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The Single Volume Scatter Camera Project

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Abstract*- The Single Volume Scatter Camera (SVSC) Collaboration is a multi-institution effort led by Sandia National Laboratories to develop portable neutron imaging systems for a variety of applications in non-proliferation and arms control. Current state-of-the-art kinematic neutron imaging systems consist of distributed scintillator volumes in which the position, time, and energy of multiple interactions are used to reconstruct a neutron's incoming direction. Such systems suffer from poor geometrical acceptance and are ultimately limited in performance by the size of the individual scintillator cells. The SVSC project aims to improve the geometrical acceptance by up to an order of magnitude by reconstructing multiple neutron interactions within the same scintillator volume. The corresponding size reduction also enables closer inspection, further improving detection rates. In addition, the imaging performance is no longer limited by the size of individual cells, but by how well two interactions in the volume can be reconstructed: component-level improvements such as improved light output of the scintillator or timing properties of the photodetector could lead to overall imaging performance improvements without a full-scale re-design of the system. Several detector design concepts are being explored with different methods to reconstruct the neutron trajectory. These include a single scintillator volume with high photodetector coverage in which interaction positions would be reconstructed using the position and arrival times of detected photons: this design concept requires excellent single photon timing resolution. A second design concept is the optically segmented approach in which only the spatial position along the bar needs to be reconstructed. Finally, an optical coded aperture mask could be used to reconstruct the interaction positions. Each of these concepts are undergoing rapid development paths in parallel. The concept, overall program goals, and current progress up to date will be presented.

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I. INTRODUCTION

The Single Volume Scatter Camera (SVSC) project aims to develop a portable kinematic neutron imaging system. In comparison to the current state-of-the-art implementation, a single scintillator volume is used to reconstruct multiple neutron interactions, rather than distributed volumes. If successful, a single-volume neutron scatter camera would result in an estimated order of magnitude improvement in detection efficiency [1], in addition to potentially vastly improving the size, weight and power of the instrument. The reduced size would also allow for closer inspection of an object, further improving detection rates and also improving imaging resolution.

The success of the instrument relies on accurately reconstructing the time, position, and energy of neutron-proton interactions within the volume of scintillator. The reconstruction of the incoming neutron direction is dependent on the incoming neutron energy, E_n, and the energy after the first interaction, E_n':

$$\cos\theta = \sqrt{\frac{E_{n'}}{E_n}}.$$

For fission energy neutrons, $E_n{}'$ is determined by the non-relativistic neutron time-of-flight equation, requiring knowledge of the position and time of two neutron interactions:

$$E_n{}' = \frac{1}{2} m_n \left(\frac{\Delta \mathrm{d}}{\Delta t}\right)^2.$$

Finally, E_n is determined by directly measuring the energy deposited in the first interaction. Figure 1 illustrates this procedure.

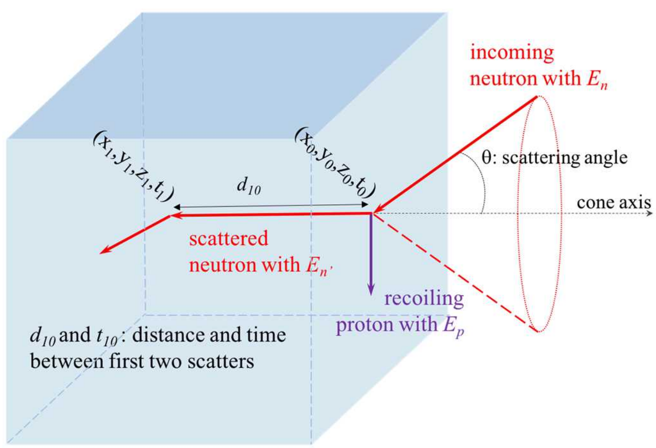

Figure 1: An illustration of kinematic neutron imaging. The incoming neutron interacts twice within the scintillator volume: its energy and direction (up to a conical ambiguity) are reconstructed with the position, time, and energy of the two interactions.

II. DESIGN CONCEPTS

Several implementations of this concept are being explored, requiring different methods to reconstruct the two interactions. The direct reconstruction method [1] is required for a single monolithic scintillator volume: the neutron interactions are reconstructed based on the incoming photon arrival times and locations on the faces of the cube. The optically segmented approach [2] employs an array of rectangular scintillator bars that are read out on both ends: only the position along the bar is reconstructed, while the other two dimensions are determined by which bar the scintillation event occurred in. These two design concepts are being developed experimentally to determine which will have the best imaging performance.

