

Current status of an optically-segmented single-volume scatter camera for neutron imaging

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Abstract. The Single-Volume Scatter Camera (SVSC) approach to kinematic neutron imaging, in which an incident neutron's direction is reconstructed via multiple neutron-proton scattering events, potentially offers much greater efficiency and portability than current systems. In our first design of an Optically-Segmented (OS) SVSC, the detector consists of an 8×8 array of $5 \times 5 \times 200$ mm³ bars of EJ-204 scintillator wrapped in Teflon tape, optically coupled with SensL J-series 6 x 6 mm Silicon Photomultiplier (SiPM) arrays, all inside an aluminum frame that serves as a dark box. The SiPMs are read out using custom (multi-GSPS) waveform sampling electronics. In this work, construction, characterization, and electronics updates are reported. The position, time, and energy resolutions of individual bars were obtained by measuring different scintillators with different reflectors. This work was carried out in parallel at the University of Hawaii and at Sandia National Laboratories and resulted in the preliminary design of the camera. Monte-Carlo simulations using the Geant4 toolkit were carried out for individual scintillator bars, as well as the array setup. A custom analysis using ROOT libraries in C++ simulated the SiPM response from Geant4 photon hits. This analysis framework is under development and will allow for seamless comparisons between experimental and simulated data.

1. Introduction

Neutron scatter imagers aim to measure incident neutron direction using the kinematics of multiple neutron scattering. Possible applications for these imagers covers a wide range of scenarios, like finding special nuclear material, treatment of nuclear waste, non-proliferation, nuclear medicine, and astrophysics, among others [1, 2]. The optically-segmented SVSC design offers high efficiency, neutron-gamma discrimination, and portability, compared to current available system.

This work describes the tests carried out for selecting the scintillator with the best performance. Updates on the status and challenges for operating of the current prototype

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are reported. In parallel with addressing the challenges of the full array, an alternative array was implemented. Simulations of the detector were carried out using muons to reproduce the full-waveform signals of the SiPM for calibration purposes.

2. Imaging theory for neutron double-scatters

To measure a neutron's incoming direction using the kinematic imaging technique, it must scatter off a proton in two different scintillating bars. During a scatter, part or all of the neutron energy is transferred to a proton. The reconstruction of the incident neutron energy E_n , can be obtained by the relation: $E_n = E_p + E_{n'}$, where E_p is the proton recoil energy and $E_{n'}$ is the neutron energy after the first scatter. The proton recoil energy can be estimated by measuring the intensity of the light at the bar ends. $E_{n'}$ is determined by the time-of-flight (Δt) and the distance (Δd) between the first and the second scatter, as:

$$E_{n'} = \frac{1}{2}m_n v^2 = \frac{1}{2}m_n \left(\frac{\Delta d}{\Delta t}\right)^2 \quad (1)$$

where m_n is the mass of a neutron, v is the speed of the scattered neutron, and d is the distance between the two scatters. A back-projected cone of possible source location can be obtained from the reconstruction of the neutron direction, as:

$$\cos \theta = \sqrt{\frac{E_{n'}}{E_n}}. \quad (2)$$

The kinematics are illustrated in the Figure 1 [3].

3. Detector description

The optically-segmented SVSC consists of an array of $64 \times 5 \times 5 \times 200$ mm³ bars of EJ-204 scintillator wrapped in Teflon tape, optically coupled to two SensL J-series 6×6 mm² SiPM arrays with silicone rubber interface EJ-560. Each SiPM array is connected to a board, obtained from Ultralytics, for reading individual channels. The scintillators, the SiPMs, and the interconnect boards were placed in a light-tight aluminum enclosure. The OS-SVSC camera prototype is shown in Figure 2.

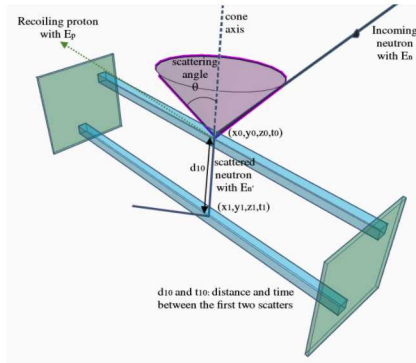


Figure 1. Double scatter event in the SVSC.



