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# AIDAinnova

Advancement and Innovation for Detectors at Accelerators

Horizon 2020 Research Infrastructures project AIDAINNOVA

## MILESTONE REPORT

# DESIGN AND TEST OF SCINTILLATING TILES OR STRIPS WITH LARGE ACTIVE AREA SUITABLE FOR LARGE AREA DETECTORS

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**Abstract:**

Test stands to study the response and timing properties of plastic scintillator bars read out with SiPMs, and to investigate the potential for gamma-neutron separation of different plastic scintillator materials have been constructed and commissioned.

The design of a detector based on plastic scintillator tiles was completed. The detector module is composed by a 3x5 matrix of 225 $cm^2$ tiles. The light readout of each tile is achieved by 4 Silicon Photomultipliers directly coupled to the scintillator. A dedicated fast front end electronics is integrated onto the tile. The detector module can be used as a standalone unit or can be replicated in order to cover large areas. The performance of the scintillator tiles has been verified. A time resolution of 300 ps, light yield of 230 photo-electrons for a MIP and an efficiency better than 99.8% were achieved.

For more information on AIDAinnova, its partners and contributors please see http://aidainnova.web.cern.ch/

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## Delivery Slip

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## Executive summary

*Three different test systems for large-area scintillator elements have been constructed and commissioned. The first system, built up at MPG-MPP, provides the capability to study the spatial distribution of response and time resolution of scintillator bars with double-sided SiPM-based readout. This setup can be used both in test beam areas and in the laboratory with a radioactive soure. The second system, constructed at JGU, serves to investigate the response of different scintillator materials to neutrons and photons, supporting the development of calorimeter systems which also provide particle identification capabilities. The third system is a demonstrator module of a large-area scintillator tile with four-fold SiPM readout built at INFN-BO, demonstrating the timing capability of such a system for future experiments.*

# 1. INTRODUCTION

Organic scintillators offer a fast response and high light yield for moderate cost, making them an excellent choice for the application in large area detectors for particle physics. Silicon PhotoMultipliers (SiPMs) provide advantageous properties such as good timing, compactness, and high Photon Detection Efficiency (PDE). Scintillating tiles with direct SiPM readout, pioneered for application in hadron calorimeters for electron-positron colliders, allow compact detectors with high granularity and good time resolution to be built.

In applications with moderate or low particle rates, reduced granularity can be used to reduce the number of electronic channels and thus system complexity and cost. Examples for applications of such detectors are near detector calorimeter and muon systems for long-baseline neutrino experiments and for beam dump experiments. The use of scintillators in such detectors results in the need of large-area elements with modern photon detector readout via SiPMs. To avoid compromising detector performance by the reduced granularity, specific designs of the scintillator elements are required to ensure adequate spatial and time resolution as well as particle identification capabilities.

To study different geometrical configurations of larger scintillator strips and tiles with direct SiPM readout, test benches capable of studying elements of the required size both in beam tests and in the laboratory have been deployed and their performance demonstrated with realistic prototypes. In this context, precision timing is emerging as a key capability in future detectors.

To study the timing capability of large scintillator elements read out by multiple SiPMs, a prototype module has been constructed, demonstrating performance and scalability of the technology. In addition to a very good timing performance, the choice of tiles with four-corner readout guarantees the determination of the $x$, $y$ coordinates with a single active layer and a good tolerance against hit rate variations. Studies performed on similar scintillator-based detectors show that this technology is suitable for detectors exposed to an integrated dose of about 100 kRad/year. Moreover the construction and assembly procedure is modular and therefore can be easily shared among different production sites, which is paramount for the construction of large area detectors. With the prototype we demonstrate how it is possible to build large area detector based on 225 cm$^2$ area scintillating tiles with direct SiPM readout. The modular structure and the very competitive cost render this system suitable to multiple applications in high energy physics and beyond.

# 2. SCINTILLATOR STRIPS AND TILES FOR NEUTRINO EXPERIMENTS

## 2.1. A TEST BENCH FOR SCINTILLATOR STRIPS

For the DUNE Near Detector [1] an electromagnetic calorimeter that, together with a high-pressure TPC, will provide a precise reconstruction of neutrino interactions on Argon, is planned. This calorimeter has to provide energy and directional reconstruction for photon showers, neutron identification and energy reconstruction as well as muon/pion separation. These performance goals suggest the choice of a highly granular calorimeter, which, given the large volume of the detector and the fine sampling required for good photon energy reconstruction, would result in a very high channel count when implemented purely based on the CALICE-developed SiPM-on-tile technology [2]. At the same time, the low event rate and low particle density of neutrino interactions does not require a very high granularity from an occupancy point of view, making granularity requirements purely performance motivated.

A promising strategy to reduce channel count, and with this system complexity, is the use of larger scintillator bars with double-sided readout instead of small scintillator tiles. Here, time and spatial resolution is achieved by combining the signals collected on both sides. To assess the potential of this technique, a dedicated test stand that enables the testing of scintillator bar prototypes both in particle beams and with a radioactive source in a laboratory setting has been constructed at MPG-MPP. This test stand is based on the scintillator tile test stand documented in [3].

