



Article

RADiCAL—Precision Timing, Ultracompact, Radiation-Hard Electromagnetic Calorimetry

Thomas Anderson ¹, Thomas Barbera ², Bradley Cox ¹, Paul Debbins ³, Maxwell Dubnowski ¹, Kiva Ford ², Maxwell Herrmann ³, Chen Hu ⁴, Colin Jessop ², Ohannes Kamer-Koseyan ³, Alexander Ledovskoy ¹, Yasar Onel ³, Carlos Perez-Lara ¹, Randal Ruchti ^{2,*} , Daniel Ruggiero ², Daniel Smith ², Mark Vigneault ², Yuyi Wan ², Mitchell Wayne ², James Wetzel ³, Liyuan Zhang ⁴ and Ren-Yuan Zhu ⁴ 

¹ Department of Physics, University of Virginia, Charlottesville, VA 22904, USA

² Department of Physics and Astronomy, University of Notre Dame, Notre Dame, IN 46556, USA

³ Department of Physics, University of Iowa, Iowa City, IA 52242, USA

⁴ Department of Physics, California Institute of Technology, Pasadena, CA 91125, USA

* Correspondence: rrruchti@nd.edu; Tel.: +1-574-302-7181

Abstract: To address the challenges of providing high-performance calorimetry in future hadron collider experiments under conditions of high luminosity and high radiation (FCC-hh environments), we conducted R&D on advanced calorimetry techniques suitable for such operation, based on scintillation and wavelength-shifting technologies and photosensor (SiPM and SiPM-like) technology. In particular, we focused our attention on ultra-compact radiation-hard EM calorimeters based on modular structures (RADiCAL modules) consisting of alternating layers of the very dense absorber and scintillating plates, read out via radiation hard wavelength shifting (WLS) solid fiber or capillary elements to photosensors positioned either proximately or remotely, depending upon their radiation tolerance. RADiCAL modules provide the capability to measure simultaneously and with high precision the position, energy and timing of EM showers. This paper provides an overview of the instrumentation and photosensor R&D associated with the RADiCAL program.

Keywords: fast-timing; electromagnetic calorimetry; radiation-hard detectors



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1. Introduction

The R&D objective and goals of RADiCAL are focused on the development of precision EM calorimetry for future hadron colliding beam experiments and are directed toward addressing the Priority Research Directions (PRD) for calorimetry listed in the DOE Basic Research Needs (BRN) workshop for HEP instrumentation [1].

Approach: To construct an array of ultracompact RADiCAL modules to explore the potential of ultracompact EM calorimetry capable of precision timing, energy and position measurements and specialized particle identification in high radiation fields [2]. Reaching the objective requires R&D on radiation-hard and fast-response scintillators, wavelength shifters and fiberoptic elements and photosensors.

Objective: To establish a performance baseline for RADiCAL modules through instrumentation capable of delivering an EM energy resolution approaching $\sigma/E = 10\%/\sqrt{E} \oplus 0.3/E \oplus 0.7\%$ [3], a timing resolution $\sigma_t < 50$ ps [4] and position resolution for the shower centroid within a few mm [5]. This initial effort uses radiation-hard optical elements but is instrumented with currently available SiPM photosensors, which are adequate for beam tests to establish and characterize a performance baseline for the RADiCAL technique but will not be performant if placed in high radiation areas. Once the time/energy/position baseline is established, R&D will be focused on the further development and refinement of radiation-hard optical components and new photosensors to replace those with vulnerabilities.

Our goals are:

1. To develop candidate instrumentation capable of operation in the FCC-hh endcap region up to $|\eta| \leq 4$ with an EM energy resolution indicated above, noting that for $|\eta| \leq 2.5$, the environmental conditions are expected to be 100 Mrad ionization dose and 3×10^{16} 1 MeV n_{eq}/cm^2 [3]. This effort will include further optical material development and R&D on radiation-hard photosensors to replace conventional SiPM;
2. To identify future directions and candidate instrumentation with the potential for operation at the FCC-hh in endcap/forward regions, where the operating conditions are foreseen to be a sobering 500 Grad ionization dose and 5×10^{18} 1 MeV n_{eq}/cm^2 [3]. To reach and function in this domain will require further creative innovations in optical materials and photosensor development.

2. Materials and Methods

Schematics of RADiCAL modules are shown in Figure 1, consisting of interleaved layers of LYSO:Ce tiles of 1.5 mm thickness and tungsten plates of 2.5 mm thickness, each of cross-sectional area 14×14 mm², stacked to a total depth of 114 mm corresponding to $25 X_0$ or 0.9λ . The Molière radius of the structure is 13.7 mm, resulting in an ultracompact structure both transversely and longitudinally. The light produced in the LYSO:Ce tiles is then wavelength-shifted (WLS) and collected using specialized rad-hard (high OH⁻ content) quartz capillaries containing liquid wave shifter or organic plastic or ceramic filaments in the capillary cores. The use of radiation-hard materials is essential, and extensive measurements of the radiation hardness of the scintillators LYSO:Ce, wave-shifting liquids and ceramics and capillaries have been studied extensively [2,6–9].

