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Crilin: A novel calorimeter proposal for the $\sqrt{s} = 10$ TeV Muon Collider — Simulations and prototype tests results

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ABSTRACT

Among the Future Collider proposals the Muon Collider offers unique advantages for advancing research at the energy frontier. However, the beam induced background (BIB), from muon decays the collider ring, poses a significant challenge for detector design and event reconstruction. Despite the use of tungsten conical absorbers in the forward regions, an irreducible component of BIB enters the detector, characterized by low momentum and out-of-time arrival component respect the bunch crossing. The BIB flux on the barrel inner face of the electromagnetic calorimeter is about 300 particles per cm^2, with a total ionizing dose of 10 kGy/y and a neutron fluence of $10^{14}\,n_{1\ MeV}\,cm^{-2}\,y^{-1}$. To mitigate BIB effects, innovative solutions are needed. One promising development is Crilin (CRystal calorImeter with Longitudinal INformation), a semi-homogeneous electromagnetic calorimeter based on lead fluoride crystals (PbF_2) read by UV-extended silicon photomultipliers. This novel calorimeter proposal, featuring high granularity, longitudinal segmentation and excellent expected timing, offers the potential to mitigate BIB effects and achieve a high energy resolution (less than $10\%/\sqrt{E\,[\mathrm{GeV}]}$. This paper will present simulation results on the performance of Crilin and recent experimental test results from Crilin prototype, highlighting its potential in the challenging Muon Collider environment.

1. Introduction

Among the landscape of the future colliders proposals, the Muon Collider [1] stands out as one of the most promising next-generation facilities for high-energy physics. Proposed by the International Muon Collider Collaboration (IMCC) [2], it is designed to collide beams of muons and antimuons at multi-TeV center-of-mass energies. The use of muons in a collider introduces unique advantages compared to existing facilities. Due to their mass, approximately 200 times that of the electron, the energy losses from synchrotron radiation and beamstrahlung are negligible. This allows high center-of-mass energies within a circular geometry. Moreover, since muons are elementary particles, they provide clean collisions, with all the energy available in the interaction and without partonic effects or quantum chromodynamics (QCD) backgrounds, unlike hadron colliders. These characteristics make the Muon Collider both a precision and a discovery machine. However, collisions at the Muon Collider are significantly affected

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by an intense machine-induced background [3] resulting from muon decays. Due to their short lifetime, muons decay in flight along the accelerator ring, producing high-momentum secondary particles that interacting with the machine materials, can generate an intense flux of tertiary particles known as beam-induced background (BIB). Even with the implementation of conical tungsten absorbers, called nozzles, placed in the forward region of the detector around the beam pipe, a residual component of BIB particles still enters the detector volume, making event reconstruction particularly challenging. Dedicated simulation studies performed using the FLUKA software tool [4] have shown that BIB particles are primarily characterized by low momentum and a broad arrival time distribution with respect to the bunch crossing [3]. These features can be effectively exploited to mitigate their impact both through optimized detector design and advanced reconstruction techniques at the software level.

2. Electromagnetic calorimeter requirements

In order to fully exploit the broad physics potential of a $\sqrt{s}$ = 10 TeV Muon Collider [1], the electromagnetic calorimeter (ECAL) is a crucial subsystem of the detector. Its performance is essential for the precise reconstruction of final-state particles over a wide energy range, from low-energy Standard Model processes to high-energy signatures potentially indicating new physics. Given the unique experimental environment of a Muon Collider, characterized by the BIB, the ECAL must combine high-resolution measurements with robust background suppression capabilities. The main ECAL requirements for the Muon Collider detector are the following:

- **High energy resolution**, with a stochastic term better than $10\%/\sqrt{E\,[\mathrm{GeV}]}$ to enable precision measurements at low energies, and a minimal constant term to ensure good performance at the TeV scale.
- **Excellent arrival time resolution** $< 100\,\mathrm{ps}$ to filter out the out-of-time component of the BIB particles while preserving most of the signal.
- **High granularity** to minimize the overlap of BIB hits within the same ECAL cell, allowing for better separation between BIB and signal hits contribution.
- **Longitudinal segmentation** to distinguish electromagnetic showers from BIB particles with respect to the signal, based on their different longitudinal development.
- **Radiation Resistance** in order to maintain stable performance. In the ECAL barrel region, due to the BIB, the expected neutron fluence reaches $10^{14}\,\mathrm{n_{1MeV}/cm^2}$ per year, with an associated total ionizing dose of 10 kGy per year.

