RD_Mucol/LNF 2024

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The Muon Collider [1] is envisioned as a future high-energy physics facility, capitalizing on the distinctive characteristics of muons. Compared to electrons, muons emit considerably less synchrotron radiation, enabling more efficient high-energy collisions. However, their limited lifetime and decay products introduce significant Beam-Induced Backgrounds (BIB), posing a considerable challenge for detector technologies, particularly for the electromagnetic calorimeter (ECAL). In the ECAL region, simulations indicate a particle flux of approximately 300 particles per cm^2, predominantly photons (96%) and neutrons (4%), with an average photon energy of 1.7 MeV. The presence of BIB results in a demanding operational environment for the Muon Collider. To quantify radiation effects, a FLUKA simulation at $\sqrt{s} = 1.5$ TeV was performed to estimate the Total Ionizing Dose (TID) and neutron fluence across the detector interface. In the ECAL barrel region, the expected neutron fluence reaches 10^{14} $n_{1\mathrm{MeV}}/\mathrm{cm}^2$ per year, with an associated total ionizing dose of 1 kGy per year.

A W-Si sampling calorimeter inspired by the CALICE design was initially considered as a reference technology. Despite its advantages, this option involves significant complexity and cost. As an alternative, the Crilin calorimeter [2] is introduced in this study. This semi-homogeneous crystal calorimeter offers a cost-effective yet high-performance solution, specifically designed to mitigate the challenges associated with BIB in the Muon Collider environment.

1 Crilin Calorimeter: Concept and Key Characteristics

The Crilin calorimeter is being explored as a potential solution for the electromagnetic calorimetry requirements of a future Muon Collider. It utilizes an array of high-density crystal matrices, where each unit is read independently by two channels, each integrating a pair of Silicon Photo-Multipliers (SiPMs). This semi-homogeneous architecture provides notable advantages, including precise timing, fine granularity, longitudinal segmentation, resilience to radiation, and cost-effectiveness.

1.1 Structural Design and Optimization

To comply with the stringent demands of the Muon Collider, the Crilin calorimeter is designed to achieve a timing resolution below 100 ps, crucial for mitigating Beam-Induced Backgrounds (BIB) and isolating physics signals. The fine spatial resolution, defined by a cell size of $10 \times 10\,\mathrm{mm}^2$, enables efficient separation of background events from actual particle interactions, reducing occupancy per channel.

The calorimeter comprises five detection layers, each 45 mm in length (40 mm for the crystal and 5 mm for the readout system), ensuring effective longitudinal segmentation. This segmentation is essential for distinguishing and suppressing spurious showers originating from BIB. Compared to a conventional W-Si calorimeter, which typically requires 40 layers, the Crilin design reduces the number of readout channels and associated electronics by a factor of 10. This optimization results in a more compact and cost-efficient detection system, making it an attractive candidate for future collider experiments.

1.2 Material Selection and Radiation Hardness

The Crilin calorimeter relies on radiation-resistant crystals, such as PbF_2 [4] and $PbWO_4$-UF [5], which have demonstrated stable performance under high radiation exposure. PbF_2 crystals retain their optical transmittance after exposure to Total Ionizing Doses (TID) up to 260 kGy, as tested at the Calliope gamma Facility (ENEA NUC-IRAD-GAM Laboratory). $PbWO_4$-UF crystals, on the other hand, withstand doses up to 1.5 MGy [3][1].

In addition to crystal selection, SiPMs have undergone extensive radiation qualification. Hamamatsu S14160-3010PS SiPMs, with a 10 μm pixel size, exhibit only a minor increase in dark current when subjected to a neutron fluence of 10^{14} $n_{1\text{MeV-eq}}/\text{cm}^2$ and a TID of 10 kGy. This performance surpasses that of the S14160-3015PS model with a 15 μm pixel size, confirming their suitability for prolonged operation in a high-radiation environment. Given the anticipated radiation levels at the Muon Collider—approximately 1 kGy/year TID and a neutron fluence up to 10^{14} $n_{1\text{MeV-eq}}/\text{cm}^2$—the use of radiation-hard materials is essential to ensure the longevity and reliability of the calorimeter system.

