RD_Mucol/LNF 2022

M. Boscolo, C. Cantone, F. Colao (Ass.), E. Di Meco (Laur.),
E. Diociaiuti (AdR), P. Gianotti, A. Liedl, M. Rotondo, I. Sarra

in collaboration with "LNF-SEA"
S. Ceravolo (Tec.)
in collaboration with "LNF-SPCM"
M. Arpaia (Tec.), T. Napolitano, A. Zossi (Tec.)

The Muon Collider is being proposed as a next-generation facility for accelerator physics experiments. It has unique advantages both with respect to hadron colliders, permitting exact knowledge of the initial state and free from QCD background, and with respect to e^+e^- colliders, because a Muon Collider can reach higher energies (due to very reduced beam bremsstrahlung) and can exploit the larger Higgs-muon Yukawa coupling. In particular, a Muon Collider can produce Higgs bosons in the s-channel with a 64 pb cross-section with negligible beam radiation losses.
However, a proton-driven Muon Collider has two points to solve: 1) cooling of muons and 2) neutrino radiation. Those points make this project not yet ready for implementation but the R&D is particularly interested to demonstrate its feasibility with a proof of principle. Moreover, the Muon Collider environment is not as clean as one might expect, since the presence of the beam-induced background (BIB), produced by the decay of muons and subsequent interactions, may pose limitations on the physics performance. Although the BIB can be partially mitigated by a proper design of the machine-detector interface, for instance using two shielding tungsten nozzles in the detector region, it poses requirements on the detector development.
The LNF group is involved in two major activities:

1. Muon pair production by annihilating positrons with electrons in a low Z material target (LEMMA).

2. The development of the barrel electromagnetic calorimeter Crilin.

1 Machine Studies Activity

Details of the activity could be found in References [1], [2], and [3].

2 Crilin Activity

BIB particles at a Muon Collider have a number of characteristic features: low momentum, displaced origin, and asynchronous time of arrival. The BIB flux has been simulated to be in the order of 300 γ/cm^2 on the surface of the electromagnetic calorimeter (ECAL), with the energy spectrum peaked at around 1.8 MeV. One of the most promising options for ECAL, proposed by the CALICE collaboration, is a sandwich of tungsten and silicon sensors that combines a mature technology with the possibility to implement fine segmentation. The derived ECAL barrel section designed for the Compact Linear Collider (CLIC), on which the current Muon Collider detector design is based, is composed of 64 million 5×5 mm^2 silicon sensors sampled with lead in 40 layers. Future developments should implement a precise timing measurement in these sensors (<100 ps) in order to make them usable at a Muon Collider. Although the high granularity is a clear advantage, the associated number of electronic readout channels is a nontrivial technological problem. Moreover, the cost of such a system exceeds the cost of other solutions. LNF group proposes a

cheaper alternative as an electromagnetic barrel calorimeter for the Muon Collider: Crilin, a semi-homogeneous crystal calorimeter with longitudinal information. Crilin has a modular architecture made of stackable and interchangeable sub-modules composed of matrices of lead fluoride (PbF_2) crystals, where each crystal is individually read out by two channels composed by the series of two UV-extended surface mount Silicon Photomultipliers (SiPMs) each. It can provide high response speed, good pileup capability, great light collection (hence good energy resolution) throughout the whole dynamic range, resistance to radiation, and fine granularity scalable with the transverse size of the crystals.
The longitudinal segmentation is crucial to distinguish signal showers from BIB. Adapting crystals' transverse and longitudinal dimensions to maximize the signal/background ratio, our goal is to achieve a similar or better performance than the silicon-tungsten ECAL proposed by CLIC. This, combined with a substantial reduction of the cost by an estimated factor of ten, could be a clear indication of the quality of our technology choice. First studies on ECAL crystal dimensions have shown that a basic configuration with $10\times10\times40$ mm^3 allows a good separation of BIB from the signal with O(5 GeV) energy deposit per crystal. In this regard, the choice of 10 μm pixels, with the measured Light Yield (LY) of 1 p.e./MeV would guarantee excellent linearity in the response. R&D work on Crilin is currently being carried out in synergy with other collaborations, facilitated in part by participation in the AIDAinnova research network. In particular, we are working together with S. Martellotti (INFN-LNF) and M. Moulson (INFN-LNF) in charge of the KLEVER Small Angle Calorimeter. Klever SAC is an independently proposed, highly granular, longitudinally segmented, fast crystal calorimeter with SiPMs readout and performance requirements similar to those for Crilin. The first test beam measurements with individual PbF_2 and PWO crystals were performed in the summer of 2021 at the Frascati BTF and the SPS North Area, followed by additional tests in fall 2022 in which some of the first commercially available samples of PWO-UF were also tested. These tests were focused on understanding the best possible time resolution that can be obtained, studying the systematics of light collection in the small crystals, and validating the Crilin choices of SiPMs and the design of the readout amplifier. In autumn 2022, a single cell prototype (Proto-0) composed by $10\times10\times40$ mm^3 crystals of PbF_2 (4.3 X0) and PWO-UF (4.5 X0) were exposed to the high-energy electron beam (60–120 GeV) at the SPS H2 beamline. Each crystal was viewed by a matrix of four Hamamatsu 14160-4010 SiPMs (4×4 mm^2, 10 μm pixel size), which were read out in pairs, providing independent readout channels for the left and right sides of the crystal. A timing resolution better than 50 ps has been achieved for energy deposits greater than 1 GeV, see Fig.1.

