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Evaluation of two thermal neutron detection units consisting of ZnS/^{6}LiF scintillating layers with embedded WLS fibers read out with a SiPM

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ABSTRACT

Two single channel detection units for thermal neutron detection are investigated in a neutron beam. They consist of two ZnS/^{6}LiF scintillating layers sandwiching an array of WLS fibers. The pattern of these units can be repeated laterally and vertically in order to build up a one-dimensional position sensitive multi-channel detector with the needed sensitive surface and with the required neutron absorption probability. The originality of this work arises from the fact that the WLS fibers are read out with SiPMs instead of the traditionally used PMTs or MaPMTs. The signal processing system is based on a photon counting approach. For SiPMs with a dark count rate as high as 0.7 MHz, a trigger efficiency of 80% is achieved together with a system background rate lower than 10^{-3} Hz and a dead time of 30 μs. No change of performance is observed for neutron count rates of up to 3.6 kHz.

1. Introduction

A one-dimensional position sensitive detector for thermal neutrons is currently under development at PSI, in the framework of the upgrade of the engineering diffractometer POLDI [1] installed at the Swiss neutron spallation source (SINQ) at PSI. To allow a simultaneous measurement of the axial and transverse strain components during in situ deformation measurements, the actual ^{3}He detector module will be replaced by two oppositely placed scintillation detector modules. The main requirements for the new detector are a detection efficiency of 65% at 1.2 Å, a time resolution below 1 μs (standard deviation), a channel width of about 2.5 mm, a system background rate below 3×10^{-3} Hz/channel, a sustainable count rate of 4 kHz/channel and a gamma sensitivity below 10^{-6} at 1.3 MeV.

The worldwide supply shortage of ^{3}He which started in 2009 stimulated the development of alternatives to ^{3}He gas detectors for thermal neutron detection [2]. One of these alternatives is based on ZnS/^{6}LiF or ZnS/$^{10}B_2O_3$ scintillators combined with wavelength shifting (WLS) fibers for collecting the scintillation light. This technology is now widely used and well established. The two single-crystal time-of-flight diffractometers *SENJU* [3,4] and iBIX [5] at J-PARC, as well as the engineering diffractometer VULCAN [6,7] and the powder diffractometer POWGEN3 [8] in ORNL are examples of instruments currently in operation which are equipped with detectors based on this technology. Up to now, all the detectors of this kind use photomultiplier tubes (PMTs) or multi-anode photomultiplier tubes (MaPMTs) to read out the WLS fibers. The feasibility to use silicon photomultipliers (SiPMs) has not been proved yet. Nevertheless, the use of SiPMs for the new POLDI detector is very attractive because of their high packing fraction and their insensitivity to magnetic fields, two important characteristics in this project since the space in the POLDI experimental area is very limited and tests of samples in high magnetic fields are foreseen.

Two variants of a single channel detection unit which can constitute an elementary building block for a one-dimensional position sensitive multi-channel detector have been investigated in a neutron beam. The detection units consist of ZnS/^{6}LiF scintillating layers with embedded WLS fibers read out with a silicon photomultiplier (SiPM). In this paper, we present the design of the detection units, the signal processing system and the measurements of the probability of neutron capture, the light yield distribution for the capture of neutrons, the trigger efficiency, the system background rate, the count rate capability.

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2. Material and method

2.1. The detection units

Fig. 1 shows the schematic of the two detection units which were tested in the present work. They consist of two $ZnS/^{6}LiF$ scintillating layers (ND2:1 from Applied Scintillation Technologies [9]) sandwiching an array of WLS fibers (Y11(200)M from Kuraray [10]) with a diameter of 250 μm. The fiber pitch is 0.6 mm and 0.8 mm for the 4-fiber and 3-fiber detection units, respectively. In the 450 μm thick layer (bottom layer), three or four grooves of 300 μm width and 300 μm depth are machined. The fibers are glued into the grooves with an optical epoxy (EJ500 from Eljen technology [11]) and the top scintillating layer 250 μm thick is glued with the same optical epoxy.

On one side, the fibers are cut along the edge of the sandwich and polished. Then, an aluminum foil acting as a mirror is glued to improve the light yield on the other side of the fibers where the photodetector is connected. On this side, the fibers are glued together into the hole of a plexiglas holder and polished. Figs. 2 and 3 show a picture of the sandwich before and after assembling with a fiber holder.

