Nuclear Instruments and Methods in Physics Research A 1069 (2024) 169973

Contents lists available at ScienceDirect

Nuclear Inst. and Methods in Physics Research, A

journal homepage: www.elsevier.com/locate/nima

Developing an alternative calorimeter solution for the future Muon Collider: The Crilin design

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A R T I C L E I N F O

Keywords:
Electromagnetic calorimeter
Muon Collider
SiPMs
Crystals

A B S T R A C T

The Crilin calorimeter represents a novel approach in the development of electromagnetic calorimeters for future colliders, especially for a Muon Collider. This paper details the design and performance of the innovative semi-homogeneous Crilin calorimeter, highlighting its capabilities in mitigating beam-induced backgrounds (BIB) while maintaining excellent time resolution (less than 50 ps), longitudinal segmentation, and fine granularity. These performances are achieved throughout a series of stackable and interchangeable lead fluoride (PbF_2) crystal matrices readout by surface-mount UV-extended Silicon Photo-multipliers. Simulated and experimental results demonstrate the Crilin design's potential to work as an efficient and cost-effective alternative to traditional electromagnetic calorimeters. Crilin radiation tolerance is discussed, as measured in several irradiation campaigns, as well as timing performances during a beam test at CERN-H2 with 120 GeV electrons for the latest prototype, Proto-1. Additionally, a description of the results from a recent beam test conducted at the LNF Beam Test Facility with 450 MeV electrons is provided, aiming to measure light yield losses due to irradiation.

1. Introduction

A Muon Collider [1] has been proposed by the International Muon Collider Collaboration (IMCC) as a future facility for high-energy physics research by leveraging the unique properties of muons. Unlike electrons, muons produce significantly less synchrotron radiation, allowing for more straightforward high-energy collisions. However, the short lifetime of muons and their decay products generate substantial Beam-Induced Backgrounds (BIB), presenting a significant challenge for detector technologies, particularly for the electromagnetic calorimeter (ECAL). In particular in the ECAL region a flux of 300 particles per cm^2 through the ECAL surface mainly photons (96%) and neutrons (4%), with an average photon energy 1.7 MeV. Moreover, because of the BIB, a highly challenging environment is anticipated for the Muon Collider. As a result, a FLUKA simulation at $\sqrt{s}$ = 1.5 TeV was conducted by the IMCC collaboration [2], with the aim to determine the Total Ionizing Dose (TID) and neutron fluence levels expected on the whole detector interface. For the ECAL barrel region, the expected neutron fluence and the total ionizing dose (TID) per year are 10^{14} n_{1MeV}/cm^2 and 1 kGy respectively. A CALICE-like W-Si sampling calorimeter [3] represents right now the baseline choice, however, despite its benefits, this technology is quite complex. This paper introduces the Crilin calorimeter [4], a semi-homogeneous, longitudinally segmented electromagnetic calorimeter based on Cherenkov PbF_2 crystals with UV-extended SiPM readout, that features fine granularity, excellent timing, good pileup capability and energy resolution, along

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https://doi.org/10.1016/j.nima.2024.169973
Received 30 June 2024; Received in revised form 7 October 2024; Accepted 9 October 2024
Available online 15 October 2024

with improved radiation resistance. Its modular architecture, featuring stackable and interchangeable sub-modules, allows crystals granularity, transversal and longitudinal dimensions scaling to maximize performance offering a cost-effective and high-performance alternative, specifically designed to address the challenges posed by BIB in the Muon Collider environment.

2. Crilin calorimeter design and performance

The Crilin calorimeter design employs a series of matrices of high-density crystals, each independently read out by two channels consisting of a series of two Silicon Photo-Multipliers (SiPMs). This semi-homogeneous design offers several advantages, including improved timing and granularity, longitudinal segmentation, radiation resistance, and moderate cost.

