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Crilin: a semi-homogeneous crystal calorimeter for the muon collider

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The Crilin calorimeter introduces a new concept in the development of electromagnetic calorimeters for future colliders, particularly for a Muon Collider. It is based on a unique semi-homogeneous design, using stackable, interchangeable matrices of lead fluoride (PbF_2) crystals employed as high-density Cherenkov radiators, read out by surface-mount UV-extended Silicon Photo-multipliers. This structure allows reducing the beam-induced backgrounds (BIB) present at a Muon Collider, while maintaining excellent time resolution (below 50 ps), longitudinal segmentation, and high granularity. Both simulated and experimental results show the Crilin design as a promising, efficient, and cost-effective alternative to conventional electromagnetic calorimeters proposed for future colliders. The paper also discusses Crilin's radiation tolerance, based on multiple irradiation campaigns, and reports on its timing performance during a beam test at CERN-H2 with 120 GeV electrons for the latest prototype, Proto-1. Additionally, the results of a recent beam test at the LNF Beam Test Facility with 450 MeV electrons are presented, focusing on measuring light yield losses due to irradiation in a setup mimicking the experimental operations.

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1. Introduction

A Muon Collider [1] has been proposed by the International Muon Collider Collaboration (IMCC) as a future collider in the energy frontier. In general, lepton colliders allow cleaner physics analysis, for the absence of partonic effects and quantum chromodynamics backgrounds. Unlike electrons, muons produce significantly less synchrotron radiation, allowing for more energy-efficient acceleration to high-energy. However, the short lifetime of muons complicates the accelerating chain and the storage ring operation, and their decay products inside the detector-machine interface produce large Beam-Induced Backgrounds (BIB), which stand as a significant challenge for detector systems. In particular, through the surface of the electromagnetic calorimeter (ECAL), BIB generates a flux of 300 particles per cm^2, consisting predominantly in photons (96%), with an average energy of 1.7 MeV, and neutrons (4%). This background therefore not only deposits energy in the detector at the same time of the bunch crossing, worsening the energy resolution, but also, when integrated in the years-long Muon Collider operation, damages the ECAL itself. For this reason, 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) (1 kGy/y) and neutron fluence ($n_{1\mathrm{MeV}}/\mathrm{cm}^2/y$) expected on the ECAL barrel region.

The baseline choice as ECAL for a Muon Collider was initially leaning towards a CALICE-like W-Si sampling calorimeter [3]. Despite its benefits, this technology is quite complex and expensive. This paper introduces the Crilin longitudinally-segmented electromagnetic calorimeter [4], featuring a unique semi-homogeneous design, based on Cherenkov PbF_2 crystals readout by UV-extended SiPMs. This design allow achieving fine granularity (with 1×1 cm^2 cells), excellent timing (below 50 ps), good pileup capability, and improved radiation resistance. All these features go along with an excellent energy resolution in the background-free case, which, when the BIB is taken into account, reaches anyway sufficient values.

2. Crilin Calorimeter Design and Performance

The Crilin calorimeter design consists of a series of matrices of high-density crystals, each independently read out by two electronic channels connected to a series of two Silicon Photo-Multipliers (SiPMs). This semi-homogeneous design brings together the advantages of homogeneous calorimeters, foremost the enhanced energy resolution, with longitudinal segmentation and flexibility.

2.1 Design Features

In order to fullfill the Muon Collider requirements, Crilin should show a timing resolution below 100 ps, essential for distinguishing fake showers induced by BIB from physics signals. The fine granularity, with a cell area of $10 \times 10\,\mathrm{mm}^2$, helps to disentangle between the energy deposited by BIB and by high-energetic particles, by decreasing the hit density in each cell. The overall design incorporates five layers of 45 mm length (40 mm crystals and 5 mm readout), providing longitudinal segmentation, which is crucial to veto fake showers due by BIB.