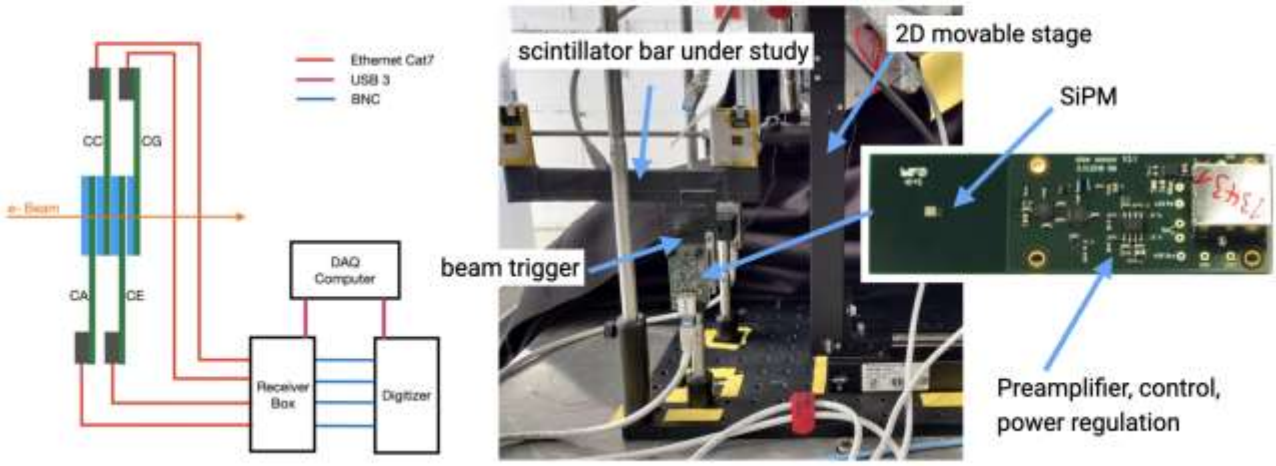


*Fig. 1 Test stand to study scintillator bars and tiles in test beams. Left: Schematic of the setup showing a configuration of two tiles under test and two tiles for triggering. Right: Photograph of the setup used at the DESY test beam, with a tigger telescope and a 24 cm long, 3 cm wide scintillator bar with double-sided readout under study. The inset on the very right shows the front-end board that houses SiPM, preamplifiers and control circuitry.*

Figure 1 shows the setup of the test stand in its configuration for particle beams. The test stand uses a PicoTech Picoscope 6804E for waveform digitization, operated with 4 connected channels to enable a sampling frequency of 2.5 GS/s. The power supply for the front-end amplifiers, the SiPM bias voltage and the analog signals are carried on CAT-7 cables from the sensor boards (shown in Fig 1 right) to a custom-built receiver box. This box splits the analog signals for digitization, and provides the required supply voltages driven by one USB-A connection to the DAQ computer, which also controls the Picoscope via its USB-3 interface. A standard laptop is sufficient, enabling a system designed for maximum portability. Installation of the test setup and full connection in a beam area at DESY could be performed within 2 hours.

For the measurements, a 3x3 $cm^2$ scintillator tile and a small 5x5 $mm^2$ scintillator cube are used as a beam trigger upstream of the scintillator bar under study. The bar can be moved with few micrometer accuracy by a remote-controlled translation stage, enabling a scan of its full active area.

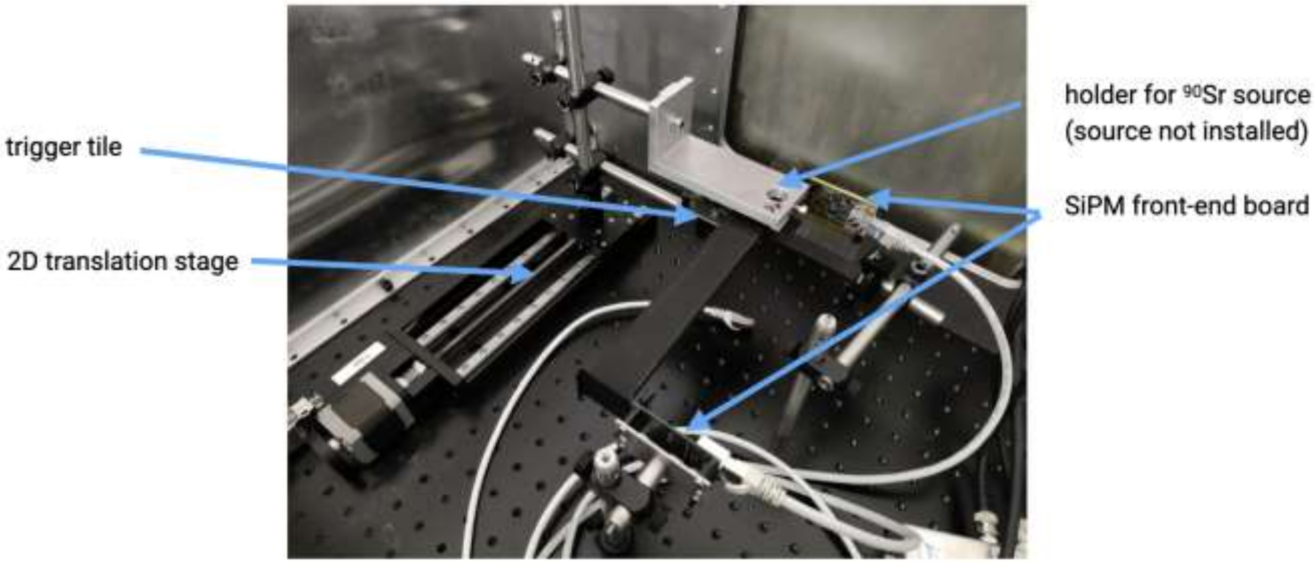


*Fig. 2 Adaption of the scintillator bar test stand shown in Fig. 1 for laboratory operation with a $^{90}$Sr source.*

