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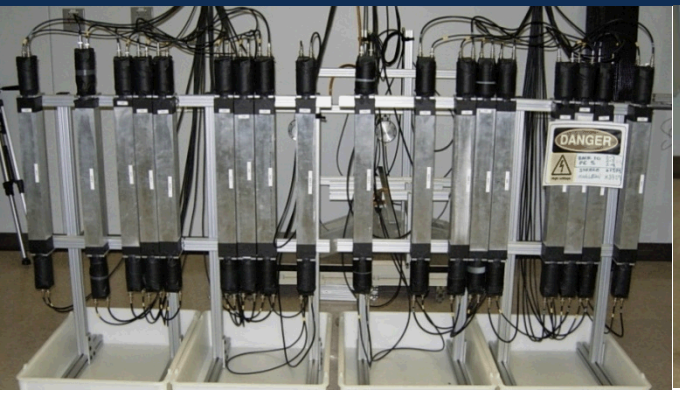

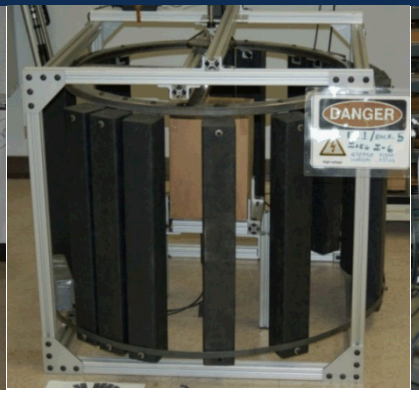


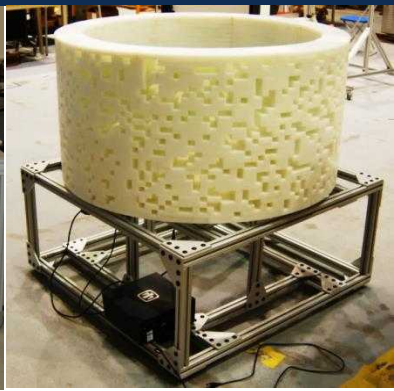

Feasibility Demonstration of Two-Dimensional Time-Encoded Fast Neutron Imaging Using a Single Detector Pixel

Peter Marleau

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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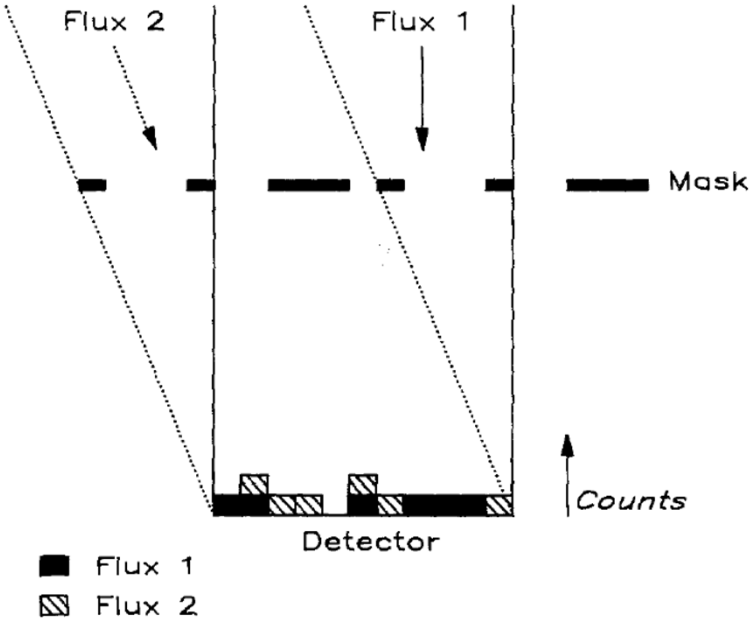
Outline

- Coded Aperture Imaging.
  - How does it work.
  - Sources of systematic uncertainty.
- Time encoded Imaging.
  - One dimensional proof of concept.
  - Two dimensional feasibility demonstration.
- Detector response.
- Point source studies.
- Extended source studies.

Coded aperture imaging

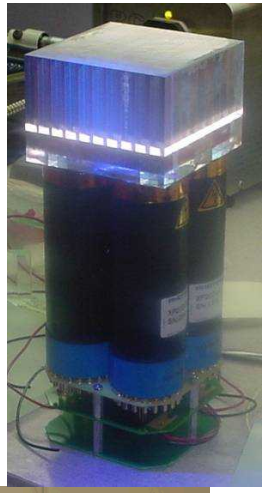
- Can't lens energetic neutrons (or gammas)
- A coded aperture is ~ an extension of pinhole imaging.
- Aperture is used to modulate the flux emitted by an unknown source distribution
  - Modulated flux intensity is measured at the detector plane by a position sensitive detector
  - Each detector measures some combination of source and background.



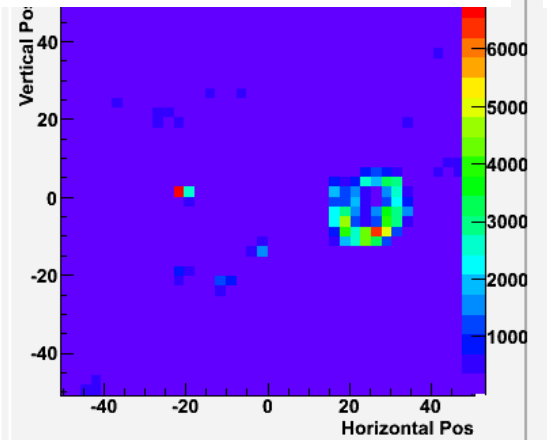
Carolli et al, Space Science Reviews 45 (1987), 349-403