Crilin's design, including only five layers, compared to 40 layers of a W-Si calorimeter, significantly reduces the number of channels and associated costs by a factor of about 10. This reduction in complexity and cost, combined with the flexibility 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 showed no significant decrease in transmittance after exposure to Total Ionizing Doses (TID) of up to 350 kGy, while $PbWO_4$-UF crystals can cope with TID up to 2 MGy [7]. In addition to the crystals, also the SiPMs have been tested for radiation hardness. In particular, the chosen model, i.e., Hamamatsu S14160-3010PS (with a 10 μm pixel size), have shown a minor increases in dark current after a neutron fluence up to 10^{14} $n_{1\text{MeV-eq}}/cm^2$ and a TID up to 10 kGy, with respect to the Hamamatsu S14160-3015PS model (with a 15 μm pixel size), as shown in [7], confirming that they have a proper resistance to be employed in a Muon Collider ECAL.

2.2 Performance Evaluation

The Crilin design has undergone extensive simulation and experimental validations, showing promising performances. Simulations show an energy resolution of $\sigma_E/E \approx 4.8\%/\sqrt{\text{E(GeV)}} \oplus 0.2\%$ for photons. This performance is competitive with traditional sampling calorimeters, as the ones proposed for future colliders, and is naturally degraded by the BIB contribution reaching a sufficient resolution of $\approx 15\%/\sqrt{\text{E(GeV)}} \oplus 0.8\%$. Further optimization on the clusterisation algorithms is ongoing in order to better employ the longitudinal information to suppress fluctuations due to BIB. Results are summarised in Figure 1.

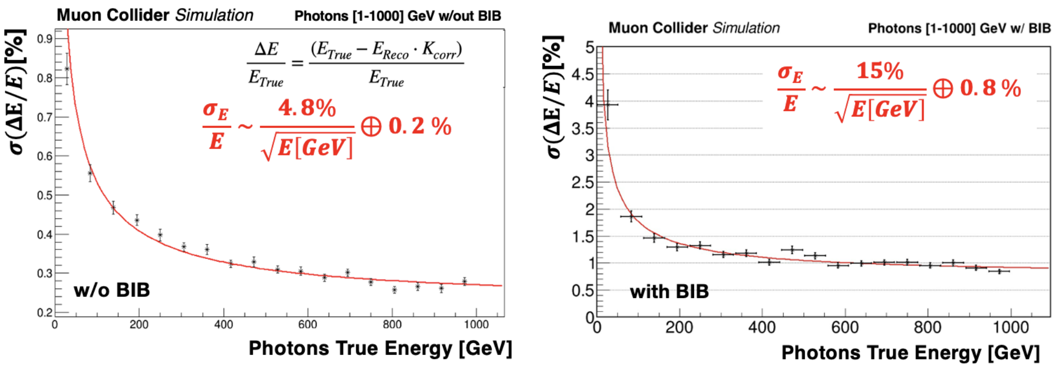

Figure 1: Energy resolution simulated in the Muon Collider framework with and without BIB contributions.

Two small prototypes have been developed and fully tested, to understand the timing and light collection properties: Proto-0, including two crystals and four channels, and Proto-1, embedding two layers of 3×3 crystal matrices, readout by a total of 36 channels, demonstrated excellent time resolution (in the order of 20 ps) and good agreement with Monte Carlo simulations from the point of view of energy deposition. For R&D purposes, in Proto-1 two different ways of connecting the two readout channels for each crystal were tested using the two different layers: the first layer had the SiPMs connected in series, the second one in parallel, both readout by a custom Front End Electronics 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 show the higher energy deposit). For the series and parallel layers (Fig. 2) the time resolution is less than 40 ps for energy deposits greater than 1 GeV.

