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LANTERN: A Cylindrical Time-Encoded Dual Particle Imager

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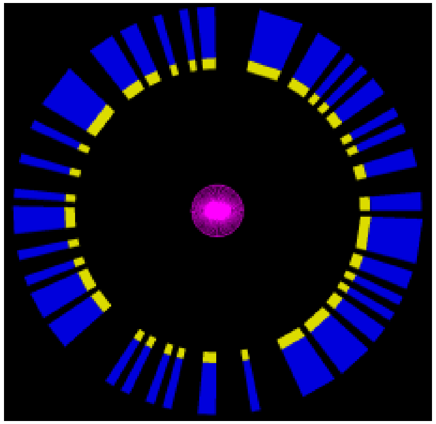
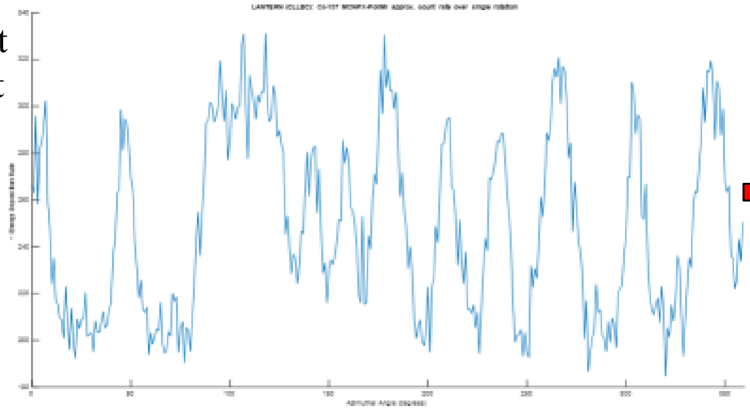
Cylindrical Time-Encoded Imaging

- **A rotating coded mask modulates a static source, producing a detector count rate over time that resembles the mask pattern.**
- **The size of the detector compared to the distance to the inner layer of the mask dictates the count rate over time.**

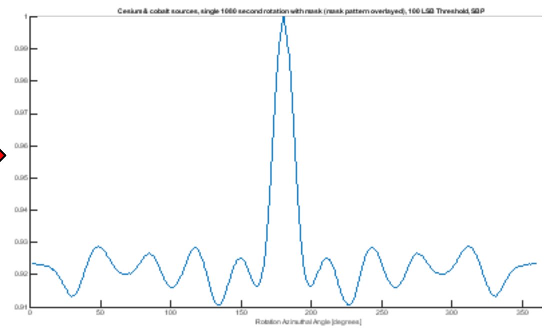
Top View



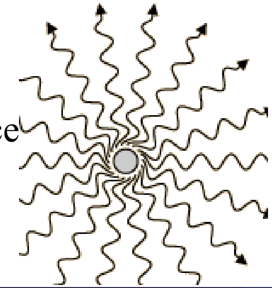
Collect Count Rate



Deconvolved Image



n,γ source



Motivation

NNSA Nuclear Nonproliferation Mission Statement

Preventing nuclear weapons proliferation and reducing the threat of nuclear and radiological terrorism around the world are key U.S national security strategic objectives that require constant vigilance. NNSA's Office of Defense Nuclear Nonproliferation works globally to prevent state and non-state actors from developing nuclear weapons or acquiring weapons-usable nuclear or radiological materials, equipment, technology, and expertise.