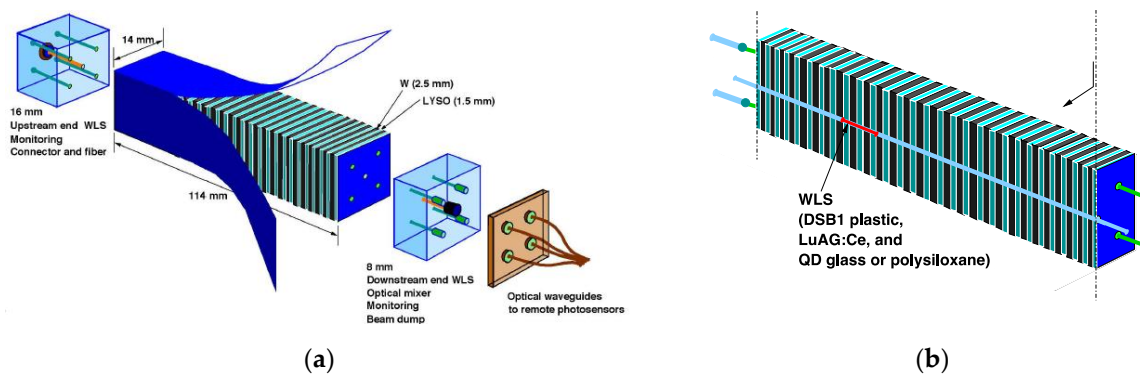


Figure 1. (a) Schematic of a RADiCAL module which is scaled to the Molière radius of EM showers in a W/LYSO:Ce sampling calorimeter. The beam enters from the upper left and exits the lower right in this view. Light from the scintillation tiles is wave-shifted in capillaries or filaments that penetrate through the full length of the module to photosensors positioned at the ends of the module or remotely via fiberoptic waveguides. (b) A half-section of a RADiCAL module indicating two energy (E-type) capillaries penetrating the full length of the module and a timing (T-type) capillary superimposed to show its WLS filament (highlighted in red) positioned in the region of shower max for an EM shower.

Two types of WLS capillaries are utilized: E-type for energy measurement in which the WLS runs the full length of the module, and T-Type for precision timing measurement in which WLS is positioned locally in the region of EM shower maximum.

E-type capillaries are of 1.0 mm outer diameter and 0.4 mm inner diameter, with their cores filled with EJ309/DSB1 liquid wavelength shifter over their full length, and are read out with SiPM and low-gain amplifiers at the downstream ends only. For improved radiation hardness [6], LuAG:Ce WLS filaments of 114 mm in length and 1.15 mm in diameter will replace the liquid-filled capillaries with two benefits: photosensors can be placed at both upstream and downstream ends to measure the signal timing; the use of liquid WLS is avoided.

T-type capillaries are of 1.15 mm outer diameter and 0.95 mm inner diameter with 15 mm long and 0.9 mm diameter DSB1 organic plastic WLS filament positioned in the core at shower max. The remainder of the capillary core upstream and downstream is filled with quartz rods and fused to the capillary wall forming a solid quartz waveguide. For improved radiation hardness, rad-hard LuAG:Ce WLS filaments of 1.0 mm diameter and 15 mm length are positioned near the shower max. These filaments are optically connected via quartz rods of 1.0 mm diameter to photosensors positioned at upstream and downstream ends, should rad-hard devices be available. In both cases, the signals from the SiPMs are amplified at high gain for timing measurement and at low gain for local energy measurement at shower max.

Figure 2 show a schematic of the upstream face of a RADiCAL module, as a particle beam would see it as it enters the module. Indicated are the transverse placement locations of four WLS capillaries/filaments, which can be configured in different ways to measure energy, time and position. For shower position determination, the spatial localization of an EM shower is provided by the signal amplitudes of the energy measurements from the capillaries. Note that at shower max, the EM shower radius is significantly smaller than the Molière radius ($R_M = 13.7$ mm) and is given approximately by the radiation length of the structure ($X_0 \sim 4.5$ mm) [5]. Capitalizing on this, the shower position can be localized within a module to within a few mm, beneficial for event reconstruction under high pileup conditions in endcap and forward regions of experiments and for distinguishing nearby showers from decays of highly boosted objects.

