SoNDe

Solid-State Neutron Detector

INFRADEV-1-2014/H2020

Grant Agreement Number: 654124

Deliverable Report: D1.2 Materials Report

This project is funded by the Horizon 2020 Framework Programme of the European Union. Project number 654124.

Project and Deliverable Information Sheet

<table>
<tr><td rowspan="8">SoNDe Project</td><td colspan="2">Project Ref. No. 654124</td></tr>
<tr><td colspan="2">Project Title: Solid-State Neutron Detector SoNDe</td></tr>
<tr><td colspan="2">Project Website: http://www.fz-juelich.de/ics/ics-1/DE/Leistungen/ESS/SoNDe-Projekt/</td></tr>
<tr><td colspan="2">Deliverable ID: D1.2</td></tr>
<tr><td colspan="2">Deliverable Nature: Materials Report</td></tr>
<tr><td rowspan="2">Deliverable Level: PU</td><td>Contractual Date of Delivery: 31.10.2015</td></tr>
<tr><td>Actual Date of Delivery: 24.11.2015</td></tr>
<tr><td colspan="2">EC Project Officer: Bernhard Fabianek</td></tr>
</table>

Document Control Sheet

<table>
<tr><td rowspan="6">Document</td><td colspan="2">Title: Solid-State Neutron Detector SoNDe</td></tr>
<tr><td colspan="2">ID: MaterialsReport-D1.2</td></tr>
<tr><td>Version: 1.0</td><td></td></tr>
<tr><td colspan="2">Available at:</td></tr>
<tr><td colspan="2">Software Tool: MS Word 2011</td></tr>
<tr><td colspan="2">Files: MaterialsReport-Deliverable-D1.2.docx</td></tr>
<tr><td rowspan="4">Authorship</td><td>Written by</td><td>Günter Kemmerling,
Sebastian Jaksch, FZJ</td></tr>
<tr><td>Contributors</td><td></td></tr>
<tr><td>Reviewed by</td><td>Sebastian Jaksch, FZJ</td></tr>
<tr><td>Approved</td><td>Sebastian Jaksch, FZJ</td></tr>
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List of Abbreviations

FZJ	Forschungszentrum Jülich, Jülich Research Centre
H8500	Type of MaPMT used in the SoNDe project
JCNS	Jülich Centre for Neutron Science
LLB	Laboratoire Léon-Brillouin
ESS	European Spallation Source
IDEAS	Integrated Detector Electronics AS
MaPMT	Multi-anode Photomultiplier Tube
ROSMAP	IDEAS code name for counting electronics
TOF	time-of-flight

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Executive Summary

This report details the process for finding feasible materials for the use within the SoNDe project, focusing on the scintillation materials, which convert the neutron into detectable light, and the used photomultipliers for the detection of said light.

Several alternatives are considered and the choice for the current prototype is rationalized. The current prototype is using ^{6}Li-glass as a scintillator and a Hamamatsu H8500 as a photomultiplier.

Introduction

Within the SoNDe-project a neutron detector based on a solid-state scintillator is to be developed. Such detectors have already been in use for a long time and offer some attractive properties. The relatively high density of the scintillation material allows for thin neutron converters with high detection efficiency and a well-defined interaction point of the neutron. As a result of the low thickness, scintillation detectors also have almost no parallaxes effects and usually offer a high time resolution for the neutron capture.

The special characteristic of the neutron detector in SoNDe is the ability to cope with extremely high count rates of about 20 MHz at 10% dead time on a 1 m^2 detector area, associated with a position resolution of 6 x 6 mm^2 or 3 x 3 mm^2. In order to achieve these goals, a proper selection of the scintillator material and the light sensor is necessary, which is discussed in this report.

Solid-State Scintillators for thermal neutron detection in SoNDe

Today, there are essentially two types of solid state scintillators used for the detection of thermal neutrons, Li-glass and LiF/ZnS scintillators. In both types of scintillators the Lithium content is enriched with the isotope ^{6}Li, which offers a high cross section for neutron capture via the reaction

$$n + {}^{6}\mathrm{Li} \rightarrow \alpha + {}^{3}\mathrm{H} + 4.78\ \mathrm{MeV}$$

The secondary particles of this reaction lose their energy within the surrounding scintillator material in close distances to the interaction point. This gives rise to the emission of light, which is to be detected with a light sensor.

