Frascati Physics Series Vol. 76 (2024)
8TH YOUNG RESEARCHERS' WORKSHOP 'PHYSICS CHALLENGES IN THE LHC ERA'
May 13 and 16, 2024

CHARACTERIZATION AND IRRADIATION STUDY FOR THE CRILIN ELECTROMAGNETIC CALORIMETER

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Abstract

The Crilin calorimeter is an innovative calorimetric system, specifically designed and optimized for use in the environment of a future Muon Collider. It employs a unique semi-homogeneous architecture, consisting of stackable and interchangeable matrices of lead fluoride (PbF_2) crystals, which serve as high density Cherenkov radiators. These crystals are read out by surface-mount UV-extended Silicon Photomultipliers (SiPMs). This design enables the discrimination of beam-induced backgrounds (BIB) present at a Muon Collider from genuine physics events by leveraging the excellent time resolution (below 50 ps), longitudinal segmentation, and high granularity. The paper describes Crilin and its timing performance for its latest prototype, Proto-1, based on a beam test conducted at CERN-H2 with 120 GeV electrons. Additionally, the results from a recent beam test at the LNF Beam Test Facility with 450 MeV electrons are presented, focusing on measurements of light yield losses due to γ-ray irradiation.

1 Introduction

The Muon Collider [1], proposed by the International Muon Collider Collaboration (IMCC), is a next-generation particle accelerator aimed at exploring high-energy physics. By colliding muons, it offers advantages over traditional electron-positron and hadron colliders. Unlike protons, muons are point-like particles, so there is no presence of quantum chromodynamics backgrounds; also, their larger mass implies that there are less synchrotron radiation losses compared to the electrons case. This enables higher collision energies in a compact design, ideal for probing new energy scales. A multi-TeV Muon Collider would enable the study of Higgs interactions, dark matter, and allow for unprecedented precision testing of the Standard Model.

Despite these promising prospects, the Muon Collider faces several challenges. In terms of detectors, the primary concern is beam-induced backgrounds (BIB), which consist of secondary and tertiary particles produced by interactions between muon decay products and machine elements. Specifically, for each bunch crossing, the electromagnetic calorimeter (ECAL) experiences a BIB flux of 300 particles per cm^2, primarily consisting of photons (96%) with an average energy of 1.7 MeV, and neutrons (4%). This background not only affects the detector's energy resolution but, over years of operation, can cause damage to the ECAL itself. A FLUKA simulation at $\sqrt{s} = 1.5$ TeV [2] estimated the Total Ionizing Dose (TID) and neutron fluence levels across the detector interface, predicting a yearly neutron fluence of 10^{14} n_{1MeV}/cm^2 and a TID of 1 kGy/year for the ECAL barrel region.

A CALICE-like tungsten-silicon (W-Si) sampling calorimeter [3] was initially considered as the baseline ECAL design, however this technology, though beneficial, is complex and costly. This paper presents an alternative: the Crilin electromagnetic calorimeter [4], featuring a longitudinally-segmented, semi-homogeneous design based on PbF_2 Cherenkov crystals read out by UV-extended SiPMs. This design allows for achieving fine granularity (with 1×1 cm^2 cells), excellent timing (below 50 ps), good pileup capability, and improved radiation resistance.

2 Crilin Calorimeter Design and Performance

The Crilin calorimeter employs a modular architecture consisting of stackable and interchangeable sub-modules, composed of matrices of high density crystals. Each crystal is independently read out by two electronics channels, consisting of a series of two UV-extended surface mount SiPMs.

This semi-homogeneous design combines the benefits of homogeneous calorimeters, particularly their improved energy resolution, with the addition of longitudinal segmentation and greater flexibility.

2.1 Design Features

In order to meet the Muon Collider's requirements, Crilin needs to achieve a timing resolution of under 100 ps. This is crucial for separating fake showers caused by BIB from actual physics signals, for which the time of arrival on the ECAL surface is synchronous with respect to bunch crossing. Its fine granularity, with a cell size of 10×10 mm^2, helps separate the energy deposited by BIB from that deposited by high-energy particles by reducing the number of hits in each cell. The overall design includes five layers, each 45 mm long (comprising 40 mm crystals and 5 mm for the readout), providing longitudinal segmentation that is essential for identifying and rejecting fake showers caused by BIB.