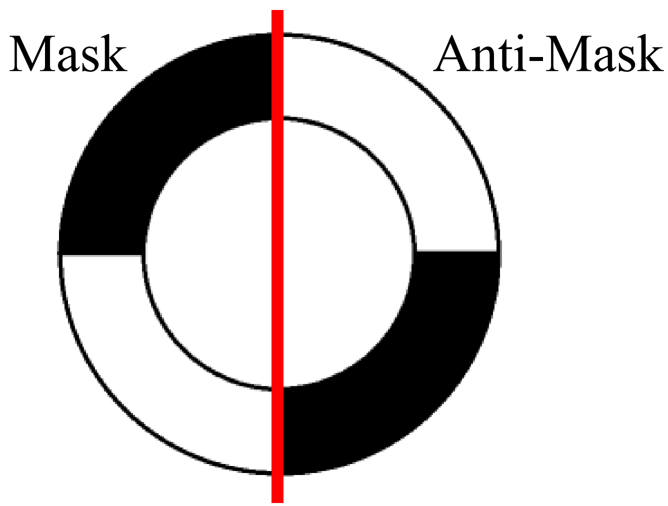
- **Nonproliferation applications: source verification and search operations, forensics, post-event operations (deterrent capability)**
- **Effective Fieldable Instrument: Compact, cost-effective fast neutron/gamma imagers**
- **Project Goal: Retain image quality when transitioning from a large to small diameter coded mask.**

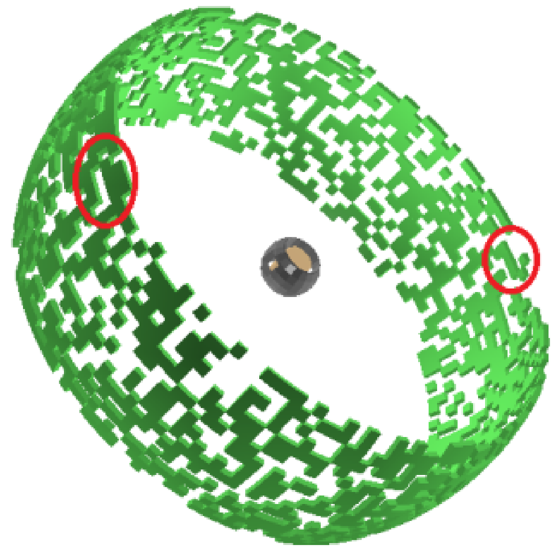
PROJECT PLAN

- **PHASE 1: design and implement initial system**
  - design mask bed
  - compare coded aperture patterns
  - implement 1-3 layered designs
- **PHASE 2: simulate and implement design refinements**
  - use MCNP for tungsten side wall effectiveness
  - Evaluate tradeoffs for weight, size, SNR, and image resolution
  - Compare LANTERN designs for specific applications
- **PHASE 3: project validation and advancement**
  - more sophisticated imaging and coded aperture techniques
  - measurement campaigns

Coded Aperture Optimization

- **Ideal Coded Aperture → Uniformly Redundant Array (URA)**
  - Autocorrelation results in a delta function
- **Random Pattern**
  - Can be optimized with several techniques: Great Deluge Algorithm, Ant Colony Optimization, spread functions
  - Can utilize experimentally derived sensing matrices
- **Mask Anti-Mask Pattern (currently utilized by Sandia's COGNIZANT)**
  - Half the mask is a mirror opposite of the other half
  - Usually relies on random pattern optimization

