



Technical Notes

A first prototype of C_6D_6 total-energy detector with SiPM readout for neutron capture time-of-flight experiments

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ABSTRACT

Low efficiency total-energy detectors (TEDs) are one of the main tools for neutron capture cross section measurements utilizing the time-of-flight (TOF) technique. State-of-the-art TEDs are based on a C_6D_6 liquid-scintillation cell optically coupled to a fast photomultiplier tube. The large photomultiplier tube represents yet a significant contribution to the so-called neutron sensitivity background, which is one of the most conspicuous sources of uncertainty in this type of experiments. Here we report on the development of a first prototype of a TED based on a silicon-photomultiplier (SiPM) readout, thus resulting in a lightweight and much more compact detector. Apart from the envisaged improvement in neutron sensitivity, the new system uses low voltage (+28 V) and low current supply (~50 mA), which is more practical than the ~kV supply required by conventional photomultipliers. One important difficulty hindering the earlier implementation of SiPM readout for this type of detector was the large capacitance for the output signal when all pixels of a SiPM array are summed together. The latter leads to long pulse rise and decay times, which are not suitable for time-of-flight experiments. In this work we demonstrate the feasibility of a Schottky-diode multiplexing readout approach, that allows one to preserve the excellent timing properties of SiPMs, hereby paving the way for their implementation in future neutron TOF experiments.

1. Introduction

Total energy detectors (TEDs) in conjunction with the pulse-height weighting technique (PHWT) were invented at Oak Ridge National Laboratory (ORNL) in 1967 [1]. Since then, they have been extensively used at neutron time-of-flight (TOF) facilities to measure neutron capture cross sections of interest for astrophysics [2] and nuclear technologies [3,4]. Fig. 1 shows a pictorial record illustrating the evolution of TEDs at different facilities, which is representative of the state-of-the-art in this field at different times. Apart from their earlier version of Moxon-Rae detectors [5], the first TEDs used with the PHWT were based on cylindrical cells of small volume (~300 cm³) filled with a nonhydrogenous liquid scintillator (C_6F_6) [1] (see Fig. 1-a). However, the large capture cross section of fluorine induced contaminant capture events in the detector itself, an effect regarded as *neutron sensitivity*.

Thus, in an effort to reduce the background related to the neutron sensitivity of the detector, the scintillation liquid was later replaced by deuterated benzene (C_6D_6) [6] (Fig. 1-b). Additional efforts to further reduce the neutron sensitivity were undertaken at CERN n_TOF in year 2000 [7] (Fig. 1-c). Commercial (Bicron) detectors were customized with thinned Al capsule walls (front wall of 1 mm and side walls of 0.4 mm), removable TEFLON expansion tubing and a photomultiplier tube (PMT) (Photonis XP1208) with a boron-free glass window. Finally, perhaps the major change since their invention was the carbon fiber based C_6D_6 TEDs developed at FZK [8] (Fig. 1-d). They consisted of carbon fiber cell detectors (wall thickness of 0.4 mm) with no quartz window featuring a volume of 1.0 liter (78 mm × 127.3 mm ø) and a PMT (EMI-9823) with a quartz window. Later, this type of C_6D_6 detector was further refined in terms of safety aspects [9]. For a more

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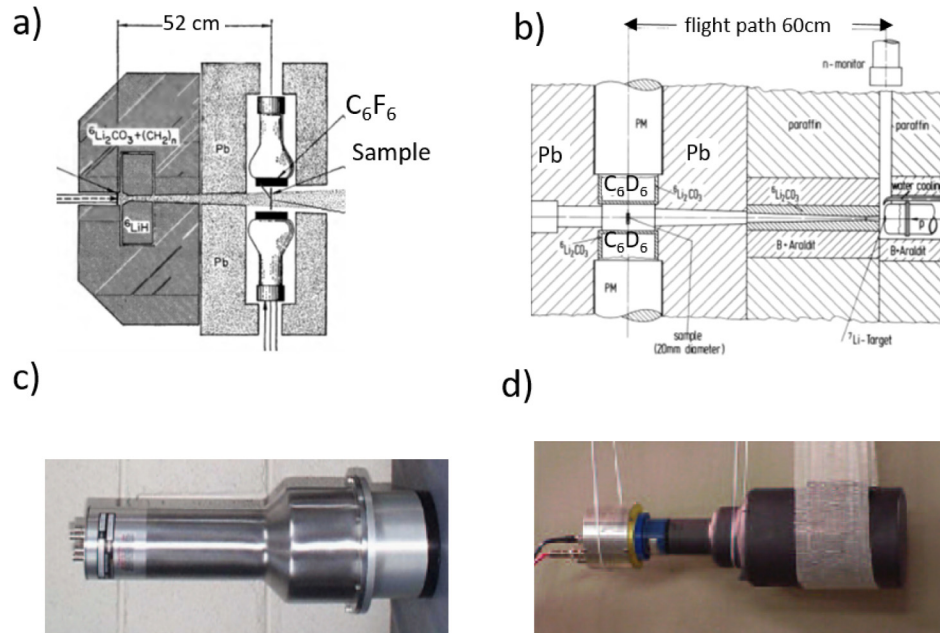


