Detection of thermal neutrons using $\text{ZnS}(\text{Ag}):^6\text{LiF}$ neutron scintillator read out with WLS fibers and SiPMs

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Abstract

In this paper we present the development of a 1-dimensional multi-channel thermal neutron detection system for the application in neutron scattering instrumentation, e.g. strain-scanning diffractometers. The detection system is based on $\text{ZnS}(\text{Ag}):^6\text{LiF}$ neutron scintillator with embedded WLS fibers which are read out with a SiPM. A dedicated signal processing system allows to suppress the SiPM dark counts and to extract the signals from the neutron absorption events.

For a single-channel detection unit which represents the elementary building block of this detection system we achieved a neutron detection efficiency of $\sim 65\%$ at $1.2\text{ \AA}$, a background count rate $< 10^{-3}\text{ Hz}$ and a gamma-sensitivity $< 10^{-6}$ (measured with a ^{60}Co source), while the dead time is $\sim 20\text{ }\mu\text{s}$ and the multi-count ratio is $< 1\%$. This performance was achieved even for SiPM dark count rates of up to $\sim 2\text{ MHz}$.

Keywords: thermal neutron detector, Silicon photomultiplier (SiPM), Multi-pixel photon counter (MPPC), $\text{ZnS}(\text{Ag}):^6\text{LiF}$ scintillator, WLS fiber

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1. Introduction

In the framework of an upgrade program for the time-off-flight diffractometer POLDI operated at the neutron spallation source SINQ at the Paul Scherrer Institute a new one-dimensional position sensitive detector for thermal neutrons based on the $\text{ZnS}(\text{Ag}):^6\text{LiF}$ scintillator is under development. The POLDI instrument [1] is used as a strain scanner to investigate residual stress in engineering materials and components. In order to allow a simultaneous measurement of the axial and transverse strain components during in-situ deformation measurements, the upgrade program is aiming for two oppositely placed detector banks each consisting of two one-dimensional 400-channel modules replacing the current single ^3He wire chamber. The main requirements for the detector are a channel width and height of 2.5 mm and 200 mm, respectively, a detection efficiency of $> 65\%$ at $1.2\text{ \AA}$, a time resolution better than $1\text{ }\mu\text{s}$, a background count rate below $3 \cdot 10^{-3}\text{ Hz/channel}$, and a gamma-sensitivity below 10^{-6} [2, 3].

2. Neutron detection units

Fig. 1 shows the schematic cross section of the sensitive volume of a single-channel neutron detection unit. This unit represents the elementary building block of the multi-channel system and it is build up by four times two layers of $\text{ZnS}(\text{Ag}):^6\text{LiF}$

neutron scintillation screens ND2:1 from Scintacor [4], formerly known as Applied Scintillation Technologies. Twelve WLS fibers Y11(400)M from Kuraray [5] are placed in grooves which are machined in the thicker scintillation screen (0.45 mm thickness) and are covered by the thinner scintillation screen (0.25 mm thickness). The stack is glued with optical epoxy EJ-500 from Eljen Technology [6] and has a total height of 2.8 mm and a width of 2.4 mm. Each individual single-channel unit is wrapped with thin aluminum foil to prevent optical cross-talk between adjacent channels.

On one side of the detection unit the fibers are cut, polished (see Fig. 2) and covered with an aluminized Mylar foil which acts as a specular reflector to increase the light yield at the other end of the fibers which is connected to the photosensor. Here the WLS fibers are bundled and glued into a 1.1 mm diameter hole in a plexiglas holder and polished afterwards, too.

As the $\text{ZnS}(\text{Ag}):^6\text{LiF}$ scintillator is opaque and the ranges of the ^3H and ^4H fragments originating from the neutron capture on ^6Li are rather short compared to the size of the detection unit, the scintillation light is not distributed uniformly within the sensitive volume of a detection unit but only one or a few WLS fibers will collect the light. To ensure anyhow a uniform illumination of the $(1 \times 1)\text{ mm}^2$ sensitive area of the SiPM the WLS fiber bundle is coupled to the SiPM with a so-called optical expander in between. This expander is a $\sim 2\text{ mm}$ long clear multiclad fiber with a diameter of 1.2 mm which is polished on both ends.

During our investigations we firstly built single-channel and three-channel prototypes with a length of 50 mm (see Fig. 2 for a three-channel prototype) and the results presented in this

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paper were achieved with these detection units. In a second step we increased the sensitive length of the detection units to 200 mm which is the desired channel dimension in vertical direction for the detector modules of the new POLDI instrument [2, 3].

