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# Timing and position response of a block detector for fast neutron time-of-flight imaging ☆

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ABSTRACT

Our research effort seeks to improve the spatial and timing performance of a block detector made of a pixilated plastic scintillator (EJ-200), first demonstrated as part of Oak Ridge National Laboratory's Advanced Portable Neutron Imaging System. Improvement of the position and time response is necessary to achieve better resolution and contrast in the images of shielded special nuclear material. Time-of-flight is used to differentiate between gamma and different sources of neutrons (e.g., transmission and fission neutrons). Factors limiting the timing and position performance of the neutron detector have been revealed through simulations and measurements. Simulations have suggested that the degradation in the ability to resolve pixels in the neutron detector is due to those interactions occurring near the light guide. The energy deposition within the neutron detector is shown to affect position performance and imaging efficiency. This examination details how energy cuts improve the position performance and degrade the imaging efficiency. Measurements have shown the neutron detector to have a timing resolution of $\sigma=238$ ps. The majority of this timing uncertainty is from the depth-of-interaction (DOI) of the neutron which is confirmed by simulations and analytical calculations.


## 1. Introduction

Fast neutron interrogation is desirable for certain applications because it is highly penetrating and can cause fissions. The basis of operation for associated particle based imaging systems is illustrated in Fig. 1. Inside of the deuterium–tritium (DT) neutron generator, an ion source of deuterons and tritons is accelerated via an electric field and collides with a DT target. Because of the relative cross-sections, 98% of reactions are DT reactions. The other reactions are DD and TT reactions. When a DT reaction occurs, an alpha particle and a neutron are emitted,

$$ {}^{2}_{1}\mathrm{H} + {}^{3}_{1}\mathrm{H} \rightarrow {}^{4}_{2}\mathrm{He}(3.5\ \mathrm{MeV}) + {}^{1}_{0}\mathrm{n}(14.1\ \mathrm{MeV}) $$

where the alpha and the neutron are emitted with trajectories oriented approximately 180° apart. The associated particle detector detects interaction location and time of the alpha particle. By combining the alpha particle information with the DT target location, the direction and starting time of each associated neutron is determined. The neutrons from the DT reaction can pass through, scatter off of, or induce fissions in the inspected object. Additionally, gammas are created from inelastic scatter and fission interactions. These neutrons and gamma rays may be detected by an array of block detectors placed in the location of the neutron detector shown in Fig. 1. Based upon all these observables, images of the interrogated object can be constructed, as described in Refs. [1,2]. Prototype associated particle imaging systems, such as the Nuclear Materials Identification System (NMIS) [3] and Advanced Portable Neutron Imaging System (APNIS) [4], are being developed in order to image and characterize shielded special nuclear material (SNM). The block detector examined herein is the detector used in APNIS.

Pixelated block detectors are widely used in and researched for medical imaging, especially imaging utilizing time-of-flight (TOF) positron emission tomography [5–8]. Designs and techniques developed for and used in pixelated block detectors for medical imaging (e.g., light sharing between photodetectors, light guide to improve position response, and readout) have been adapted to detect fast neutrons. In order to achieve better resolution and contrast in the images of shielded SNM taken with associated particle imaging systems, this work identifies and examines the limits inherent to this block detector design.

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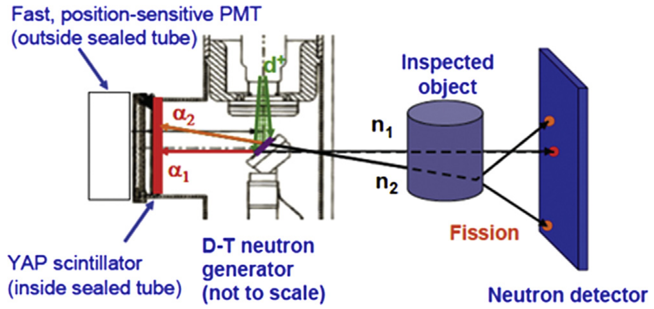


**Fig. 1.** In tagged neutron interrogation, the associated particle detector detects the alphas from the DT reaction within the DT neutron generator. The neutron associated with the detected alpha particle passes through or interacts with the inspected object. The neutron or its interaction product(s) may be detected in the neutron detector [1].

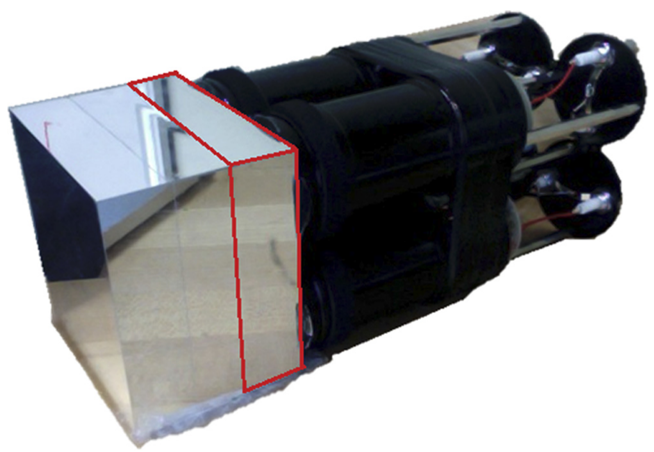

**Fig. 2.** The block detector based upon Oak Ridge National Laboratory design for APNIS. The red boxes outline the segmented light guide. Located to the left of the light guide is the 10 × 10 EJ-200 array. Located to the right of the light guide is the 2 × 2 array of PMTs. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this article.)