1.3 Performance Evaluation

The Crilin ECAL has undergone extensive simulation and experimental validation, demonstrating promising performance. Simulations indicate an energy resolution of $\sigma_E/E \approx 4.8\%/\sqrt{E} \oplus 0.2\%$ for photons. This result is competitive with traditional sampling calorimeters, exhibiting good calorimetric properties, although naturally degraded by the BIB contribution, leading to a resolution of approximately $15\%/\sqrt{E}$. Further optimization of the clustering algorithms is ongoing to better exploit the longitudinal information and suppress fluctuations due to BIB. Figure 1 summarizes these results.

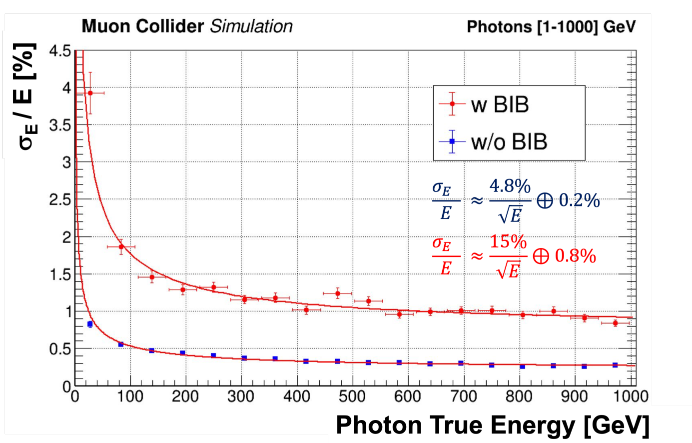

Figure 1: Simulated energy resolution in the Muon Collider framework with and without BIB contributions.

[1]Dose values measured in air.

Two preliminary prototypes have been developed and tested. Proto-0 [6], featuring two crystals and four channels, and Proto-1, integrating two layers of a 3×3 crystal matrix read out by 36 channels, demonstrated excellent time resolution (on the order of 20 ps) and good agreement with Monte Carlo simulations, validating the design's performance. For R&D purposes, two different SiPM circuit configurations were tested: the first layer had two readout channels per crystal connected in series, while the second layer had them connected in parallel. In August 2023, Proto-1's timing performance was evaluated with a 120 GeV electron beam at CERN-SPS H2, testing different configurations by measuring time differences between the two layers and between channels within the same crystals. The central elements of the matrix, where the highest energy deposits occur, were analyzed. As shown in Figure 2, for both the series and parallel layers, the time resolution remained below 40 ps for energy deposits greater than 1 GeV.

