Crilin:
a semi-homogeneous calorimeter for a future Muon Collider

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Introduction

- **Muon colliders (MC)** have great potential for high energy physics especially in the TeV range. However, the jet reconstruction is affected by the **Beam Induced Background (BIB)** due to $\mu \rightarrow e^+ e^- \nu_\mu$ decay and following interactions;

- The present MC ECAL barrel is based on W and Si pad layers. This choice can be very expensive. Moreover, this type of calorimeter would need a huge number of channels and would be characterized by low time resolution.

- **Time of arrival and high-granularity are key factors.** This means that a finely segmented calorimeter that can implement timing reconstruction should be favored for this type of collider.
• Based on CLIC detector, with modification for BIB suppression.

• Dedicated shielding (nozzle) to protect magnets/detector near interaction region.
Beam Induced Background

• The interaction of the beam muons decay products with the machine elements (mainly with nozzles) produces a pervasive flux of secondary and tertiary particles that eventually may reach the detector.

They are produced within few tens m from the interaction point by muons primary decays.
Secondary muons are also produced up to 200 m from the interaction point.

• BIB strongly depends on Center of Mass (CM) energy and machine design;
• Expected BIB on the ECAL barrel \(\sim 300 \, \gamma/cm^2/\text{events}.\)
Muon Identification with the calorimeter

Calorimeter longitudinal segmentation improves the high $p_T$ muons track reconstruction obtained from muon detector.

- BIB can be subtracted using information from energy releases.
- Muons and BIB have a very different behavior in the longitudinal energy release.

Energy released in ECAL barrel by one BIB bunch crossing

Energy released in ECAL barrel by uniformly distributed prompt muons in the ($\theta, \phi$) space
Muons and BIB leave two different signatures in the ECAL barrel

- The BIB produces most of the hits in the first layers of the calorimeter while muons produce a constant density of hits after the first calorimeter layers.

- Since the BIB hits are out-of-time wrt the bunch crossing, a measurement of the hit time performed cell-by-cell can be used to remove most of the BIB.
The Crilin Calorimeter

• The goal is to build a crystals calorimeter, fast, relative cheap, and with high granularity (both transversal and longitudinal) optimized for muon collider.

• Our proposed design, Crilin, is a semi-homogeneous electromagnetic calorimeter made of Lead Fluoride Crystals (PbF₂) matrices where each crystal is readout by 2 series of 2 UV-extended surface mount SiPMs.

• It represents a valid and cheaper alternative to the W-Si Muon Collider ECAL.
b-jet reconstruction and resolution simulation on a 40 mm thick and 10 x 10 mm$^2$ of cell area of Crilin ECAL compared to the W-Si one. The performance are quite similar.
Radiation hardness

FLUKA simulation for the BIB at $\sqrt{s}=1.5$ TeV

- Neutron fluence $\sim 10^{14} \text{n}_{1\text{MeVeq}}/\text{cm}^2\text{year}$ on ECAL.
- TID $\sim 100 \text{ krad/year}$ on ECAL.
Two crystals were used to evaluate PbF$_2$ radiation hardness, by comparing their transmittance before and after irradiation, with or without Mylar wrapping.

Photons: Exposed to $^{60}$Co source up to 4.4 Mrad.

**After a TID ~ 80 krad no significant decrease in transmittance observed**, suggesting a saturation effect caused by the damage mechanism.
Neutrons: 14 MeV neutrons with a total fluence of $10^{13}$ n/cm$^2$ on for 1 hour and 30 minutes. Results, evaluated 14 days after the irradiation, show that there is no alteration in the transmittance spectrum.
Crilin Prototype

• Four layers of 5×5 PbF₂ crystals each readout by thin SMD SiPMs by Hamamatsu.
• The operational temperature will be 0/-10°C.
• Proto-0: one layer with 2 crystals, it showed promising results in 2021 Cern Test Beam.
• Proto-1: two sub-modules, each composed of a 3×3 crystals matrix.
• New 15 μm SiPMs already tested with the new front-end electronics.
The SiPMs board is made of:

- **36 15 μm Hamamatsu SiPMs** — each crystal has **two separate readout channels connected in series**.

- Four SMD blue LEDs nested between the photosensor packages.
The Mezzanine Board for 18 readout channels:

1. Pole-zero compensator and high speed non-inverting stages;
2. 12-bit DACs controlling HV linear regulators for SiPMs biasing.
3. 12-bit ADC channels;
4. Cortex M4 Processors.
Mechanics

- Crystal matrix cases made of ABS plastic;
- Locking plates;
- Hydraulic connectors that transport dry gas in each module;
- Seals in between the modules.
- Tedlar windows at the endcaps.