III. MONOLITHIC DETECTOR

The monolithic design relies on accurately measuring the time and position of individual photon hits impinging on all sides of the scintillator volume. The event position, time, and expected number of observed photons for multiple interactions in the volume are reconstructed by maximizing a likelihood function:

$$\mathcal{L} = \frac{e^{-\mu}\mu^{n}}{n!}\prod_{i=1}^{n}\sum_{j=1}^{N}\frac{\mu_j}{\mu}P_{ji}.$$

The index j refers to the particular interaction within the volume and i is an index over the list of all detected photons. The expected total number of detected photons from all interactions is μ, and for the jth interaction μ_j. N and n are the total number of interactions and the total number of detected photons for an interaction, respectively. Finally, P_{ji} is the probability that a photon emitted from the jth interaction at time t_j and position d_j was observed in a given photodetector pixel, denoted by index k, and at time t_i:

$$P_{ji} = \frac{\Omega_{jk(i)}Q_{k(i)}e^{\frac{-d_{jk(i)}}{\lambda}}}{4\pi\sum_k \frac{\Omega_{jk}}{4\pi}Q_k e^{\frac{-d_{jk}}{\lambda}}} f(t_i - t_j - \frac{d_{jk(i)}n}{c}).$$

The terms in the probability function include the scintillation pulse shape, $f(t)$, where the time is adjusted for the propagation time of the photon traveling at a velocity $v = n/c$ from the interaction location to the photodetector pixel. The term $\Omega_{jk(i)}/(4\pi)$ represents the solid angle coverage of the interaction for a particular photodetector pixel. $Q_{k(i)}e^{-d_{jk(i)}/\lambda}$ accounts for the photodetection efficiency of a given pixel ($Q_{k(i)}$) and for bulk optical attenuation of the photons traveling to a particular pixel. Finally, the remainder of the denominator ensures a normalized probability of the jth interaction based on the total probability of detecting a photon from that interaction. The feasibility of this approach has been explored with a detailed optical simulation in Geant4 [1], and improvements to its accuracy are on-going. We are also exploring with simulations the feasibility of position reconstruction using an optical coded aperture in front of the photodetector.

The accuracy of the event reconstruction is highly dependent on the single photon detection efficiency, the gain, spatial, and timing resolutions, as well as scintillation parameters such as the rise and fall time of the scintillation pulse and the total light output. We have performed characterizations of multiple photodetector types in terms of single photon detection efficiency, and gain/timing resolutions, along with pixel cross talk and after-pulsing. Scintillator characterizations are also on-going, and include high-fidelity characterizations of the pulse shape and the neutron light output [3][4].

The current prototype, shown in Figure 2, consists of a 50x50x50 mm block of EJ-204 scintillator, with two Hamamatsu H12700 multi-anode PMTs reading out two sides of the device. Traces are digitized with CAEN's 32 channel units based on the drs4 (domino-ring sampler) switched capacitor array chip: the V1742 has 5 GS/s sampling frequency and 12-bit resolution. Electronics and photodetector characterizations are underway, after which upgrades to either the electronics and/or photodetector will be implemented. Custom drs4-based 16-channel data acquisition boards have been developed and characterized for this project [5], and are expected to be used for the next prototype. Current scoping is underway to determine if currently available Silicon Photomultipliers (SiPMs) have the necessary dark count rate and timing for this application.

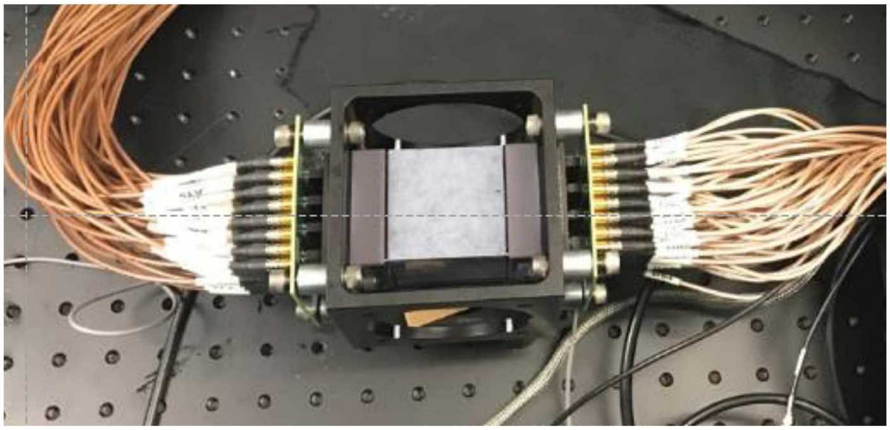

Figure 2: The current monolithic scintillator prototype. Currently, two sides of the scintillator are read out with photodetectors. The remaining four sides are coupled to black paper with optical grease.

