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Advancement and Innovation for Detectors at Accelerators

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MILESTONE REPORT

Definition of the assembly method and of the ASIC specifications for a dual read-out calorimeter prototype

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Abstract:

This document summarises (1) the assembly procedure required to build a dual-readout calorimeter prototype designed for hadronic containment (had-size prototype) and (2) the ASIC specifications required to read out the highly granular modules equipped with Silicon PhotoMultipliers (SiPMs).

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Executive summary

The main goal of this subtask is to develop the technology to build a hadronic-size dual-readout prototype made of 16 modules, ~13×13×250 cm^3 each, targeting a standalone hadronic resolution in the range of 30 – 40 %/√E for both single hadrons and jets, while maintaining a resolution for isolated electromagnetic (em) showers close to 10%/√E with a constant terms of ~1% or below. The R&D study aims to identify modular and scalable solutions for both the construction strategy and the readout scheme.

Section 2 describes the hadronic-size layout and the energy resolution expected for single particles with the selected absorber material and the sampling fraction achievable using stainless steel tubes with a 2 mm outer diameter, filled with 1 mm clear and scintillating fibres. Finally, the tooling and the assembly procedure is described together with the first mechanical precision achieved.

Based on the results from the latest beam tests with an electromagnetic-size prototype, section 3 justifies the characteristics of the selected SiPMs. The sensors need to fit in the rear part of the detector material and need to be operated in a linear regime with particles up to 100 GeV. Finally, two possible readout architectures are identified and the specifications that an ASIC should have to fulfil the dual-readout requirements are summarised in dedicated tables.

1. INTRODUCTION

Dual readout is a calorimetric technique able to overcome the limits due to non-compensation by simultaneously detecting scintillation and Cherenkov lights. Scintillating photons provide a signal related to the energy deposition in the calorimeter by all ionising particles while Cherenkov photons provide a signal almost exclusively related to the electromagnetic shower component. For these reasons, by looking at the two independent signals, it is possible to measure, event by event, the electromagnetic fraction and to properly reconstruct the primary hadron energy. Several prototypes were constructed by the DREAM/RD52 collaboration based on different active media and absorber materials providing a technology that is now mature for application [1].

In 2021, an electromagnetic-size (em-size) prototype was built and qualified on beam. The prototype consists of 9 modules, each made of 320 brass capillaries (with a 2 mm outer diameter and a 1.1 mm inner diameter) equipped, alternately, with scintillating (BC-10 from Saint Gobain) and clear (SK-40 from Mitsubishi) fibres to allow the dual sampling. The light produced in the fibres is read out with PMTs for all the modules except for the central one, named the highly granular module. In fact, the highly granular module was equipped with 320 SiPMs, each of them connected to an individual fibre to collect either the scintillating or the Cherenkov light [2]. The prototype was built using commercially available capillaries; a solution that could be considered for mass production using (1) components machined with high precision by external companies and (2) an assembly solution that guarantees the required mechanical precision. Finally, a scalable readout system capable to operate all SiPMs has been qualified and the possibility to extend it towards a much larger number of sensors is under study.

Based on the previous experience and on the Geant4 simulation, we discuss (1) the assembly procedure under finalisation for building all the modules needed for a prototype designed for hadronic containment (had-size prototype) and (2) the ASIC specifications required to read out the highly granular modules equipped with SiPMs.

2. ASSEMBLY PROCEDURE

2.1. CAPILLARY TUBE CHOICE

The absorber structure of the em-size prototype was built using brass capillary tubes, with a cross section of about 10 × 10 cm^2 and a length of 1m. The capillaries have a 2 mm outer diameter and a 1.1 mm inner diameter. The assembly procedure is described in a technical paper [3]. We performed both analytical and simulation studies to choose the baseline options in terms of both material and dimensions. The quality of the capillary tubes was tested over samples coming from different producers and, for all of them, the results were very good. A detailed Geant4 simulation was carried out to compare the performance for a had-size prototype considering an absorber material made either in brass or in stainless steel. Electromagnetic and hadronic energy resolutions as a function of the energy for the two choices are shown in Figure 1. In the same simulation, the effects of the containment were also studied. As a result, we decided to use 2.5 m long tubes made of stainless steel. Even if the energy resolution obtained with this material is slightly worst, the price is much cheaper and the difference in performance does not justify the usage of brass.