Figure 2. The optically segmented Single-volume scatter camera prototype.

The acquisition system consists of customized electronics developed at the University of Hawaii. It features board stacks that use 32 IRS3d application-specific integrated circuits (ASICs) with eight channels each, 128 channels per module. The readout is typically at 2.8 GS/s.

4. Experimental setup

Two independent experiments were set up to characterize individual $5 \times 5 \times 190 \text{ mm}^3$ of organic plastic scintillator bars. These measurements are presented in more detail [4]. In both cases, the ends of the test bars were optically coupled to two SensL J-series SiPMs with optical grease. Only fast from the devices were used. The acquisition was carried out by the DRS4 evaluation board [5]. The considered scintillators were those with the highest light yield values: EJ-200, EJ-204, EJ-230. EJ-276 was considered as well, given its pulse-shape discrimination capabilities.

For each sort of scintillator, three surface reflectivities were tested: wrapping the test bars with enhanced specular reflector (ESR); wrapping the test bars with diffusive Teflon plumber's tape; and using only the total internal reflection with no surface treatment for the test bars.

4.1. Single bar testing with ^{90}Sr

The test was carried out at the University of Hawaii (UH). It used a ^{137}Cs source for performing an energy calibration and a ^{90}Sr source for the position resolution study. The DRS4 board was self-triggered on a coincident signal with a threshold of 7 mV in both ends. The source was placed in a lead collimator to limit the distribution of betas along the test bar to approximately 2 mm. The collimator was mounted on a motorized stage that moves along the length of the test bar at designated intervals. The setup is shown in Figure 3. Repeated measurements were performed in order to study systematic effects.

4.2. Single bar testing with ^{22}Na

At Sandia National Laboratories (SNL), the test bars were characterized using a back-to-back annihilation gammas emitted from a ^{22}Na source. The trigger for the system consisted of a $5 \times 5 \times 5 \text{ mm}^3$ stilbene crystal wrapped in Teflon, optically coupled to a single channel J-series SiPM, mounted in a motorized linear stage. The test bar was placed opposite the trigger scintillator; the longitude of the bar was parallel to the motor motion. The ^{22}Na source was placed equidistant between the trigger and the test bar. The setup is shown in the Figure 4.

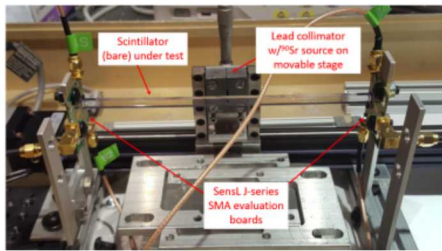


Figure 3. Testing device at UH.

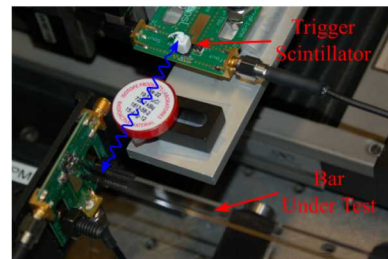


Figure 4. Testing device at SNL.

4.3. Single bar test results

The position of the interaction along the bar can be obtained by measuring the difference of arrival time at each end or measuring the log of the charge amplitude ratio using the pulses from both ends. The log of the charge amplitude ratio, as a function of the interaction position (z), is expected to be linear:

$$\ln \frac{A_1}{A_2} = \frac{L}{\lambda} - \frac{2z}{\lambda}, \quad (3)$$

where A_1 and A_2 are the pulse heights of channel 1 and 2, L is the total length of the bar, and λ is the effective attenuation length. This assumes that λ is the only source of light loss. The