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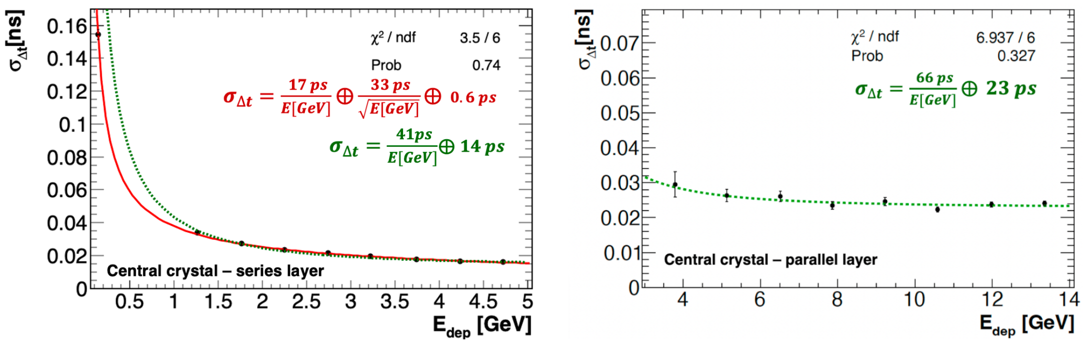

Figure 2: Time resolution as a function of the energy deposit in the most energetic crystal of the layer, for the series layer also a time resolution measurement with 450 MeV electron beam was added and included in the solid-red line fit.

The time resolution studied using the time difference between the two layers was also well within the requirements. Indeed, as shown with the Double Sided Crystal Ball fit in Figure 3, a $\sigma_{\Delta t}$ of 45 ps is found. Actually, this result is mainly dominated by the digitiser board synchronisation jitter, which was measured to be $O(32\,\mathrm{ps})$ for the board-to-board (layer-layer in this case) case and $O(10\,\mathrm{ps})$ for the channel-to-channel case.

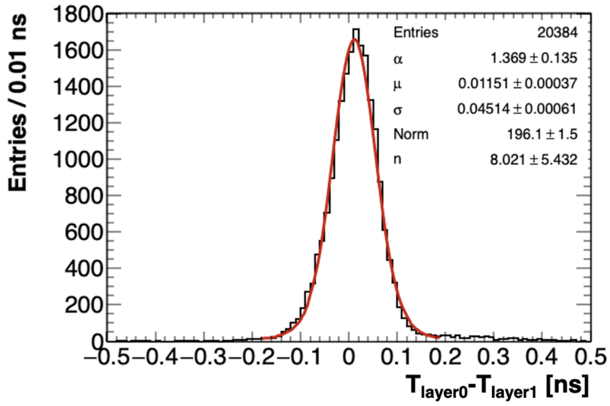

Figure 3: Time resolution for the time difference between the two most energetic crystals coming from different layers. A Double Sided Crystal Ball fit is applied and shows a resolution of 45 ps, mainly dominated by the digitiser board-to-board jitter.

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 γ-irradiation. The 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 with Co-60 γ rays, studying the light response in terms of charge. Crystals were tested with two different wrappings, i.e. Teflon and Mylar, reaching in both cases a TID up to 80 kGy, and the light yield (LY) loss was evaluated by looking at the variation in charge and number of photo-electrons: the results in terms of $N_{p.e.}$ variation are summarised in Figure 4.

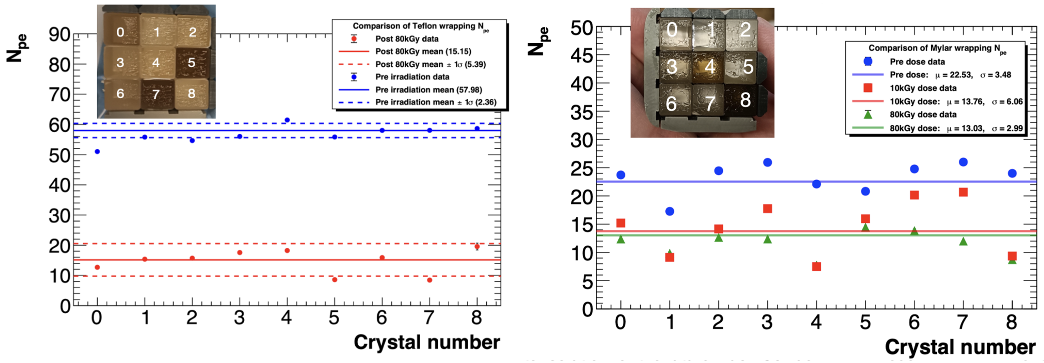

Figure 4: Variation of the number of photo-electrons after exposure to a TID up to 80 kGy with two different wrappings configuration, Teflon (top-panel) and Mylar (bottom-panel). For the Mylar case an intermediate LY measurement was performed at 10 kGy (green markers and line). For both cases a picture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