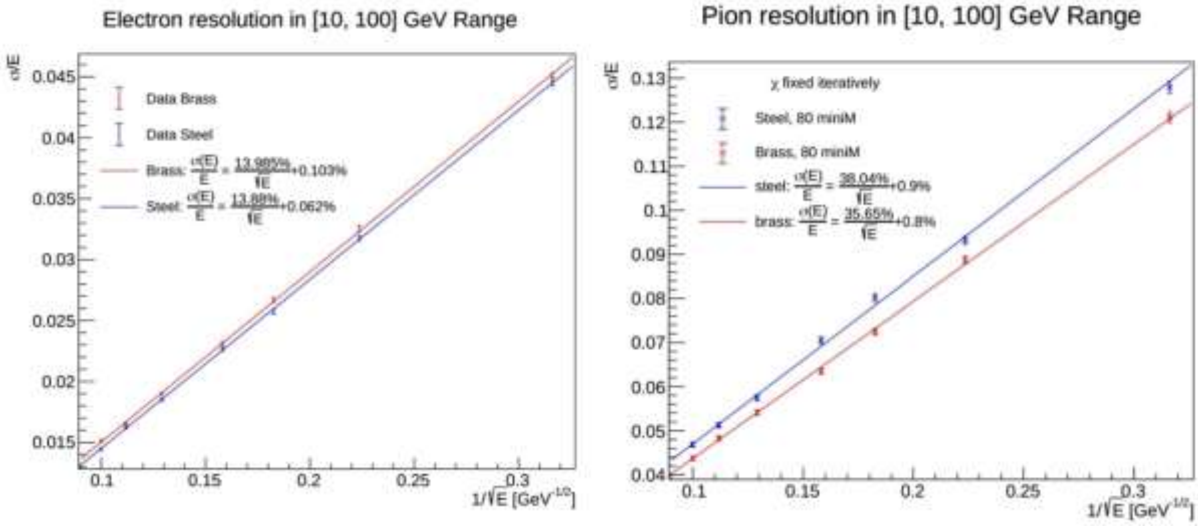

Figure 1: Electromagnetic (left) and hadronic (right) resolution for the had-size dual-readout calorimeter prototype simulated with brass or stainless-steel tubes as absorber material. The tubes considered in the simulation have a 2mm outer diameter, 1.1mm inner diameter and they are 2.5 m long for both materials.

2.2. MODULE LAYOUT

The had-size prototype layout is shown in Figure 2. We foresee the construction of 16 towers, positioned as shown in the figure. Each tower of dimensions 13x13 cm^2, called a Module, is in turn made of 5 Mini-Modules, which constitutes the elementary cell. Each Mini-Module is made of 16 layers of 64 tubes each, for a total of 1024 channels. Half of them will be equipped with clear fibres (to collect the Cherenkov light) and half with scintillating fibres.