Figure 2 shows the adaption of the test stand for laboratory measurements using a $^{90}$Sr source. Since the electrons from the source typically do not penetrate more than 1 cm of plastic scintillator, a single trigger cube is used underneath the scintillator bar. Here, the source and the trigger are moved by the translation stage, again providing the possibility for full scans of more than 20 cm long bars. The reconfiguration from the beam to the laboratory layout can be done in less than one hour.

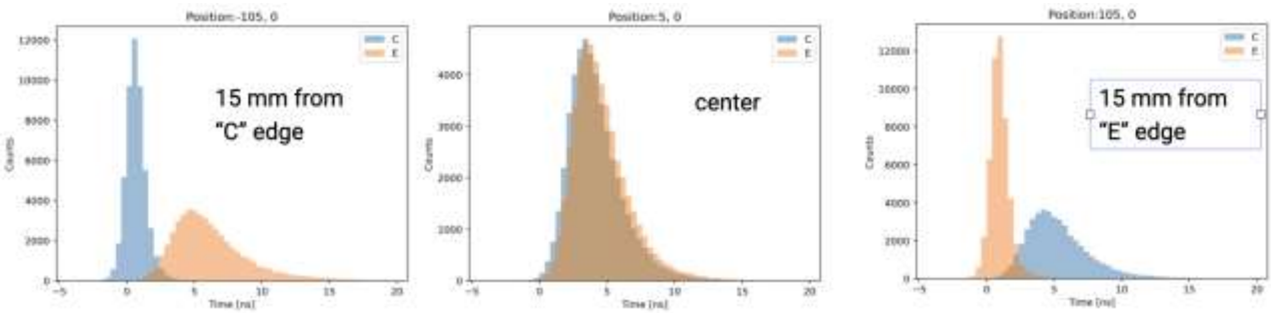


*Fig. 3 Measurement of the time distribution of the photon signals collected on both sides of a 24 cm long scintillator bar (readout channels "C" and "E") for different positions along the bar, measured in the DESY test beam.*

Figure 3 shows one example measurement taken with a 24 cm long scintillator bar recorded in the DESY testbeam. Here, the time distribution of the detected photons, reconstructed from the recorded analog waveforms, is shown for different beam positions along the scintillator bar. The measurement demonstrates that, based on the difference in time distribution, a reconstruction of the position of the beam is possible. At the same time, the bar is also able to provide sub-ns time resolution for the impact time of the particle.

This and other measurements performed both at the DESY test beam and in the laboratory with a $^{90}$Sr source demonstrate the usability of the test stand for detailed studies of scintillator bar prototypes.

## 2.2. A TEST BENCH FOR NEUTRON/GAMMA SEPARATION

With respect to a calorimeter for a future high energy collider, the electromagnetic calorimeter for the DUNE Near Detector should also have the capability to measure neutrons, requiring concretely a correct identification of the particle causing the energy deposit and timing capabilities to measure the energy with the time-of-flight technique. While extensive tests of the timing capabilities have already been performed with the CALICE AHCAL prototype, a new test bench has been developed at the Johannes Gutenberg University (JGU) Mainz with the aim to study neutron/gamma separation in different scintillating materials.

A schematic view of the test setup is shown in Figure 4 (left). A 15 MBq AmBe source allows for the detection of a few neutrons per minute on the 3x3 $cm^2$ tile under test. The source also emits photons at a similar rate as neutrons, but they can be shielded with a 2.5 cm thick lead block reducing their rate by about 75%. This leads to three possible modes of operation: without the source, only signals from cosmic rays are recorded at a rate of about 9 per minute; with the source and no shielding, the data contain signals from cosmic rays, photons and neutrons at a total rate of about 28 particles per minute; adding shielding, the same particles are still contributing, but the fraction of photons is strongly reduced and therefore these runs are called "neutrons + cosmics" and provide data with a rate of about 18 particles per minute. Two scintillator strips read out by conventional photomultipliers can be used as trigger or veto for cosmic rays. The signal on the tile under test is read out by a SiPM connected to a preamplifier and recorded with a Keysight MSOS254A oscilloscope with a bandwidth of 2.5 GHz and a sampling rate of 5 GSample/s. The whole setup is enclosed in a dark box. The photograph on the right of Figure 4 shows the actual setup with the scintillator strips for cosmic ray trigger/veto both below the tile under test, without the source and before closing the dark box.