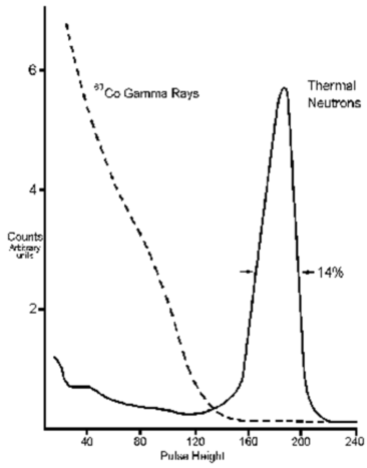

Fig. 1. Pulse height spectrum of Li-glass scintillator showing the pulse heights from neutron capture relative to that of ^{60}Co-gamma rays (brochure from scintacor, formerly AST).

Li-glass scintillators are described in [1]-[4] and are available in different types. For thermal neutron detection GS20 type glass scintillators are favorable, which contain 6.6 weight-percent of the ^{6}Li isotope. This high ^{6}Li content offers already with 1 mm thickness a detection efficiency of about 75% for thermal neutrons. GS20 glass

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scintillators are doped with Cerium as an activator, which mainly determines the properties of light emission. There are up to 6600 photons emitted per neutron capture ([5]) with a peak maximum at 390 nm wavelength. The decay time of the light emission is very fast, about 60 ns. As the material is transparent, the full amount of photons can be measured outside with an adequate light sensor. The gamma sensitivity of GS20 Li-glass is strongly dependent on the gamma energy; for gamma energies of less than 1 MeV the detection of gammas can be suppressed by pulse height discrimination methods, but for higher energies it is an issue, as these gammas cannot be distinguished from neutrons.

Ceramic scintillators based on a mixture of LiF and ZnS are also often used for neutron detection ([6]-[8]). These LiF/ZnS-scintillators are usually doped by Ag as an activator and have a very high light yield of up to 180000 photons per neutron capture with a peak maximum at 450 nm. Unfortunately both major components are opaque. Thus, due to the self-absorption of the emitted light the thickness is limited to 450-500 µm, which impacts detection efficiency. Another drawback of such scintillators is the rather high decay time of the light emission, which is a few µs and which limits the count rate capability. The gamma sensitivity can be reduced to 10^{-5} by pulse shape discrimination methods ([9]).

The high count-rate capability to be achieved in SoNDe requires a short signal processing time. Pile-up effects, which occur due to overlapping signals have to be avoided as this behavior hinders a discrimination between neutrons and gammas or makes it even impossible. As the length of the output pulses of the light sensor is closely related to the length of the light emission of the scintillator, the decay time of the scintillator has a high impact on the achievable high count-rates. In this respect the GS20 Li-glass scintillator, with a decay time faster by about a factor of 20, is clearly advantageous over the LiF/ZnS scintillator. This is also true related to the detection efficiency. As the LiF/ZnS scintillator is opaque, its thickness is limited due to light detection constraints. Since the number of neutron capture is dependent on the thickness, the detection efficiency is thereby also limited. As long as the environment of the detector doesn't show gammas with energies higher 1 MeV, the GS20 Li-glass scintillator also provides a simple and fast discrimination between neutrons and gammas by pulse height selection. Thus, the properties of the GS20 Li-glass scintillator seem to be superior over the LiF/ZnS scintillator to achieve the goals given in the SoNDe-project.

Light Sensor Device

The light sensor for the SoNDe detector should provide a fast and efficient detection the scintillator light and allow for the reconstruction of position information with a resolution of 6 x 6 mm^2 or 3 x 3 mm^2.

There are different methods to extract the position information from the light created by the neutron capture of the scintillator. A common method is based on the Anger principle [10], which is shown in Fig. 2.

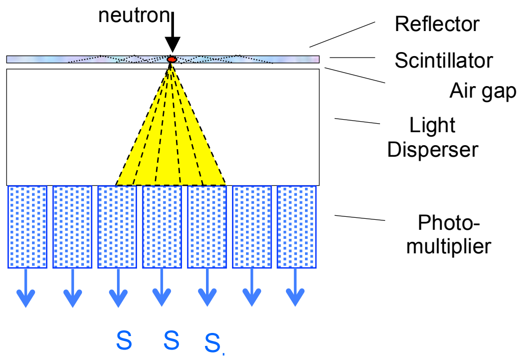

Fig. 2. Position reconstruction by Anger method based on photomultiplier light sensors (from [11])

The light created by the neutron capture within the scintillator is spread over several light sensor devices. By analyzing the light sensor signals, the position of the neutron capture can be calculated with a precision, which is much lower than the size of the light sensor devices. Unfortunately, the Anger method requires the determination of the light sensors that are hit by the emitted light and a digitization of their analog signals for the position reconstruction. This is typically a rather time consuming process, which limits the count rate capability of such detectors. Furthermore, the Anger method always occupies the area of several light sensors by one neutron capture. A much faster approach is the usage of a pixelated light sensor structure, where only one pixel is involved per neutron event. This method is realized within the SoNDe project. Together with the selection of a scintillator, which allows for a neutron/gamma discrimination by setting a comparator threshold, the count rate capability of the detector can be improved drastically.