Neutron coded aperture imager

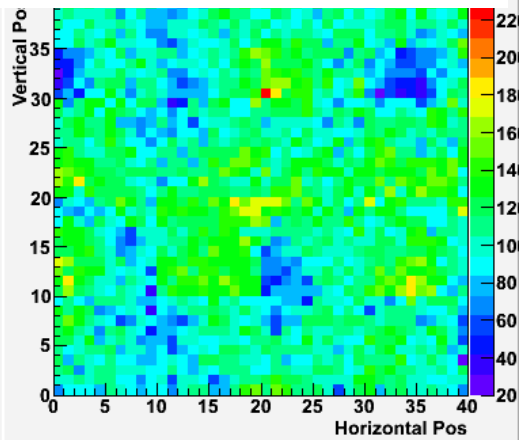
- ORNL/SNL fast neutron coded aperture imager developed for arms control treaty verification.
- Image plane consists of 16 organic scintillator pixelated block detectors
  - Each block consists of a 10x10 array of 1 cm. pixels.
  - PSD and pixel id accomplished by 4 photomultiplier tubes.
- Mask plane consists of 2.5 to 10 centimeters of HDPE.



Reconstructed image



Raw counts



Detector developed in collaboration with ORNL: P. Hausladen, J. Newby, M. Blackston

Pixelated Image Plane – calibration and characterization

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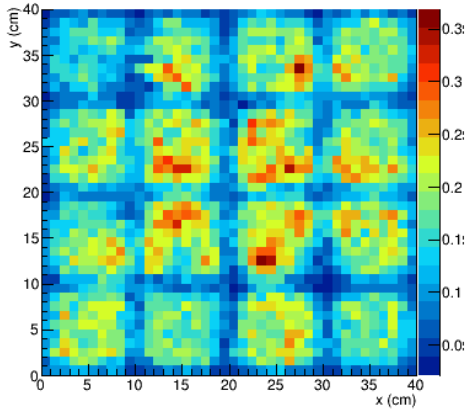
- Systematic variation across the position sensitive detector is a limiting factor for imaging-based tasks.
- Each “block detector” in the position-sensitive image plane has 10 x 10 pixels read out with Anger logic.

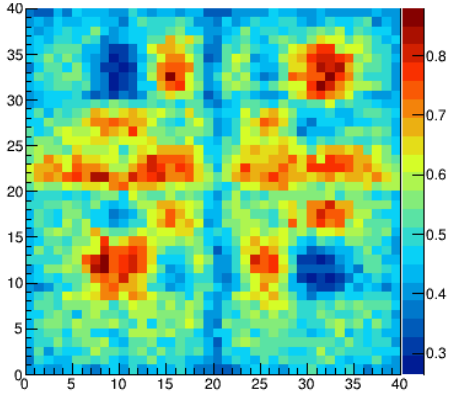
Pixelated Image Plane – calibration and characterization

- Must measure, calibrate, and characterize 64 channels/1600 pixels.
  - Pixel dependent energy resolution.
  - Pixel misidentification.
  - Pulse shape discrimination.

Experimental Data

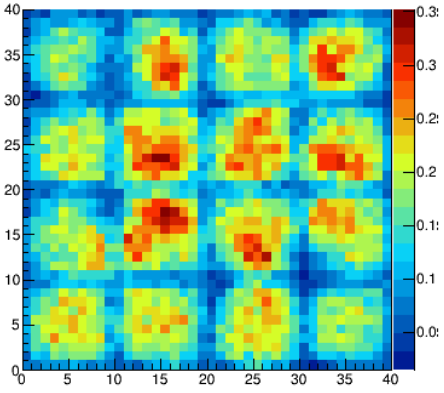


Simulation



$\chi^2/ndf = 6.83$

Simulated Response
(with characterization data)

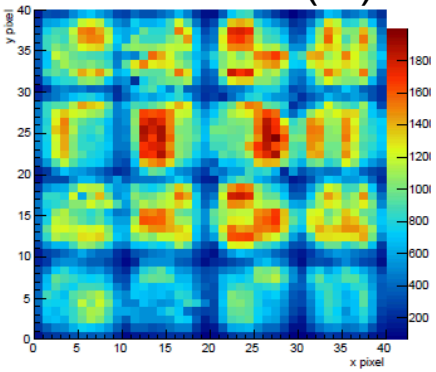


$\chi^2/ndf = 1.96$

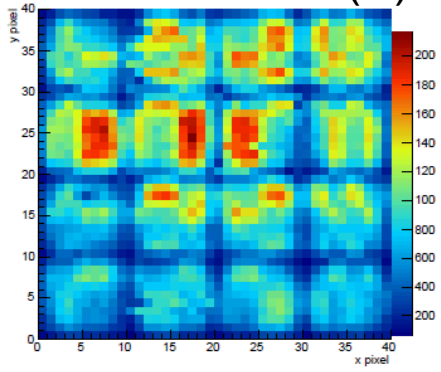
Pixelated Image Plane – mask/antimask

- Much of the pixel to pixel response variation can be corrected for by making both a mask (M) and antimask (A) measurement.
  - 90 degree rotation of mask for Modified Uniformly Redundant Arrays (MURAs).
- M-A removes counts that are not affected by the presence of the mask (scatter, uneven backgrounds, etc.)
- (M-A)/(M+A) corrects for variation in sensitivity between pixels.