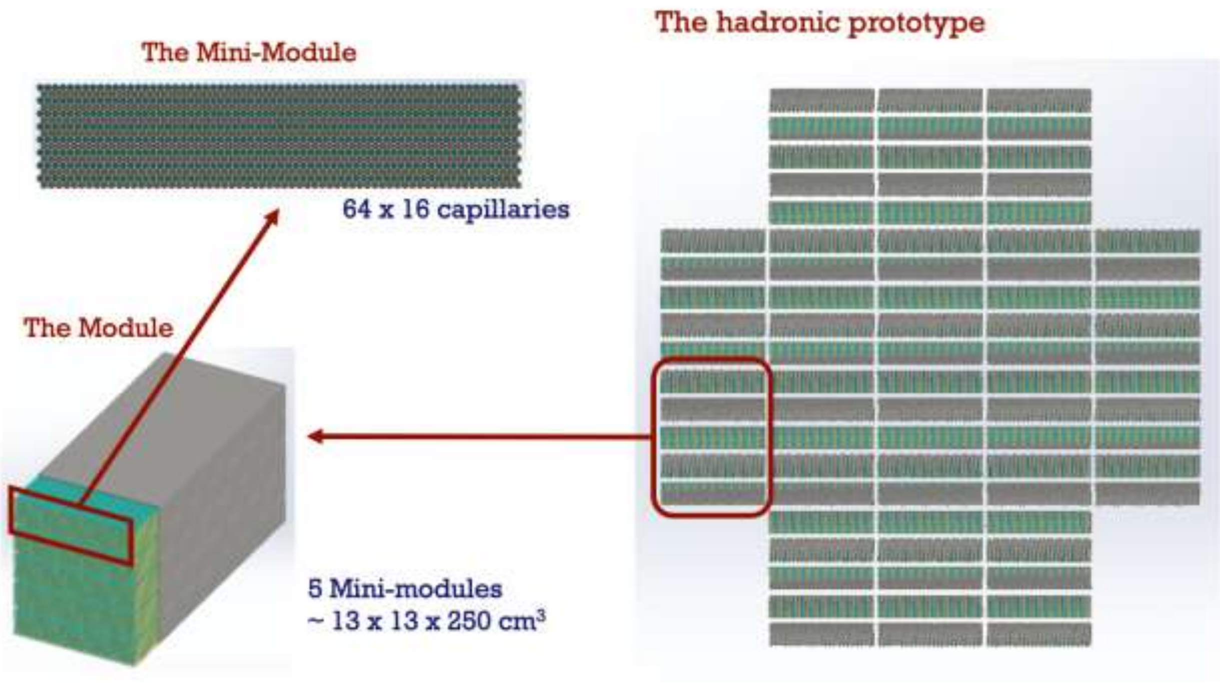

Figure 2: Layout of the had-size prototype structure. The whole prototype, the division in towers (Module) and the elementary cell (Mini-Module).

2.3. GLUING PROCEDURE

The high quality of the capillary tubes found on the market allowed us to simplify the jigs used for the assembly procedure with respect to the strategy previously used for the em-size prototype [3]. The module is built by gluing layers of capillary tubes (one at the time) on top of a reference structure, machined with a 10 µm precision. The assembly is performed in a class 10000 clean room in order to have a temperature- and humidity-controlled area, with a good degree of cleanliness. The tubes are pre-aligned on a granite table (Figure 3 right) and a jig, shown in the same figure, allows you to handle the layer of tubes using a vacuum system. The vacuum acts on 6 plexiglass plates positioned at 30 cm from each other along the tubes. The plexiglass plates are equipped with a combination of double-sided tape and kapton, to temporarily hold the tubes. The handling jig is suspended on a crane by means of chains attached to rotating pins. The jig is also used as a support to deposit the glue (Figure 4 left) and to position the pre-aligned layer of tubes on top of the ones already stacked on the reference structure. The glue used for assembly is Araldite 2011 and it is rolled in small quantity on each layer before the final placement (Figure 4 center). After all the layers have been stacked and glued, a closure plate, rectified with a 10 µm precision, is positioned on the top of the module and the glue is left to set overnight. The first assembled module is shown on the left of Figure 5.

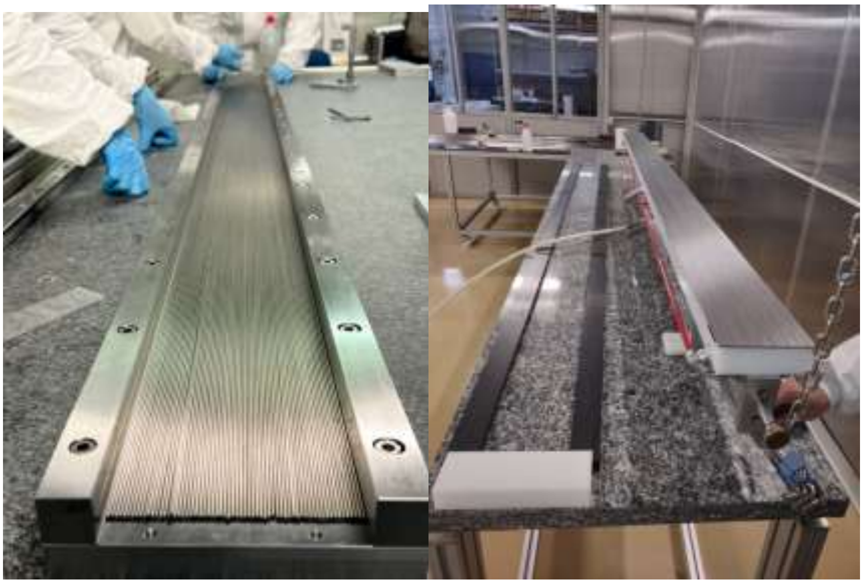

Figure 3: Left: The assembly reference structure anchored to the granite table, with a layer of tubes already in position. Right: Jig for tube handling and positioning.

Figure 4: Left: the glue is rolled in small amount on the tube surface while the tubes are kept on the jig by means of the vacuum system. Center: the jig allows you to position the layer of tubes on the top of the previously stacked tubes. Right: The plexiglass plates equipped with a double-sided tape and kapton, used to hook the tubes with the vacuum system.