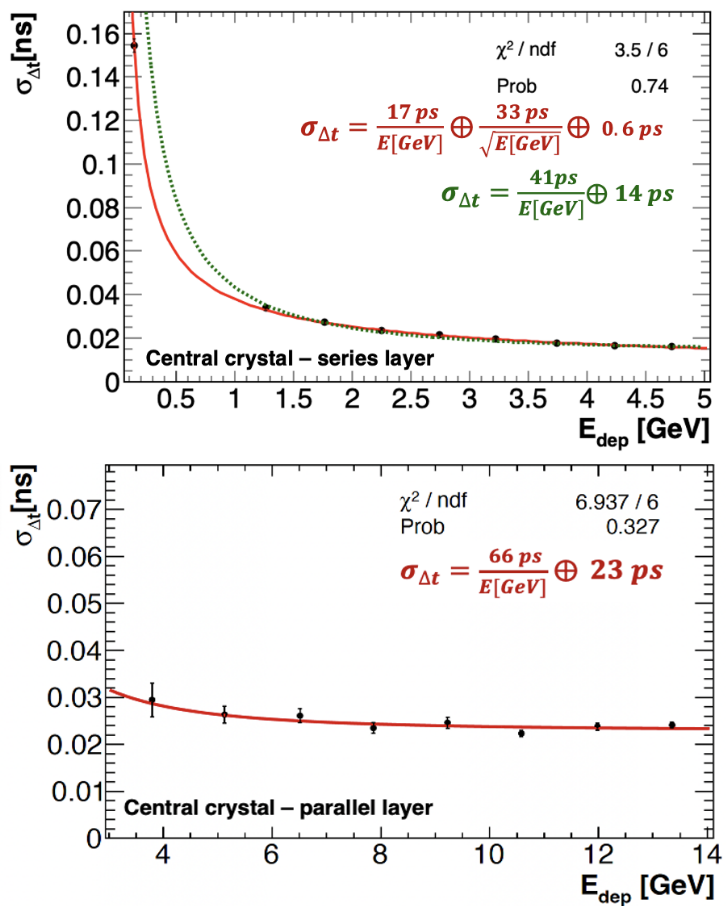

Figure 2: Time resolution as a function of the energy deposited in the crystal with the highest energy deposit. A time resolution measurement with a 450 MeV electron beam was added for the series layer (solid red line fit).

The time resolution achieved using the time difference between the two most energetic crystals from different layers was well within requirements. As shown in Figure 3, a Double Sided Crystal Ball fit yielded a $\sigma_{\Delta t}$ of 45 ps, primarily dominated by digitizer board synchronization jitter, measured to be $\mathcal{O}(32\,\text{ps})$ for board-to-board cases and $\mathcal{O}(10\,\text{ps})$ for channel-to-channel cases.

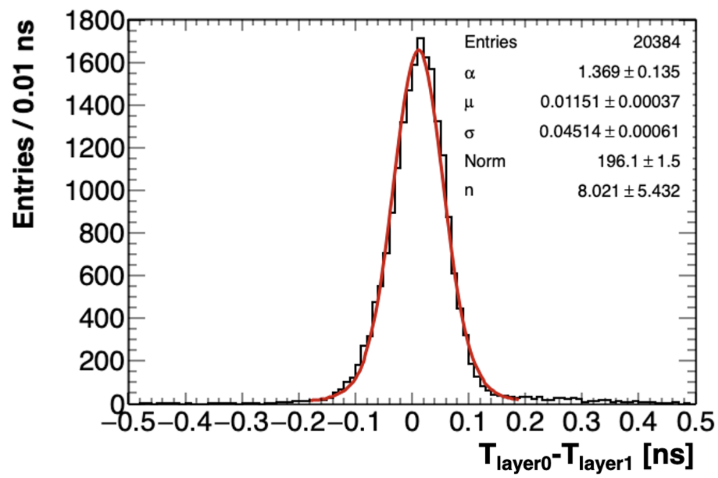

Figure 3: Time resolution for the time difference between the two most energetic crystals from different layers. A Double Sided Crystal Ball fit yields a resolution of 45 ps, mainly dominated by digitizer board-to-board jitter.

In April 2024, a final Proto-1 test was conducted at the Frascati Beam Test Facility (BTF) to systematically study light yield loss due to γ-irradiation. A 450 MeV electron beam with single-particle bunches was used to center the beam on each crystal of the series layer before and after irradiation, measuring charge deposition. Crystals were tested with two different wrappings—Teflon and Mylar—each subjected to a total ionizing dose (TID) of up to 80 kGy. Light yield (LY) loss was evaluated by analyzing variations in charge and the number of photoelectrons. Figure 4 summarizes the $N_{p.e.}$ variations.

This test provided critical insights into the prototype's components:

- Significant variability was observed in crystal response to radiation, despite vendor claims of high-purity ($> 99.9\%$) PbF_2 powders used in crystal growth.
- Crystals exhibited noticeable transparency loss, appearing uniform along the longitudinal axis.
- Teflon wrapping became damaged and brittle, indicating that Mylar should be preferred, despite its suboptimal reflectivity for UV Cherenkov light.
- SiPM dark counts increased significantly with absorbed dose: pedestals for the no-dose (3 MeV ENE[2]), 80 kGy (18 MeV ENE), and 160 kGy (24 MeV ENE) cases show a significant widening of the σ, indicating an increase in dark current with the absorbed dose.).

Further studies are required to better understand these effects, which appear to be more significant than those attributable solely to transmittance loss. Future irradiation tests will include monitoring the response of the crystal-SiPM system with a blue laser and isolating SiPMs to disentangle the contributions of photon detection efficiency (PDE) and transmittance loss.[3]

[2]Equivalent Noise Energy.

[3]Photon Detection Efficiency (PDE) of a SiPM is the product of quantum efficiency, fill factor, and Geiger probability, typically ranging from 20% to 50%, depending on wavelength and design.