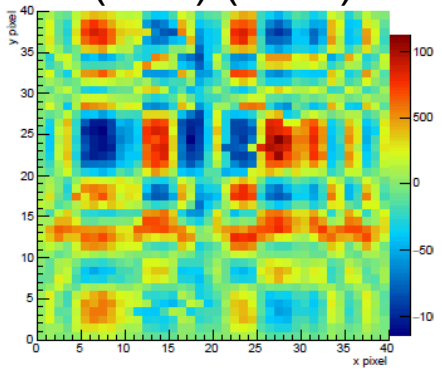
Mask data (M)



Anti-mask data (A)



(M-A)/(M+A)



Pixelated Image Plane – shifts over time

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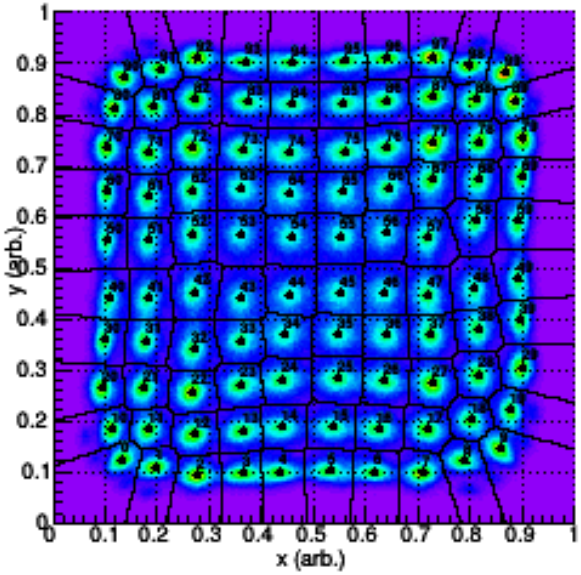
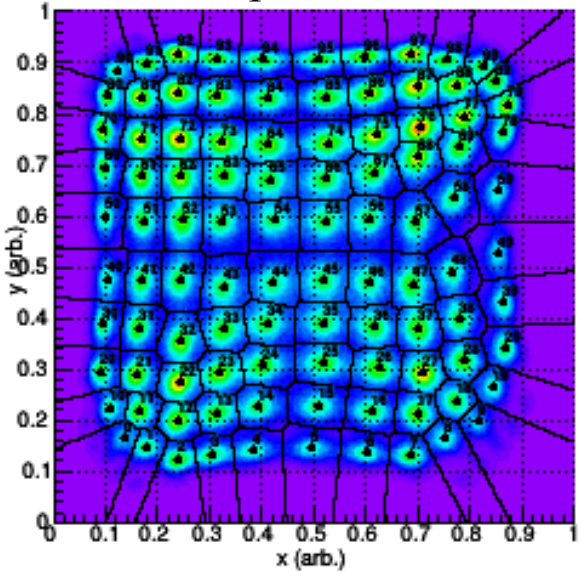
- If detector response “shifts” occur between two measurements to be compared, false negatives can occur.
  - Per-detector “look-up table” maps PMT ratios to pixel ID.
- Short-term strategy: Regular calibrations to reduce the impact of shifts.