Scintillator	σ_t (ps)	σ_z (mm)		σ_E/E (%)	
		^{22}Na	^{90}Sr	^{22}Na	^{137}Cs
EJ-200, bare	155 \pm 2	13.35	14.27	16.7	14.1
Teflon	154 \pm 3	10.29	7.65	14.5	15.8
ESR	145 \pm 3	11.14	12.09	16.6	12.2
EJ-204, bare	136 \pm 3	10.08	10.67	15.7	14.7
Teflon	142\pm2	8.06	6.54	13.1	14.3
ESR	125 \pm 3	8.59	9.64	17.6	12.2
EJ-230, bare	141 \pm 3	9.61	8.86	17.8	15.0
Teflon	142 \pm 2	8.39	6.32	22.6	13.9
ESR	156 \pm 3	10.17	8.52	23.4	13.0
EJ-276, bare	183 \pm 5	12.13	13.51	17.8	14.1
Teflon	171 \pm 2	9.29	9.54	16.5	14.1
ESR	177 \pm 4	11.65	10.45	15.0	11.3

Table 1. Summary of results with statistical (for σ_t). Position resolution measurements binned for energies between 300-400 ke Vee.

difference of time is expected to be linear:

$$t_1 - t_2 = \frac{z}{v} - \frac{L - z}{v}, \quad (4)$$

where v is the velocity of light within the bar. For each interaction, the values for time and amplitude of equations 3 and 4 were evaluated. The distribution of each source position was fit to a Gaussian function. Plots of mean and sigma of $\ln \frac{A_1}{A_2}$ and $t_1 - t_2$ as a function of the position were generated to characterize each scintillator/finishing. The position resolution was calculated as $\frac{\sigma_{avg}(z)}{m(z)}$, where σ_{avg} is the average of the standard deviation and m is the slope of a first order polynomial fit to the mean. The values of both, the position resolution using amplitude σ_z^A , and using time σ_z^t were combined to form the Best Linear Unbiased Estimator (BLUE) [6].

The time, position, and energy resolutions are summarized in Table 1. The best performing scintillator was EJ-204 wrapped with Teflon. EJ-230 reported comparable results; nevertheless, EJ-204 was preferred because it has a better light yield, desirable for detecting lower energies. Despite the differences between both setups, the measured position resolutions reported good agreement. The time-based position presented less sensitivity to systematic effects than the amplitude-based position [4].

5. Current detector status

Initial results using the full array for detecting muons showed crosstalk among neighboring channels. A test study, using a laser directly on the SiPM array, showed crosstalk up to 10% of the original signal. Complementary studies demonstrated the crosstalk was grouped in quadrants along the array, signals near the quadrant border don't affect channels located in a different quadrant. We concluded that this effect is due to several interfaces in the readout chain, specifically due to Samtec connector QTE-040-03, and likely in the SiPM array itself. Some options being considered to eliminate the crosstalk effect are customized arrays and smaller connectors.

5.1. Alternative array

An alternative array was built to learn more about the performance of the prototype components. It consists of four $5 \times 5 \times 190$ mm³ EJ-204 wrapped in Teflon, placed in the marked pixels

shown in Figure 5. The location of the bars was selected to avoid crosstalk and to be more likely to acquire double-scatter events. The bars are coupled with optical grease to SiPM arrays the ends. The acquisition was performed by two DRS4 eval kits daisy-chained for coincident triggering. An AmBe source was placed in front of bar 1 (B1) of the 4-bar layout. The trigger was set for coincident events in pairs of bars, where bar 1 was set for the first neutron-scatter and bars 2, 3, and 4, for the second scatter. By measuring the time of the signals at the end of the bars, the system was able to detect neutrons based on a cut on the average velocity, being within the expected range for the source spectrum (4.57 cm/ns for a neutron of 11 MeV), the velocity histogram is shown in Figure 6.

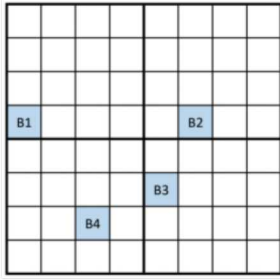


Figure 5. Layout of the alternative array.