2.1. Design features

In order to match the Muon Collider specification Crilin must achieve a timing resolution of less than 100 ps, essential for distinguishing BIB from physics signals. The fine granularity, with a cell area of $10 \times 10\,\mathrm{mm}^2$, aids in differentiating between BIB and actual particle interactions (reducing the hit density in each cell). The design incorporates five layers of 45 mm length (40 mm crystals and 5 mm readout), providing longitudinal segmentation that is crucial for identifying and mitigating fake showers caused by BIB. Crilin's design, requiring only five layers compared to the 40 layers of a W-Si calorimeter, significantly reduces the number of channels and associated costs by a factor of 10. This reduction in complexity and cost, combined with the compactness of the design, makes Crilin an attractive alternative for future collider experiments. The chosen crystals, i.e. PbF_2 [5] or alternatively $PbWO_4$-UF [6] crystals, have shown good radiation resistance performances. Indeed, PbF_2 crystals have demonstrated no significant decrease in transmittance after exposure to Total Ionizing Doses (TID) of up to 350 kGy, while $PbWO_4$-UF crystals withstand up to 2 MGy [7]. In addition to the crystals, SiPMs have been deeply tested for radiation hardness. Hamamatsu S14160-3010PS SiPMs with a 10 μm pixel size have shown a minor increases in dark current after been exposed to a neutron fluence up to 10^{14} $\mathrm{n_{1MeV\text{-}eq}/cm^2}$ and a TID up to 10 kGy with respect to S14160-3015PS model with a 15 μm pixel size as shown in [7], confirming their suitability for use in the Crilin calorimeter under expected radiation levels. These measurements test the longevity and reliability of the calorimeter in the high-radiation environment such as the Muon Collider one.

2.2. Performance evaluation

The Crilin ECAL has been subjected to extensive simulation and experimental validation, demonstrating promising performance metrics. Simulations show an energy resolution of $\sigma_E/E \approx 4.8\%/\sqrt{\mathrm{E(GeV)}} \oplus 0.2\%$ for photons. This performance is competitive with traditional sampling calorimeters, showing good overall calorimetric properties, naturally degraded by the BIB contribution reaching a sufficient resolution of $\approx 15\%/\sqrt{\mathrm{E(GeV)}} \oplus 0.8\%$. Further optimization on the clusterisation algorithms is ongoing in order to better employ the longitudinal information to suppress fluctuations due to BIB. Results are summarized in Fig. 1.

Two preliminary prototypes have been developed and fully tested. Proto-0 [8], featuring two crystals and four channels, and Proto-1, embedding two layers of 3 × 3 crystal matrix readout by a total of 36 channels, demonstrated excellent time resolution (on the order of 20 ps) and good agreement with Monte Carlo simulations, validating the design's performances. For R&D purposes two different SiPMs circuital setups were tested for the two different layers: the first layer had the two readout channels for each crystal connected in series, the second one in parallel, both readout by a custom Front End Electronics

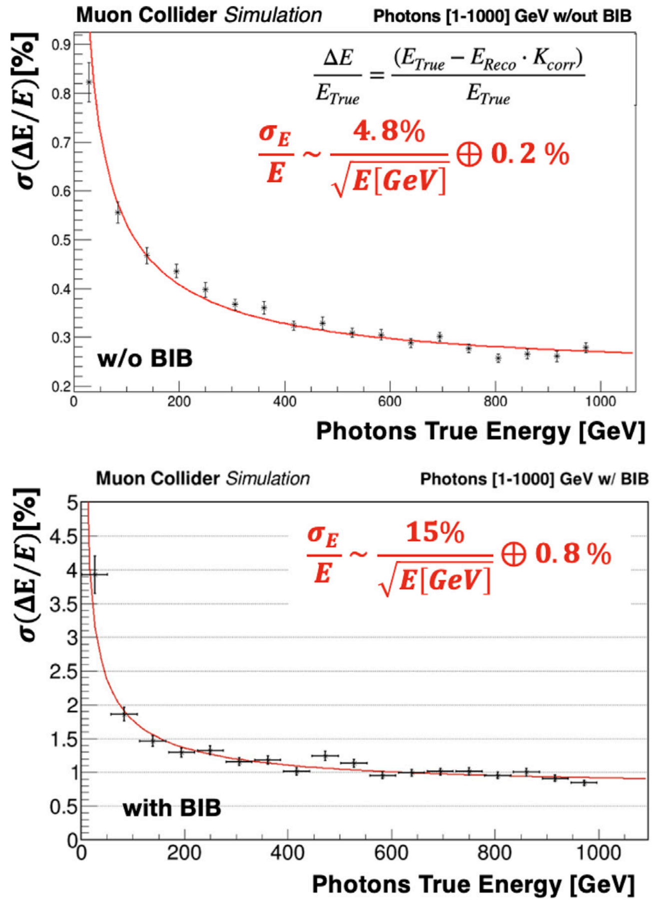

Fig. 1. Energy resolution simulated in the Muon Collider framework with and without BIB contributions.

described in [4]. In August 2023, Proto-1 timing performances were evaluated with a 120 GeV electron beam at CERN-SPS H2 beam-line in different configurations, with time differences between the two layers or between the two channels of the same crystals, always looking at the central elements of the matrix (which shows the higher energy deposit). For the series and parallel layers (Fig. 2) the time resolution is less than 40 ps for energy deposit greater than 1 GeV.