In order to have a compact geometry and to achieve fast light response, the design employs dense Cherenkov radiators, i.e. PbF_2 [5], or alternatively $PbWO_4$-UF [6] scintillating crystals. These materials have shown good radiation resistance, with no significant losses in transmittance after exposure to TID of up to 350 kGy (PbF_2) and 2 MGy ($PbWO_4$-UF) [7]. Additionally, the chosen SiPM model (Hamamatsu S14160-3010PS, 10 μm pixel size) has been validated for TID up to 10 kGy and neutron fluence up to 10^{14} n_{1MeVeq}/cm^2 [7].

Compared to the 40 layers found in a W-Si calorimeter, Crilin's design is expected to utilize just five layers: this drastically reduces the number of readout channels and overall costs by about 90%. The significant reduction in complexity and expense, along with its design flexibility, makes Crilin an appealing alternative for use in future collider experiments.

2.2 Performance Evaluation

The Crilin design has been extensively tested through simulations and experiments, demonstrating highly promising performances.

Proto-1, which consists of two layers of 3×3 crystal matrices with 36 readout channels in total, showed excellent timing resolution and strong agreement with Monte Carlo simulations in terms of energy deposition. For research and development purposes, Proto-1 tested two different methods of connecting the readout channels for each crystal: in the first layer, the SiPMs were connected in series, and in the second layer, they were connected in parallel. Both layers were read out using custom Front End Electronics. In August 2023, the timing performance of Proto-1 was evaluated at CERN's SPS H2 beamline using a 120 GeV electron beam. The time differences between the two channels of the same crystal were measured, focusing on the central crystal - which experiences the highest energy deposits - for each layer. For both the series and parallel connections (fig.1), the time resolution was less than 40 ps for energy deposits exceeding 1 GeV, demonstrating performance well within the Muon Collider's stringent requirements.

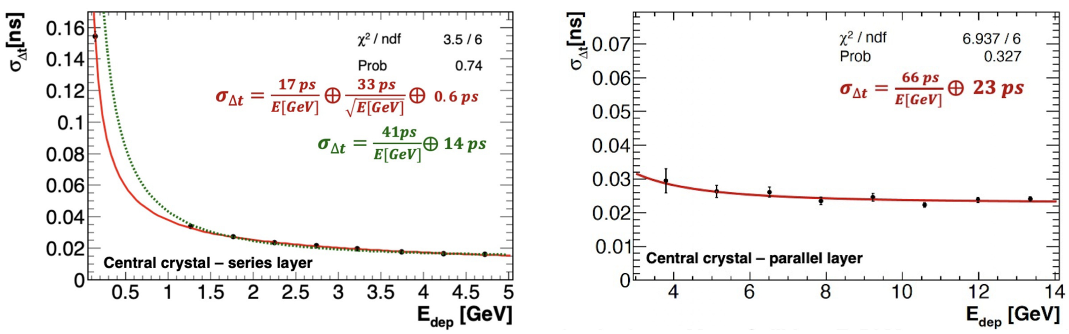

Figure 1: *Proto-1 time resolution as a function of the energy deposit in the most energetic crystal of the layer, for the series read-out module (left panel) and the parallel read-out module (right panel). For the series layer, a time resolution measurement with a 450 MeV electron beam was added and included in the solid-red line fit.*

2.3 Radiation Resistance Evaluation

In April 2024 a final test beam on Proto-1 was performed at the Frascati Beam Test Facility (BTF), in order to observe light yield loss due to exposure to high levels of ionising γ-ray radiation. The chosen TID of 80 kGy corresponds to about eight times the total expected ionising dose for the full duration of the Muon Collider experiment. The choice of such a high radiation rate was made in order to test the limits of the Crilin technology within a large safety margin.

The BTF 450 MeV electron beam (with particle multiplicity per bunch set to 1) was fired on each crystal of the series layer, before and after irradiation from a ^{60}Co source, studying the light response in terms of charge. Crystals were individually wrapped in a reflective material (both Teflon and Mylar were tested). The experimental steps are reported in tab.1.