In order to realize a pixelated sensor structure, currently only multianode photomultiplier (MaPMT) and arrays of silicon photomultiplier (SiPM) are the only feasible options. Single photomultiplier tubes or single SiPM modules usually need a larger guard space around the sensitive area, which decreases the overall neutron sensitive area and thereby also the overall detection efficiency.

MaPMTs are based on the common light detection method of vacuum tubes with a photosensitive cathode and several dynode stages, at which electron acceleration by electrical fields is used to yield a multiplication of the initial charge. SiPMs are based on a microstructure of photosensitive semiconductor diodes, which are operated in the breakthrough mode, such that an absorbed photon results in a charge avalanche at the anode of the diode (avalanche photodiode).

Both, MaPMTs and SiPMs, are available with a sufficient sensitivity to 390 nm light and both types provide also pixelated sensor structures of 6 mm x 6 mm or 3 mm x 3 mm. With respect to magnetic fields, SiPMs are much less sensitive but their gain shows a larger dependence on temperature changes. Anyhow, there are publications ([12]) showing that SiPMs undergo radiation damage effects with thermal neutrons at integrated doses, which are considerably lower than instrument life times at neutron sources (at the ESS for a SANS instrument approximately 5×10^{14} neutrons/cm^2 are expected over a lifetime of 10 years). Currently, this is a very important disadvantage of SiPMs which rules out their usage for neutron detection.

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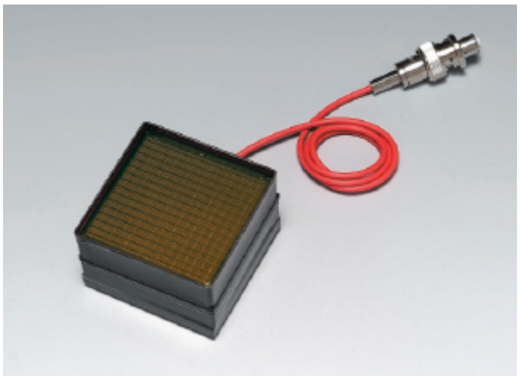

Fig. 3. Hamamatsu H8500 multianode photomultiplier with high voltage cable (picture from Hamamatsu). The device has got a sensitive area of 89% and pixel sizes of about 6 mm x 6 mm.

There are two types of MaPMTs produced by Hamamatsu, H8500 and H9500, which are suitable solutions for the SoNDe detector type. Both models have an overall size of 52 mm x 52 mm with only a small guard ring around the sensitive area such that a sensitive area of 89% can be achieved. Due to the small dead space, this MaPMTs offer scalable and modular detector designs with the possibility to build large detector areas by stacking several modules close together.

Also the electrical properties of the H8500 and H9500 fit well with high rate applications. The overall maximum current for a MaPMT anode is 100 μA. Taking into account that the MaPMTs typically are operated at a gain of 10^6 and that a neutron event will deliver about 400-500 photons per pixel, this should allow for rates of more than 1 MHz per module.

MaPMTs or devices with similar capabilities from other suppliers, such as the PLANACON photodetector [13], have been considered. However in any case there were technical reasons, which rendered the devices unsuitable for being used in the SoNDe detector concept. In the case of the PLANACON photodetector the readout time was to large to accommodate the needed high time resolution.

Conclusion

In this report we rationalized and detailed the choices made for the scintillator material as well as for the used MaPMT.

In case of the scintillator material we decided to use ^{6}Li-glass due to the good optical properties, the easy handling as well as the good neutron conversion characteristics. This allows us to have a material, where the maximum output of photons to the MaPMT is achieved and in parallel to have a good neutron/gamma discrimination.

The MaPMT was chosen due to its high native resolution combined with a high count-rate capability. Moreover, PMTs have shown little to no degradation under high neutron fluxes, leading to an improved lifetime. Also, by its high time-resolution, this type of MaPMT allows for a very sensitive TOF neutron detector.

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