Measurements were made of timing and position performance and compared to Monte Carlo simulations in order to detail the understanding of important design considerations affecting performance of pixelated block detectors used in TOF-based imaging. Moreover, analytical timing calculations are made to improve confidence in the measured and simulated response.

## 2. Simulation and experimental methods

### 2.1. Design of the block detector

The design of the neutron detector (see Fig. 2) uses a 10 × 10 array of Eljen's EJ-200 plastic scintillator [9]. Plastic was chosen for the neutron detector for several reasons. Plastics, specifically polyvinyl toluene (PVT), have large optical path lengths (4 m) and are highly hydrogenous ($5.17 \times 10^{22}$ H-atoms/cm$^3$). EJ-200 has a fast rise time (0.9 ns) and good scintillation efficiency (10,000 photons/MeVee). In addition, EJ-200 is relatively inert, easy to machine, and low cost compared with other scintillation materials. The $1 \times 1 \times 5$ cm$^3$ pixels have smooth cut surfaces on all sides and 3M's Enhanced Spectral Reflector on each side except for the one coupled to the light guide. The array of pixels is optically coupled to the segmented light guide. The segmented light guide, whose design is discussed in Ref. [10], is used to improve the linearity of the position response and improve contrast resolution. The pixels, reflector, and light guide are bonded with an optical epoxy (DYMAX OP-20). The neutron detector is read out with four fast 2-in. Hamamatsu H10570 photomultiplier tubes (PMT) arranged in a 2 × 2 array, which is bonded to the light guide with a semi-permanent optical epoxy (MG Chemicals RTV615-1P). Anger logic is utilized for electronic readout, and associated methods are used for image reconstruction.

### 2.2. Experimental setup

The neutron source used in our experiments was a Thermo Scientific API 120 DT generator located at Oak Ridge National Laboratory. The face of the neutron block detector was positioned approximately 30 cm from the tritium target. All measurements utilized three Agilent Acqiris DC282 digitizers (2 GHz, 10 bits). Each digitizer was set to acquire two channels at 4 GSa/s with a user selectable voltage range. The four PMTs from the neutron detector and a Burle 8850 PMT reading out the associated particle detector were directly connected to the digitizer. The voltage ranges for each channel were individually set to minimize wasted range and clipped (i.e., out of range) signals. The neutron block detector PMTs and the alpha particle detector PMT were readout with 2 V ranges and a 500 mV range, respectively. The digitizer recorded waveforms after utilizing the built-in anti-aliasing filter. The low pass filter was set at 700 MHz to reduce high frequency noise throughout the waveforms. A set of waveforms were acquired anytime a signal in one of the neutron detector PMTs reached the threshold level of 60 mV, corresponding to approximately 0.01 nC of total charge collected.

In order to isolate the timing performance of the neutron block detector, the timing performance of the associated particle detector had to be determined, which was done with two reference detectors. The two reference detectors were made of a 2 mm thick pixel of EJ200 attached to a Hamamatsu H6533 PMT. The timing performance of the reference detectors was found by taking a coincidence measurement with $^{22}$Na. Finally, the reference detectors were then placed in front of the DT generator in the same position that the neutron block detector was for the experiment. This allows the timing performance of the reference detectors to be removed from the coincidence measurement with the associated particle detector. Because the reference detectors do not necessarily have the same timing performance, a system of equations was used:

$$\begin{cases} \sigma^2_{\mathrm{ref_A}} + \sigma^2_{\mathrm{ref_B}} = \sigma^2_{\mathrm{sys_{ref}}} \\ \sigma^2_{\mathrm{APD}} + \sigma^2_{\mathrm{ref_A}} = \sigma^2_{\mathrm{sys_A}} \\ \sigma^2_{\mathrm{APD}} + \sigma^2_{\mathrm{ref_B}} = \sigma^2_{\mathrm{sys_B}} \end{cases}.$$

The knowns are the systems' time variance: reference detectors ($\mathrm{sys_{ref}}$), the associated particle detector with the first reference detector ($\mathrm{sys_A}$), and the associated particle detector with the second reference detector ($\mathrm{sys_B}$). Thus, with three equations and three unknowns, this system of equations is solved for the timing performance of the associated particle detector:

$$\sigma^2_{\mathrm{APD}} = \frac{\sigma^2_{\mathrm{sys_A}} + \sigma^2_{\mathrm{sys_B}} - \sigma^2_{\mathrm{sys_{ref}}}}{2}. \quad (1)$$

All the data was acquired using the same settings for the digitizer, except for varying the voltage range where appropriate. The performance of this design of the associated particle detector is explored further in Ref. [11].

### 2.3. Post-processing

Only the full energy peak for the alpha detector was used, but no energy cut was made for the neutron detector in post-processing. The time pickoff employed was a simple digital