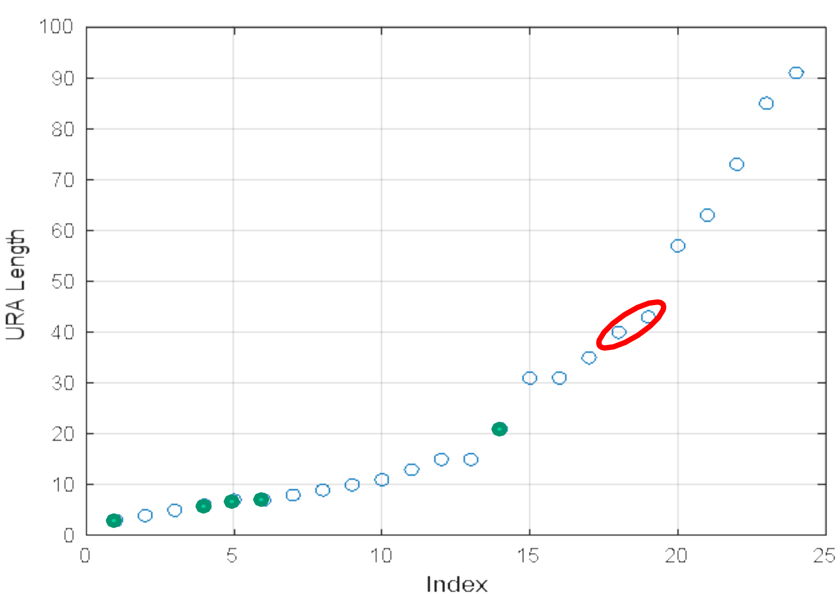




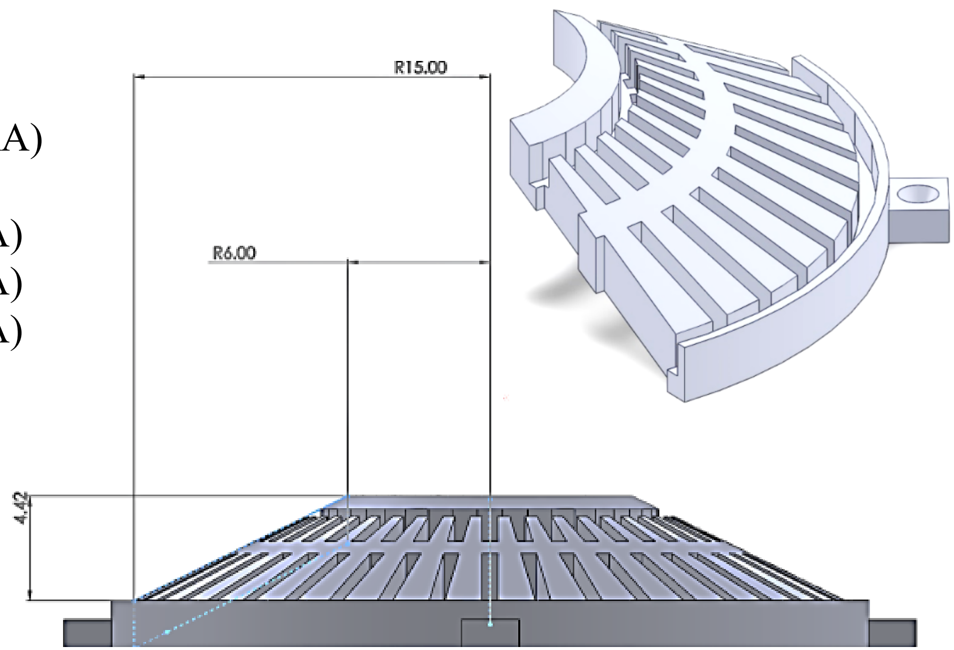
Sandia COGNIZANT mask-antimask cTEI configuration