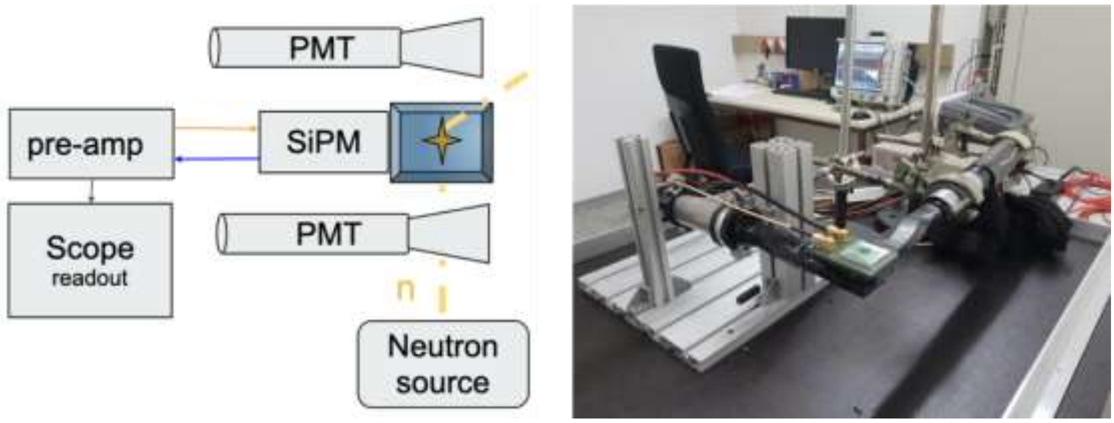


*Fig. 4 Test stand to study neutron/gamma separation for a scintillator tile read out by a SiPM. Left: schematic view of the setup. Right: Photograph of the setup without the AmBe source and before closing the dark box.*

In order to distinguish the signals generated by neutrons from those generated by photons or cosmic rays, the Pulse Shape Discrimination (PSD) technique can be used. The neutron-induced signals have a longer tail with respect to the amplitude than the other ones. Therefore integrating over two different time intervals and building the ratio of the deposited charges allows for discrimination between the two signatures and can be used for particle identification. The currently used preamplifier (CAEN A1423B) shapes the signal into a bipolar form, deforming the signal too strongly to effectively use tail integration for PSD. However, exploiting the possibility to record the full signal shapes with the oscilloscope, the number of photoelectrons in the tail of the signal can be counted and used for discrimination instead.

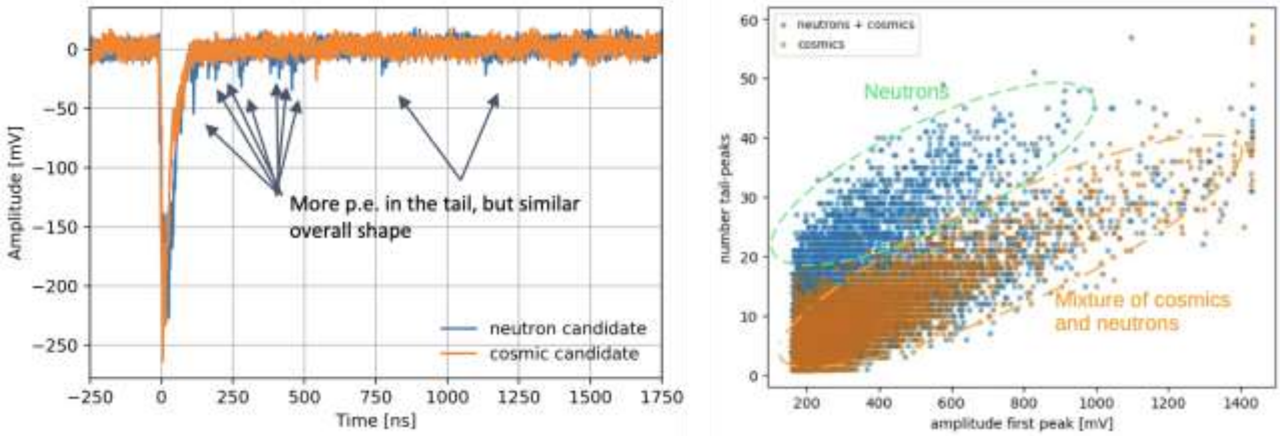


*Fig. 5 Left: typical signal shapes for a neutron and a cosmic candidate, showing the different number of photoelectron peaks in the tail of the signal. Right: number of tail-peaks vs. amplitude of the first peak for a neutrons + cosmics run and for a cosmics run.*

Figure 5 shows a typical signal for a neutron candidate with several single or few photoelectron peaks in the tail and a typical signal for a cosmic candidate with very few such peaks. Plotting the number of tail-peaks versus the amplitude of the first peak shows two well separated regions. The one with a high number of tail-peaks and relatively low amplitudes is almost exclusively populated by neutrons, while the remaining region contains both neutrons and cosmics. The ratio between the number of tail-peaks appears to be a good discriminating variable and the distributions for cosmics and neutrons can be obtained from the pure cosmics run and from the subtraction of the known rate of cosmics from the neutrons + cosmics data, respectively. In the subtraction the distribution for the remaining photons after shielding is assumed to be identical to that of cosmics and the rate is based on the estimate mentioned above. First results with this method using an EJ-276G tile are shown in Figure 6. Removing 95% of cosmics, a purity of about 87% with an efficiency of about 77% can be obtained for neutrons. However, relying on the knowledge of the cosmic ray and photon distributions and rates and subtracting them to estimate the neutron distribution consistutes a large source of uncertainty, as can be seen also from the fluctuations leading to negative entries in the neutron distribution in Figure 6. This uncertainty can be reduced exploiting the cosmics veto capability of the setup, which was not yet included in the analysis.