The data collected are currently being analyzed, but some preliminary conclusions are already apparent:

- The time resolution obtainable from the combination of either crystal, PbF_2, or PWO-UF, with the chosen SiPM and CRILIN electronics, is excellent, with the final time resolution expected to be significantly better than required for the KLEVER SAC.
- The light yield for PWO-UF is approximately twice that for PbF_2; the time resolution for PbF_2 is slightly better.
- For either crystal, the light produced is highly localized on the rear face of the short crystal, requiring some care with the segmented readout.
- The Crilin electronics performed very well; KLEVER should evaluate the possibility of faster shaping to obtain better double pulse discrimination.

In order to validate the design choices, we have built a larger prototype, called Proto-1, see Fig.2. The prototype has been designed by A. Saputi (INFN-Ferrara) and produced at CERN.

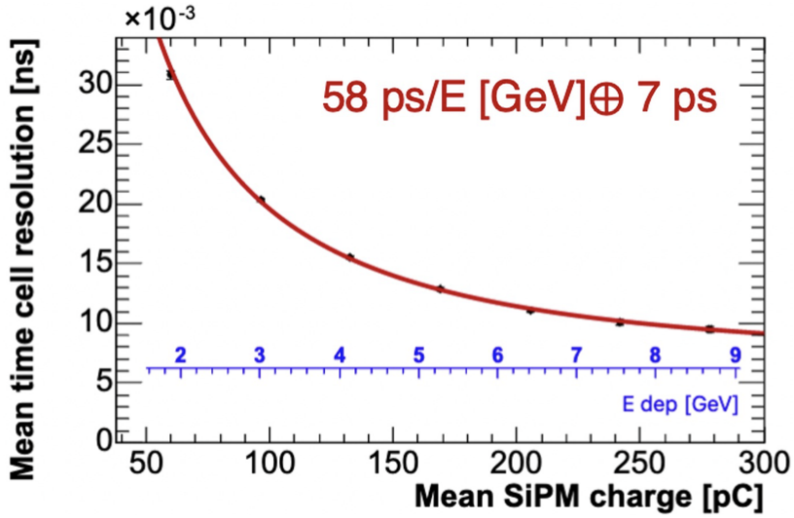

Figure 1: *Time resolution evaluated as the* σ *of* $\frac{T1-T0}{2}$ *distribution of the two SiPMs channels for seven charge slices.*

The design has been optimized with the simulation studies starting from dimensions of 0.7 M_R and 8.5 X0 ($\sim$ 0.3 λ_i). This size comes from a compromise of an acceptable containment of 100 GeV electrons and cost constraints. Results will be extrapolated to the optimum length of the Muon Collider calorimeter of the order of 20 X0. The proposal is to build Proto-1 with two layers of 3x3 PbF_2 crystals, each read out with UV-extended SiPMs (Hamamatsu S14160-3010 PS SMD sensors) as already done in Proto-0. These new SiPMs were already tested with an ultra-fast blue laser (400 nm, 100 ps) and the new electronics front-end (FEE) that showed a dynamic range from 0 to 2 V, a rise time of $\sim$ 2 ns with full signal in $\sim$ 70 ns and a time resolution less than 50 ps even at a charge as low as 100 pC ($\sim$ 250 Np.e.).