3. The Crilin calorimeter

To address the specific detector requirements for a $\sqrt{s}$ = 10 TeV Muon Collider, Crilin (Crystal Calorimeter with Longitudinal Information) [5] represents an innovative semi-homogeneous calorimeter based on crystals matrices interspaced and read out by surface-mounted UV-extended silicon photomultipliers (SiPMs). As illustrated in Fig. 1, the design features a modular architecture composed of stackable and interchangeable submodules, each consisting of high-density PbF_2 [6] crystal matrices. Each individual crystal cell has dimensions of $10 \times 10 \times 40\ \mathrm{mm}^3$ and is read out by a 2×2 matrix of SiPMs, grouped into two separate readout channels. The proposed calorimeter layout includes 6 crystal layers, reaching a total of approximately 26 radiation lengths (X_0) in depth. This configuration aligns with the key ECAL requirements outlined in the previous section. In particular, the Cherenkov light produced in the PbF_2 crystals enables the generation of fast signals, allowing the possibility to achieve excellent time resolution. Additionally, the small transverse size of the crystal cells, combined with the semi-homogeneous layered architecture, ensures both high granularity and effective longitudinal segmentation — features that are essential for accurate electromagnetic shower reconstruction and efficient background suppression.

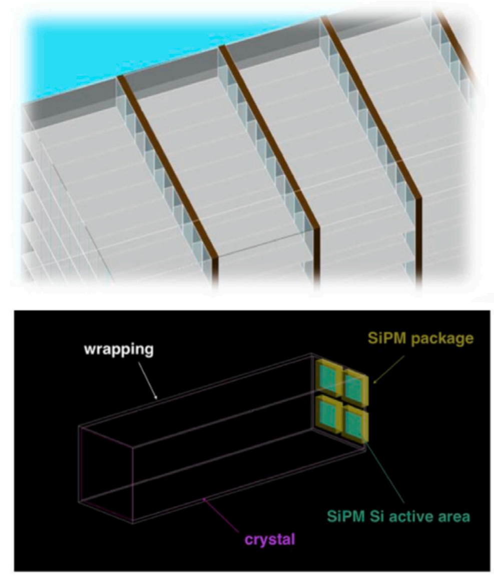

Fig. 1. Top: Schematic illustration of the Crilin calorimeter structure, showing the stacked crystal layers interleaved with SiPM readout planes. Bottom: Schematic representation of a single crystal cell, highlighting the SiPM configuration.

4. Performance evaluation

The performance of the Crilin calorimeter has been evaluated through dedicated simulation studies and experimental test campaigns. In particular, detailed simulations within the Muon Collider software framework [1] were conducted by fully integrating Crilin into the detector geometry. An energy resolution of $\sigma_E/E = 4.8\%/\sqrt{E\,[\mathrm{GeV}]} \oplus 0.2\%$ was achieved for a photon sample with energies ranging in [1, 1000] GeV. This result is competitive with those of conventional sampling calorimeters and confirms the promising intrinsic performance of Crilin. A degradation in energy resolution was observed when the contribution of the BIB is included, leading to a stochastic term of $\approx 10\%/\sqrt{E[\mathrm{GeV}]}$. This preliminary result is based on a non-optimized clustering algorithm. Further studies are currently ongoing to refine the reconstruction strategy and enhance the performance from background contamination. On the experimental side, intensive test campaigns were performed, based on two preliminary prototypes of Crilin: Proto −0 and Proto −1 [7]. Proto −0 represents the first and simplest prototype version, consisting of two crystals arranged in a single layer. In contrast, Proto −1 features a more advanced configuration with two layers of 3×3 crystal matrices. In particular Proto −1 was also designed to investigate two different readout configurations. In the first layer, the SiPMs associated with each crystal cell were connected in series, while in the second layer they were connected in parallel. Both configurations were read out by a custom front-end electronics system.

4.1. Radiation resistance

A first experimental test campaign was conducted to evaluate the radiation tolerance of the calorimeter's individual components and investigate different design options. For the CRILIN calorimeter, the baseline crystal material is PbF_2, with $PbWO_4$-UF considered as an alternative. To assess the radiation hardness of both crystal types, a total ionizing dose (TID) irradiation campaign was carried out at the ENEA Calliope facility using a ^{60}Co γ source [8]. Transmittance measurements were performed along the longitudinal axis of the crystals each with same dimensions. PbF_2 crystals exhibited no significant degradation in transmittance after a TID > 350 kGy. While the $PbWO_4$-UF crystals showed no observable transmittance degradation after a TID > 2 MGy.