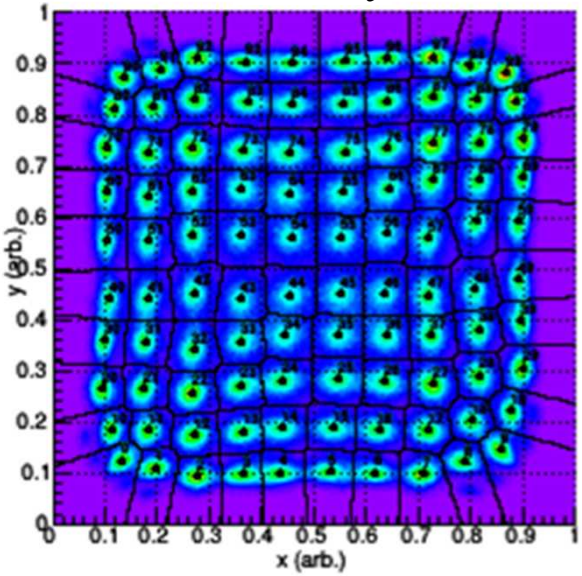
Feb 2015



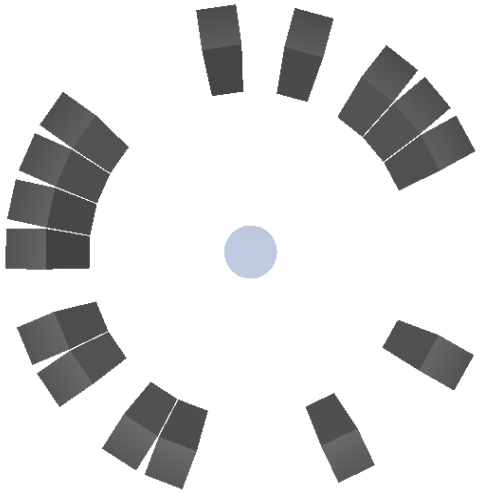
Apr 2015

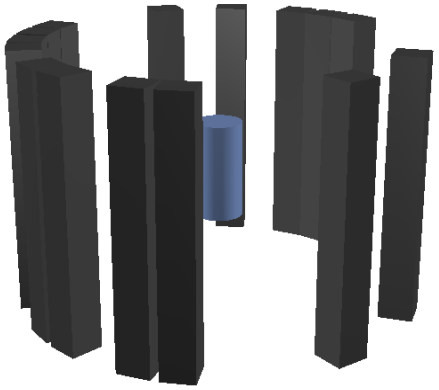


Overlay



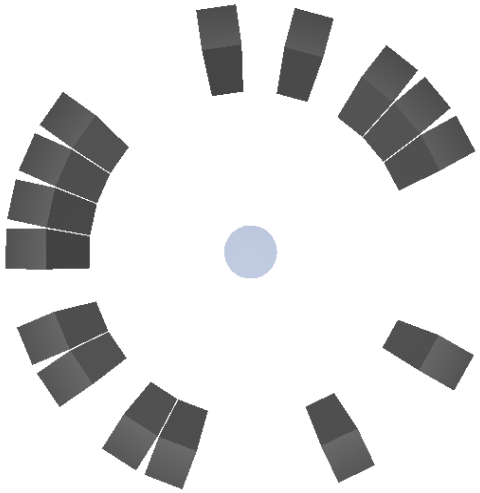
Time Encoded Concept – early work 1D

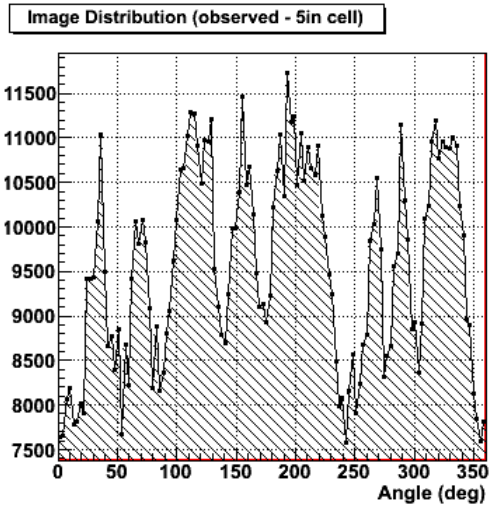


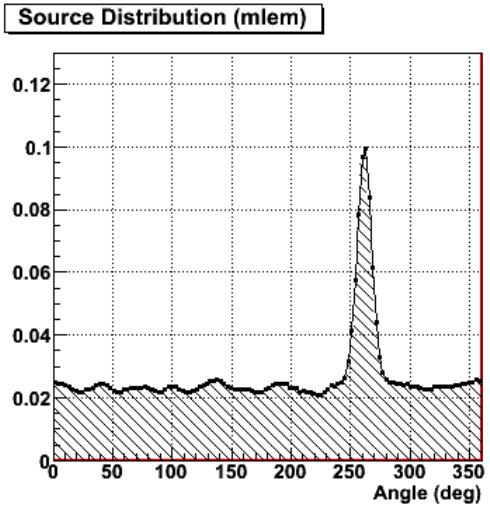


- Map spatial modulation to time modulation in the rate of a single central detector.
  - Spatial resolution is expensive. Time resolution in detectors is ~free!
  - Systematic variation over the phase of a rotation is very low.
- Mask can be made thick without worrying about “off-axis” effects.

Time Encoded Concept – early work 1D



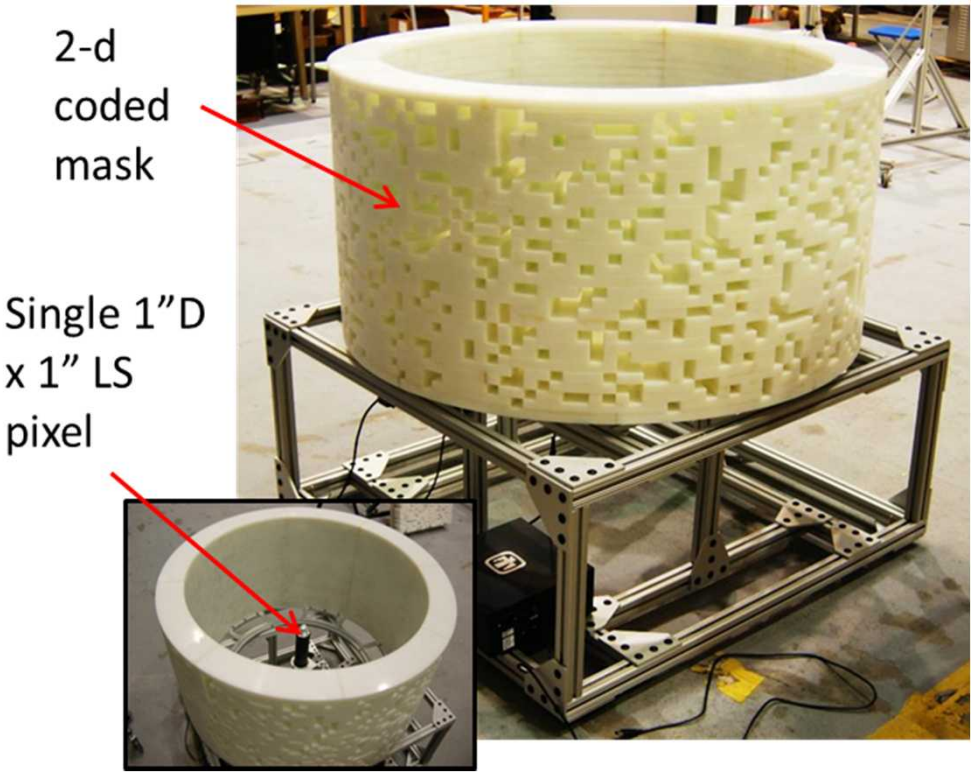




- Proof of concept was established with a single 5” diameter EJ-301 liquid organic scintillator detector and a 29 element, 1-D MURA mask (4” thick HDPE).
- Counts as a function of rotation angle can be unfolded into a one dimensional image.

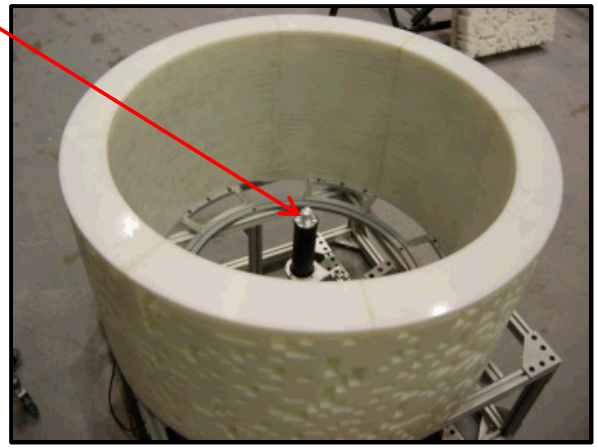
Time Encoded Imaging in Two Dimensions?