Fig. 1. (a) First TED set-up based on C_6F_6 at ORNL in 1967 [1]. (b) Set-up with improved neutron sensitivity C_6D_6 detectors at the FZK (Forschungszentrum Karlsruhe) research centre [6]. (c) Optimized commercial C_6D_6 detectors at CERN n_TOF [7]. (d) C-fiber based ultra-low neutron-sensitivity C_6D_6 set-up [8].

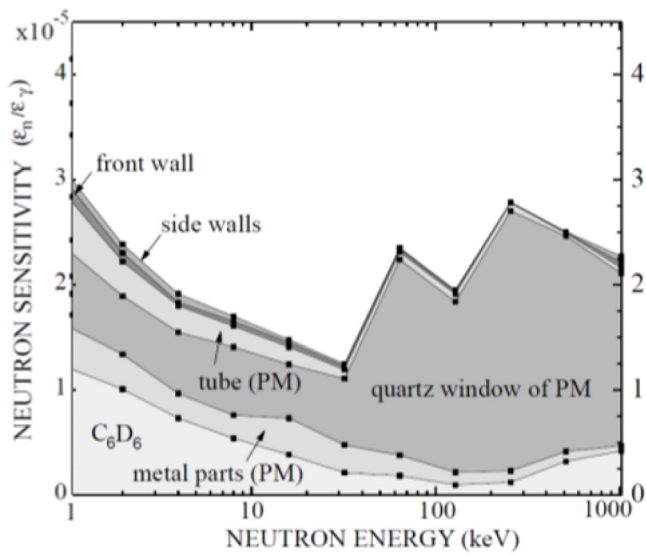


Fig. 2. Depiction of the contribution of different detector elements to the neutron sensitivity for the C-fiber based C_6D_6 . Source: Adapted from Ref. [8].

extensive discussion on the evolution of TEDs the reader is referred to Ref. [10].

In summary, the aim to improve neutron sensitivity has mainly driven the development of TEDs over the last five decades. Presently, however, an important contribution to the neutron sensitivity is still due to the bulky PMT. This is demonstrated in Fig. 2 (adapted from Ref. [8]), which shows the measured neutron sensitivity as a function of the neutron energy. As it can be observed in this figure, the main elements still hindering a further reduction of the detector neutron sensitivity are the quartz window of the PMT and other PMT structural materials such as the PMT metallic parts (dynodes) and the tube itself. This is most evident in the ~ 100 keV neutron energy range. Accurate cross section measurements in this energy range are relevant to study,

for example, nucleosynthesis of heavy elements during shell C-burning ($kT \sim 90$ keV) in massive stars [2].

In this work we report on a rather radical change in TEDs, consisting in the replacement of the bulky PMT by a lightweight and compact array of silicon photo-multiplier (SiPM) sensors [11–13]. In addition to the expected improvement in neutron sensitivity [8,14], SiPMs offer several additional advantages. Firstly, they are insensitive to magnetic fields and thus, one can also avoid the mu-metal commonly used with PMTs in this type of experiments. This is certainly the case of the experiments at n_TOF and other spallation facilities, where a strong magnet is commonly used along the neutron beam line to deflect in-beam charged particles. Additionally, the SiPM operates with a low voltage supply below 100 V, which is generally more practical than the high voltage (\sim kV) power supply needed by conventional PMTs. Finally, given the small current drawn by the SiPM sensor it may become feasible to use a battery as power supply, which could help in reducing high-frequency noise which sometimes is picked-up via the mains power supply.