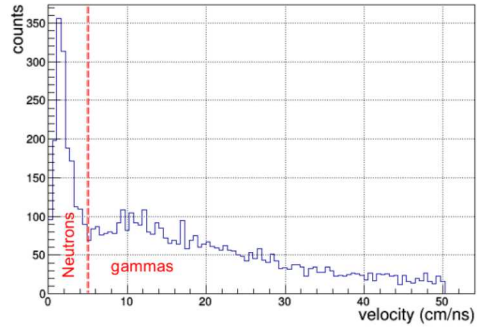


Figure 6. Histogram of the particles velocity between the two scatters.

6. Simulations

Muons are one option for calibrating the position and event time of the detector bars after assembly. Muons were generated using CORSIKA (COsmic Ray SIMulations for KASCADE), a Monte Carlo based Software for simulation of extensive air showers, version 76900. The position distribution, flux, and energies for muons are determined by the altitude, the atmosphere, and the magnetic field on the detector location. CORSIKA can parametrize most of these variables. In GEANT4, version 10.04, five thousand vertical muons (less than 10° from the zenith) obtained from CORSIKA, with altitude and atmosphere parameters for UH, were injected randomly over a rectangular area of 5.1 cm x 20 cm on the x-z plane. The muons were aimed 7 cm from the center of the optically segmented prototype. Expected energy deposition was obtained for each bar. Recreation of waveforms with GosSiP [7], an MC based Generic framework for the simulation of Silicon Photomultipliers, was used for tracking the path of the muons through the scintillator array. Preliminary results are shown in Figures 7, 8 and 9.

7. Conclusions

The best scintillator and reflector pair for the OS-SVSC system was EJ-204 wrapped with Teflon. Two independent setups obtained consistent results between measurements, within uncertainties. Measurements of time-based position resolution turned out to be more robust than amplitude-based position resolution. The differences in mechanical construction, optical coupling, and other possible systematic variations affect directly the amplitude measurements, which affect the calculation of position and energy resolutions. These variations must be controlled and calibrated. Nevertheless, achievable position resolution is expected to be less than 1 cm.

Results of an alternative array filled only with four bars, but consistent in materials and geometry with the prototype, demonstrated the capability of detecting neutron double-scatter events from an AmBe source. Moreover, the alternative array was able to distinguish between

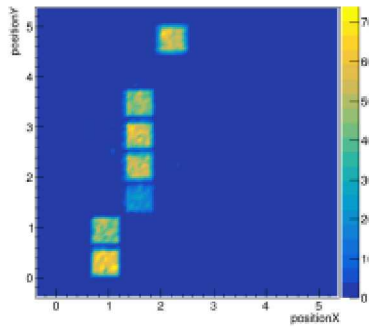


Figure 7. Photons detected at one SiPM array of the simulated SVSC detector due to a passing muon.

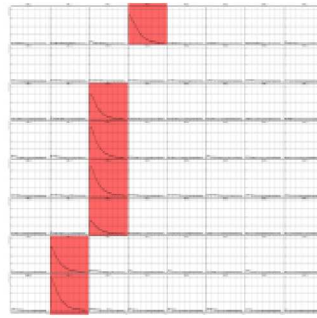


Figure 8. Waveforms simulated from the detected photons of Figure 7.

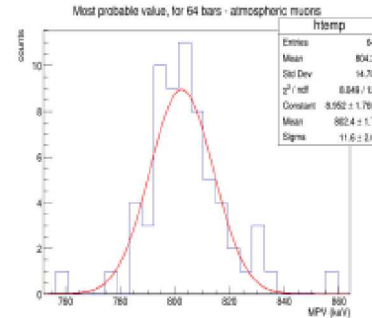


Figure 9. Histogram of the most probable value of the energy deposited by muons in the 64 bars.

neutrons and gammas via velocity. The reported velocities are in the expected range for neutrons coming from the AmBe source.

Full framework simulation development is undergoing. Interconnected simulations of the array, the SiPMs and muons have been carried out with specialized software. Muons were injected to the array as a method for simulating the calibration. Expected values for the energy deposition in each bar in the simulations were measured. The measurements will be compared with real ones, once the full prototype is operational.

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