Also the time resolution achieved using the time difference between the two most energetic crystals of different layers was well within the requirements. Indeed, as shown with the Double Sided Crystal Ball fit in Fig. 3, a $\sigma_{\Delta t}$ of 45 ps is found. This result is mainly dominated by the digitizer board synchronization jitter which was measured to be $\mathcal{O}(32\,\mathrm{ps})$ for the board-to-board case and $\mathcal{O}(10\,\mathrm{ps})$ for the channel-to-channel case.

In April 2024 a final test beam on Proto-1 was performed at the Frascati Beam Test Facility (BTF) with the aim to systematically study light yield loss due to γ-irradiation. For this purpose, the BTF 450 MeV electron beam (with particle multiplicity per bunch set to 1) was used, centering the beam on each crystal of the series layer before and after irradiation, looking at the charge deposition. Crystals were tested with two different wrappings, i.e. Teflon and Mylar, reaching in both cases a TID up to 80 kGy. The light yield (LY) loss was then evaluated looking at the variation in charge and number of photo-electrons: the results in terms of $N_{p.e.}$ variation are summarized in Fig. 4. This test was crucial to understanding several characteristics of the prototype components:

- There is a considerable variability in crystals' response to radiation, even if the vendor claims to use of high-purity (>99.9%) PbF_2 powders for crystal growth.

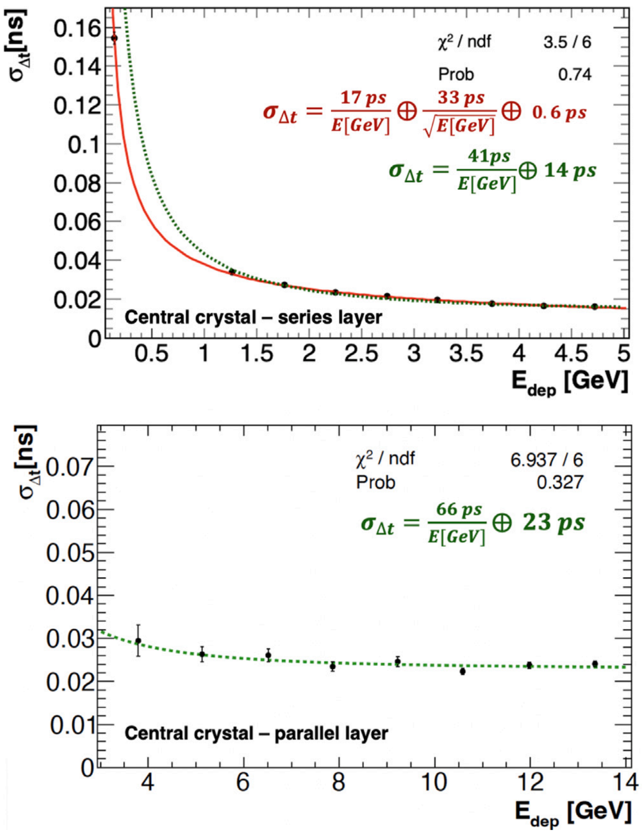

Fig. 2. Time resolution as a function of the energy deposit in the most energetic crystal of the layer, for the series layer also a time resolution measurement with 450 MeV electron beam was added and included in the solid-red line fit.

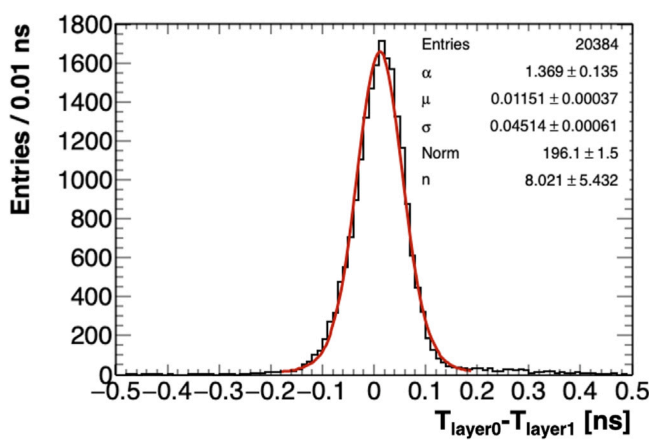

Fig. 3. Time resolution for the time difference between the two most energetic crystals coming from different layers. A Double Sided Crystal Ball fit is applied and shows a resolution of 45 ps, mainly dominated by the digitizer board-to-board jitter.