The SiPM readout approach, however, poses an important technical challenge. Commercially available SiPMs consist of a single pixel or arrays of them, with a typical pixel size between 1 mm^2 and $6 \times 6 \text{ mm}^2$. Each pixel features a parallel network of thousands of micro-metric single-photon avalanche photodiodes (μ SPADs) with an electrical sum-capacitance that can be as low as ~ 10 -to- 100 pF. This leads to excellent pulse time properties for a single pixel with very steep rise-times and pulse widths of a few ns. However, a large number of pixels are needed in order to read out a C_6D_6 cell. Individual pixel readout becomes impractical, even with largest available pixels, due to the huge number of acquisition channels required. On the other side, directly merging many pixel signals into a common single readout channel results in a very high summed capacitance, leading to wide pulses with slow rise and recovery times. This effect makes SiPM arrays impractical or useless for the rapidly varying and high instantaneous count rates characteristic of TOF neutron capture experiments. In this work we report on a signal-based multiplexing readout approach, that allows one to preserve the good time-response of the individual pixels, thereby paralleling the time response of a conventional PMT. This readout approach and design methodology are described in Section 2. Section 3 describes the technical details of the readout board and the assembly

of a functional prototype utilizing the C_6D_6 cell of a commercially available detector. The response signals of the new prototype are compared with those of a conventional PMT-based C_6D_6 in Section 4. Last, Section 5 summarizes the main results and discusses the next steps of this project.

2. Methodology and signal multiplexing

In this work we use the commercial SiPM ArrayJ 60035-64P-PCB [15] from ON Semiconductor (previously SensL). It consists of an array of 8×8 pixels covering a surface of 50×50 mm². Each pixel has a size of 6×6 mm² and embeds 22 292 μ SPADs with a size of 35 μ m each. The diodes are fabricated with a p-on-n technology, thereby covering the scintillation photon wavelength down to 350 nm with a maximum quantum efficiency at 425 nm. This sensitivity matches perfectly well with the ~ 425 nm peak-wavelength of the C_6D_6 based scintillation detector. A schematic drawing of a single pixel is shown in Fig. 3.

In this type of SiPM array each of the 64 pixels has two possible readout channels. The anode readout is the so-called standard output, with a typical capacitance of about 3.4 nF and a total signal width in the range of ~ 100 ns. More interestingly for TOF experiments, there is a fast terminal that features a much smaller capacitance of about 200 pF and a pulse-width of only 3.2 ns. Experiments with TEDs typically use between two and four data acquisition channels, depending on the number of C_6D_6 detectors used [1,7,16]. Therefore, for a new TED detector based on SiPM arrays it becomes expensive and impractical to read out all the individual pixels. A set-up with four C_6D_6 detectors with 64 pixel SiPM arrays would require at least 256 acquisition channels. Instead, the sum signal has to be worked out. As discussed before, a direct sum of all pixels poses several problems. First, connecting all (or several) channels together merges also the dark noise from all of them. This means that even when one or a few pixels have been fired, the dark current from all pixels contribute to the noise in the sum signal. Additionally, the output capacitance of the channels is also added. This is of particular concern for TOF experiments, as the large capacitance increases both the rise and decay times. Fig. 4 shows a SPICE simulation made with LTSpice (Linear Technology Corp., Analog Devices) in order to illustrate this effect. In the simulation a narrow impulse signal (3 ns) is read out at a shunt capacitance equaling the sum of that of the 64 pixels (12.8 nF) of the ArrayJ-60035-64P-PCB SiPM. The signal readout from a single pixel at the fast terminal (200 pF) is shown for comparison.

To overcome this problem, among the different multiplexing methods available [17] the signal-driven approach [18] has been investigated in this work. This method is based on a network of Schottky-diode pairs. A Schottky diode is a metal–semiconductor diode with very fast switching times ~ 100 ps and a very low output capacitance of a fraction of pF. This makes it well suited to preserve the good timing characteristics of the fast SiPM signals. In the network, every Schottky-pair node is forward biased and directly connected to a fast SiPM output (see Fig. 5). In this way, only the contribution from SiPM pixels with a net charge signal is transferred to the common fast readout channel, while the fast outputs from non-firing pixels do not contribute to the sum signal.

The next section describes the steps undertaken in order to effectively implement this approach in a proof-of-concept prototype.