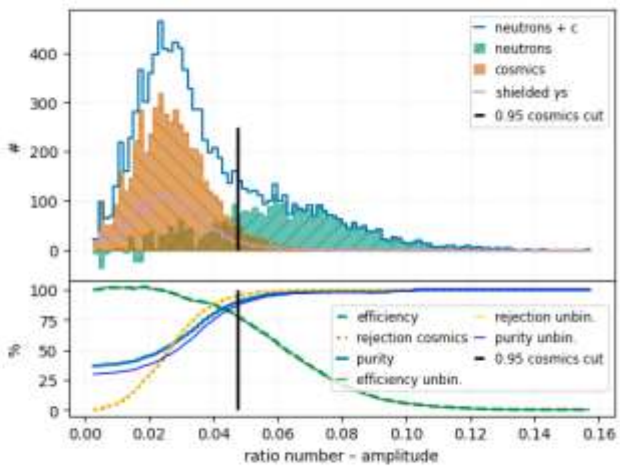


*Fig. 6 Separation between cosmics and neutrons using the ratio between the number of tail-peaks and the amplitude of the first peak as a discriminating variable.*

Optimisations of the data analysis are still ongoing, but the test setup is deemed to be a suitable tool for the characterisation of scintillating materials in terms of their neutron/gamma separation capabilities. In the near future, the setup will be improved with a more suitable preamplifier, in order to have a more realistic expectation of the performance with the readout electronics of the final detector.

# 3. SCINTILLATING TILES WITH DIRECT SIPM READOUT FOR LARGE AREA DETECTORS

## 3.1. TILE PROTOTYPE

The basic unit of the detector is a cast organic scintillator EJ200 from Eljen company. The tile dimensions are (150x150x10) $mm^3$. Each tile is read out by four SiPMs placed at the tile corners, either engraved into slots dug in the scintillator near the corners. An example of prototype with the four SiPMs connected to flex cables and glued in slots engraved at the tile corners is shown in Fig. 7.

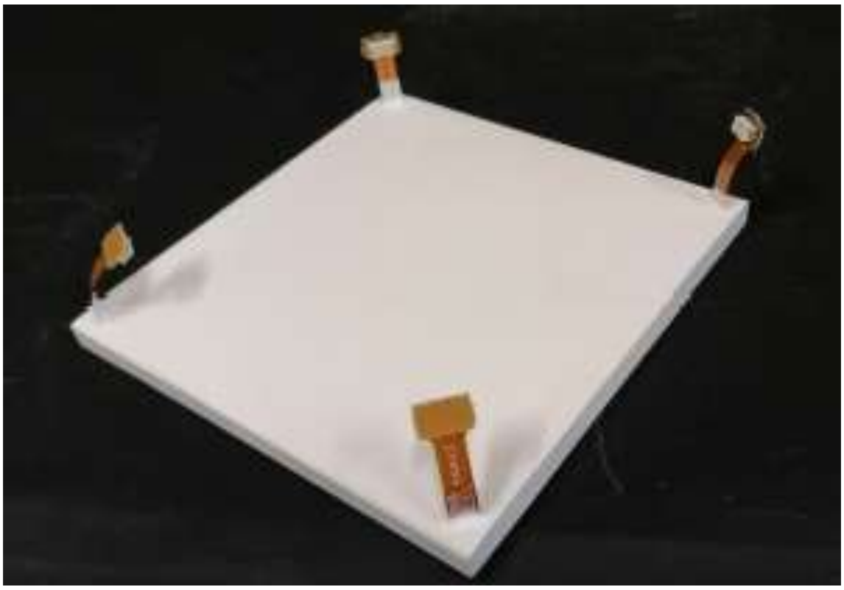

*Figure 7: Scintillator tile with four SiPM glued inside grooves near the corners*

The tiles are painted with three layers of reflective painting Eljen EJ-510.

### 3.1.1 SiPM LIGHT READOUT

The tiles are read out by four SiPMs, Hamamatsu S14160-6050HS, with $6 \times 6$ $mm^2$ active area. The other characteristics of the SiPMs are reported on table 1. The V-I curve of every SiPM has been measured and the breakdown voltage ($V_{\mathrm{break}}$) determined. SiPMs with similar $V_{\mathrm{break}}$ have been grouped on each tile. The SiPMs are mounted on short Kapton flex cables that ensure the connection with the motherboard (see Section 3.1.2). The flex cable end hosting the SiPM is glued to the tile via optical glue Eljen EJ-5005. The other end is connected to the motherboard attached to the tile surface, where the Front-End Electronics (FEE) is located.

| | |
|---|---|
| Number of cells | 1 |
| Pixel pitch | 50 μm |
| Number of pixels | 14331 |
| Vbreak | 38 V |
| PDE | 50% |
| Gain | 106 |
| Dark count current | 2.5 μA |
| Crosstalk probability | 7% |

*Table 1: SiPM characteristics*

### 3.1.2 Frontend Electronics

The FEE for the tile prototypes is hosted on a Printed Circuit Board that is attached on the tile itself as shown in Fig.8.