- Crystals showed an evident loss in transparency which appeared uniform in the longitudinal axis.
- The Teflon wrapping got damaged and brittle, this favors a choice of Mylar, even if its reflection of UV Cherenkov light is inferior.
- SiPM dark counts increased significantly with the absorbed dose as shown from the pedestals in Fig. 5.

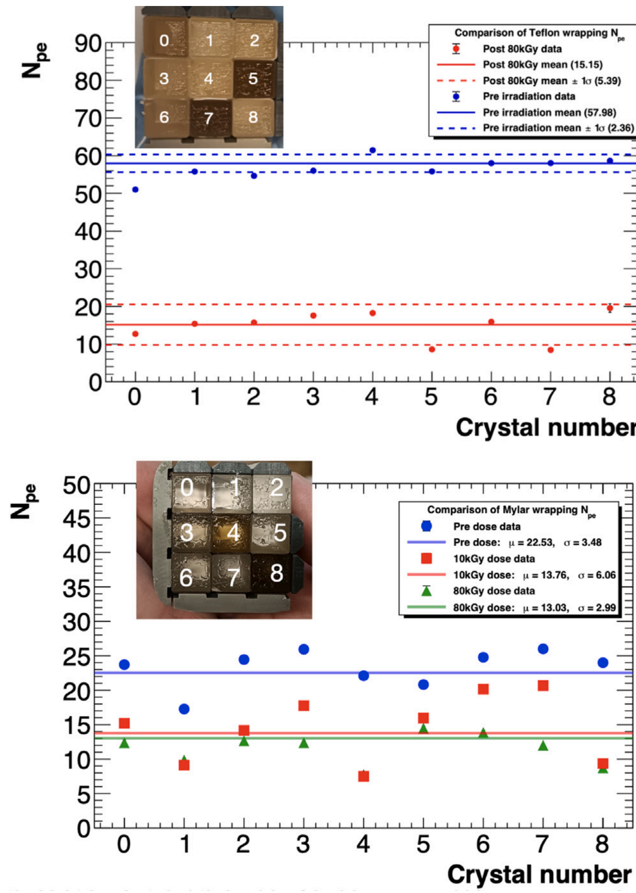

Fig. 4. Variation of the number of photo-electrons after exposure to a TID up to 80 kGy with two different wrappings configuration, Teflon (top-panel) and Mylar (bottom-panel). For the Mylar case an intermediate LY measurement was performed at 10 kGy (green markers and line). For both cases a picture of the crystal matrix after the test was added to show the visible loss in transmittance and the crystal number association.

New tests are needed to better understand these effects that appear to be much more significant than the contribution coming only from the transmittance loss. Further tests will be performed in future irradiation sessions by monitoring with a blue laser the response of the crystal-SiPMs systems and the SiPMs alone, in order to disentangle PDE and transmittance loss.

2.3. New prototype

A new prototype consisting of 5 layers of 9 × 9 crystal matrices will be fully developed, built, and tested during 2025, reaching 2 Molière Radii, 22 radiation lengths. The mechanics and electronics will have a significant advance from the Proto-0 and Proto-1 designs. An aluminum matrix with 50–100 μm thickness will hold the crystals and a thicker (2 mm) external envelope will surround the matrix also providing cooling through micro-channels. Moreover a micro-coaxial Kapton strip will provide SiPM polarization and readout independently for each channel of two SiPMs in series. An overall connector will be placed at the back of the 5 assembled modules. A sketch of the final Crilin version is shown in Fig. 6. This final version will provide enough coverage to finely study the energy resolution performances together with the timing information.

3. Conclusions

The Crilin calorimeter represents a promising alternative to traditional sampling calorimeters for the future Muon Collider, addressing