See A. Saputi’s poster: “Mechanical Design for an Electromagnetic Calorimeter for Muon Collider”
Cooling System

Total heat load estimated: **350 mW per crystal.**

- Cold plate heat **exchanger** made of copper mounted over the electronic board.
- **Glycol based water solution** passing through the deep drilled channels.
FEE and SiPMs test

- Two 15 μm SiPM in series;
- Front End Electronics;
- Picosecond UV laser source by Hamamatsu.
- 40GS/s oscilloscope for data taking.

Three sets of measurement performed changing:
1. The oscilloscope sample rate;
2. The laser repetition rate;
3. The peak amplitude of the waveform.
Digitized signals (40 GS/s)
- dynamic range: 0-2 V;
- Fast rising edge $\sim 2$ ns;
- Full width of $\sim 70$ ns;
- Timing reconstruction performed using Constant Fraction method on a lognormal fit.
- Impressive time resolution ($\ll 100$ ps).

40 GS/s

\[
\begin{align*}
\eta &= -0.736 \pm 0.024 \\
\sigma &= -2.50 \pm 0.07 \\
t_{\text{peak}} &= 19.69 \pm 0.03 \\
N &= 4.93 \pm 0.13
\end{align*}
\]
1. Timing vs oscilloscope sample rate

- Strong dependence from the sample rate since the time resolution at 2.5 GS/s is twice the one at 40 GS/s.

2. Timing vs laser repetition rate

- The laser repetition rate scan shows a constant behaviour meaning that the waveform stays unchanged in the 50 kHz-5MHz range.
3. Timing vs mean charge and number of photo-electrons.

Six different waveform peak amplitude values. For each of this runs we looked at charge and reconstructed time distribution extrapolating respectively the mean value and the RMS.

- **Charge to N\text{p.e.} conversion:**
  - $100\ \text{pC} = 248\ \text{p.e.}$

Time resolution is already **less than 40 ps even at low charges** (50\ pC - 124\ p.e) and an impressive **constant term b of $\sim 13$ ps**.
Conclusions

Crilin is a semi-homogenous calorimeter with **longitudinal segmentation** and **excellent timing resolution**. Before the construction of the prototype the single components were evaluated. In particular:

- Irradiation studies of crystals indicated no significant damages up to 80 krad TID and $10^{13}$ n/cm$^2$ fluence$^*$;
- Preliminary two-crystals test beam at BTF with 500 MeV in July 2021 and at Cern in August 2021
  - **promising results in terms of time resolution:** $<100$ ps, $\sim$1p.e. / MeV (expected energy resolution $<10%/\sqrt{E}$)

**Next steps:**

- Irradiation studies on SiPMs up to $\sim10^{14}$ $n_{1MeVeq}/cm^2$;
- Test Proto-1 performances with 500 MeV electrons at BTF and with a high energy beam (>100 GeV) at CERN (before the end of 2022).

$^*$ [arxiv:2107.12307v3](https://arxiv.org/abs/2107.12307v3)
Backup slides
Irradiation sources

Calliope facility:
• pool-type gamma irradiation;
• 25 $^{60}$Co source rods producing photons with $E_\gamma =1.25$ MeV and an activity of $1.97 \times 10^{15}$ Bq.

| Irradiation Step | Dose in air [krad] |
|------------------|-------------------|
| I                | 30.2              |
| II               | 89.88             |
| III              | 2082              |
| IV               | 4031.8            |
| V                | 4435.5            |

Table 1. Irradiation steps and corresponding total dose absorbed by the crystals

FNG facility:
• Neutron source based on T(d,n)$\alpha$ fusion reaction;
• 14 MeV neutrons with a flux up to $10^{12}$ neutrons/s in steady state or pulsed mode.
• CERN H2 beamline;
• Setup designed to allow measurements with 20-120 GeV electrons and tagged photons produced with 120 GeV electron beams
Test Beam-2

PRELIMINARY

Time resolution results for Crilin SiPMs regarding 120 GeV electrons.

\[
\sigma_i = \sqrt{\frac{P_0^2}{E} + \frac{P_1^2}{E^2}}
\]
Constant fraction and fit window optimization

We minimized the time resolution scanning in CF and fit window upper limit. The fit window is given by: 

\[ [T_{\text{peak}} - 12 \text{ ns}, T_{\text{peak}} + T_{\text{fit max}}] \]

Best constant fraction: 30%

Best \( T_{\text{fit max}} - T_{\text{peak}} \) : 0.5 ns