One final detector unit will consist of 25 modules with 16 channels each. Fig. 3 shows the first 16-channel module. Each single-channel detection unit is mounted individually and can be replaced in case of damage without affecting the other units. The SiPMs are not soldered on the printed circuit board but contacted with spring contacts. This offers the possibility to exchange the SiPMs in case of a necessary replacement due to radiation damage or the use of new devices with improved properties. This 16-channel module is currently operated in the POLDI experimental area at the neutron spallation source SINQ at PSI. The first measurements show no significant variations in the performance of the detection units compared to the shorter prototype units.

3. Signal processing

The purpose of the signal processing system is to suppress the intrinsic SiPM dark counts and to identify the neutron absorption event in the scintillator. This is done by analysing the temporal distribution of the SiPM signals which are originating from either intrinsic SiPM dark counts or from detected photons of the scintillation event.

3.1. SiPM

The SiPM which is used to read out the detection units is the MPPC S12571-025C from Hamamatsu [7] with a sensitive area of $(1 \times 1) \text{ mm}^2$. The intrinsic dark count rate is in the order of 100 kHz. As the detector will be operated in a radiation environment, this dark count rate is expected to increase during operation due to an increase of the concentration of radiation induced defects in silicon [8]. Actually, a long-term measurement in the POLDI experimental area showed an increase of the SiPM dark count rate of about 100 kHz/mm² per year of operation.

In order to ensure a long-term operation the signal processing system needs to be able to deal with higher dark count rates than the intrinsic dark count rate of the SiPM. In our tests higher dark count rates were induced by illuminating the SiPM with an LED.

3.2. Signal processing system

The signal processing system is shown in Fig. 4 as a block-diagram and was explained in detail recently [9, 10]. We repeat here the main aspects: The system chain consists of a high band-width amplifier, a leading-edge discriminator, a filter, and an event generator unit. The threshold of the discriminator is adjusted sufficiently low so that all amplified and shaped SA-signals from the amplifier are accepted. The discriminator will create only one standard SD-signal independent of how many SiPM cells were triggered simultaneously by SiPM cell-to-cell

crosstalk. This kind of "digitization" allows to reduce the background count rate of the detector through the suppression of the cell-to-cell crosstalk events [3]. Unfortunately there is no way to suppress the correlated one-cell SiPM signals which are spread in time, usually called afterpulses, as their time structure looks similar to the time distribution of photons originating from a neutron absorption event. Consequently a SiPM with lowest possible afterpulsing probability was chosen for this work.

In the next step the filter unit analyses the temporal distribution of the SD-pulse sequence. For this analysis different algorithms are possible, as discussed in [2, 3, 9] and [11]. For the work presented in this paper, a filter based on a multistage "single-pulse elimination" scheme as described in [9] was used. It is based on a consecutive delayed self-coincidence of the SD-pulse sequence. Fig. 5 shows in the upper part a single basic filter stage which can be supplemented by any number of the same basic units and in the lower part the signals passing through this unit stage.

The requirement to pass a filter stage is a pulse at the filter input which shows up with a preceding pulse within the time interval defined by the width of the internal gate (retriggerable mono-flop type) signal. As a consequence single pulses and always the first pulse of a sequence of consecutive pulses are removed from the input sequence.

In this filter scheme the number N of consecutive filter stages and the width of the internal gate signals of the filter stages are tunable to optimize the performance of the system. It turned out that the suppression of the SiPM dark counts mostly depends on the gate width of the first filter stage and the total number of consecutive filter stages, while longer width values for the gates of the following stages lead to a better transmission and consequently better identification of extended pulse sequences corresponding to neutron scintillation events.

In case of an "identified" neutron absorption event SF from the filter the event generator (a retriggerable mono-flop with adjustable pulse width) is triggered and creates a neutron event signal SN. The system is now blocked for the duration of the SN signal and consequently no second SN pulse can be generated. This kind of blocking time is necessary to avoid multiple triggers from the same scintillation event which might happen due to the long emission time of the scintillator. As the event generator is a retriggerable mono-flop the actual blocking time is automatically adjusted corresponding to the strength of the signal at the filter output and is equal or longer than the actual adjusted pulse width, e.g. for a set value of 15 μs the actual blocking time is $\sim 20 \mu\text{s}$.

4. Measurements

The main characteristic properties of a neutron detector are the neutron detection efficiency which is the product of neutron absorption probability and trigger efficiency, the time resolution, the background count rate, the gamma-sensitivity, the multi-count ratio and the rate capability. These properties are not independent of each other but a trade-off and need to be optimized according to the application and requirements of the

detector. Due to the limited space here we only present the main results, a detailed overview can be found in [10].

The measurements with the neutron detection units were performed with an $^{241}\text{AmBe}$ neutron source providing $2 \cdot 10^4$ fast neutrons per second. The source itself was placed in the center of a $(0.8 \times 0.8 \times 0.8) \text{ m}^3$ moderator block made of polyethylene blocks and inside a tube made of lead with a wall thickness of 5 mm to shield the detection units from the 60 keV gamma-rays from the α -decay of ^{241}Am . The detection units under investigation were located in a small cavern $\sim 5 \text{ cm}$ away from the source.