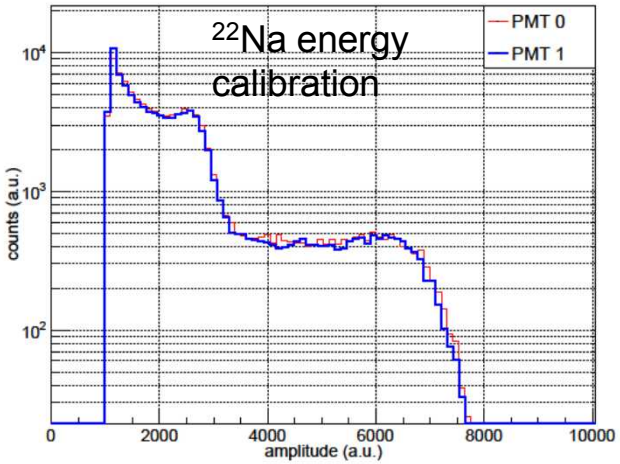
- Ok, it can be done in one dimension, but can it be done in two?
- Proof of concept of a single pixel coded aperture imager.
- Single 1” diameter x 1” tall EJ-309 liquid scintillator cell digitized by a CAEN 250 MHz desktop digitizer.
- Mask is cylindrical consisting of 27 vertical rows of 149 high-density polyethylene (HDPE) mask elements.
- Each element is an arc segment with an angular width of 2.4 degrees and height of 1.9 cm.
- The inner diameter is 45 cm and the outer is 55 cm.