Despite showing a sufficient level of operation after exposure to extreme TID, this test also helped to observe several unexpected facts regarding the prototype components. Indeed, there is a considerable variability in crystals' response to TID, despite the vendor claim about the usage of high-purity (> 99.9%) PbF_2 powders for crystal growth. Moreover, the Teflon wrapping got damaged and brittle, motivating the choice of Mylar as wrapping, even if its reflection of UV light from Cherenchov radiation is inferior. Finally, SiPM dark current increased significantly with the absorbed dose, as shown in Figure 5.

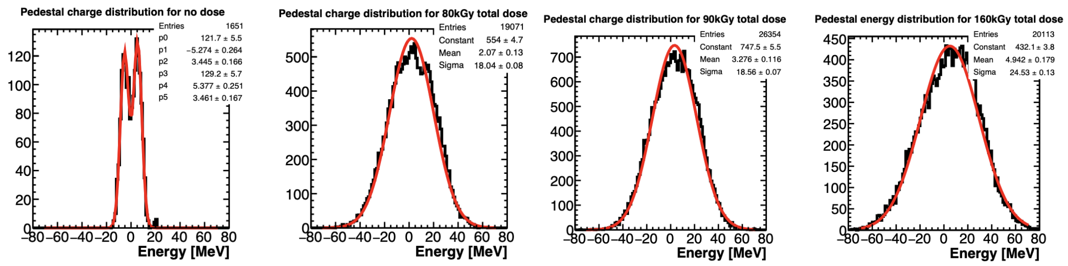

Figure 5: SiPM pedestals for the no-dose, 80 kGy, 90 kGy, 160 kGy cases. The evident change in the pedestals' widths shows the increase of dark current with the absorbed dose.

Further tests are needed to better understand these unexpected effects, which are more significant than the contribution coming only from the transmittance loss, and 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 photon detection efficiency (PDE) and transmittance loss.

2.3 Future prototype

A new prototype consisting of 6 layers of 7×7 crystal matrices will be fully developed, built, and tested during 2025, reaching 1.7 Molière Radii and 25.6 radiation lengths. The mechanics and electronics will be improved with respect to the Proto-0 and Proto-1 designs. An aluminum matrix with 200 μm thickness will keep the crystals in place, and a thicker (2 mm) external envelope will cool the prototype through micro-channels. Moreover, a micro-coaxial Kapton strip will provide

SiPM polarization and readout independently for each channel of two SiPMs in series, and an overall connector will be placed at the back of the 5 assembled modules. This final version will provide enough coverage to finely study the energy resolution performances together with the timing information.

3. Conclusions

The Crilin calorimeter stands as a promising alternative to traditional sampling calorimeters proposed for future colliders. It is, in particular, optimized for the future Muon Collider, addressing the challenges posed by beam-induced backgrounds (BIB), while allowing improved timing and cost efficiency. Its unique semi-homogeneous design, employing a series of matrices of high-density crystals interspaced by readout layers with Silicon Photon-Multipliers (SiPMs), has demonstrated excellent time resolution (below 45 ps) in beam tests and good energy resolution in simulations, even in the presence of BIB. Nonetheless, a beam test performed right after irradiation also showed unexpected effects. The observed variability in crystal response, damage to Teflon wrapping, and increased SiPM dark counts emphasize the need for further studies. Summarizing, the Crilin calorimeter represents a significant step forward in calorimeter technology, offering a high-performance, cost-effective solution for future colliders, and in particular for a Muon Collider. A significant milestone awaits in 2025 when a substantially larger prototype will be developed and built, covering 1.7 Molière Radii, 25.6 radiation lengths, and 1 interaction length, marking a significant advancement in the calorimeter design.

4. Acknowledgment

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