The light yield loss was evaluated by looking at the variation in charge and number of photoelectrons:

$$N_{pe} = \frac{Q}{e \cdot G_{FEE} \cdot G_{SiPMs}}, \quad (1)$$

where e is the fundamental charge and G_{FEE} and G_{SiPMs} are the gain of the Front End Electronics and the SiPMs, respectively. The results in terms of N_{pe} variation are summarized in fig.2.

Table 1: *Beam test experimentation steps for radiation resistance evaluation. For each of these steps, the charge response for each crystal was evaluated.*

Step	Wrapping	TID on PbF_2 [kGy]	TID on SiPMs [kGy]
I	Teflon	-	-
II	Teflon	80	80
III	Mylar	-	80
IV	Mylar	10	90
V	Mylar	80	160

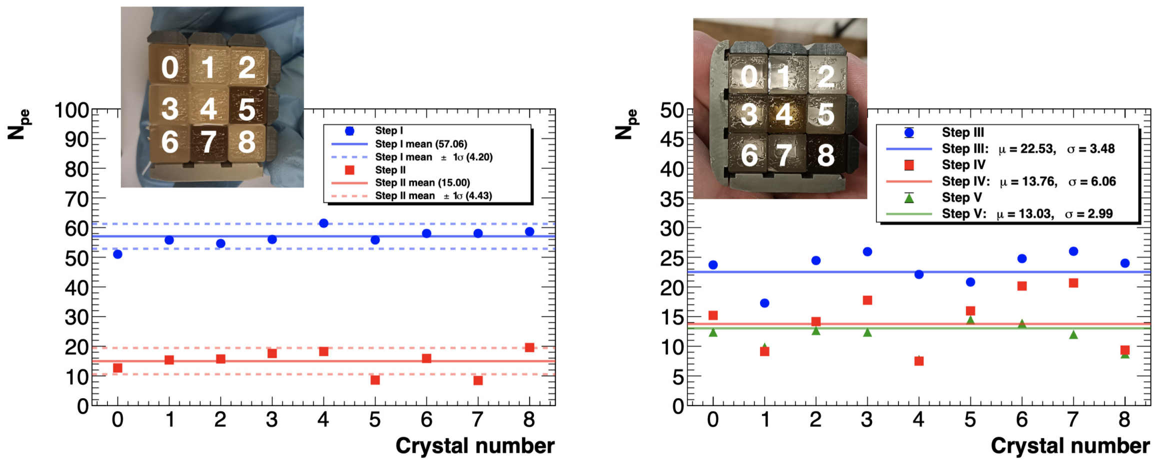

Figure 2: *Left panel: number of photo-electrons estimated for each crystal in the runs with Teflon wrapping (steps I and II). Right panel: number of photo-electrons estimated for each crystal in the runs with Mylar wrapping (steps III, IV and V). The μ and σ of the distributions were obtained by a Gaussian fit of the data points. For both cases, a picture of the crystal matrix after the test was included to show the visible transmittance loss and the crystal enumeration choice.*

In addition to demonstrating adequate operation at lower energies after exposure to extreme TID, this test revealed several noteworthy characteristics of the prototype's components. One key finding was the significant variation in the crystals' response to TID, despite the manufacturer's claim of using high-purity ($> 99.9\%$) PbF_2 powders in the crystal growth process. Additionally, the Teflon wrapping around the crystals showed signs of damage, becoming brittle over time, which led to the decision to switch to Mylar wrapping, even if it is less effective at reflecting UV light produced by Cherenkov radiation. Lastly, the SiPM dark current increased substantially with the absorbed radiation dose, as illustrated in fig.3, indicating that the radiation had a non negligible effect on the SiPMs' performance.

Further testing is required to gain a clearer understanding of these effects, which cannot be only attributed to the crystals' transmittance loss. Future irradiation sessions will involve closely monitoring the crystal-SiPM systems and the SiPMs individually using a blue laser. This approach will help to distinguish between two key factors: the Photon Detection Efficiency degradation in the SiPMs and the reduction in transmittance through the crystals. By isolating these contributions, the tests aim to better identify the root causes of performance decline and determine how each component is affected by radiation.