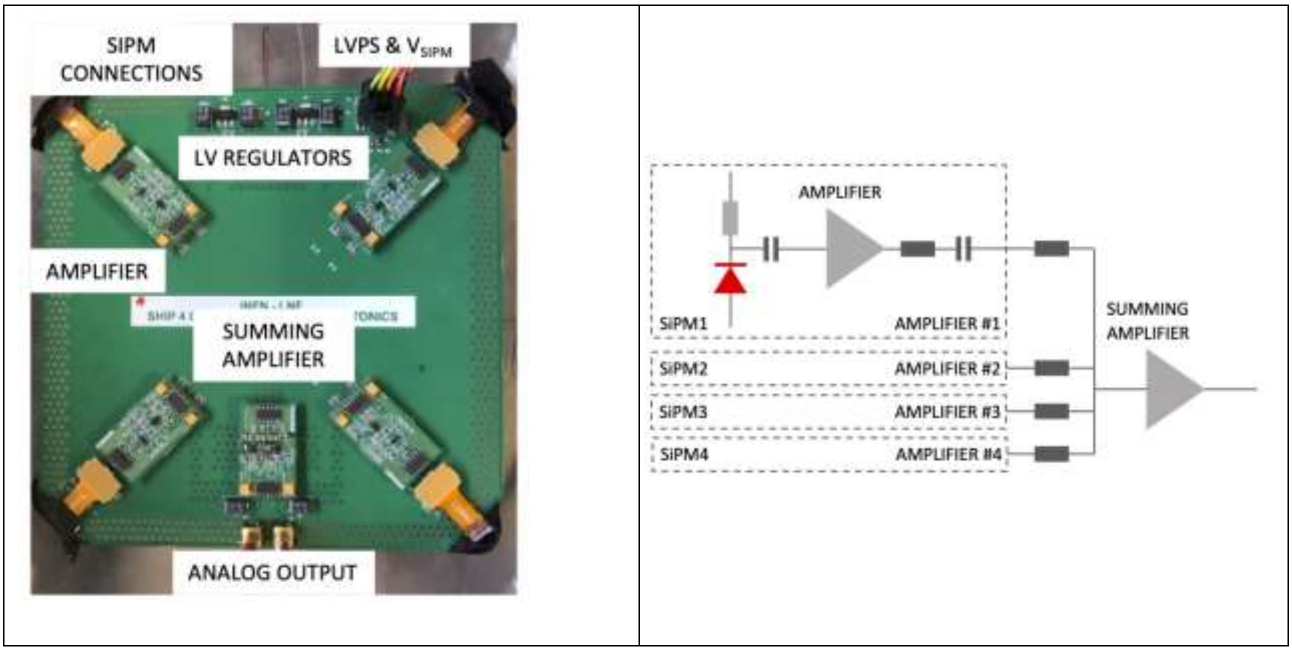


*Fig 8: Readout PCB and electronics overview.*

The time resolution depends on both signal slew rate and noise, therefore photon collection must be maximised by means of large area SiPMs and high bandwidth readout electronics. Unfortunately, large area SiPMs have a large parasitic capacitance that increases the amplifier input noise, reducing the overall signal-to-noise S/N ratio. A reduction of the parasitic capacitance could be achieved by connecting SiPMs in series, but this configuration requires higher supply voltages and reduces the signal amplitude and therefore it is not the best choice for a topology where SiPMs are spread over a large area.

For our readout topology, SiPMs instrumented with individual preamplifiers followed by a common summing point is a preferable solution as it allows local signal amplification and the possibility of adjusting the shaping time both at the preamplifier input and at the common summing point. The readout circuit block diagram is shown in Figure 9: each SiPM output is amplified and combined with signals from the other amplifiers by means of a summing amplifier. The summing amplifier output is, finally, routed to a digitizer. The mother board connections have been designed to equalise the propagation delay of the signals from the four (local) SiPM amplifier.

The mother-board PCB includes connectors for flex cables, SiPM bias circuits and low-voltage regulators. Four layers PCBs have been used for proper impedance signal routing traces and low-impedance supply voltage distribution

The SiPMs are connected to the preamplifier via low impedance short kapton flex cables allowing easy replacement of the full readout circuit in case of failures.

Because of the SiPMs large parasitic capacitance (of the order of 2 nF), front-end preamplifiers with low input impedance must be used.

A current conveyor scheme was chosen for the frontend amplifier, implemented by means of a NPN BFR92A RF transistor as shown in Figure 9.

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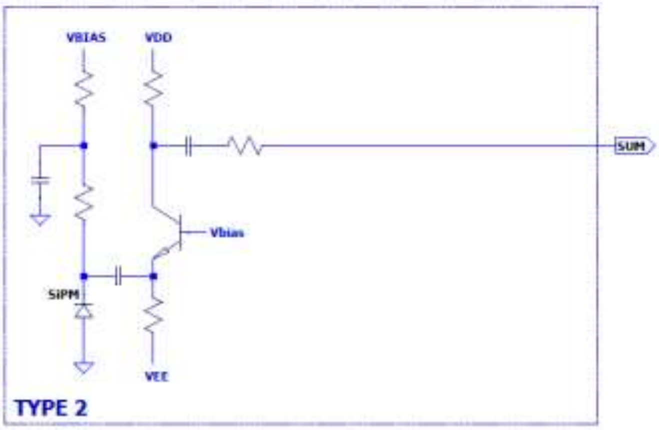


*Figure 9: Frontend amplifier circuit*

The circuit is AC coupled, allowing baseline fluctuation suppression using low capacitance values.