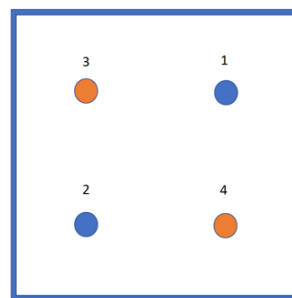


Figure 2. Schematic of capillary placement in a RADiCAL module as seen from the beam entry (upstream) face. In the arrangement shown, positions 1 and 2 are for T-type capillaries; positions 3 and 4 are for E-type capillaries; however, all four capillaries could be used for energy measurement (E-type) or for timing measurement (T-type), depending upon experimental preference.

3. Discussion of Experimental Results

For the CMS Endcap Upgrade Down Select Process in preparation for HL-LHC (held in 2015), a 4×4 array of such RADiCAL modules was tested in the CERN H4 beamline with electrons of energies $20 \text{ GeV} < E < 200 \text{ GeV}$. For that specific test, all 16 of the modules were instrumented with E-type capillaries only. More recently, at the Fermilab Test Beam Facility (FTBF), using beam electrons of energy $12 \text{ GeV} < E < 28 \text{ GeV}$, in December 2021 and June 2022, tests were carried out with a single RADiCAL module instrumented with two E-type and two T-type capillaries and a single RADiCAL module instrumented with four T-type capillaries. Data analysis from these recent tests is currently in progress.

3.1. Experimental Measurement of Energy Resolution

For the beam tests of a 4×4 array carried out at CERN in the H4 beamline, the active volume of the array was $56 \text{ mm} \times 56 \text{ mm} \times 114 \text{ mm}$, and there were 64 independent readout channels for this structure, with 4 E-Type DSB1 WLS capillaries per module, each capillary connected by a clear fiber waveguide to its own individual HPK SiPM photosensor having $15 \mu\text{m}$ square pixels. Figure 3 show the structure of the array, and Figure 4 display the measured energy resolution. In these studies, the (rad-hard) DSB1 WLS capillaries were

compared with (non-rad-hard) 0.94 mm diameter Y11 WLS fibers indicating comparable results.



Figure 3. (a) The 4×4 modular array during assembly. (b) Fiber optic waveguides used to transmit the WLS light to SiPM photosensors positioned outside of the beam region for this specific test. In the picture, the incoming electron beam is incident from the left on the 4×4 modular array enclosed within the white mechanical housing.

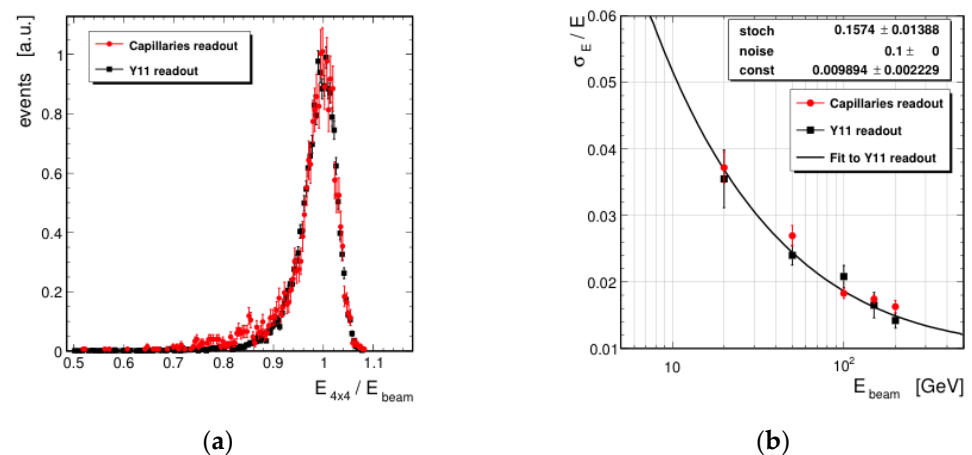


Figure 4. (a) Energy resolution for the 4×4 W/LYSO array using capillary WLS readout (red) compared to Y11 double clad WLS fiber readout (black), as measured using an electron beam in the CERN H4 beam line. Electron beam energy is 100 GeV. (b) Energy resolution as a function of beam energy for the 4×4 W/LYSO array. These results indicate performance leading to a 1% constant term.

The energy resolution achieved was: $\sigma_E/E = 15.7\%/\sqrt{E} \oplus 0.1/E \oplus 1\%$. The desired constant term and stochastic term indicated in Section 1 above can be improved by increasing the sampling fraction (the thickness of the LYSO:Ce scintillation tiles), by improved coupling between the scintillation tiles and the wave shifting capillaries and by slightly extending the length of the module (number of W and LYSO:Ce layers in the module).

3.2. Expectations for Timing and Spatial Resolution

A GEANT4 simulation has been carried out for a RADICAL module of the type shown in Figure 1b [4,5] and guided and qualified by the measurements described in Section 3.2 above. A WLS capillary (T-type) is assumed to be inserted into the center of the module with the DSB1 WLS filament located in the region of EM shower maximum for 50 GeV electron showers. In this study, the simulation assumed only a single SiPM for readout, which is positioned at the downstream end of the WLS timing capillary, while in reality, timing measurement is possible with SiPM placed at both upstream and downstream ends of such capillaries.

