# Studies for a High-Resolution Two-Dimensional Time Encoded Neutron Imager

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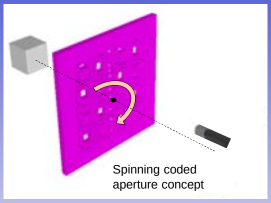
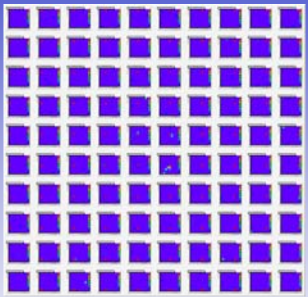
## Introduction

Time encoded imaging (TEI) is a new approach for energetic radiation detection that produces images by inducing a time-dependent modulation of detected particles. Briefly, in time-encoded neutron imaging, a time modulation of a detected neutron signal is induced—for example, a moving mask that attenuates particles with a time structure that depends on the source position. Time-encoded imaging is in many ways analogous to coded aperture imaging; the *spatial* modulation of a particle flux induced by a fixed mask on a *position-sensitive image plane* is replaced by the *time* modulation of a particle flux induced by a moving mask on one or a few *time-sensitive detectors*. TEI-based detectors use single-scatter events and have a low channel count, reducing complexity and cost while maintaining high efficiency with respect to other radiation imaging techniques such as double-scatter or coded aperture imaging. The scalability of TEI systems makes them a very promising detector class for weak source detection. Conceptually, the spatial-temporal analogy with coded aperture imaging extends to the high-resolution, two-dimensional imaging regime. We have considered various detector designs for high-resolution imaging, with the goal of simple and low-cost detector systems for arms control treaty verification applications, among others.

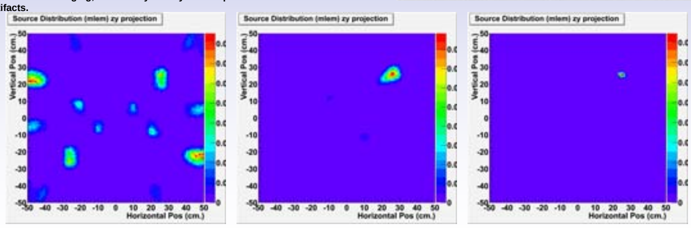
## Simulation studies of high-resolution, two-dimensional time-encoding imagers

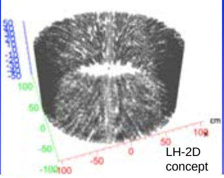
- Various designs under consideration: spinning coded aperture, 2-D LIGHTHOUSE, etc.
- Conceptually, spatial → temporal analogy with coded aperture technique extends to high-resolution two-dimensional imaging.
- Practically, two issues arise.
  - Difficult to achieve the modulation as a function of position for a mechanically moving mask.
  - Size of detector element, and thus system effective area, is limited by desired imaging resolution.\
- Studies of point source imaging are successful; extended sources will pose greater challenge.

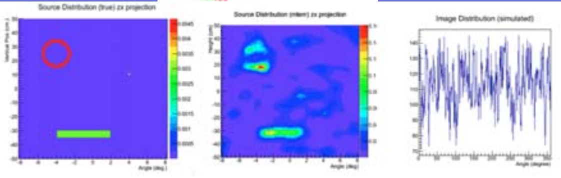


**Above: In the spinning coded aperture concept, a 2d coded aperture mask spins on its axis, producing a different time modulation in the detector as a function of source position. Right: point source imaging over a coarsely pixilated source space, demonstrating successful reconstructions over the full space for a random mask spinning coded aperture. Below: Point source reconstruction for spinning coded aperture in three configurations. Left: 19x19 URA mask pattern, detector on axis. Middle: 19x19 URA mask pattern, detector off axis. Right: Random mask pattern. For time-encoded imaging, the near-symmetry of URA patterns results in undesirable artifacts.**

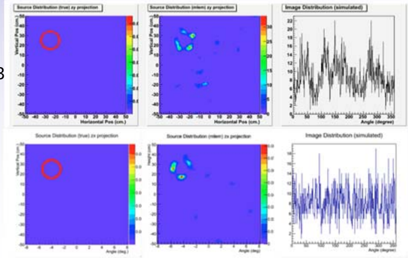


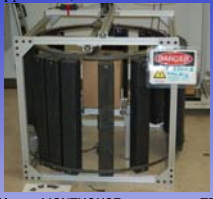

3 cm central detector; 36000 s multi-source reconstruction. Left: source distribution as simulated (ring, point, rectangle). Right: raw "observed" (simulated) time modulation pattern on the single detector. Middle: MLEM reconstruction of the source distribution.