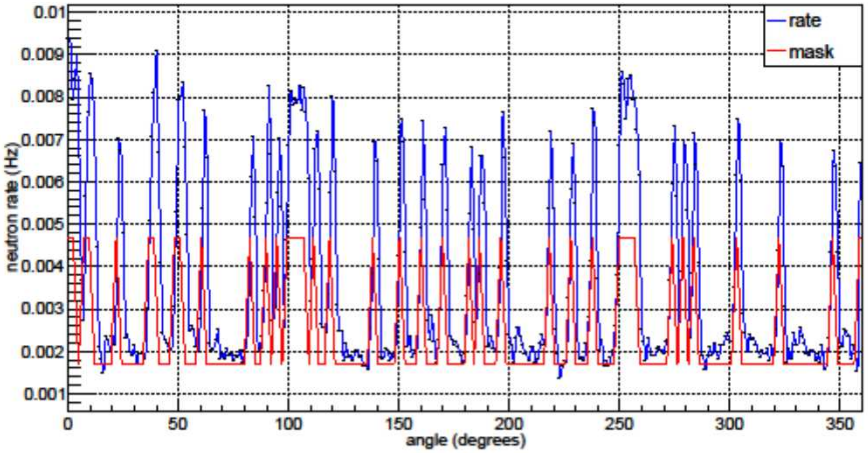
TEI-2D system - calibrations

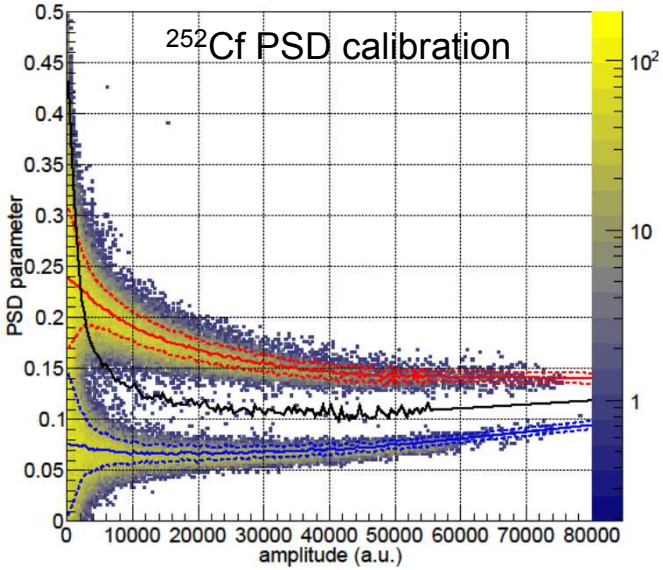
1”D x 1”
LS pixels





^{252}Cf – 1 cm from mask

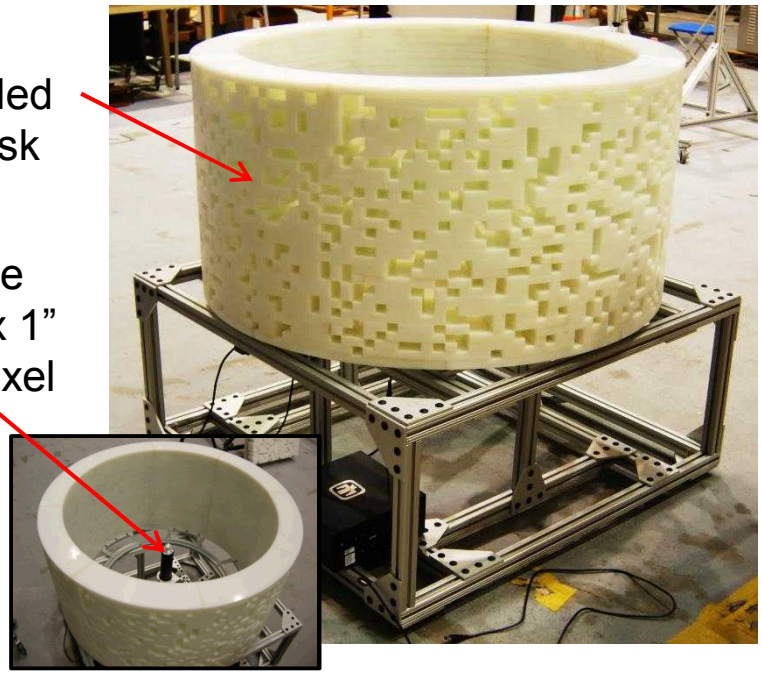




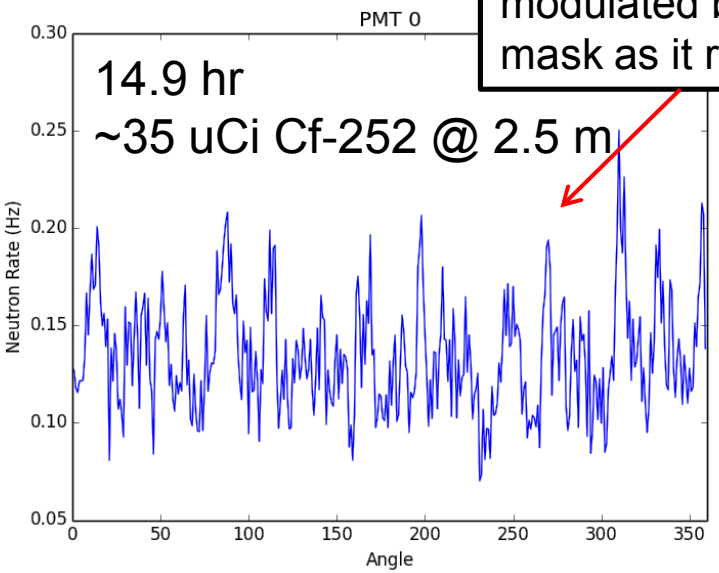
TEI-2D system

2-d coded mask

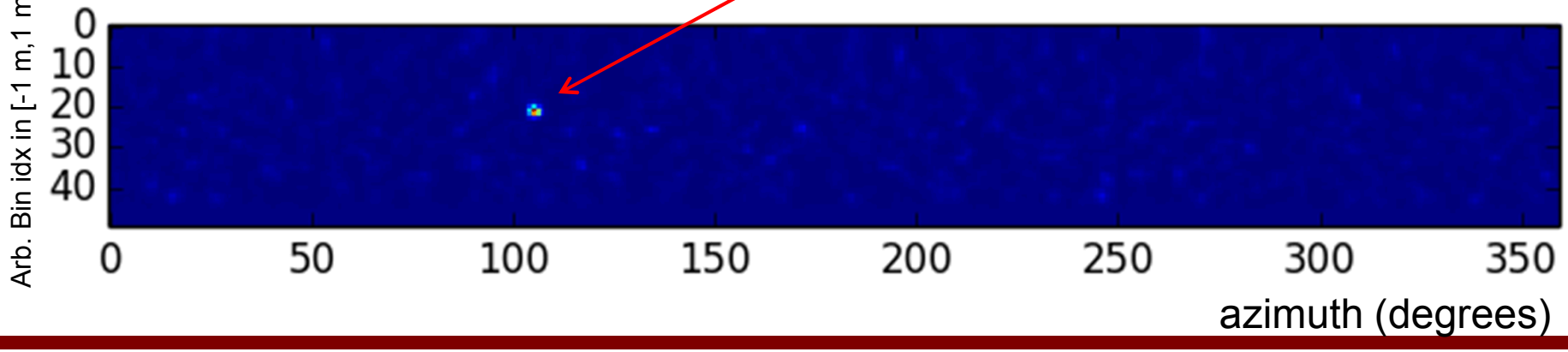
Single 1”D x 1” LS pixel



Single pixel rate is modulated by the mask as it rotates.



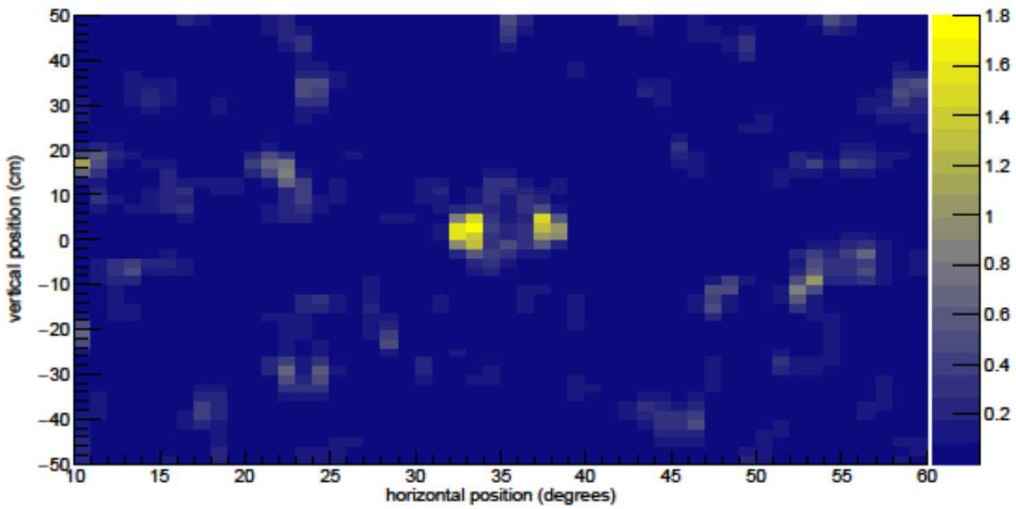
Modulation pattern is unfolded to 2-D image



