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Demonstration of two-dimensional time-encoded imaging of fast neutrons

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ABSTRACT

We present a neutron detector system based on time-encoded imaging, and demonstrate its applicability toward the spatial mapping of special nuclear material. We demonstrate that two-dimensional fast-neutron imaging with 2° resolution at 2 m stand-off is feasible with only two instrumented detectors.

1. Introduction

Time-encoded imaging (TEI) is an approach to directional fast neutron or gamma detection that has the potential to reduce cost and complexity compared to current imaging systems. TEI is in many ways analogous to coded-aperture imaging, in which the spatial modulation of a particle flux is induced by a fixed mask and detected by a position-sensitive detector. Rather than modulating the particle flux in space, TEI modulates the particle flux in time. The modulated flux is detected by a small number of time-sensitive detectors as opposed to highly pixelated position sensitive detectors in the case of coded-aperture imaging. Essentially, a moving mask that attenuates incoming particles results in a time structure that depends on the source location.

A TEI system addresses serious drawbacks of other neutron and gamma imaging systems. For example, the neutron scatter camera [1,2] and Compton imagers rely on multiple interactions in order to determine the trajectory of incoming particles. Such systems inherently suffer from low efficiency, while requiring multiple planes instrumented with high channel count, position-sensitive detectors. Coded-aperture systems [3] also require high channel count, position sensitive detectors, which can be a source of systematic uncertainty in the detector response. In contrast, a single detector with a time-modulated collimator encodes directional information in the time distribution of detected events.

We foresee two transformative advantages of TEI. First, a new design space is opened for effective and low-cost imaging systems. Time-encoding based imaging systems have a low channel count, reducing cost and increasing robustness by simplifying system integration, calibration, and reducing systematic uncertainties. Second, the angular resolution of the image reconstruction depends primarily on the collimator design: it is effectively decoupled from the method used for particle detection, which drives the detection efficiency as well as the energy resolution for gamma imaging. Thus, in a time-encoding imager, both angular resolution and energy resolution can be independently optimized. There is, however, a tradeoff between the desired angular resolution of the image and sensitivity to the source. Because a single mask element must completely block a point source from the detector's view, there is a limit to how large the detector(s) can be while maintaining the high imaging resolution yielded by smaller mask elements. Therefore, the system must be optimized for the desired application, taking into account the typical distance from the source.

Finally, there are a number of theoretical and technical challenges associated with a time-modulated mask. In coded-aperture imaging, the mask pattern is typically chosen to minimize correlations: for example, Uniformly Redundant Arrays, or URAs, are based on binary sequences with delta-function autocorrelation functions, or system point-spread functions [4]. Modified Uniformly Redundant Arrays, or MURAs, are binary sequences with the constraint that they have a correlational inverse which is unimodular. Such patterns not only have a delta-function point spread response, but image with an optimal signal to noise ratio for point-like sources [4].

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Neutron sources in the context of nuclear nonproliferation applications are generally not ideal: the sources may be extended rather than point-like. In such cases, the optimized signal to noise ratio is not typically achieved with the ~ 50% open fraction, or throughput, of MURAs. In addition, the particle source is not infinitely far away, and the effective attenuation of fast neutrons requires thick masks: the image is not the perfect correlation between the source and mask, but includes secondary effects in addition to a background component. For these reasons, a random mask pattern is used for these studies, allowing the freedom to choose an open fraction suited to extended sources. It has been shown that a random pattern is sufficient at limiting artifacts in the reconstructed image, although there is a possibility that correlations exist in long random sequences [5].

Here we report the results of laboratory demonstrations of the TEI concept applied to two-dimensional imaging of distributions of SNM with a prototype system. We first describe the construction of the detector system, calibrations, and data acquisition and analysis in Section 2. Next, measurements and results of three imaging scenarios are presented in Section 3.

2. Detector system

The goal of our two-dimensional TEI prototype was to demonstrate proof of feasibility for high resolution image reconstruction. As such, the major driver was to design a mask-detector geometry that achieves a relatively high intrinsic angular resolution. Smaller sensitive detector volumes were chosen for better imaging resolution at the cost of lower sensitivity. Dwell times reported here have the potential to be reduced with a fully optimized system.