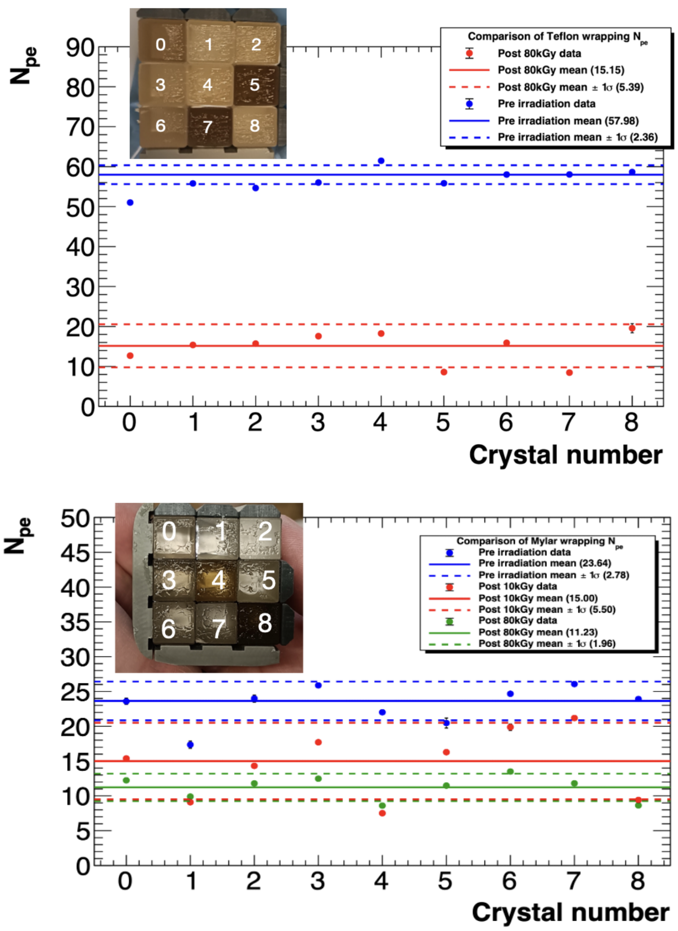

Figure 4: Variation in the number of photoelectrons after exposure to a TID of up to 80 kGy with two different wrapping configurations: Teflon (top) and Mylar (bottom). For Mylar, an intermediate LY measurement was performed at 10 kGy (green markers and line). Crystal transmittance loss is also visible.

1.4 New Prototype

A new prototype consisting of five layers of 7×7 crystal matrices will be fully developed, built, and tested during 2025, reaching 2 Molière Radius, 22 radiation lengths.

The mechanics and electronics will have significant changes compared to the previous prototypes. An aluminum matrix with 150 µm thickness will hold the crystals, and a thicker (2.5 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 five assembled modules. A sketch of the final Crilin version is shown in Figure 5. This final version, featuring a total of 2 M_R and 22 X_0, will provide enough coverage to finely study the energy resolution performances together with the timing information.

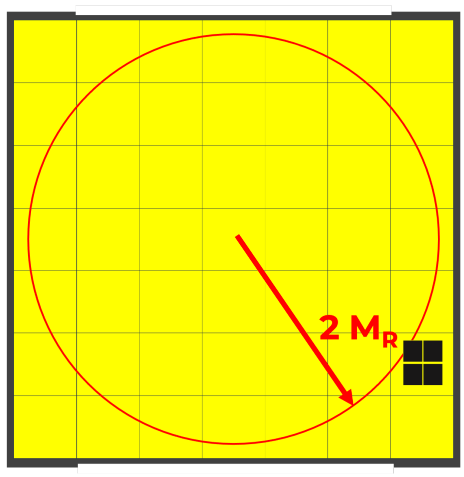

Figure 5: Sketch of the final prototype embedding five layers of 7×7 crystal matrices.

2 Thesis

- V. L. Ciccarella, "Characterization and irradiation studies for the Future Muon Collider electromagnetic calorimeter", master thesis at the Università degli Studi La Sapienza.