The effective channel width is defined by the area covered by the fibers. It is about 2.4 mm. The additional space to a total width of 7 mm is used for handling purposes only. The length of the structure is 50 mm.

In a later multi-channel detector, this 2.4 mm wide groove/WLS fiber pattern without the additional handling space will be repeated to cover the needed sensitive area. In order to obtain the required neutron absorption probability, several such sandwiches will be stacked together (Fig. 4). A 4-sandwich detector would have a thickness of 2.8 mm and its intrinsic time resolution would be below 0.4 μs for all neutron wavelengths between 1 Å and 6 Å. The intrinsic time resolution is defined as the standard deviation of the neutron travel time from the moment it enters the detector to the moment it is absorbed in it.

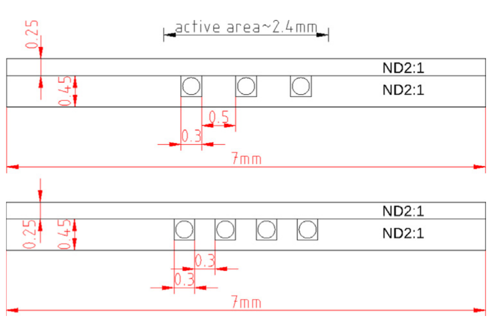

Fig. 1. Cross-section of the detection units with three fibers (top) and four fibers (bottom).

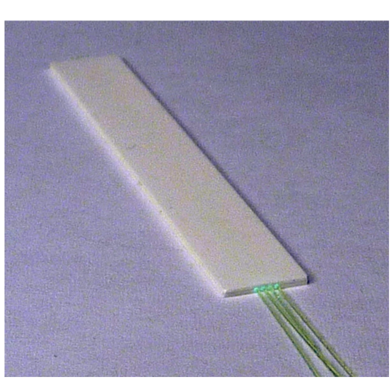

Fig. 2. The 4-fiber detection unit before assembling with a fiber holder.

Fig. 3. A detection unit ready to be connected to a SiPM.

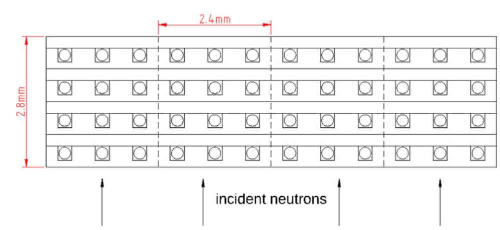

Fig. 4. Cross-sectional view of a possible multi-channel detector repeating laterally and vertically the pattern of the single channel detection unit with three fibers. The channels are delimited by the dashed lines. Each channel contains 12 WLS fibers.

The ^{6}Li concentration in the scintillating layers has been determined with a neutron transmission measurement. It amounts to 1.4×10^{22} atoms/cm^3. The hydrogen concentration amounts to about 2.4×10^{22} atoms/cm^3 and 4.8×10^{22} atoms/cm^3 in the scintillating layers and in the WLS fibers, respectively.

The SiPM used in this test is a 1×1 mm^2 S12571-025C MPPC from Hamamatsu [12]. It is operated at room temperature, at the recommended overvoltage of 3.5 V. In this condition, the SiPM has a PDE of 35% at 480 nm (the emission peak of the WLS fibers), a crosstalk probability of 22% [12], a dark count rate of 70 kHz and an afterpulse probability below 3% [13].

2.2. The signal processing system

The signal processing system is based on a photon counting approach. Two reasons make this approach feasible. First, the $ZnS/^{6}LiF$ scintillator is relatively slow and consequently, the photons to detect are sufficiently spaced out in time to be counted individually. Second, the SiPMs have an excellent photon counting capability.

Fig. 5 shows the block diagram of the signal processing system. The SiPM signal is amplified and shaped by a wide band-width amplifier. The output of the amplifier is fed into a fast leading edge discriminator with a threshold set at 0.5 photoelectron. The discriminator is set in burst guard mode so that its output signal stays high as long as the input is over the threshold. The duration of the output for a single photoelectron is 8 ns.