3. Prototype assembly and materials

Following the methodology of the Schottky-diode network discussed in the previous section, a printed circuit board (PCB) was developed. In this prototype we used the SMS7621-005LF SMD Schottky diodes from Skyworks with SOT-23 packaging. They feature a very low capacitance of 0.25 pF and a characteristic switch time of only 10 ps. A schematic drawing of the bias and readout circuit is shown in Fig. 6. The SiPM

array is reverse biased with +28 V at the common cathode terminal (e.g. 3 V beyond breakdown voltage), whereas the Schottky-diode pairs network is forward biased with -30 V at the common cathode. The latter is capacitively coupled to a 50 ohm Lemo connector, where the sum signal is read out.

Two customized Bicron C_6D_6 detectors from the n_TOF Collaboration (described in Section 1) were available for these tests. One of them was used as reference for comparison, whereas the other detector was dismantled and the aluminum cell containing 1 liter of C_6D_6 (EJ-315 [19]) was used for the assembly of the new prototype with the SiPM sensor. Previous optical grease was cleared from the quartz window using high-purity (99%) isopropanol and a new layer of optical grease (Saint-Gobain B630) was applied. The SiPM used was the ArrayJ 60035-64P-PCB described in the previous section. To mitigate the light loss due to the geometric mismatch between the small and square SiPM and the large cylindrical C_6D_6 cell, an adaptor disc made from polylactic acid (PLA) was designed to fit over the surface of the cell quartz window not covered by the SiPM sensor (see Fig. 7). Further, to optimize photon collection efficiency the inner and outer sides of the disc were made from white and black PLA, respectively, in order to ensure the light-tightness of the C_6D_6 cell. In this prototype the SiPM covered only 33% of the total quartz window surface. Correspondingly, a factor of ~ 3 reduction in the number of photons collected in the SiPM can be expected, when compared to the PMT. As it will be discussed later, this led to a significant reduction in the amplitude of the SiPM- C_6D_6 pulses, when compared to the reference PMT- C_6D_6 detector.

The prototype assembly was covered with black tape and, additionally, a layer of semi-rigid metallic tape was used to further protect it from external light and to fix the photosensor to the C_6D_6 cell.

Fig. 8 shows a picture of the fully assembled prototype (left) and the conventional PMT-based C_6D_6 detector (right). The height of the new prototype is only 12 cm, to be compared with the 42 cm size of the conventional one. More importantly, the large material reduction is expected to reduce significantly the neutron sensitivity of the new TED.

4. Results and discussion

Measurements were carried out using a ^{137}Cs source placed at ~ 5 cm distance from both detector cells. Thirty pulses obtained with the C_6D_6 with SiPM readout are shown in Fig. 9. The average pulse rise time is 7 ns (10-to-90% pulse-height interval), the average pulse width 14 ns FWHM and the decay time 14 ns (90-to-10% pulse-height interval). All signals show an undershoot at the decay component, which extends up to about 150 ns. The latter aspect requires further research and probably can be improved by optimization of the output impedance of the Schottky network down to the resistive 50 ohm of the readout stage. Similar undershoots have been observed in previous studies [20] and are also reported for the fast-output terminal in the SiPM data-sheet [15]. The signal-to-noise ratio (SNR) is of 23 dB (or equivalently a voltage-level ratio of 16). For comparison, another set of hundred pulses measured with the PMT- C_6D_6 are shown in Fig. 10. On average, they show a rise time of 9 ns, a width of 15 ns FWHM and a decay time of 16 ns. The SNR is of 49 dB (which corresponds to a voltage ratio of 286). As discussed before, the superior pulse-height and SNR of the PMT- C_6D_6 can be ascribed, to a large extent, to the better optical and geometric matching between the PMT and the quartz window. Additionally, a portion of the SiPM signal may be lost due to the incomplete impedance matching, which is reflected in the undershoot shown in Fig. 9. If needed, an amplifier could be also added to the last stage of the SiPM readout circuit in order to enhance the net sum-signal. It is worth to mention that, although the FWHM width of the fast SiPM output is only ~ 1.4 ns, the cell recovery time is significantly larger, of about 50 ns. This may represent a limitation for the measurement of very high-count rates (above ~ 10 MHz), when compared to the conventional PMT-readout. Such effect will be investigated with neutron beam at CERN n_TOF in future tests. Comparing