Regarding the SiPMs radiation hardness, a dedicated experimental test was performed at the Frascati Neutron Generator (FNG-ENEA) facility, using 14 MeV neutrons with a fluence of up to 10^{14} $n_{1\text{MeV}/cm^2}$. The dark current was measured before and after irradiation for two different SiPM models featuring different pixel sizes: 15 μm (SMD S14160-3015PS) and 10 μm (SMD S14160-3010PS). Results indicate that the 10 μm pixel SiPMs are the more suitable choice for CRILIN, as they exhibit a significantly lower increase in dark current after irradiation.

4.2. Crystal light-yield loss

To further characterize the PbF_2 crystals, a dedicated test beam campaign was carried out at the Beam-Test Facility of the Laboratori Nazionali di Frascati (BTF-LNF) with the aim to study the light yield (LY) loss after a γ-irradiation. A 450 MeV electron beam with single-particle multiplicity was used to scan one 3 × 3 crystal matrix of the Proto −1 prototype, more specifically just the first layer with the series SiPM connection. For each crystal, the charge deposition was measured both before and after irradiation, up to a TID of 80 kGy. Fig. 2 presents the measured LY variation after irradiation for two different crystal wrapping materials: Teflon and Mylar. The LY degradation was evaluated by analyzing variations in the collected charge and the number of photoelectrons. From this test it was observed:

- a marked variability in the response of the crystal to radiation, despite vendor claims of high-purity (≥ 99.9%) PbF_2 powders used in crystal growth;
- a uniform transparency loss along the longitudinal axis of the crystal after irradiation;
- a Teflon wrapping became damaged and brittle after irradiation, suggesting that Mylar may be a more reliable option, despite its lower reflectivity for UV Cherenkov light;
- a SiPM dark current increased significantly with absorbed dose.

Additional tests are planned to further investigate these unexpected effects, which appear to be more pronounced than what can be attributed solely to transmittance loss. Future irradiation campaigns will include dedicated monitoring using a blue laser to separately evaluate the response of the crystal-SiPM system and the SiPMs alone, with the goal of disentangling the contributions from photon detection efficiency (PDE) degradation and transmittance reduction.

4.3. Time resolution

Timing performance is one of the key aspects of the Crilin calorimeter and was assessed through a dedicated test beam campaign conducted at the CERN SPS-H2 beamline using a 120 GeV electron beam on the Proto −1 prototype. The time resolution was evaluated by measuring time differences between the two layers of Proto −1 as well as between channels within individual crystals. The analysis focused on the central crystal of the 3 × 3 matrix, which typically receives the highest energy deposits. As shown in Fig. 3, both the series- and parallel-connected SiPM configurations of the Proto −1 layers demonstrated a time resolution better than 40 ps for energy deposits exceeding 1 GeV. The time resolution achieved using the time difference between the two most energetic crystals from different layers was well within requirements. As shown in Fig. 4, a double sided crystal ball fit yielded a $\sigma_{\Delta t}$ of 45 ps, primarily dominated by digitizer board synchronization jitter, measured to be O(32 ps) for board-to-board cases and O(10 ps) for channel-to-channel cases.

5. The new prototype

A new Crilin prototype, currently under construction will consist of 5 layers of 7 × 7 PbF_2 crystal matrices. Compared to the previous prototypes Proto −0 and Proto −1, this version significantly extends the detector volume, reaching a depth of approximately 22 X_0 and a transverse size corresponding to about 1.7 Molière radii. To accommodate this larger and more complex configuration, a dedicated mechanical support structure has been developed. The crystals will be housed in a aluminum matrix with 150 μm of thickness, enclosed within a thicker (2.5 mm) external frame. This envelope will integrate a microchannel-based cooling system to ensure stable operation of the