Mask Test Bed

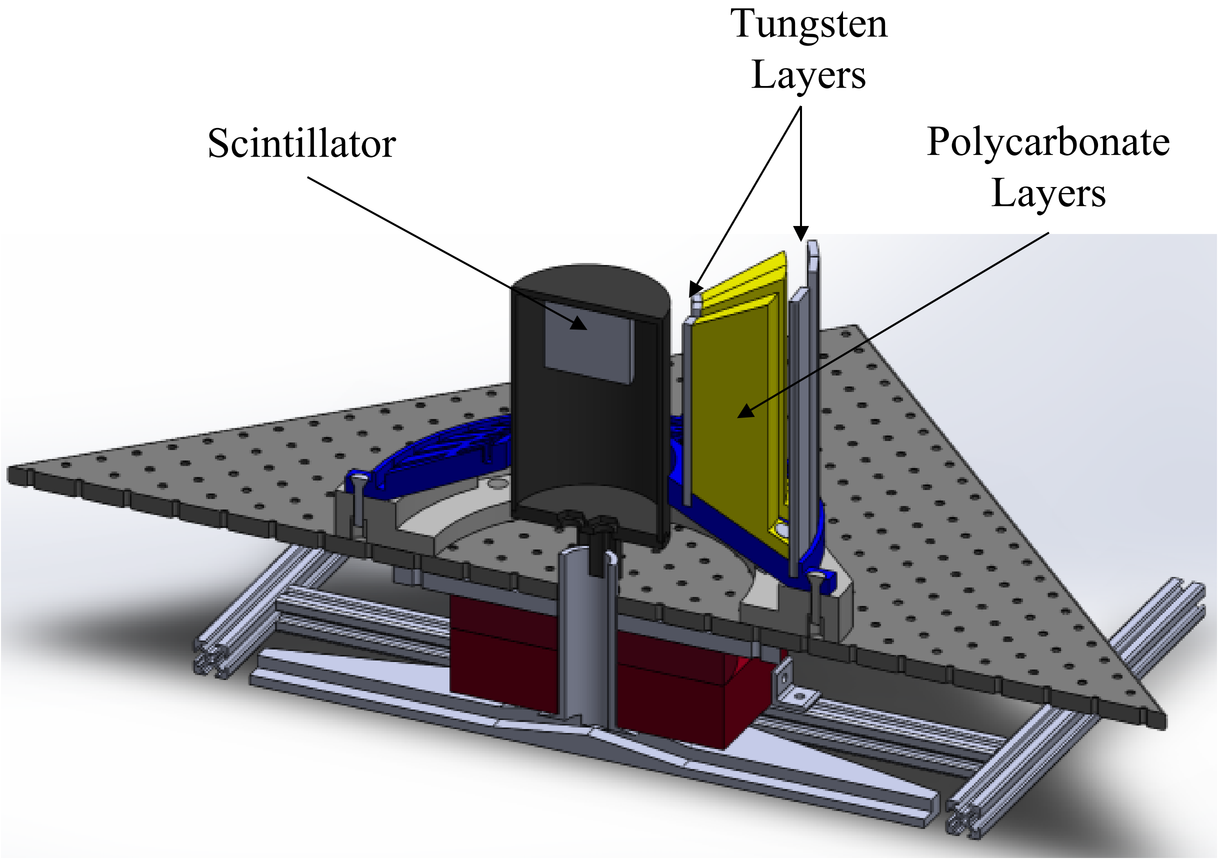
- **Design of a mask bed for testing of several unconventional cTEI masks**
- **Allows for multiple material layers and can handle a range of inner and outer mask radii**
- **Goal: Allow for even and odd numbered mask patterns (can have URAs as well as mask anti-mask patterns)**

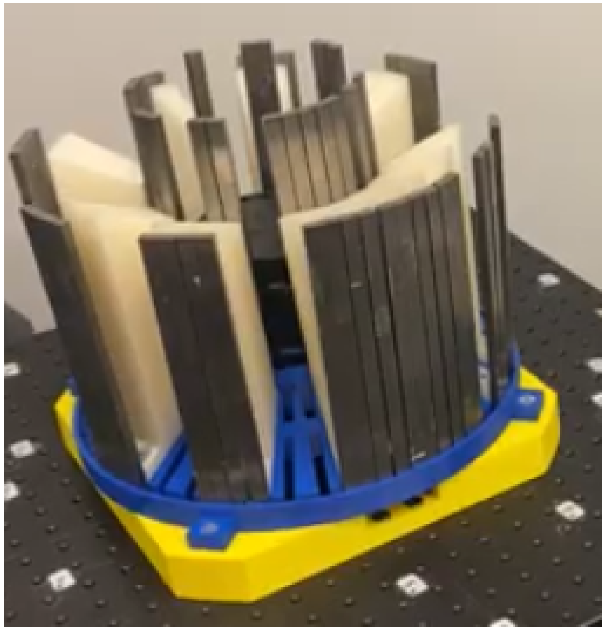


42
21 (URA)
14
7 (URA)
6 (URA)
3 (URA)