In order to verify the quality of the module, both the overall dimensions and the tube positions in the structure need to be measured. While the overall dimensions are measured with an automatic system acting as a Coordinate-Measuring Machine (CMM), the positions of each individual tube are measured with an imaging reconstruction technique.

A gauge, attached to a z-axis, controlled by a step motor, takes 17 measurements along the tube length and 6 across the module width. The z position is given by the combination of the information of the gauge and of an optical line, coupled to the z-axis. A reference measurement is taken on the granite surface and the height of the module is calculated as the difference between the module measurement and the reference. This procedure, tested in past use of the system, allows us to cancel the errors due to the mechanical movement of the tool. The map of the module height is shown in Figure 5 (right).

The measurements on the internal structure of the module are based on an imaging reconstruction technique performed through a python script. The tuning of the optimal conditions for image acquisition and analysis is ongoing and the results are still preliminary.

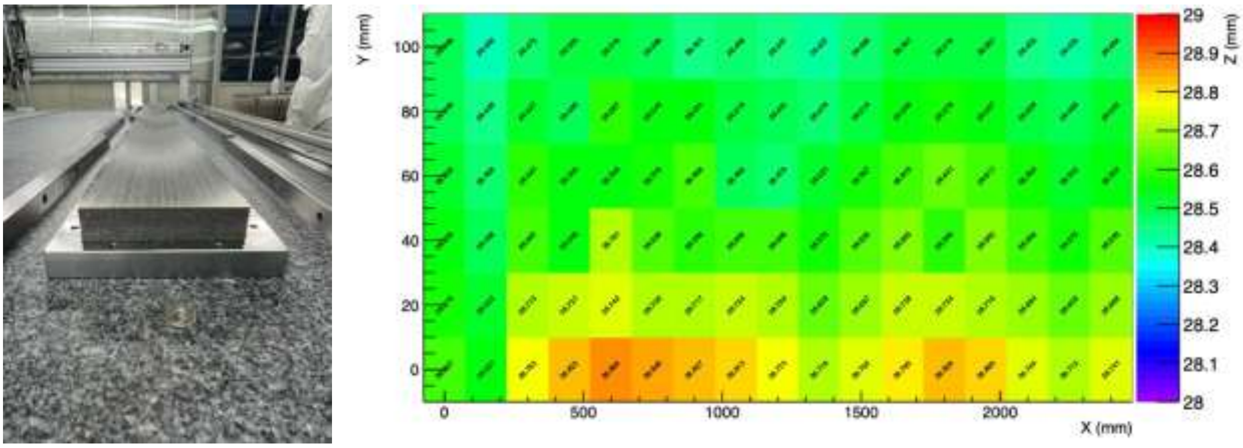

Figure 5: Left: The first mini-module assembled, still placed on the reference tool. Right: The map of the overall dimension of the first mini-module, measured with the automatic CMM-like machine.

The developed technique results to be adequate for the module assembly, despite a problem with few tubes used in the construction of the first module. In fact, values of the order of 100 μm apart from the average are clearly visible in the bottom part of the plot of Figure 5. The problem has been identified and we have good indications that this technique will make it possible to guarantee the expected precision. In addition, it allows us to build a mini-module in about 3 hours featuring an easy handling of the tubes. Therefore, we believe that this strategy can be considered the baseline solution for a scalable assembly of the dual-readout calorimeter prototype. Once the mini-module is ready, thanks to the high precision observed for both the capillaries and the fibres, we can insert the fibres into the capillaries to finalize the assembly.

3. HIGHLY GRANULAR MODULE READOUT

In this paragraph we discuss specifications for the ASIC that should be used to read out the SiPMs selected for the highly granular module. The numbers considered to define the specifications are extrapolated from the SiPM characteristics and the mechanical design. Additional requests are based on the last beam test data analysis performed with the em-size prototype.

3.1. LIGHT SENSORS AND MECHANICAL CONSTRAINS

The em-size prototype, qualified on beam in 2021, was built with 9 modules. The central (highly granular) module was equipped with 320 SiPMs (one per fibre) by Hamamatsu (S14160-1315 PS) having a sensitive area of $1.3 \times 1.3\ mm^2$ and independently read out. A yellow filter (Kodak, Wratten nr 3, with nominal transmission of ≈7% at 425 nm and ≈90% at 550 nm) was placed between the scintillating fibres and the detector to cut off the short wavelength components of the scintillating signal. In fact, yellow filters reduce the calorimeter response dependence on the shower starting point by filtering the component of the light more affected by attenuation in the fibres.

