

Crilin: CRystal calorImeter with Longitudinal Information for a future Muon Collider

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Abstract. In modern experiment, a high granularity is required in order to distinguish signal particles from background and to solve the substructures necessary for jet identification. Time of arrival measurements in the calorimeter could play an important role in HL-LHC, since a high number of pile-up collisions is expected, and the timing could be used to assign clusters to the corresponding interaction vertex. In a Muon Collider, the timing could be used to remove signals produced by beam-induced background, asynchronous with respect to the bunch crossing. The calorimeter energy resolution is also fundamental to measure the kinematic properties of jets: a finely segmented calorimeter design should be favored in order to solve the jet substructure. However, this contrasts with the requirement for high timing resolution even for signal events involving low energy deposits, such as in the case of high impulse muons. Our proposed design, the Crilin calorimeter, is a semi-homogeneous calorimeter based on Lead Fluoride (PbF₂) Crystals readout by surface-mount UV-extended Silicon Photomultipliers (SiPMs). In this paper, the development of a small prototype consisting of 2 layers of 3 × 3 crystals each is reported along with the relative results.

1. Introduction

Calorimeters are generally divided in two categories, homogeneous and sampling. The best compromise between the two technologies is sought in order to optimize experimental requirements and minimize the drawbacks associated with the limitations of standard solutions. The most recent technological developments allow this rigid distinction to be abandoned in favour of novel architectures: the Crilin calorimeter is a semi-homogeneous calorimeter based on Lead Fluoride (PbF₂) crystals readout by surface mounted UV extended Silicon Photomultipliers (SiPMs). The Crilin calorimeter can be segmented longitudinally as a function of the energy of the particles and of the background level, thanks to its modular design which enables a high degree of reconfigurability. The Crilin R&D proposal embeds a modular architecture based on stackable submodules composed of matrices of crystals, in which each crystal is individually readout by 2 series of 2 UV-extended surface mount SiPMs. Crystal dimensions are 10 × 10 × 40 mm³ and the surface area of each SiPM is 4 × 4 mm², so as to closely match the crystal surface.



1.1. Radiation environment and radiation damage

Modern HEP experiments are associated with harsh radiation environments, due to the rising need for higher intensities. This sets the minimum performance requirements to be guaranteed by the Crilin calorimeter. In the case of a future Muon Collider [1], the requirements relative to the barrel electromagnetic calorimeter (EMC) involve a 1 Mrad total ionising dose (TID) and a 10^{12} n_{1MeV}/cm² equivalent neutron fluence. Our goal is to satisfy all stated requirements with the design and development of Crilin.

2. Crystals Characterization

The characterization campaign of PbF₂ crystals was started in February 2021 at the National Laboratories of Frascati. The crystals, produced by SICCAS, have a 40 mm length, with 5×5 mm² square faces. After the evaluation of the light yield, two crystals were used to evaluate the radiation hardness of PbF₂, by comparing their transmittance before and after irradiation. The latter was carried out with either photons or neutrons. The totality of the crystals used for the irradiation tests were randomly selected from the main production batch of the Crilin prototype, so as to guarantee consistent results with the final instrument.



Figure 1. The two PbF₂ crystals used during the characterization. Left: Al Mylar wrapping. Right: “Naked” crystal.

Transmittance measurements were performed before and after each irradiation run. Crystals were irradiated both at Calliope Facility of ENEA Casaccia [2] using photons from ⁶⁰Co and at the Frascati Neutron Generator (FNG) facility of ENEA Frascati [3] using 14 MeV neutrons. Longitudinal transmission spectra were acquired for each crystal as a function of the wavelength λ in the 210 - 700 nm range, with 1 nm steps. The transmittance of the three crystal specimens was measured using a PerkinElmer Lambda 950 UV/VIS dual beam spectrometer. The longitudinal transmittance obtained at each step of irradiation is reported in Figure 2. After a 30 krad dose exposure, a significant deterioration in transmittance can be seen for wavelengths below 300 nm, along with an almost constant 25% drop for wavelengths above 300 nm. A transmission recovery of 10% is observed at 350 nm after one day of natural annealing in the dark. Any further deterioration of the transmittance after a TID approximately equal to 20 Mrad is completely negligible, indicating a saturation effect associated with the damage mechanism. This is especially true for crystals wrapped with Mylar.

After the irradiation phase, the crystals were kept in a dark box to allow natural recovery, as described in [4]. A transmission recovery of 15% is observed above 300 nm after 18 days of natural annealing since irradiation. After this, crystals were irradiated with neutrons at FNG. In about 1 hour and 30 minutes of irradiation with 14 MeV neutrons, a total 10^{13} n/cm² fluence was delivered to the first 1 cm segment of the crystals, while SiPMs received a fluence of 5×10^{11} n/cm². The gamma flux associated with the irradiation process resulted in a (negligible) 1 Gray TID for crystals.