An extremely fast electronics has been developed by the LNF group with the collaboration of D. Tagnani (INFN-Roma3) and D. Paesani (PhD Mu2e) in 2022. Crilin's FE electronics are composed of two subsystems: the SiPM board (Figure 3, right) and the Mezzanine Board (Figure 3, left). The SiPM board houses a layer of 36 photo-sensors so that each crystal in the matrix is equipped with two separate and independent readout channels, the latter being composed of a series connection of two Hamamatsu S14160-3015PS SMD sensors. The 10 μm SiPM pixel size, along with the series connection of two photo-sensors, were selected for a high-speed response, short pulse width and to better cope with the expected total non-ionizing dose (TNID) without showing an unmanageable increase in bias current during operation. The series connection of two photo-sensors further contributes to achieving a high-speed response, by effectively halving the photo-sensor equivalent capacitance. A group of four 0603 SMD blue LEDs is installed on the SiPM board, nested between the photo-sensor packages. They will be driven by means of an external nanosecond pulse generator, to allow in-situ calibration, diagnostics, and monitoring for all photo-sensors in the matrix.

All bias voltages and SiPM signals for each readout channel are transported between the SiPM board and the Mezzanine Board by means of individual 50-ohm micro-coaxial transmission lines (Samtec ERCD-040-40.00-TEU-TED-1-D). Decoupling capacitors for each channel, along with a PT1000 temperature sensor, are also installed onboard.

The Mezzanine Board provides signal amplification and shaping, along with all slow control func-

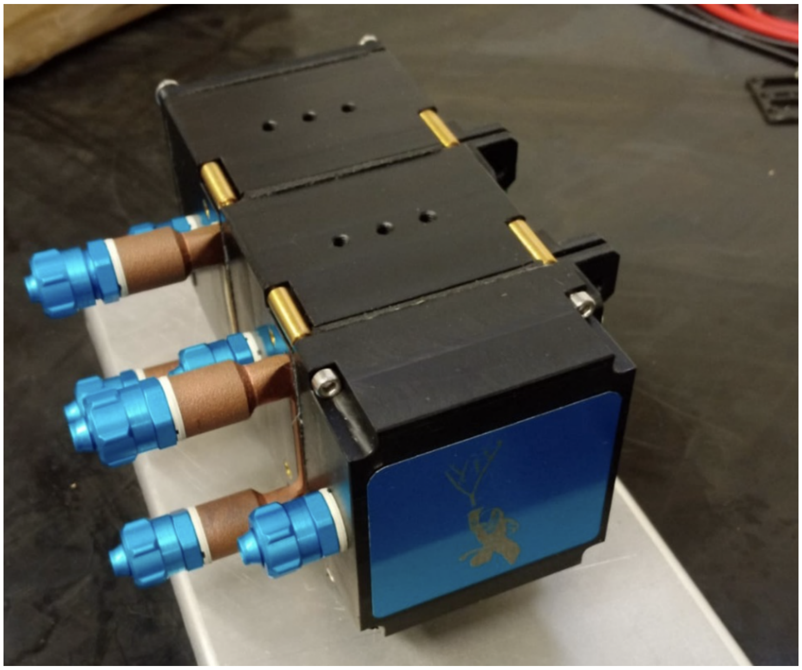

Figure 2: *Crilin larger scale prototype built at the end of 2022 (Proto-1).*

tions, for a total of 18 readout channels. Signals transmitted through the micro-coax lines, after proper termination, are amplified first by a high-speed non-inverting stage with gain 4. The first stage drives a pole-zero cancellation circuit, followed by a second non-inverting stage, which drives the digitization section with a dynamic range of 2 V and an overall gain of 8. SiPM biases are generated on-board by means of 18 high-voltage linear regulators with a 0-100 V dynamic range and a maximum current sourcing capability of 5 mA, providing individually programmable bias voltages with 0.24 V/LSB resolution, controlled via dedicated 12-bit DACs. The regulator has a nominal 3 mV peak-to-peak ripple and a 100 μs settling time. Individual bias current monitoring is carried out by means of high-voltage, high-side current sense amplifiers with a 0-5 mA dynamic range. Regulated voltages, bias currents, and the temperature of the SiPM matrix are sensed via dedicated 12-bit ADC channels, thus completing the slow control chain. An onboard LPC4078FBD100 microprocessor handles all slow control routines and monitors the operational status of each readout channel.