Figure 6 (left) shows the average number of detected photoelectrons (p.e.) produced by the Cherenkov and scintillating light generated in the central module as a function of the electron beam energy, divided by the beam energy. The results show an average value of 36.5 ± 2.4 p.e./GeV for the Cherenkov light and 204 ± 7 p.e./GeV for the scintillating light. Once corrected for the energy contained in the central module (≈ 72%), estimated with a detailed Monte Carlo simulation, we obtain a light yield of ≈ 50 p.e./GeV for the Cherenkov light and ≈ 283 p.e./GeV for the scintillating light [2].

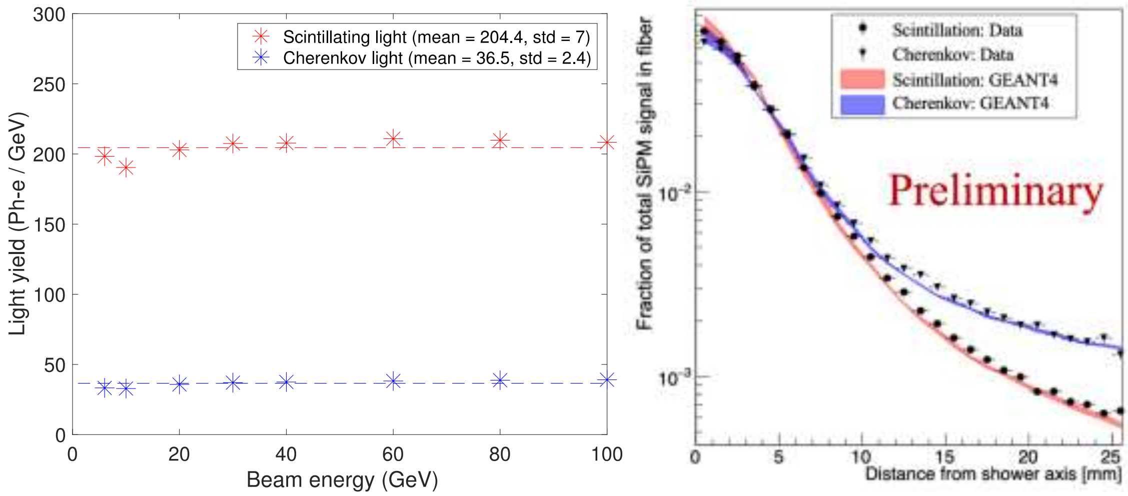

Figure 6: Left: Average number of scintillating and Cherenkov photoelectrons/GeV detected in the highly granular module as a function of the electron beam energy. Right: The plot shows the lateral profile of showers produced by 20 GeV electrons in the calorimeter module read out with SiPMs and separately measured with the scintillating and Cherenkov signals. The beam test data are compared to the results obtained with a Monte Carlo simulation that describes the experimental setup.

The highly granular module adds an unprecedented granularity to the dual readout technique. The high-resolution imaging, together with the (virtual) longitudinal segmentation that could be obtained by adding the time stamping information (i.e., the time delay between the signal measured in each SiPM with respect to a reference), could be used in future to improve the particle ID performance and to resolve complex final states containing non-isolated objects. For the time being, this information has been used to qualify the Geant4 simulation, able to precisely reproduce the shower shape as shown by the right plot of Figure 6. After having measured the centre of gravity in each event by measuring the deposited energy in the fibres, a radial distance between each fibre and the shower axis was measured. The lateral shower profile is measured by taking the fraction of scintillating and Cherenkov signals produced by the showers and recorded with SiPMs as a function of the radial distance. The values reported in the plot are averaged in radial bins of 1 mm. The Cherenkov light produced in the core of the shower (highly collimated at the beginning) falls outside the fibre numerical aperture. This could explain the wider shape measured with the Cherenkov signals [4]. The plot also shows that almost the 10% of the entire energy is released within one mm from the core of the shower (1-2 fibres). These considerations force to require SiPMs with a wide dynamic range to guarantee the operation in a linear regime.

The sensors used for the em-size prototype are not compatible with the true-scalable design we are developing for the had-size prototype. In fact, the SiPM package (2.63 × 2.1 mm^2) does not fit in the space available in the rear part of the absorber (the tube outer diameter is 2 mm). This request is even more demanding because we need to avoid light contamination between scintillating and Cherenkov light collected by neighbouring SiPMs. For this reason, we are considering SiPMs with a sensitive area of 1 × 1 mm^2 and an overall packaging of 1.1 × 1.1 mm^2, that reduces the extra space to only 100 µm . A custom PCB board will be equipped with 8 SiPMs with close-by breakdown voltages (within 100 mV) mounted to match the spacing of the fibres (2 mm).