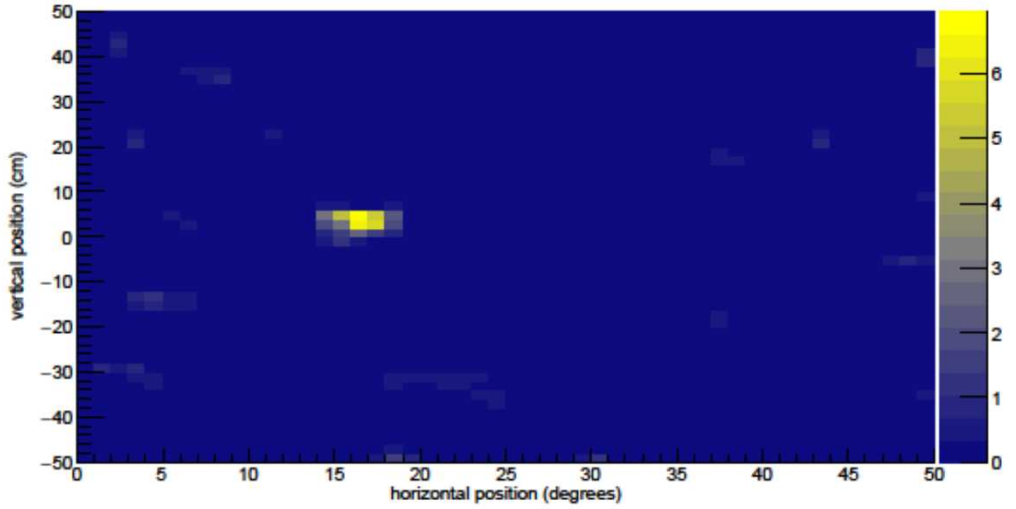
TEI-2D imaging – two point sources

Two 1.4e5 n/s ^{252}Cf point sources at 2.0 meters stand-off.

5 degree separation in 1 hour (50 mlem iterations)



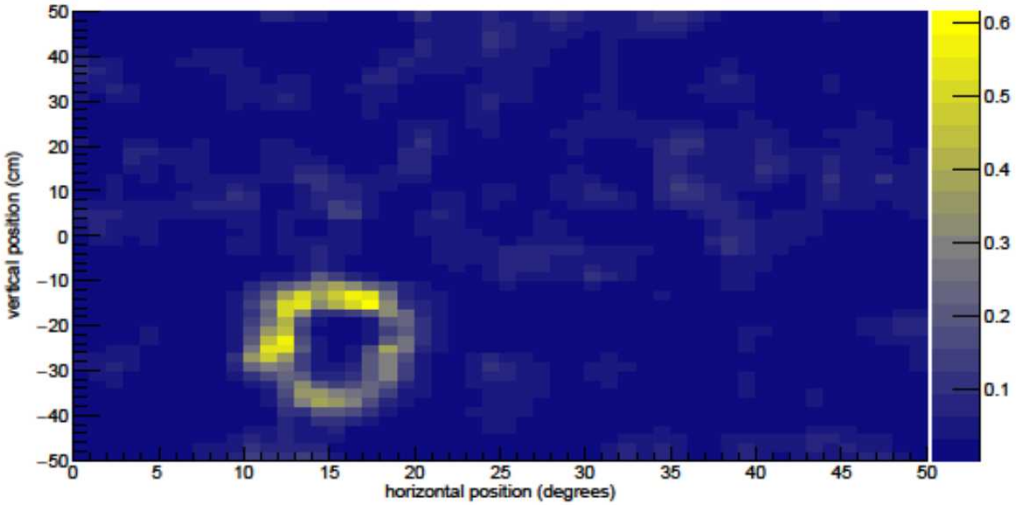
2 degree separation in 24 hours (250 mlem iterations)



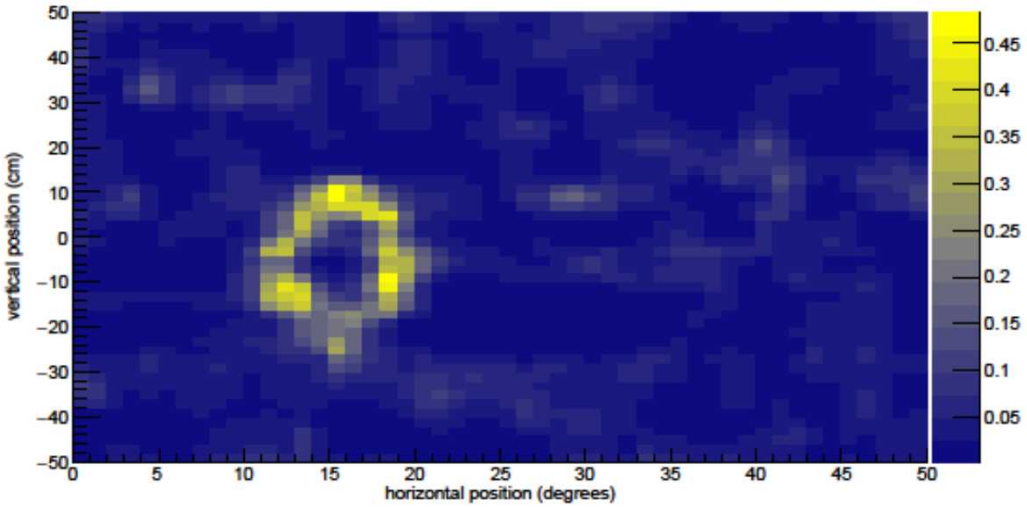
TEI-2D imaging – extended sources

A single 1.4e5 n/s ^{252}Cf source move through an extended pattern at 2 m.