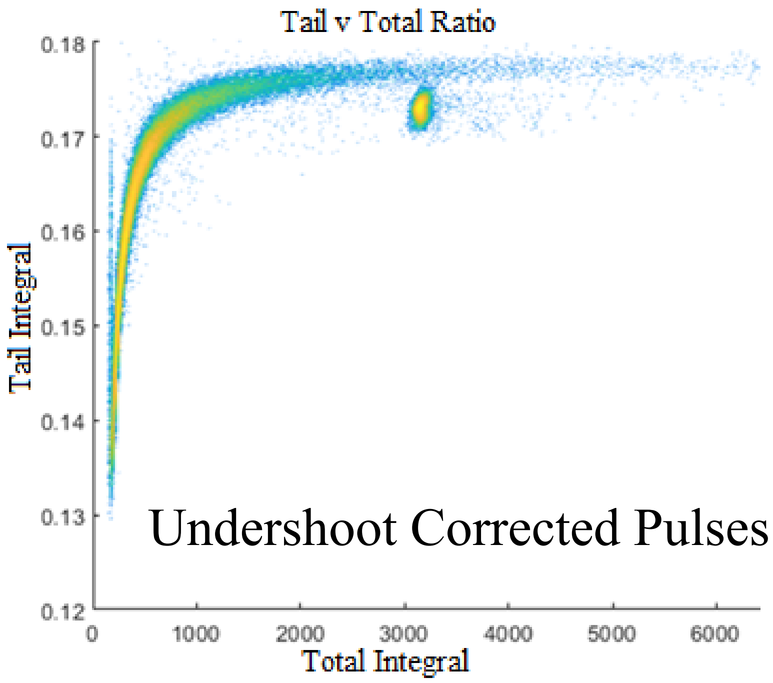
Current LANTERN Design

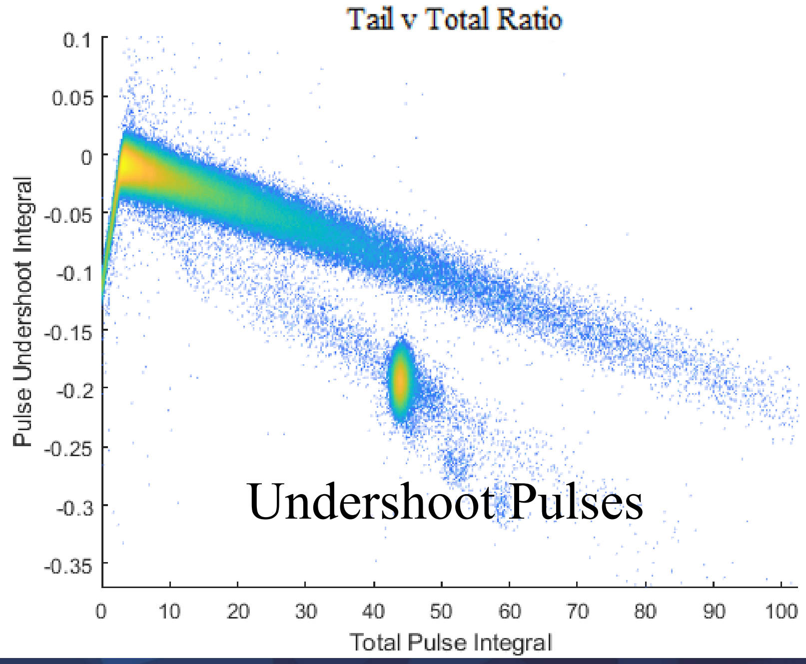




Experimental Results

- Measured an 883 µCi Cf-252 S.F. source with poly & tungsten mask & 1” CLLBC
- Prominent pulse undershoot in most waveforms
- The thermal neutron capture island has less separation from the gamma-ray band for the “fixed” pulses than the “undershoot” pulses.
- Particle classification may be done with the “undershoot” pulses as is.