Head-to-head comparison (simulation)
- Single 3 cm x 3 cm detector; ring source w/ 4.4e5 n/s (IAEA s.q.) @ 3 m.
- Top: results using spinning coded aperture
- Bottom: results using LH-2d
- Conclusion: techniques have similar performance; practical issues/limitations are most important in selecting a concept



## Prior results: Time-encoded directionality for SNM detection

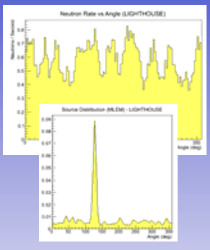
Two laboratory prototypes were built to assess time-encoded directional neutron detection in one dimension. Both image in the azimuthal dimension, for e.g. standoff source detection. Detector performance was similar to expectations from modeling. Unexpected results were obtained concerning the comparison of the two approaches, and of various PRISM geometries.

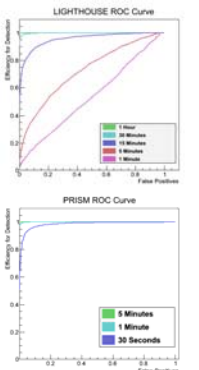


**Above: LIGHTHOUSE, a prototype TEI detector, is composed of a rotating mask surrounding a 5" LS cell. Right: Detected neutron rate vs rotation angle for a weak Cf-252 source at 5 m for 1 hr; reconstructed source distribution.**

### 'LIGHTHOUSE' Design

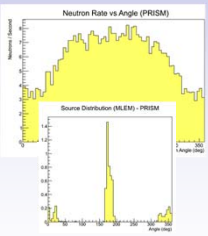
- Direct time-domain analog of 1-D coded aperture




**Above: ROC curves for source detection in the lab at 5 m standoff. Roughly a factor of 10 is attributable to larger effective area of the PRISM cell.**

**Above: Another TEI prototype, dubbed PRISM, comprises three large cells rotating together, each cell modulating the signal arriving at the others.**
**Right: Detected neutron rate in one cell vs rotation angle for a weak Cf-252 source at 5 m; reconstructed source distribution.**



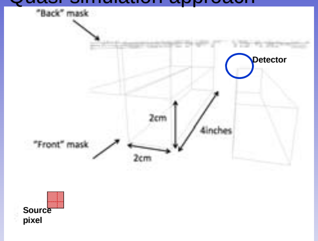

### 'PRISM' Design

- Fully active system → compact, scalable, high effective area

## Techniques: simulation & reconstruction strategies

Generically in fast neutron imaging, the effect of scattering, imperfect attenuation, and detection efficiency are significant. The most general way to account for all such effects, minimizing reconstruction errors and artifacts, is to build a system response matrix describing the probability of observations for particles emitted from each possible source position; reconstruction can then proceed using a statistically optimal technique such as maximum likelihood expectation maximization (MLEM).

### Quasi-simulation approach

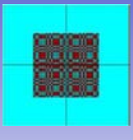



For each source pixel and each mask rotation position, build probabilities of detection by integrating attenuation of mask over possible particle trajectories. Accounts for imperfect opacity and finite pixel/detector size, but *not* scattering.

### Full simulation approach

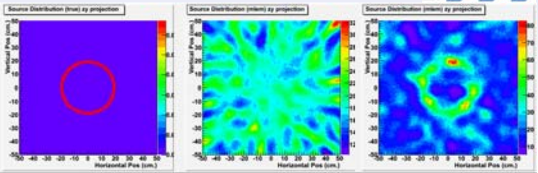
Using a full simulation of radiation transport (e.g. MCNP) can take into account all relevant effects such as scattering, but the CPU time requirements are large.

For 100x100 image space, need O(1e10) or more simulated events for reasonable image reconstruction, scaling with the statistics of the expected data itself.



### Fast modeling capability allows to explore design space

Example: For "spinning mask" concept, a single detector results in degeneracy when the source distribution (below left) is symmetric about the axis from detector to mask center (example reconstruction bottom middle). By adding detectors (right) we break the degeneracy and obtain better images (bottom right).

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