The neutron absorption probability is given by the thickness of neutron absorbing material in the flight direction of the neutron and in case of this detector it is $\sim 80 \%$. With a filter system consisting of $N = 10$ stages and by adjusting the gate width of the first gate to 30 ns and the remaining gates to 500 ns a trigger efficiency of $\sim 80 \%$ could be achieved. This leads to a neutron detection efficiency of $\sim 65 \%$. The operation point to reach $\sim 80 \%$ trigger efficiency is the reference for the following measurements and is preserved as a benchmark.

The background count rate of the detection unit as a function of the number N of filter stages is shown in Fig. 6. The three curves correspond to different values of SiPM dark count rate, namely 100 kHz, 1 MHz and 2 MHz. At the operation point where one reaches with $N = 10$ filter stages a trigger efficiency of $\sim 80 \%$ the background count rate is $\sim 10^{-3} \text{ Hz}$ even for SiPM dark count rates of up to $\sim 2 \text{ MHz}$.

Fig. 7 shows the gamma-sensitivity of the detection unit as a function of the number N of filter stages once again for different SiPM dark count rates. The sensitivity was measured with a ^{60}Co gamma source (1.3 MeV) which was calibrated with a LYSO crystal mounted onto the photocathode of a PMT to estimate the rate of photons passing through the detection unit ($10^4/\text{s}$). As shown in the figure the probability to trigger on a gamma event increases with increasing dark count rate of the SiPM. But even for a SiPM dark count rate of 2000 kHz one can achieve a gamma-sensitivity $< 10^{-6}$ in case of using 10 filter stages which corresponds to a trigger efficiency of $\sim 80 \%$.

5. Summary

In the framework of the ongoing upgrade program for the engineering diffractometer POLDI at PSI a one-dimensional position sensitive thermal neutron detector based on $\text{ZnS}(\text{Ag}):^6\text{Li}$ scintillator is under development [2, 3, 9, 10, 11]. The scintillation light is collected with embedded WLS fibers which are bundled and connected to a single SiPM. In this scheme each individual detection channel has its individual photosensor and readout channel. As the SiPMs are small and insensitive to magnetic fields the detector construction gets compact and operational in the stray field of high magnetic sample environments. A dedicated signal processing system analyses the temporal distribution of the SiPM signals and the filter suppresses the SiPM dark counts and extracts the neutron absorption event up to a SiPM dark count rate of 2 MHz ensuring performance parameters which are comparable to current detection systems based on ^3He .

Figure 1: Cross-section of the sensitive volume of a single-channel detection unit, from [10]. This single-channel unit represents the elementary building block of a multi-channel detection system. The WLS fibers are placed in grooves which are machined in the thicker scintillation layers.

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Figure 2: Prototype neutron detection unit with 3 channels and a length of 50 mm. At the front end of the detection unit the WLS fibers are cut, polished and ready to be mirrored. At the rear end the 12 WLS fibers will be bundled and connected to a single SiPM.

Figure 3: 16-channel detection module. The upper figure shows the front side of the module consisting of 16 individual single-channel detection units with a length of 200 mm. The bottom figure shows the rear side of the module. The printed circuit board contains the preamplifier circuit, a special thermistor circuit for voltage stabilisation to compensate temperature variations, 16 signal connectors for individual readout and connectors for common LV and SiPM bias voltage.

Figure 4: Diagrammatic plan of the signal processing system, from [10]. The system consists of a high band-width amplifier, a leading-edge discriminator, a multistage filter, and an event generator unit. To optimize the performance the tunable properties are the threshold (thr) of the discriminator, the number (N) of filter stages, the retriggeable gate width of the first gate(1) and the gate(2...N) of the following filter stages, and the width (b-time) of the SN output pulse of the event generator.

Figure 5: Block diagram (top) and timing diagram (bottom) of the multistage filter system, from [10]. The system is based on a consecutive delayed self-coincidence on the input SD-pulse sequence and realises a "single-pulse elimination" to suppress SiPM dark counts and to extract neutron absorption events.

Figure 6: Background count rate of the neutron detection unit as a function of the number N of filter stages for different values of SiPM dark count rate. The parameters of the filter system were fixed to achieve a trigger efficiency of $\sim 80\%$ with 10 filter stages (red circle). Even for a dark count rate of 2 MHz a quite background rate of $\sim 10^{-3}$ can be achieved.

Figure 7: Gamma-sensitivity of the neutron detection unit as a function of the number N of filter stages for different values of SiPM dark count rate. The parameters of the filter system were fixed to achieve a trigger efficiency of $\sim 80\%$ with 10 filter stages (red circle). A gamma-sensitivity $< 10^{-6}$ can be reached even for SiPM dark count rates of 2 MHz. This is comparable to ^3He counters.