The shower max timing signal is derived from a region of very small transverse size $r \sim X_0$ (see Figure 5a), a region whose radius is significantly smaller than the Molière radius.

In this small region, there are ~ 100 charged (shower) particles, clearly distinguishing EM signals from mip signals due to charged hadrons and providing a large and time-localized optical pulse. The timing resolution will be dominated by the rise time of this signal and the detected light yield within the first nanosecond of the optical pulse. Figure 5b indicate that, in simulation, timing resolutions of $30 \text{ ps} < \sigma_\tau < 50 \text{ ps}$ could be achievable with RADiCAL modules. By reading out the light from both upstream and downstream ends of timing capillaries and using several timing capillaries per module, it is the objective of the ongoing beam tests at the Fermilab FTBF to verify the actual achievable timing performance.

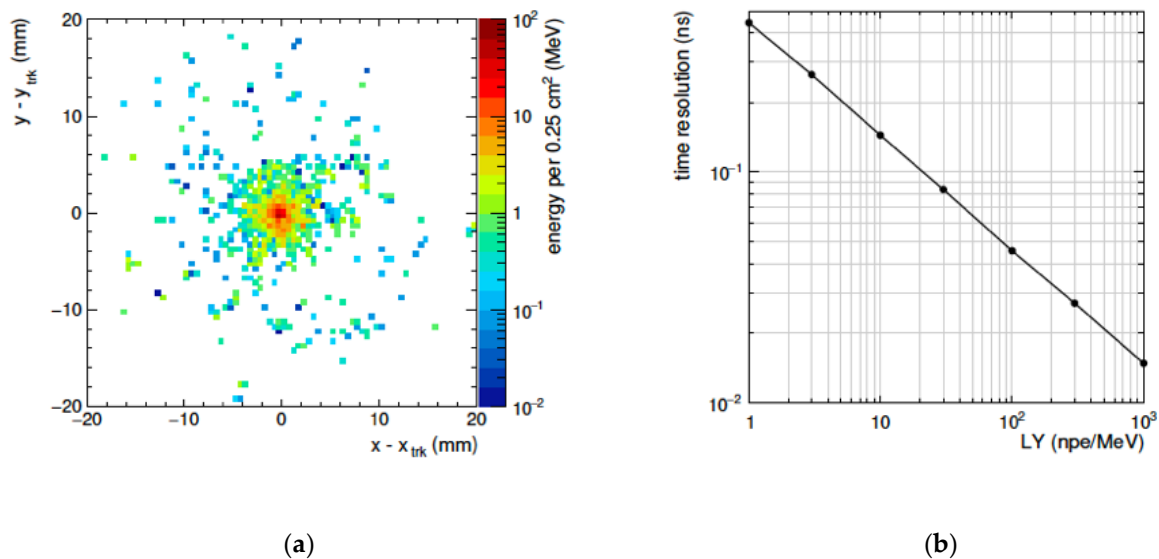


Figure 5. (a) Location of the energy in a RADiCAL module at shower max for 50 GeV electrons in GEANT4 simulation. The module itself occupies a square region of $14 \times 14 \text{ mm}^2$ at the center of the plot. (b) Timing resolution vs. detected light yield in photoelectrons per MeV, simulated for a 50 GeV electron shower. Downstream readout only in this GEANT4 simulation study.

4. Conclusions

The pattern recognition power and the potential for high-resolution measurement of both timing and energy of EM objects (electrons, positrons and gammas) in arrays of RADiCAL modules is a potentially promising technique for EM Calorimetry in future high-luminosity hadron collider experiments such as the FCC-hh. The energy resolution of a 4×4 array of RADiCAL modules was measured in a high-energy electron beam at CERN and found to be $\sigma_E/E = 15.7\%/\sqrt{E} \oplus 0.1/E \oplus 1\%$. This performance can be improved toward the desired resolution for FCC-hh by several methods: for the stochastic term, by improving the sampling fraction by using thicker scintillation tiles and further optimization of the optical coupling between the scintillating tiles and the wave shifters in the capillaries by increasing the thickness of the shifter; for the constant term, by increasing the overall module length toward $29 X_0$ by increasing the number of tungsten and LYSO:Ce layers. When assessing the timing resolution of RADiCAL modules, measuring the timing at the shower max represents new territory under study. Currently underway are beam measurements of the timing resolution and spatial precision for EM showers at the Fermilab FTBF to verify how closely the RADiCAL module conforms to expectations from the GEANT4 simulation.

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Data Availability Statement: Data are not yet available as beam testing and data collection and analysis are currently in progress.

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Conflicts of Interest: The authors declare no conflict of interest.

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