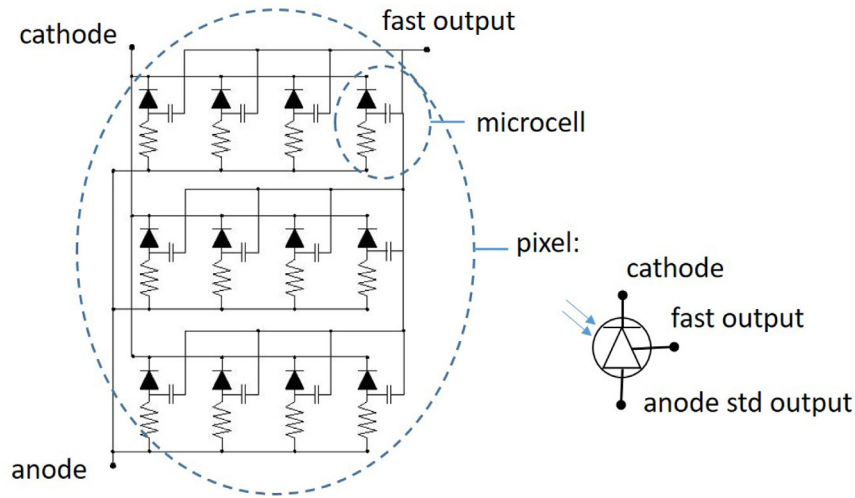


Fig. 3. Simplified representation of a single SiPM pixel embedding twelve micro-cells or μ SPADs. Each pixel can be read at the anode (standard output) and at the capacitively coupled fast output (fast output).

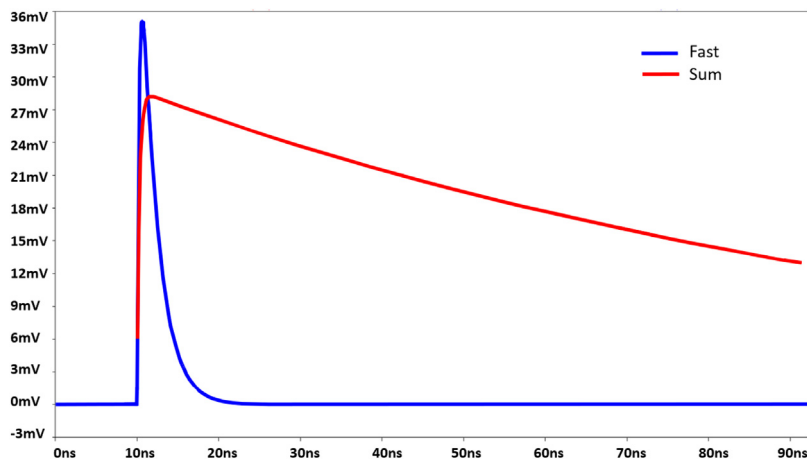


Fig. 4. SPICE simulation illustrating the effect of the capacitive load in a raw sum approach. The resulting sum signal (red) is significantly slower than the initial fast pulse from a single pixel (blue). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

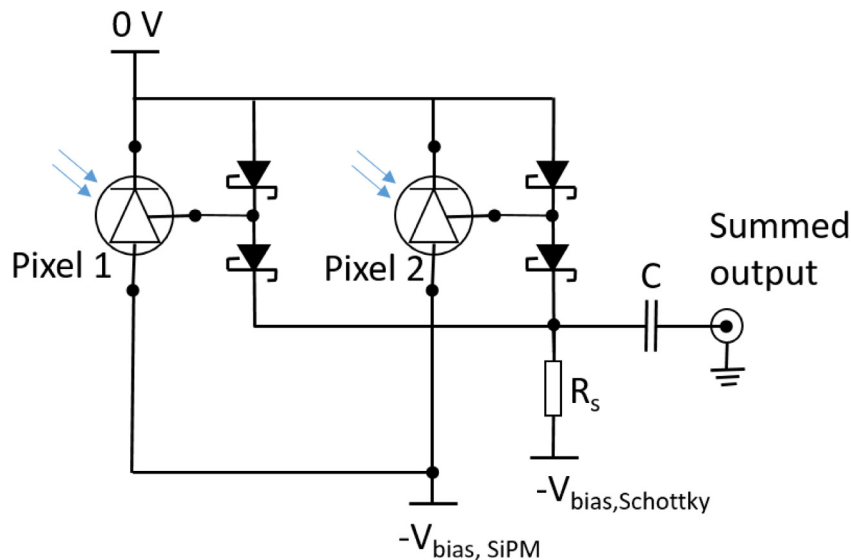


Fig. 5. Schematic layout of the network of Schottky-diode pairs applied to a two-pixel SiPM array.