The final design has a rotating cylindrical mask consisting of 27 vertical rows of high-density polyethylene (HDPE) mask elements. Each element is an arc segment with an angular width of 2.4° and height of 1.9 cm. The inner diameter of the arc segments is 45 cm, and the outer diameter is 55 cm. The thickness of the elements was chosen to sufficiently moderate neutrons resulting from fission, for which the average scattering length through HDPE over the relevant energy range is approximately 4.5 cm. With appropriately sized central detectors, this mask design gives an expected intrinsic angular resolution of ~2.5° in both horizontal and vertical dimensions. Each row is constructed from eight 1/8 arc sections machined from a single sheet of HDPE, leaving a 0.125 in. thick layer on the inner radius as a backing to secure each element to the mask. The 216 segments were then adhered together to form a single self-supporting structure. Placed at the center of the rotating mask are two one in. diameter by one in. deep aluminum cells filled with EJ-309 liquid organic scintillator, each coupled to one Hamamatsu H1949-50 two in. diameter photomultiplier tube assembly. A photo of the prototype detector as built is shown in Fig. 1.

In a study of mask designs for a traditional coded aperture imaging system, an open fraction of 30% was determined to be optimal for the extended source distributions that were used in laboratory tests [6]. This open fraction resulted in a total of 2816 mask elements and 1207 apertures. The mask pattern was chosen out of 100 randomly generated patterns: simulated image reconstruction performance was evaluated against several test distributions, and the mask with the most accurate reconstruction and the fewest artifacts was selected. The result is not an optimal pattern, but it was judged to be good enough to demonstrate the feasibility of this technique.

The mask sits on a rotation table driven by an Arcus stepper motor: the drive wheel of the motor is in contact with a rubber gear strip that runs along the inner main wheel of the rotation table. A rotary encoder is attached to the table ring to measure the angle of rotation. Finally, a metal divot attached to the rotation table passes over a switch on the stationary mask frame to mark the end of one rotation.

2.1. Electronics and data acquisition

Signals from the PMTs were digitized by a Struck SIS3316, 250 MS/s desktop digitizer. During the measurements, the detector system continuously buffered data from the SIS3316 digitizers. After a fixed dwell time, the detector was halted and the entire buffer is written to hard disk. This allowed for close synchronization of position information recorded by the encoder to the data recorded for each time period without having to use multi-threaded acquisition software. As a result, the system experienced a dead-time of ~5% during read-out.

During measurements, an Arcus controller board continuously read the encoder value, motor pulse value, and the state of the frame switch. When the switch transitioned between off and on values, a digital pin connected to a DG535 pulse generator outputted a NIM compatible signal to the clock timestamp reset of the digitizer. When a new rotation began, the readout event timestamp coincided with a time equal to zero.

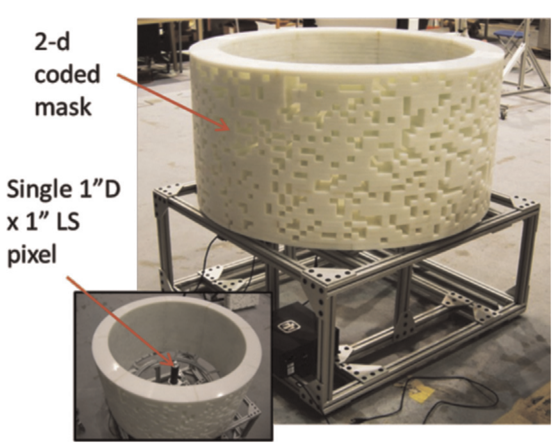

Fig. 1. Photograph of the 2-D TEI system. Two central one in. diameter by one in. thick liquid organic scintillator detectors (inset) are surrounded by a rotating high density polyethylene mask. The mask has an inner diameter of 44 cm, an outer diameter of 55 cm, and a height of 50.8 cm.

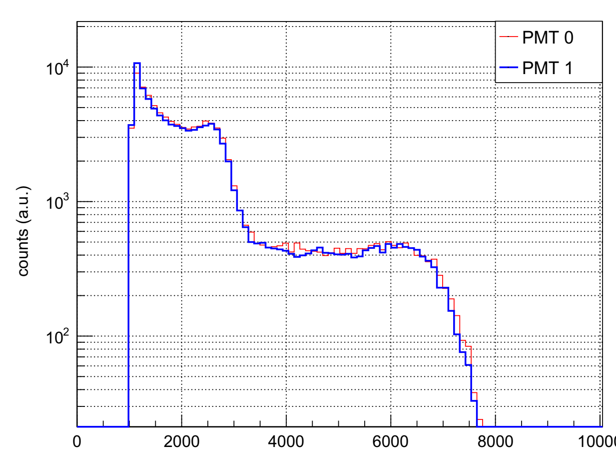

Fig. 2. The measured pulse height spectrum from the two liquid scintillator cells using a ^{22}Na gamma source.