IV. OPTICALLY SEGMENTED DETECTOR

The optically segmented approach differs from the monolithic approach by reducing both the overall channel count and the complexity of the event reconstruction. The system consists of 64 rectangular 5x5x200 mm scintillator bars, with both ends of each scintillator bar read out by SiPMs, specifically the ArrayJ-60035_64P-PCB from SensL, which consists of 64 pixels, each 6x6 mm. The necessary position reconstruction is reduced to the location of the interaction along the bar, defined as the z-axis, while x and y positions are determined by the particular SiPM pixel which measured the interaction. There are two methods that have been used to perform the reconstruction in z for a bar of length L. The first is the log ratio of the amplitudes, A_1 and A_2, which is linear in z so long as the bulk attenuation of the scintillator is accurately represented by an exponential with attenuation length λ:

$$\ln\frac{A_1}{A_2} = \ln\frac{e^{-z/\lambda}}{e^{-(L-z)/\lambda}} = \frac{L}{\lambda} - \frac{2z}{\lambda}.$$

The second method uses the difference in the time of arrival between the two readout ends, $t_1 - t_2$, which is also linear if the velocity of light within the bar, v, is constant:

$$t_1 - t_2 = \frac{z}{v} - \frac{L-z}{v} = \frac{2z}{v} - \frac{L}{v}.$$

Both methods were tested in a series of single-bar measurements to determine which scintillator material and reflector material were the best choice for the system. The event time accuracy and energy reconstruction were also characterized. Two independent testing apparatuses were used: both a Sr-90 (beta-emitting) source placed behind a 2 mm collimator and an electronically collimated (5 mm) Na-22 (511 keV gamma) source were used to scan the length of scintillator bars. Figure 3 shows a picture of both testing apparatuses. Recently published results indicate that EJ-204 wrapped in Teflon yielded sufficient position reconstruction accuracy to achieve a factor of 10 improvement in neutron double scatter efficiency compared to previous neutron scatter cameras [1][5]. The results are summarized in Table 1.

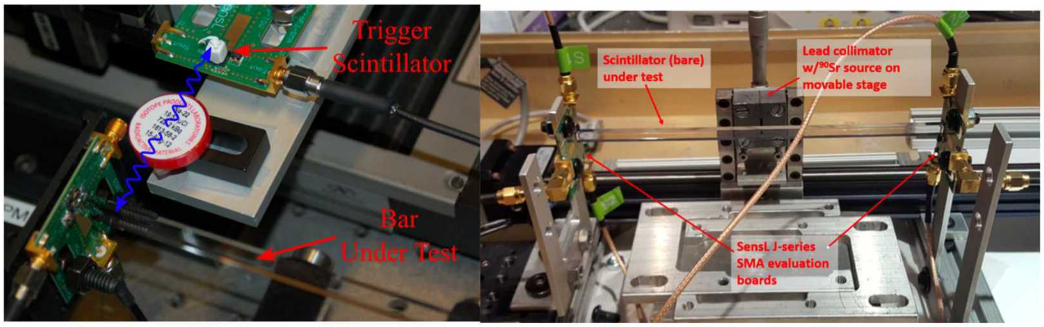

Figure 3: A picture of the Na-22 testing apparatus (top) and the Sr-90 testing apparatus (bottom). For the Na-22 apparatus, the blue lines indicate coincident and back-to-back 511 keV gammas from the source interaction in both the bar under test and a 5x5x5 mm stilbene crystal used as a trigger for the system. Taken from [6].

A bias in the event time, defined as $t_0 = (t_1 + t_2)/2$, was also observed as a function of position along the bar, presumably resulting from changes in the shape of the pulse rise as the photons propagate through the bar. This bias, which is on the order of 100 ps between the center and edge of the bar, must be calibrated for in the eventual system in order to accurately determine the event time for each interaction.

Table 1: Summary of single-bar event reconstruction results. The best overall performance, including the expected detection threshold, was measured with EJ-204 wrapped in Teflon. Taken from [6].

