timing measurement.

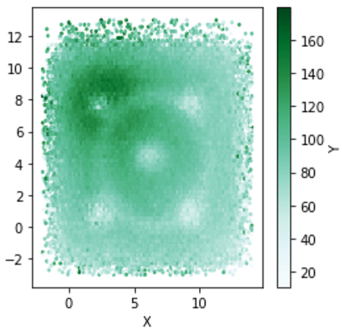


Fig. 7. Electron beam as detected in the capillaries in the RADiCAL module, with (x,y) position given by a beam wire chamber. Events were selected based on light detected in the upper left WLS capillary.

2 Module Energy and Timing Response in Electron Beam at the Location of Shower Maximum

The plot of the sum of the low gain amplitudes of all eight SiPM channels versus electron beam energy follows a linear response as shown in Fig. 8, showing a linear response. Note this functionality occurs given that the shower is fully contained a shower max (Fig. 4).

By comparing the average timing determined by the four upstream high gain SiPM channels and the four downstream high gain SiPM channels, the timing resolution of the module could be determined. The specific interest in the two wave shifters is that DSB1 is fast (3ns decay time) and LuAG:Ce is very radiation hard [12]. So their performance for timing resolution was important to assess.

The preliminary measurements of the timing resolution for each of these materials is shown in Fig. 9 for DSB1 WLS and in Fig. 10 for LuAG:Ce WLS. Extensive details of the the DSB1 analysis may be found in reference [15]. From Fig. 9, the data with DSB1 WLS indicate an energy dependence of the time resolution that follows the functional form: $\sigma_t = a/\sqrt{E} \oplus b$, where $a = 256\sqrt{\text{GeV}}$ ps and b = 17.5 ps. The time resolution measured at the highest electron beam energy for which data was recorded (150 GeV) was found to be $\sigma_t = 27 \pm 2$ ps. From Fig. 10, the equivalent for LuAG:Ce WLS is $\sigma_t = 30 \pm 3$ ps.

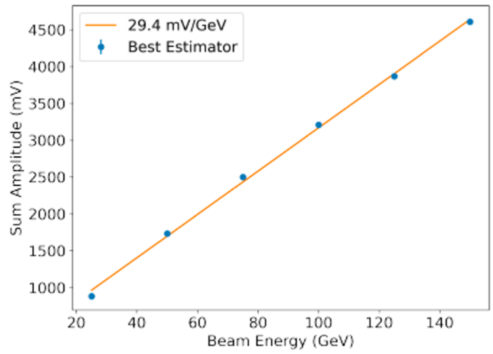


Fig. 8. The average of the low-gain signal amplitudes from the eight SiPM as a function of the energy of the electron beam, indicating that the measured "local" energy at shower max tracks the beam energy in a linear manner. This average of all eight channels is what is meant by "best estimator".

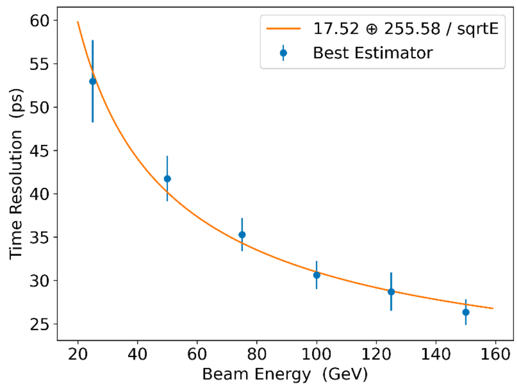
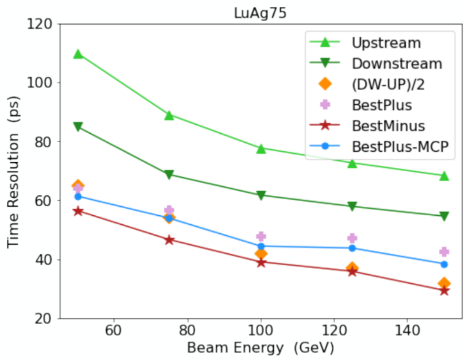


Fig. 9. Timing resolution determined from the difference in the average of timing signals from the four upstream high-gain SiPM channels and the four downstream high-gain SiPM channels. This technique is referred to as the "best estimator".



Fig; 10. Timing resolution studies for LuAG:Ce Wavelength Shifter. The red/starred measurements are the equivalent of the DSB1 "best estimator" results indicated in Fig. 9.

3 Future planning and conclusions

The results presented above in Section 3, and Figs. 9, 10 indicate that the RADiCAL modular calorimetry technique has the potential to meet and exceed the timing requirements for FCC-ee and FCC-hh applications, and additionally could serve as a potentially useful EM calorimetry approach for forward physics applications and fixed target style experiments, for time-of-flight and long-lived particles.

Of especial interest are new scintillator and wavelength shifter combinations, which can provide further improvement in timing resolution. An example of this are scintillation plates of the very fast ceramic scintillator LuO:Yb [17], which emits in the UV range 330 nm $< \lambda <$ 370 nm with a decay time ~ 1 ns. A promising WLS match for this material is the organic dye 3-hydroxyflavone (3HF). This LuO:Yb/3HF scintillator/WLS combination will be studied comparatively in upcoming beam tests with the LYSO:Ce/DSB1 and LYSO:Ce/LuAG:Ce, scintillator/wavelength shifter combinations elaborated here and in reference [15].

The potential impact of the RADiCAL research and development program, while directed toward future particle physics experimental applications, is not experiment specific, is potentially broad and significant, and can inform further developments in high energy physics instrumentation through ECFA DRD6 and CPAD9 programs. The technological innovations are versatile and could be applied in particle physics, nuclear physics, materials science, and medical physics.

Acknowledgements. We thank SPS Coordination at CERN for providing the excellent beam operation and support during the experimental run in the H2 beamline at the CERN/Prevessin site. We thank the Notre Dame Radiation Laboratory Glass Shop for the expert fabrication of the wavelength shifting capillaries. This work has been supported in part by a US Department of Energy grant DE-SC0017810, the US National Science Foundation under grant NSF-PHY-1914059, the University of Notre Dame through its resilience and Recovery Grant Program, and QuarkNet for high school teacher and student participation.

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