The identified SiPM is customised by Hamamatsu. In Table 1, we compare the main characteristics of the S14160-1315PS SiPM (sensor used in the em-size prototype) with the two candidates considered for the had-size prototype.

Parameter	S14160-1315PS	S16676-15(ES1)	S16676-10(ES1)
Effective photosensitive area (mm2)	1.3 x 1.3	1 x 1	1 x 1
Pixel pitch (mu)	15	15	10
Number of pixels	7284	3443	7772
Recommended operating voltage (Vop)	+4 V	+4 V	+5 V
PDE at the Vop (%)	32	32	18
Direct cross talk at the Vop (%)	<1	<1	<1
Dark count rate (kHz)	120 (360 max)	60 (200 max)	60 (200 max)
Gain (10^5)	3.6	3.6	1.8

Table 1: Main figures of the SiPM used for the em-size prototype compared with the SiPMs considered for the had-size prototype. The numbers are extracted from the vendor's specifications and are referred to an operating temperature T = 25°C.

For the hadronic-size prototype, we are considering the S16676-15(ES1) SiPM for the Cherenkov signals and the S16676-10(ES1) for the scintillating ones. The decision is based on the measurements performed in the 2021 beam test. In fact, one of the large constrains to be considered while using SiPMs is the dynamic range which allow us to operate the sensor in a linear regime. As shown in the table, by reducing the photosensitive area we have a reduction in the number of pixels which limits the linearity range by a factor of 2. This is not expected to be a problem for the Cherenkov light (more than 5 times less intense than the scintillating light) while it could be problematic for the scintillating light. This brings to the conclusion to consider two different options. It is worth noting that the S16676-10(ES1) SiPM has almost the same number of pixels as the S14160-1315PS but it has less detection efficiency and a gain that is about 50% lower, numbers important to be considered while defining the ASICs specifications.

3.2. ASIC SPECIFICATIONS

Readout electronics can use different strategies i.e. charge integration or waveform sampling. The implementation of the charge integration with a precise time stamp (tens of ps) is probably easier and could satisfy most of the requests set by the dual-readout fibre calorimetry although additional information on timing and signal shape may provide a powerful input for event reconstruction, enabling PFAs to be applied to dual-readout calorimeters. For this reason, we decided to define two sets of parameters, considering both strategies. The specifications in the tables are inspired by few ASICs already available (i.e. CITIROC 1A and RADIOROC from Weerok and HDSoC from Nalu Scientific), plus additional features inspired by the SiPM characterisation activity and beam test studies.

Main specifications	
Readout strategy	Charge integration
Number of channels	32 / 64
Sensitivity	0.5 p.e. (@ 2 * 10^5 SiPM gain)
Dynamic Range	0 – 320 pC (i.e. 10000 p.e. @ 2 * 10^5 SiPM Gain)
Timing resolution	< 50 ps rms (single p.e.)
Power consumption	< 500 mW
Full frame readout	Internal / external trigger (one of the two or both)
Additional features	
Single channel HV adjustment	
Single channel gain tuning	
Single channel threshold setting (required for timing and internal trigger)	
Trigger mask (required for internal trigger)	
Signal latency (≈100 ns)	
Internal TDC (optional)	

Table 2: ASIC specifications in case of charge integration readout technique.

Main specifications	
Readout strategy	Waveform sampling
Number of channels	32 / 64
Sampling frequency (GHz)	5 - 10
Input Bandwidth (GHz)	> 1
Buffer length (samples)	> 4k
Feature extraction	i.e. total charge, ToA, ToT, current-peak time …
Full frame readout	Internal / external trigger (one of the two or both)

Table 3: ASIC specifications in case of waveform sampling readout technique.

The highly granular module of the em-size prototype was read out with five A5202 boards equipped with 2 Citiroc-1A each and produced by CAEN. Even if, this is our baseline solution also for the had-size prototype, we are interested in testing any new asic that can provide better timing performances (i.e. Radioroc) and signal shape information (i.e. HDSoC) when available.

4. REFERENCES

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ANNEX: GLOSSARY

Acronym	Definition
em-size	Dual-readout prototype with electromagnetic containment
had-size	Dual-readout prototype with hadronic containment
SiPM	Silicon Photomultiplier
CMM	Coordinate-Measuring Machine