Finally, to avoid spoiling the signal time information, low impedance connections to the summing point together with a high speed amplifier must be used; in our design signals have been routed by means of 50 ohm microstrips while the summing point has been implemented using the AD8009, a very fast operational amplifier from Analog Devices.

An intrinsic time resolution of 65 ps, including the SiPM and the frontend electronics, was measured by illuminating the SiPM with fast laser pulses.

An example of a typical waveform at the summing output of the tile is presented in Fig. 10. The data was recorded by a digital scope, triggered on cosmics muons.

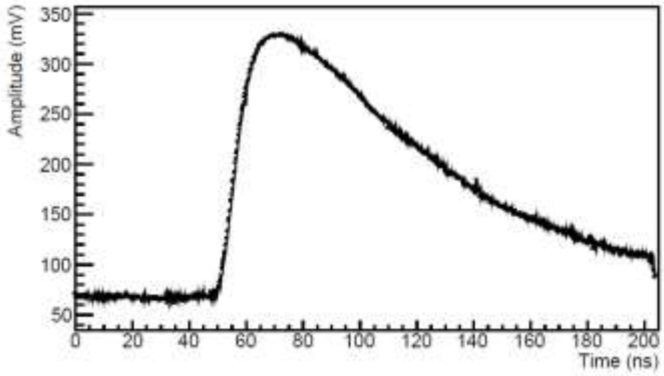


*Figure 10: Typical waveform at the summing output of a tile, triggered on cosmics*

### 3.1.3 Calibration of Light yield

In order to express the tiles light yield in number of photo-electrons, the gain of the SiPM and readout electronics has been calibrated by acquiring its signal charge spectrum produced with a low-intensity pulsed led light. The hardware setup used for this measurement consists of a light-tight climate chamber containing a single SiPM connected to the readout electronics. The light of a LED connected to a pulse generator is directed onto the active surface of the SiPM by an optical fiber, and the amplifier output signal waveforms are acquired by a digital oscilloscope, operated at 10 GS/s. The output charge was measured by integrating the signal waveform within a 200 ns window.

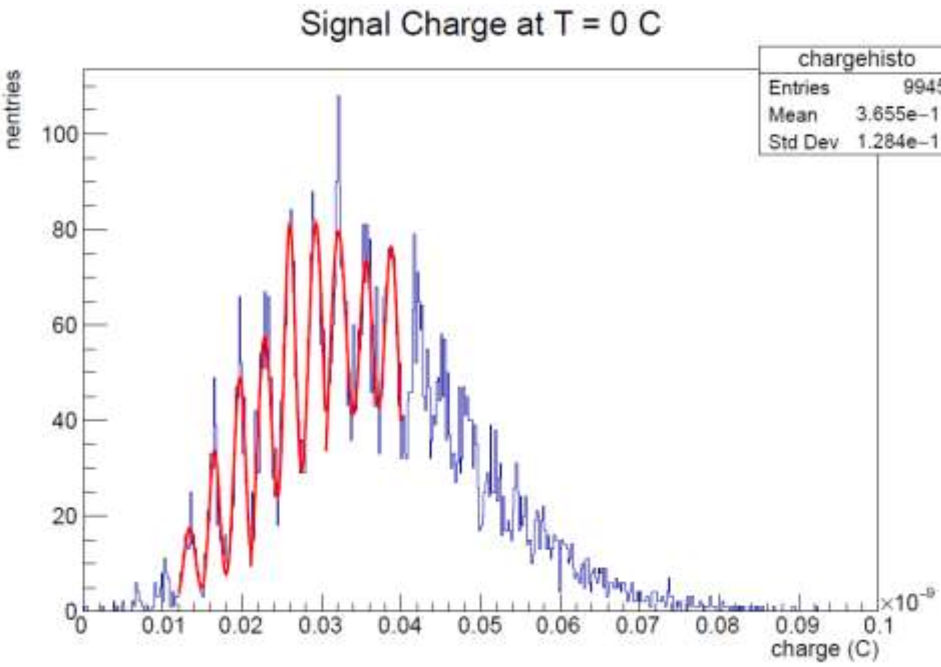


*Figure 11: SiPM charge spectrum histogram at 0 C and fitted with a sum of Gaussian distributions.*

To obtain a good separation in the charge spectrum between peaks corresponding to different number of photoelectrons, the climate chamber temperature was set to 0 C to reduce the SiPM thermal noise. In order to operate the SiPM at the same gain as at room temperature during the test beam, the bias voltage had to be adjusted to account for the breakdown voltage ($V_{break}$) dependence on temperature, keeping fixed the over-voltage. The $V_{break}$ was determined at 0 C temperature by acquiring the V-I curve with a Keysight B2901A source meter. In a V-log(I) plot, the intersection of the linear fits for the dark current region and the breakdown region provides the sought voltage, yielding a $Vbreak$ of 37.35 V. A charge spectrum, shown in Figure 11, was acquired and the peaks fitted with a sum of multiple Gaussian functions. The average distance between two adjacent peaks corresponds to the signal generated by 1 p.e.. The resulting charge produced by a single photoelectron is 3.2 ± 0.2 pC.