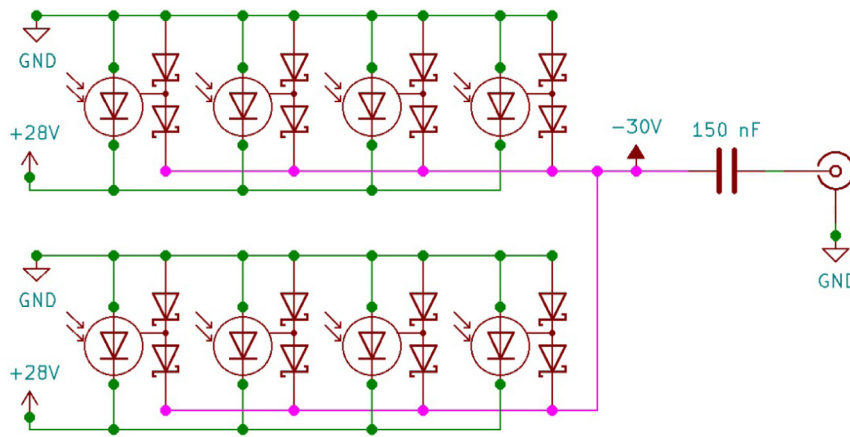


Fig. 6. Readout scheme showing a simplified Schottky network of 8 pixels. See text for details.

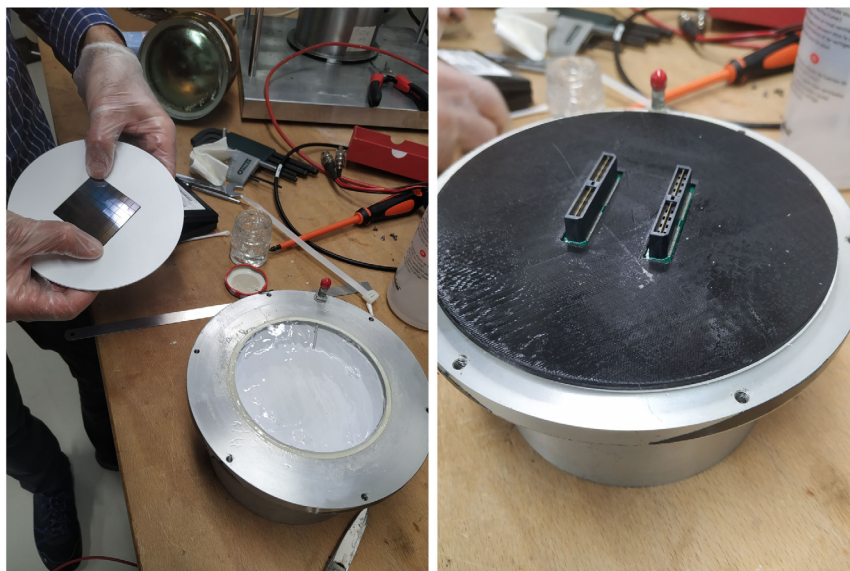


Fig. 7. The left picture shows the C₆D₆ 1 liter cell and the SiPM with the adaptor PLA disc. The picture on the right shows the C₆D₆ cell with the SiPM sensor optically coupled to it.

the pulses shown in Figs. 9 and 10 it can be concluded that with the implemented Schottky-diode network, the overall timing performance of the 64-pixels SiPM array remains similar to conventional PMT-based C₆D₆. This result is encouraging for the future development of TEDs based on silicon sensors that can be used in neutron TOF experiments with improved background conditions.

5. Summary and outlook

A prototype has been developed with the aim of demonstrating the suitability of SiPM arrays as readout sensors for fast total-energy C₆D₆ detectors to be employed in neutron capture time-of-flight experiments. The implemented Schottky-diode readout-network has allowed us to solve difficulties associated with the large sum-capacitance of the SiPM array and thus, preserve the good timing properties of semiconductor photosensors. From the point of view of the detector response, the new readout approach seems appropriate for its implementation in a TED detector for neutron capture TOF experiments.