The main effect on SiPMs associated with neutron fluence is represented by an increase in the dark current. The ratio of the leakage currents, after and before the irradiation with 9×10^{11} n_{1MeV}/cm² on SiPMs is 11 mA / 2 μ A = 6000, evaluated at the nominal bias point (41.35 V per SiPM, 82.7 V per

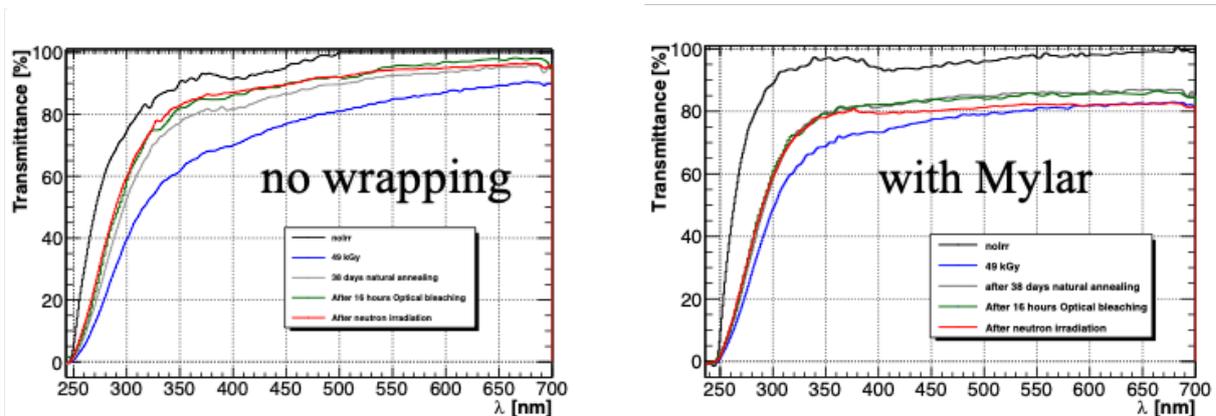


Figure 2. Longitudinal transmission at different steps of irradiation for “naked” crystal (left) and Mylar wrapped crystal (right).

series). The expected leakage current for a 0 °C operating point is less than 1 mA per series, compatible with our mechanical and electrical specifications.

In order to carry out a preliminary evaluation of the light yield, the energy response of PbF_2 to cosmic rays was measured using a single crystal ($10 \times 10 \times 40 \text{ mm}^3$), optically coupled - by means of UV clear optical grease - with two $4 \times 4 \text{ mm}^2$ SiPMs connected in a series configuration. The crystal was wrapped with a single layer of 100 μm thick Mylar foil. For this test, the polarization of the SiPMs series was performed using a TTi PLH250-P power supply, and a custom transimpedance amplifier, providing an equivalent 250 charge gain, was used to amplify the light pulses. Thanks to the high gain of the amplifier, the charge associated with a single photoelectron could be measured, as shown in Figure 3-left. This value was used to scale the Minimum Ionizing Particles (MIP) charge response, shown in Figure 3-right, and thus to determine the relative number of photo-electrons. MIP acquisitions were performed in self triggering mode and the charge distribution was fitted with a Landau distribution. From our Monte Carlo simulations, the MPV corresponding to an energy loss of $dE/dx = 11 \text{ MeV}$ was evaluated, from which, in turn, a light yield of 6 p.e./MeV is derived.

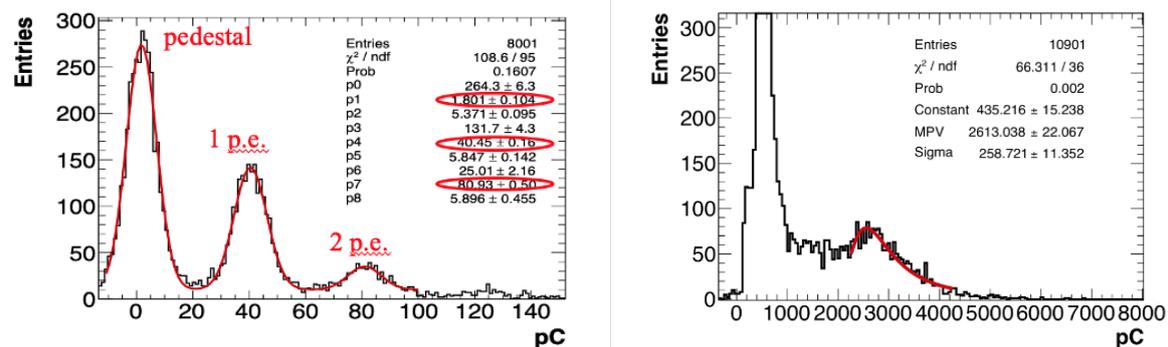


Figure 3. Charge in pC corresponding to 1 and 2 photo-electrons in randomly gated acquisitions of the SiPMs series dark counts (left). Response to cosmic rays in self triggering mode: measured charge response for MIPs (right).

3. Module-0

In order to validate the design choices relative to the opto-electronic, mechanical and cooling architecture of the calorimeter, a small scale prototype with 2 crystals and 4 amplification channels, the Module-0. In Figure 4, the rendering of the two-channel front-end board prototype with 8 SiPMs and 2 crystals is shown.