Scintillator	σ_t (ps)	σ_z (mm)		σ_E/E (%)	
		^{22}Na	^{90}Sr	^{22}Na	^{137}Cs
EJ-200, bare	155±2	13.35	14.27	16.7	14.1
Teflon	154±3	10.29	7.65	14.5	15.8
ESR	145±3	11.14	12.09	16.6	12.2
EJ-204, bare	136±3	10.08	10.67	15.7	14.7
Teflon	**142±2**	**8.06**	**6.54**	**13.1**	**14.3**
ESR	125±3	8.59	9.64	17.6	12.2
EJ-230, bare	141±3	9.61	8.86	17.8	15.0
Teflon	142±2	8.39	6.32	22.6	13.9
ESR	156±3	10.17	8.52	23.4	13.0
EJ-276, bare	183±5	12.13	13.51	17.8	14.1
Teflon	171±2	9.29	9.54	16.5	14.1
ESR	177±4	11.65	10.45	15.0	11.3
Syst. error	±7	±0.73	±0.42	±3.5	-

After determining the best performing scintillator and reflector material, the full system was assembled. Figure 4 shows the key components of the prototype system: the Teflon-wrapped scintillator bars, the SiPM array, readout/adaptor card, lattice support, and the aluminum enclosure walls. The pulses are digitized with custom developed electronics with 1 GS/s sampling rate and 12-bit resolution. Currently, measurements are underway to characterize the electronics response of the system, with a particular focus on potential sources of electronics cross talk, after which calibration and radiation measurements will proceed.

Once the electronics and imaging performance of the current prototype is characterized, our team will proceed with a second prototype to improve upon the performance of the first. One possible component improvement includes swapping the current digital acquisition electronics with an analog ASIC designed for fast timing measurements from SiPMs. We are currently exploring the performance of the TOFPET2 ASIC from PETSys Electronics [7] to serve this function. In addition, we are exploring the use of Frequency Domain Multiplexing [8] to reduce channel count while still digitizing waveforms. Other component improvements could include alternative SiPMs, or custom scintillator formulations to improve light output and pulse rise time, and potentially include pulse shape discrimination capabilities for particle identification. We have performed additional single-bar characterizations on several formulations of glass-based scintillator [9]. This work is on-going, but preliminary results indicate that current formulations have good timing performance and superior light output compared to commercial plastics. We will continue to explore different formulations to optimize physical robustness, optical transport properties such as attenuation length, and scintillation properties relevant for neutron imaging.

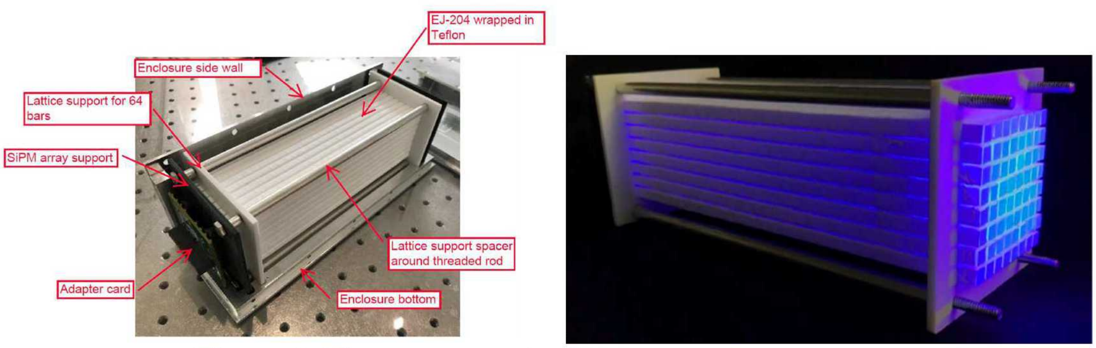

Figure 4: The current optically segmented prototype.

V. SUMMARY

The Single Volume Scatter Camera collaboration is a multi-institution effort led by Sandia National Laboratories to enable portable neutron kinematic imaging for non-proliferation and arms control applications. In addition to vastly reducing the size of the instrument compared to previous neutron kinematic imagers, the proposed device is designed to have up to a factor of ten improvement in efficiency for the required double scatter events, due to improvements in the geometrical acceptance. Other benefits include the potential for increased statistics and imaging resolution due to the ability for a portable device to be positioned closer to the object of interest. The collaboration is currently constructing the first prototypes of two different types: a monolithic volume of scintillator in which the event is reconstructed by maximizing a complex likelihood function, and an array of optically segmented scintillator bars in which the position along the bar is reconstructed with simple linear relations. Both prototypes are in the early phase of detector characterization, and component upgrades for each are being pursued in parallel. Planned upgrades include electronics, photodetectors, and scintillator materials.

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