There are, however, several aspects which need to be investigated and further optimized. One of them concerns the aforementioned effect of the signal undershoot, which can be most probably ascribed to an insufficient impedance matching between the multiplexing and final readout stages. Related to the response function itself, the measured

signal-to-noise ratio was still relatively small. To a large extent this can be ascribed to geometric effects of the prototype assembly, where a large fraction of the scintillation photons do not reach the photosensor. Additionally, this situation could be improved by using a large bandwidth amplifier, that could bring the signal to higher voltage levels, comparable to those of the PMT. Another relevant aspect that has not been discussed and needs to be considered is the dependency of the SiPM breakdown voltage and gain with temperature. Generally the thermal conditions in the measuring station of CERN n_TOF are rather stable. According to previous experience with SiPMs in that experimental conditions [10], gain fluctuations had a minor impact on the measured pulse-height spectra. Finally, there exist commercially available systems (see e.g. Ref. [21]) to compensate this type of fluctuation by adjusting the SiPM bias voltage according to a predefined dependency curve. Energy resolution is not a very relevant aspect in this type of experiments using TEDs which have an intrinsically low photon-yield but, if needed, the new detector can be supplemented with such a gain-temperature compensation system.

Our next steps towards the development of a functional TED with SiPM readout comprise a customized C₆D₆ cell with a volume and geometry, which fits better the shape of the SiPM. At present, 250 ml volume cells of C₆D₆ with a height of 100 mm and a square base surface of 50 × 50 mm² seem a reasonable choice. In terms of coping

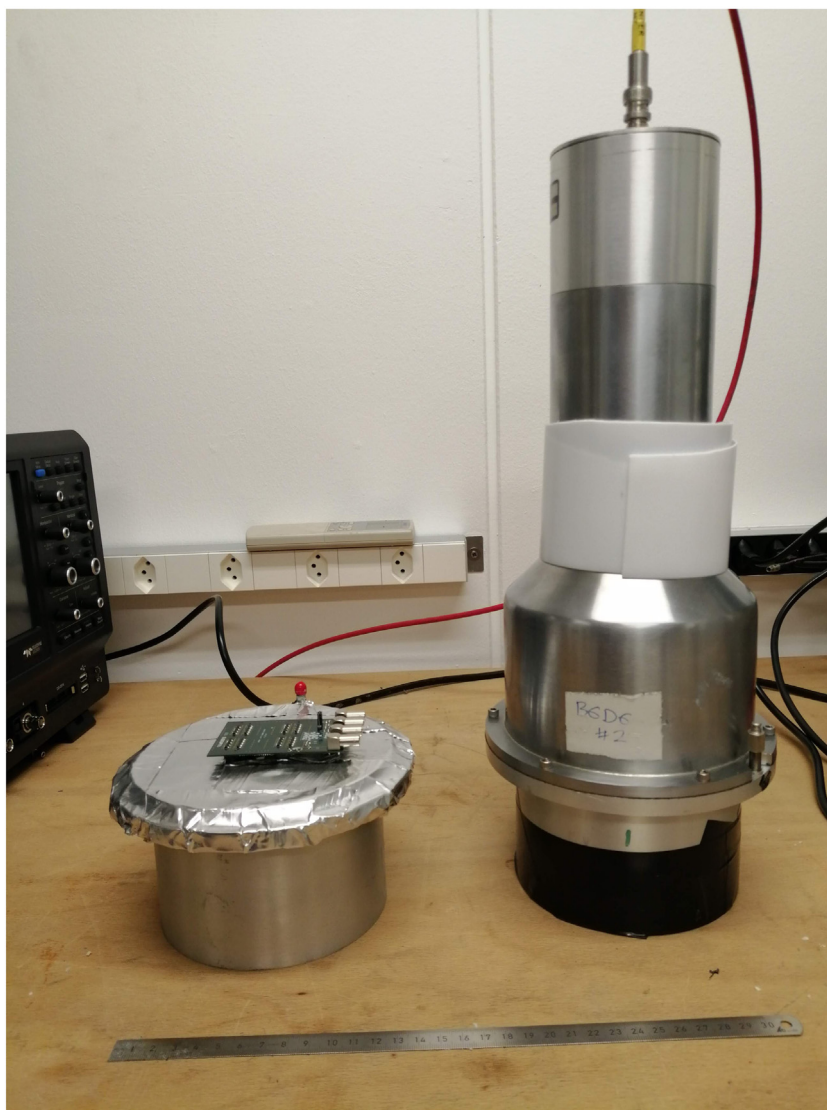


Fig. 8. Photograph showing a comparison of the new prototype with SiPM readout (left) and a conventional C_6D_6 detector equipped with PMT (right).