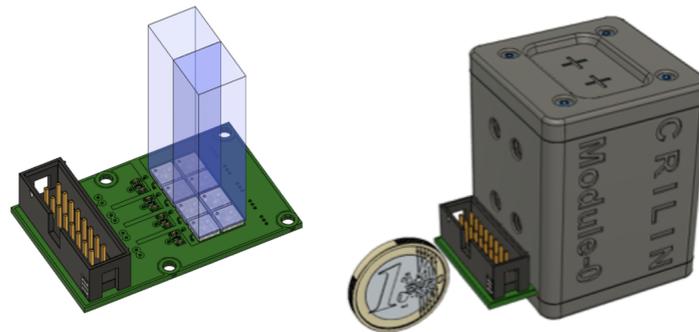


Figure 4. Rendering of the two-channel front end board prototype with 8 SiPMs and 2 crystals; crystals installed (left), Module-0 prototype (right).

At the moment of editing, the Module-0 production is ongoing. Three electronics boards have been realized at the end of May 2021. Alignment and parallelism of the SiPMs assembly have been verified via Coordinate Measuring Machine (CMM) at Laboratori Nazionali di Frascati (LNF) of INFN. The requirements are very stringent, as the overall misalignment due to SiPM placement and reflow procedures should be inferior to $100\ \mu\text{m}$. Test beams with electrons on this prototype are due in July 2021 at the new Beam Test Facility (BTF [5]) of LNF, along with studies using Cosmic Rays. The thus obtained results will drive the choice for the production of the final configuration and will be used to validate our electronics design. In figure 5 the assembling and first test of the module-0 are shown.



Figure 5. Assembling and first test of the Module-0.

4. Crilin Prototype

In the current design, the prototype consists of two submodules, each composed of a 3-by-3 crystals matrix. The submodules are arranged in a series and assembled together by screws, resulting in a compact and small calorimeter (Figure 6).

Each crystal matrix is housed in a light-tight case which also embeds the front-end electronic boards and the cooling system. The on-detector electronics and SiPMs must be cooled during operation, so as to improve and stabilise the performance of SiPMs against irradiation. Our design is capable of removing the heat load due to the increased photosensor currents after exposure to the expected $10^{12}\ \text{n}_1\text{MeV}/\text{cm}^2$

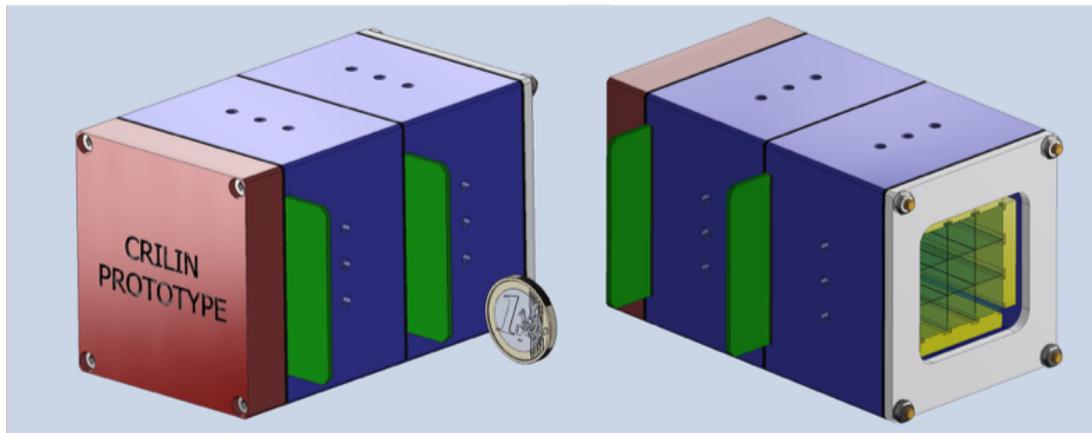


Figure 6. CAD model of Crilin Prototype.

fluence, along with the power dissipated by the amplification circuitry. The total heat load was estimated as 350 mW per channel. The Crilin cooling system, which is based on conduction and forced convection of nitrogen, will provide the optimum operating temperature for the electronics and SiPMs at around 0 °C . Gas fluxing will also prevent any condensation on SiPM or crystal surfaces.

5. Conclusion

The Crilin design wants to overcome the classic rigid distinction between homogeneous and sampling calorimeters, trying to establish a good compromise between the two in order to optimize the requirements in view of a future Muon Collider. Before the construction of the final prototype the single components were evaluated:

- Irradiation studies of Crystals and SiPMs are over and a dedicated paper will be submitted before the end of June 2021;
- A Module-0 has been assembled and a dedicated Test Beam is scheduled at BTF with 500 MeV electrons in July 2021.

A Crilin prototype, composed of 2 layers of 9 crystals each and operating at 0 °C , will be built before the end of the year (December 2021). Our goal is to test its performance with 500 MeV electrons at BTF and with a high energy beam (> 20 GeV) at CERN in 2022.

6. 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 detector RD to optimize experiment design in the multi-TeV energy regime.

The authors wish to thank the LNF Division Research and SPCM departments for their technical and logistic support and are grateful to the people in Enea Casaccia and Enea FNG facilities for their extensive collaboration during the irradiation campaign of crystals and photosensors.

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