The calibration allows to determine the tile response to cosmics in terms of number of photons collected. This number depends on the position but is always higher that 230 photoelectrons. In order to measure the efficiency and time resolution teastbeam are foreseen for the future. Past measurements on similar prototypes gave efficiencies of about 99.8% and timing resolution of about 300 ps [4].

## 3.2. MODULE PROTOTYPE

The construction of a module composed by a matrix of 3x5 tiles is almost ready. In Fig. 12 the CAD model is shown. The frontend of each tile will output the analog sum of the signal of each SiPM and a digital discriminated output. A bus system is foreseen in order to allow the settings of the thresholds for each tile as well its bias voltage. The SiPMs, already soldered on a Kapton flex cable, were characterized in a black box and the reverse I-V measurement allowed to determine the breakdown voltage for each of them. The SiPMs of the same tile were chosen with similar breakdown voltage and were glued with the optical glue inside the grooves.

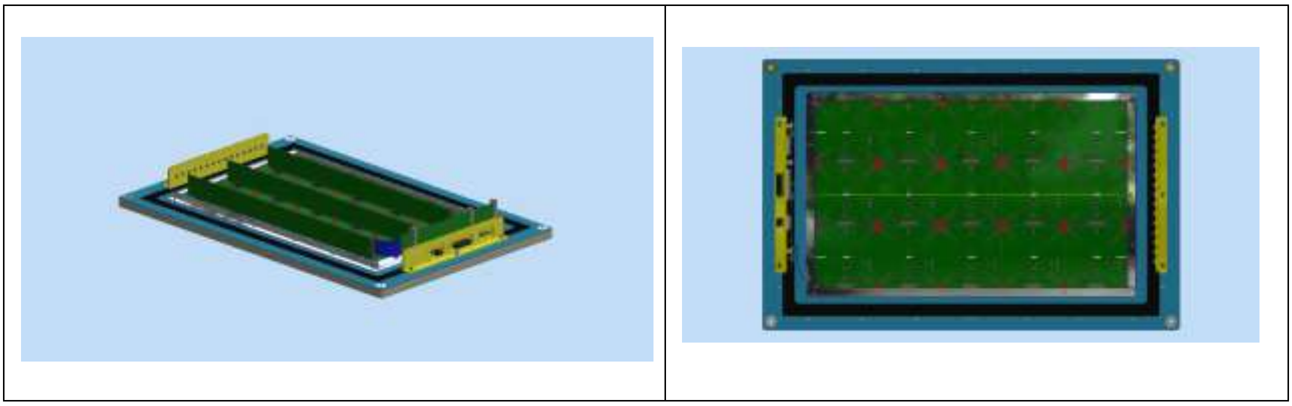

*Figure 12: CAD model of a module composed by 15 tiles*

*Figure: 13: tiles after the painting with TiO2*

After the painting with $TiO_2$ (Fig. 13), the tiles are ready to be installed in the mechanical structure, shown in in Fig. 14.

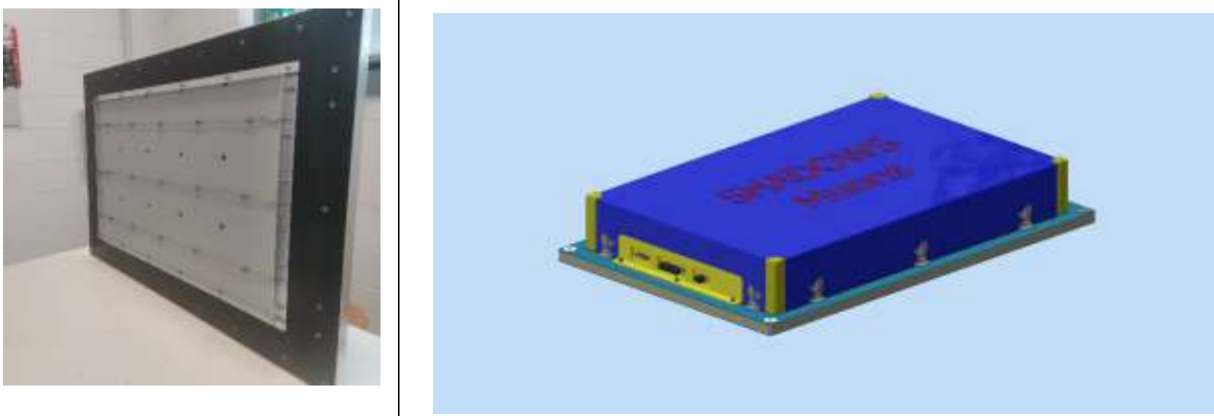

*Figure 14: mechanical structure for the hosting of 3x5 matrix of tiles.*

The tiles are covered by an Aluminium box for light tightness and Faraday cage. Connectors on a patch panel allow the access to the bus for low voltage power, bias voltages and thresholds settings. The analog signal of each tile can be readout with a digitizer while the digital discriminated output can be readout with a TDC (Time Over Threshold in this case is used to infer the corresponding number of photons).

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