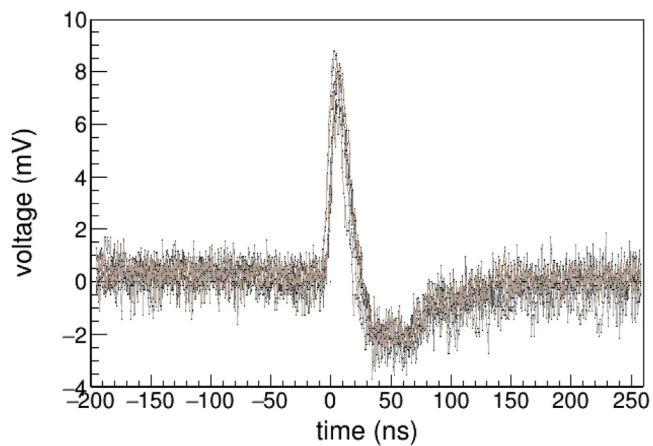


Fig. 9. Pulses measured with the prototype, showing the response of the sum of all pixels after the PCB sum-board.

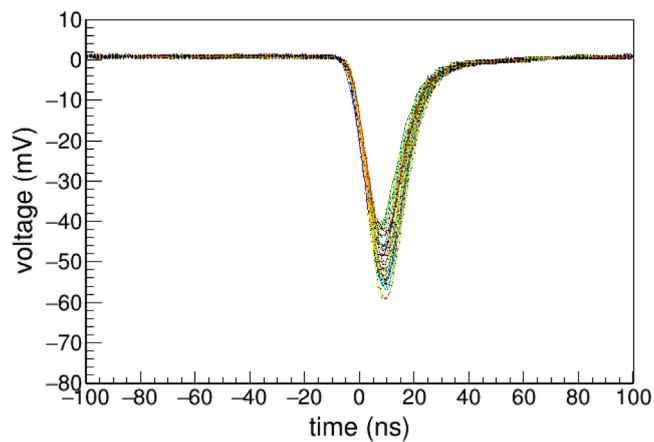


Fig. 10. For comparison, pulse shapes measured with the PMT (Photonis XP1208) readout are shown in this figure.

with the very high count rates encountered in high-luminosity facilities such as n_TOF EAR2 [22] low volume C_6D_6 cells seem to be better

suited than the ~ 1 liter cells commonly used until now. The new cell will be preferably made from C-fiber in order to preserve the low

neutron sensitivity of the detector. In this respect, tests are planned at HISPANOS-CNA (Seville) [23], in order to measure the sensitivity of the new detector to neutrons, in a similar fashion as the work reported in Ref. [8].

CRedit authorship contribution statement

J. Balibrea-Correa: Investigation, Methodology, Formal analysis, Data curation, Visualization, Writing -review & editing. **J. Leredegui-Marco:** Investigation, Methodology, Formal analysis, Data curation, Visualization, Writing -review & editing. **D. Calvo:** Methodology, Investigation, Formal analysis, Validation, Writing - original draft, Writing - review & editing. **L. Caballero:** Investigation, Methodology, Writing -review & editing. **V. Babiano:** Investigation. **I. Ladarescu:** Software. **M. Lopez Redondo:** Formal analysis. **J.L. Tain:** Investigation, Formal analysis. **A. Tolosa:** Investigation, Formal analysis. **C. Domingo-Pardo:** Conceptualization, Methodology, Supervision, Writing - original draft, Writing - review & editing, Funding acquisition, Investigation, Formal analysis, Resources. **F. Calvino:** Investigation. **A. Casanovas:** Investigation. **A. Tarifeño-Saldivia:** Investigation. **V. Alcayne:** Investigation. **D. Cano-Ott:** Investigation. **C. Guerrero:** Investigation. **M. Barbagallo:** Writing - review & editing, Investigation. **D. Macina:** Writing - review & editing, Investigation. **M. Bacak:** Investigation. **The n_TOF Collaboration:** Writing - review & editing, Resources.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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