72 hours
(100 mlem iterations)



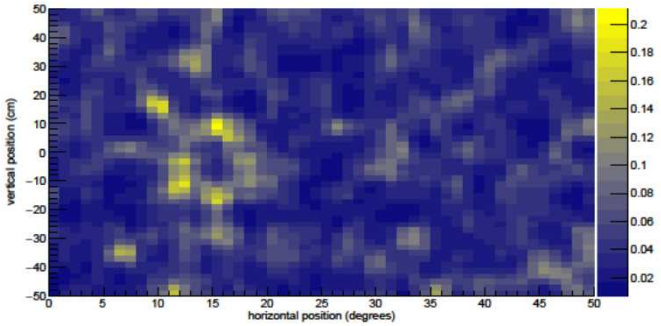
94 hours
(100 mlem iterations)



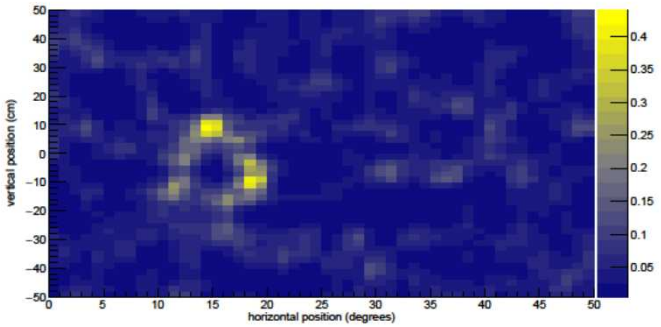
TEI-2D imaging – extended sources

A single 1.4e5 n/s ^{252}Cf source moved through an extended pattern at 2 m.

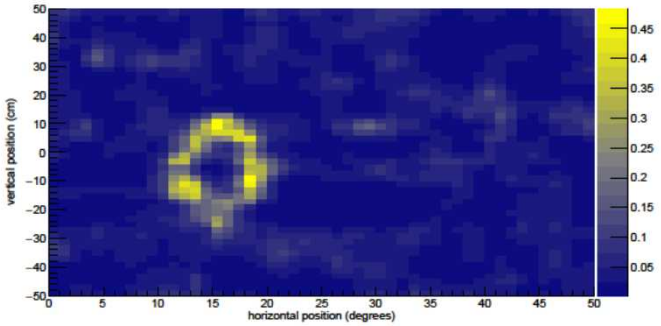
3 hours
(20 mlem iterations)



12 hours
(50 mlem iterations)



72 hours
(100 mlem iterations)



TEI-2D imaging: Coded aperture comparison (similar source distributions)

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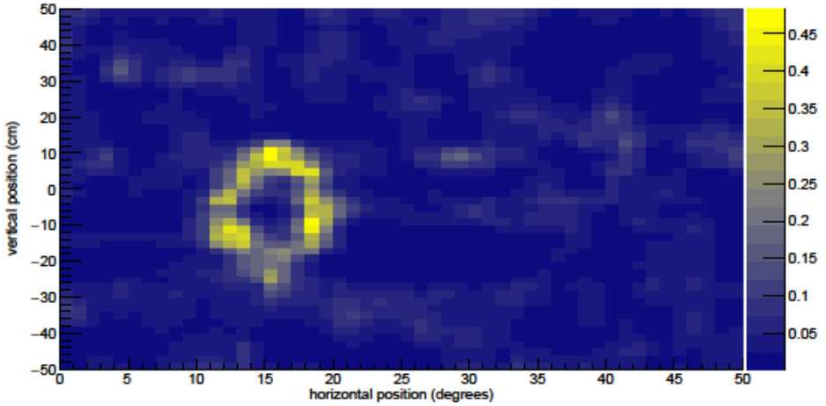
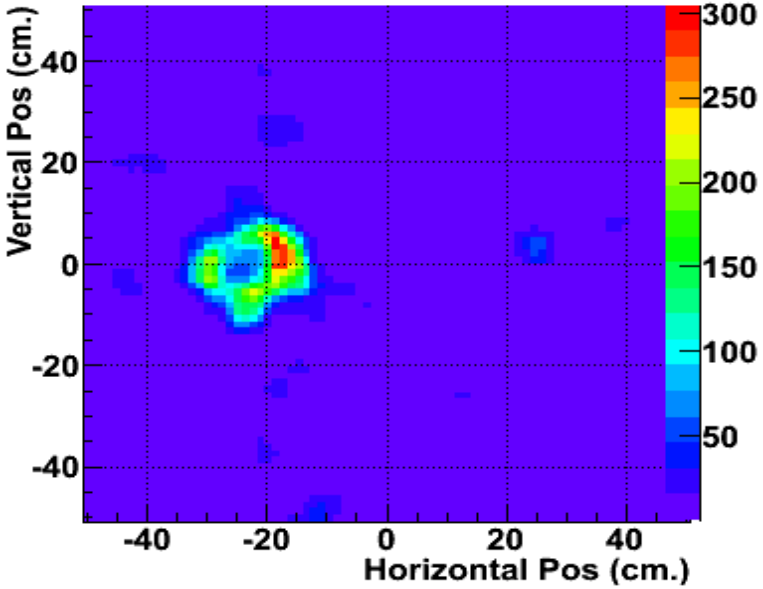
Time Encoded Imager - 72 hours



Neutron Coded Aperture -1 hour
(160 times the cross sectional area)



Conclusions and future directions

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- The time encoded imaging (TEI) concept offers the potential of high resolution 2-D imaging with reduced systematic uncertainties in the detector response.
- We successfully demonstrated proof of concept for 2-D time encoded imaging
- TEI advantages:
  1. Low systematic uncertainty.
     - Low channel count.
     - Detectors work independently; don't need to be correlated together.
  2. Geometry conducive to aperture imaging.
     - Every direction is aligned with the aperture; no "off-axis" effects.
- With a bar-type detector down the axis rotation, two improvements could be realized:
  1. Increased efficiency (area).
  2. Reduction in artifacts with multiple lines-of-site through the mask.