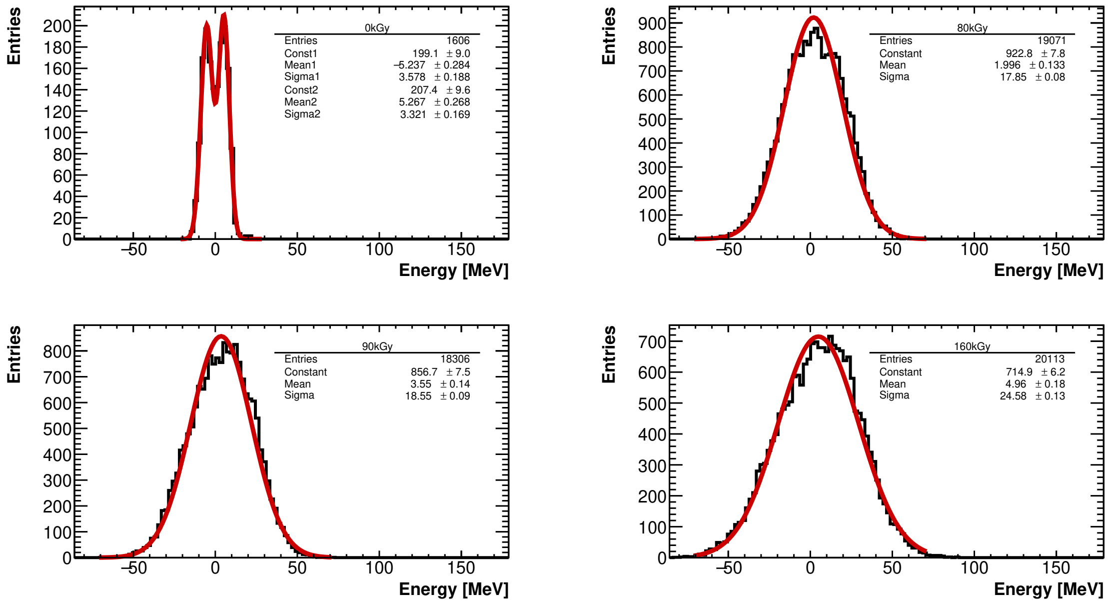

Figure 3: *SiPMs pedestals for read-out channel 11 for different datasets: step I (top left), step II (top right), step IV (bottom left) and step V (bottom right). The dose rates reported in the histograms refer to the SiPM board. The widening of the energy distribution is associated with the increase in SiPM dark counts as the absorbed radiation dose increases.*

3 Conclusions

The Crilin calorimeter offers a promising alternative to traditional sampling calorimeters for the future Muon Collider, effectively addressing the challenges posed by BIB while providing enhanced performance and cost efficiency. Its innovative semi-homogeneous design, consisting of high density crystal matrices read out by SiPMs, has demonstrated impressive time resolution and accurate energy measurements in both simulations and experimental tests.

In recent tests, Proto-1, the two-layer prototype of the Crilin calorimeter, achieved time resolutions better than 40 ps for energy deposits above 1 GeV. Additionally, the latest radiation resistance studies conducted on the prototype have revealed areas requiring further investigation, particularly concerning light yield reduction in the crystals due to TID. Variability in crystal performance, deterioration of the Teflon wrapping, and increased dark counts in the SiPMs were all observed, underscoring the need for additional studies to fully understand and mitigate these issues.

Overall, Crilin marks an advancement in calorimeter technology, offering a high-performance and cost-effective solution for future collider experiments. A key milestone is set for 2025, with the development of a significantly larger prototype that will cover 2 Molière radii and 22 radiation lengths, representing a further step for the calorimeter's R&D.

4 Acknowledgements

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 de-

tector 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 Grant Agreements No. 101006726 and No. 101004761.
The author thanks the LNF Division Research and ENEA NUC-IRAD-GAM Laboratory (Casaccia R.C.) 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. In the end, the author thanks their thesis advisors Ivano Sarra and Elisa Di Meco as well as the organizers of the LNF 'Bruno Touschek' Summer School for the opportunity to present this work.

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