The Proto-1 operational temperature will be 0/-10 °C and the performance will be validated in a dedicated test beam. Specifically, our goals are: 1) perform a complete operational test of the prototype, including operation with cooling; 2) obtain data for a complete analysis of digitized signals from the detector for electrons and minimum-ionizing particles; 3) test the cluster reconstruction capability and measure the time resolution; 4) measure longitudinal and transverse shower profile and compare with results obtained in simulation. Proto-1 will be tested in two dedicated test beams: at LNF-BTF in May 2023 and at CERN before the end of 2023.

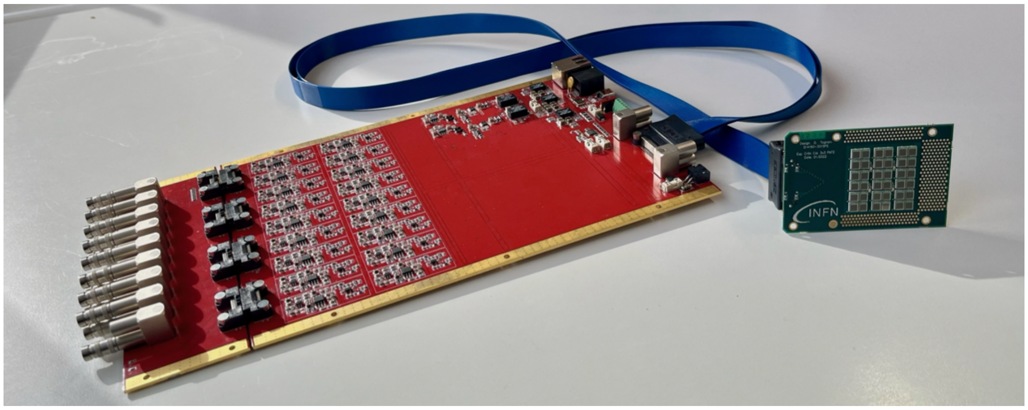

Figure 3: *Proto-1 electronics: controller board (left) and SiPM board (right) matrix.*

3 Thesis

- E. Di Meco, “Crilin: a crystal calorimeter with longitudinal information for a future Muon Collider”, master thesis at the Università degli Studi La Sapienza.

4 List of Conference Talks/Posters by LNF Authors in the Year 2022

1. E. Di Meco, Crilin: a semi-homogeneous calorimeter for a future Muon Collider, 19th International Conference on Calorimetry in Particle Physics (CALOR 2022), University of Sussex, UK.
2. D. Paesani, CRILIN: Crystal Calorimeter with Longitudinal Information, 15th Pisa Meeting on Advanced Detectors (La Biodola 2022), Isola d’Elba, Italy.
3. E. Diociaiuti, A CRystal calorImeter with Longitudinal InformatioN for a future Muon Collider, Interational Conference on High Energy Physics (ICHEP2022), Bologna, Italy.

References

1. N. Amapane et al., ”Muon detection in electron-positron annihilation for muon collider studies”, Nucl.Instrum.Meth.A 1024, 166129 (2022).
2. F. Zimmermann et al., ”Muon Collider Based on Gamma Factory, FCC-ee and Plasma Target.” JACoW IPAC 2022, 1691-1694 (2022).
3. G. Cesarini et al., ”Theoretical Modeling for the Thermal Stability of Solid Targets in a Positron-Driven Muon Collider”, International Journal of Thermophysics volume 42, Article number 163 (2021).
4. E. Diociaiuti et al., ”Crilin: CRystal calorImeter with Longitudinal InformatioN for a future Muon Collider”, Journal of Physics: Conference Series, 2374(1), 012018 (2022).
5. A. Cemmi et al., ”Radiation study of Lead Fluoride crystals”, JINST 17, no.05, T05015 (2022).
6. S. Ceravolo et al., ”Crilin: A Semi-Homogeneous Calorimeter for a Future Muon Collider”, Instruments, 2022, 6(4), 62 (2022).

7. S. Ceravolo et al., "Crilin: A CRystal calorImeter with Longitudinal InformatioN for a future Muon Collider", JINST 17, no.09, P09033 (2022).