3 List of Conference Talks/Posters by LNF Authors in the Year 2023

1. V. L. Ciccarella, Characterization and Irradiation study for the Crilin Electromagnetic Calorimeter, XXI LNF Spring School "Bruno Touschek" in Nuclear, Subnuclear and Astroparticle Physic, Frascati, IT.
2. V. L. Ciccarella, Characterization and Irradiation study for the Crilin Electromagnetic Calorimeter, 110th SIF (Italian Physical Society) National Congress, Bologna, IT.
3. R. Gargiulo, Crilin: a semi-homogeneous crystal calorimeter for the muon collider, ICHEP2024, Prague, JP.
4. R. Gargiulo, Higgs self-coupling possibilities at multi-TeV muon collider, HIGGS 2024, Uppsala, SE.
5. E. Di Meco, Developing an alternative calorimeter solution for the future Muon Collider: the Crilin design, 16th PISA MEETING ON ADVANCED DETECTORS, Elba, IT.
6. E. Di Meco, Poster: Detector design for a 10 TeV Muon Collider, 16th PISA MEETING ON ADVANCED DETECTORS, Elba, IT.
7. I. Sarra, Advancements in Muon Collider Calorimetry: Design, Testing, and Radiation Resistance of the Crilin Calorimeter Prototype, CALOR2024, Tsukuba, JP.

4 Publications

- R. Gargiulo, Vittoria Ciccarella, Elisa Di Meco, Eleonora Diociaiuti and Ivano Sarra. "Development of a sub-mm particle tracking detector based on a plastic scintillator with SiPM charge sharing", JINST 19 (2024) 12, T12006. DOI: https://doi.org/10.1088/1748-0221/19/12/T12006.

- C. Cantone, et al., ”Crilin: a semi-homogeneous crystal calorimeter for the muon collider”, PoS ICHEP2024 (2025) 1113. DOI: https://doi.org/10.22323/1.476.1113.
- A. Cemmi, et al., ”The CRILIN calorimeter: gamma radiation resistance of crystals and SiPMs”, JINST 19 (2024) 10, P10016. DOI: https://doi.org/10.1088/1748-0221/19/10/P10016.
- C. Cantone, et al., ”Developing an alternative calorimeter solution for the future Muon Collider: The Crilin design”, Nucl.Instrum.Meth.A 1069 (2024) 169973. DOI: https://doi.org/10.1088/1748-0221/19/10/P10016.
- C. Cantone, et al., ”Research and Development Status for an Innovative Crystal Calorimeter for the Future Muon Collider”, IEEE Trans.Nucl.Sci. 71 (2024) 5, 1116-1123. DOI: https://doi.org/10.1109/TNS.2024.3364771.
- C. Cantone, et al., ”Research and Development Status for an Innovative Crystal Calorimeter for the Future Muon Collider”, IEEE Trans.Nucl.Sci. 71 (2024) 5, 1116-1123. DOI: https://doi.org/10.1109/TNS.2024.3364771.

References

1. C. Accettura et al., *Towards a Muon Collider*, Eur. Phys. J. C (2023) 83: 864; DOI: `https://doi.org/10.1140/epjc/s10052-023-11889-x`.
2. S. Ceravolo et al., *Crilin: A CRystal calorImeter with Longitudinal InformatioN for a future Muon Collider*, JINST 17 P09033 (2022); DOI: `10.1088/1748-0221/17/09/P09033`.
3. C. Cantone et al., *R&D status for an innovative crystal calorimeter for the future Muon Collider*, IEEE Transactions on Nuclear Science PP(99):1-1 (2024); DOI: `10.1109/TNS.2024.3364771`.
4. A. Cemmi et al., *The CRILIN calorimeter: gamma radiation resistance of crystals and SiPMs*, JINST 19 P10016 (2024); DOI: `10.1088/1748-0221/19/10/P10016`.
5. M. Korzhik. et al., *Ultrafast PWO scintillator for future high energy physics instrumentation*, Nucl. Instrum. Meth. A 1034 (2022); DOI: `10.1016/j.nima.2022.166781`.
6. C. Cantone et al., *Beam test, simulation, and performance evaluation of PbF2 and PWO-UF crystals with SiPM readout for a semi-homogeneous calorimeter prototype with longitudinal segmentation*, Frontiers in Physics 11 (2023); DOI: `10.3389/fphy.2023.1223183`.