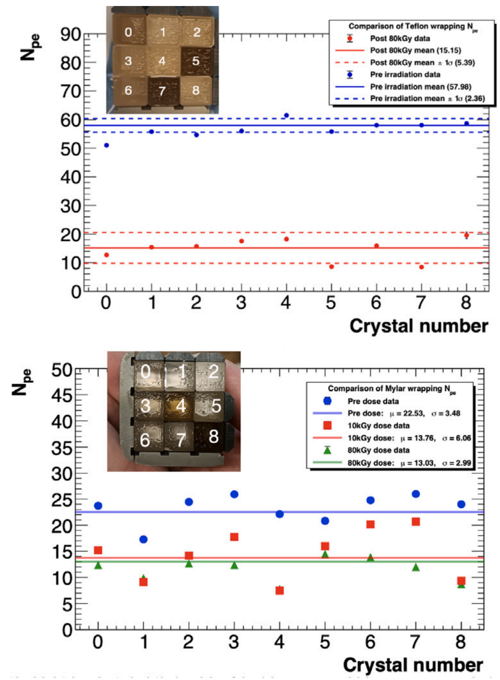

Fig. 2. Measured variation in photoelectron yield following irradiation up to a TID of 80 kGy, for crystals wrapped in Teflon (top) and Mylar (bottom). In the Mylar configuration, an intermediate measurement was taken at 10 kGy (green markers and line). A degradation in optical transmittance is also evident.

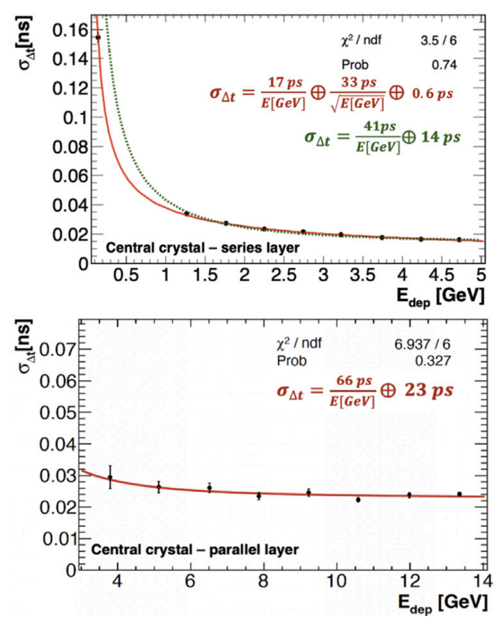

Fig. 3. Time resolution as a function of the energy deposited in the most energetic crystal. The upper plot refers to the series-connected layer of Proto −1 and includes a data point from a 450 MeV electron beam measurement (fit shown as a solid red line). The lower plot shows the corresponding results for the parallel-connected layer.

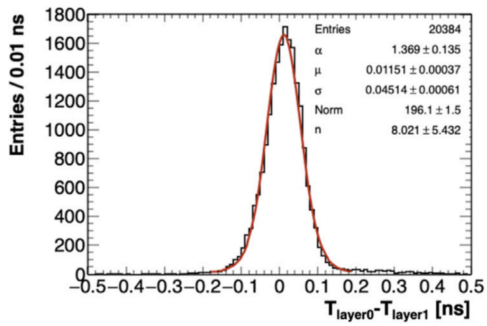

Fig. 4. Timing resolution obtained from the time difference between the two most energetic crystals located in separate layers. A Double-Sided Crystal Ball fit returns a value of 45 ps, with the dominant contribution attributed to the synchronization jitter between digitizer boards.

readout electronics. The front-end electronics have also undergone a significant upgrade. Moreover, a micro-coaxial Kapton strip will provide SiPM polarization and readout independently for each channel of two SiPMs in series. Thanks to its larger dimensions, this new prototype will enable more comprehensive performance studies. In particular, a new test campaign scheduled for 2025 will allow for the evaluation of the energy resolution, as well as further detailed investigations of the timing performance.

6. Conclusions

The Crilin calorimeter represents a compelling and innovative alternative to traditional sampling calorimeters for future collider experiments. Specifically optimized for the challenging experimental environment of a Muon Collider, it addresses the stringent requirements for timing, granularity, and radiation hardness imposed by the beam-induced background, while also aiming for improved cost-effectiveness. Its semi-homogeneous architecture – based on high-density PbF_2 crystal matrices alternated with SiPMs readout layers – has demonstrated excellent timing performance (below 45 ps) in test beams and promising energy resolution in detailed simulation studies, even under BIB conditions. However, dedicated irradiation campaigns have revealed several unexpected effects, including variability in the crystal response post-irradiation, an important degradation of the Teflon wrapping, hence further investigations are needed. In conclusion, the Crilin calorimeter represents a significant advancement in calorimetry development, offering a high-performance and scalable solution tailored for future high-energy colliders, particularly suitable for the Muon Collider detector. An important step forward is expected in 2026 with the construction and testing of a new larger prototype, featuring 1.7 Molière radii, 22 radiation lengths. This new configuration will enable more extensive performance assessments and final design optimization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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