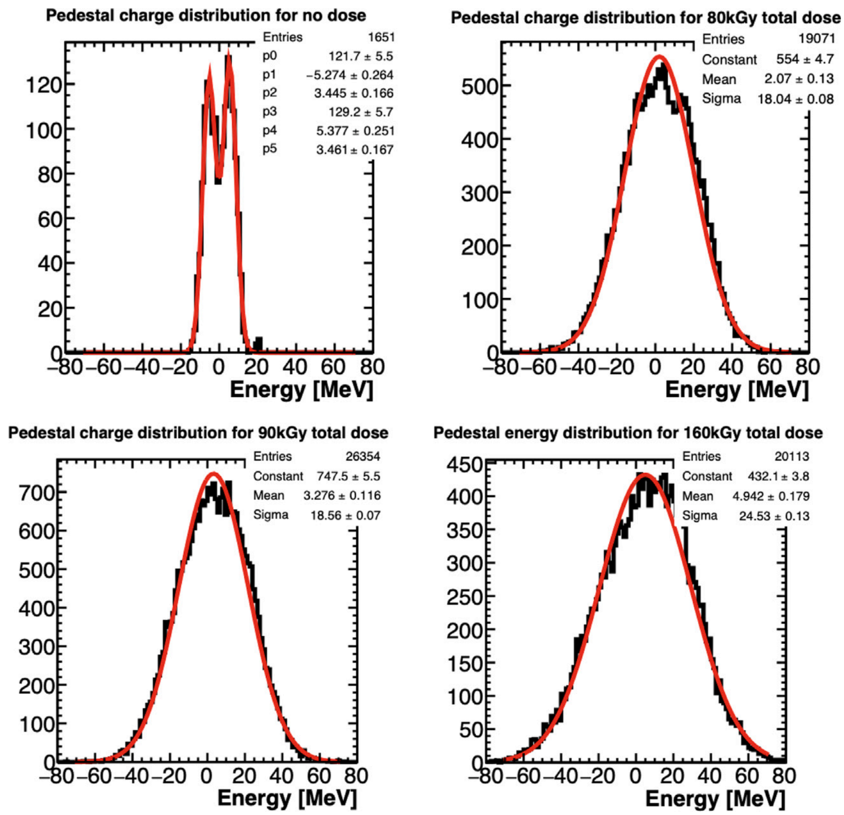

Fig. 5. SiPM pedestals for the no-dose, 80 kGy, 90 kGy, 160 kGy cases. The evident widening of the σ testifies the increase of dark current with the absorbed dose.

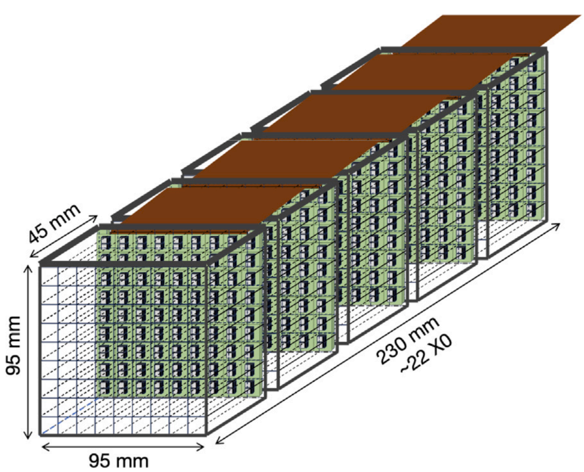

Fig. 6. Sketch of the final prototype embedding 5 layers of 9 × 9 crystal matrices.

the challenges posed by beam-induced backgrounds (BIB) while offering improved performance and cost-effectiveness. Its unique semi-homogeneous design, employing a series of matrices of high-density crystals and Silicon Photon-Multipliers (SiPMs), has demonstrated excellent time resolution and energy measurement accuracy in both simulations and experimental validations. The prototypes of the Crilin calorimeter have shown that it can achieve a timing resolution of less than 45 ps and maintain good energy resolution in the presence of BIB. Recent beam tests have highlighted great time resolutions (better than 45 ps for energy deposit greater than 1 GeV) but also areas for further investigation, particularly interesting is the light yield loss in crystals due to radiation exposure. The observed variability in crystal response, damage to Teflon wrapping, and increased SiPM dark counts emphasize the need for further studies. The Crilin calorimeter represents a significant step forward in calorimeter technology, offering a high-performance, cost-effective solution for the future Muon Collider. A significant milestone awaits in 2025 when a substantially larger prototype, covering 2 Molière Radii, 22 radiation lengths, and 1 interaction length, will be developed, marking a significant advancement in the calorimeter design.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Ivano Sarra reports financial support was provided by EU Horizon 2020 Research and Innovation Programme. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This work was developed within the framework of the International Muon Collider Collaboration (https://muoncollider.web.cern.ch), where the Physics and Detector Group aims to evaluate potential detector R&D to optimize experiment design in the multi-TeV energy regime. This work was supported by the EU Horizon 2020 Research and Innovation Programme under GrantAgreements No. 101006726 and No. 101004761.

The authors thank the LNF Division Research and ENEA NUC-IRAD-GAM Laboratory for their technical and logistic support. They also thank the BTF staff for providing the beam time and helping them get a smooth running period.

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