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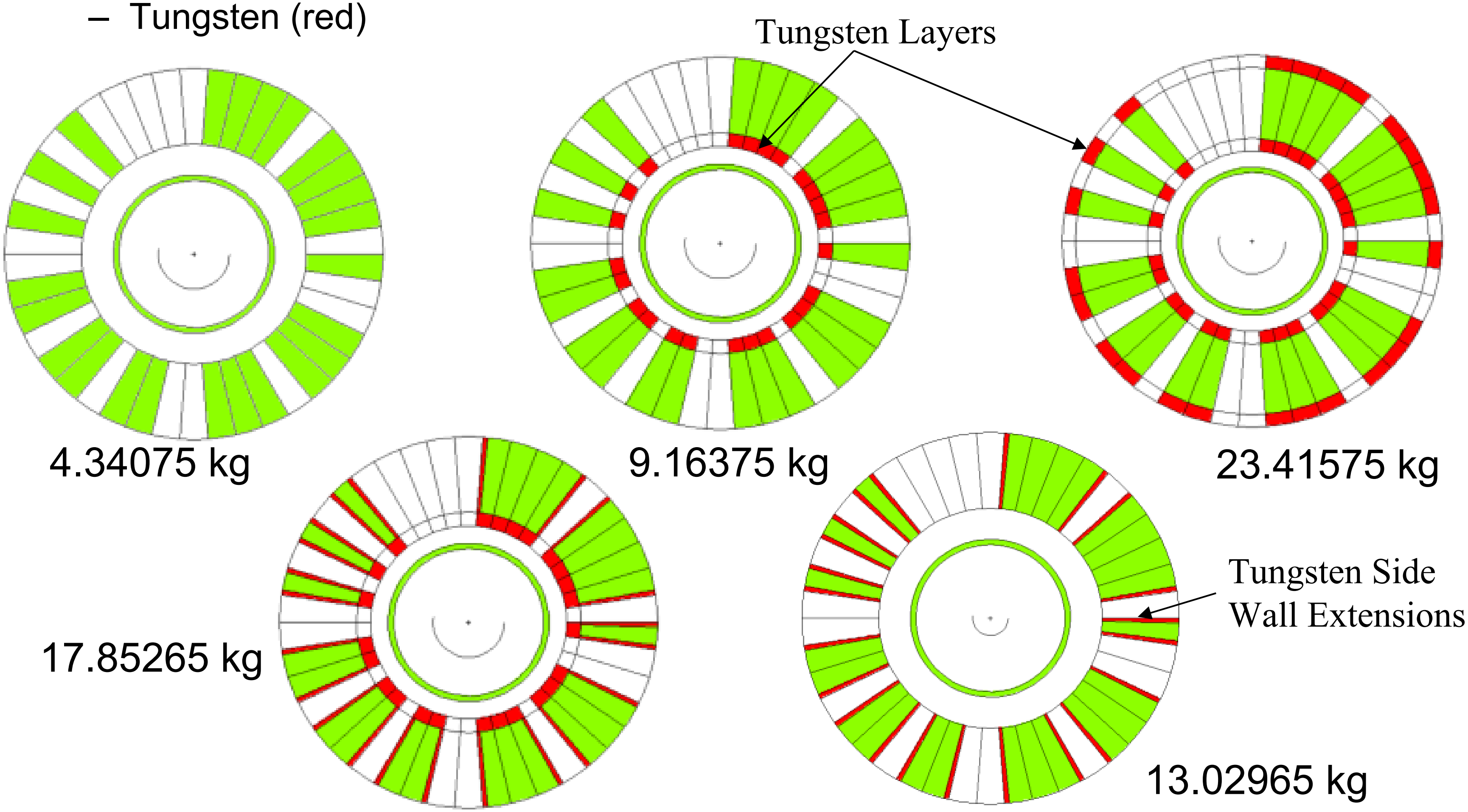
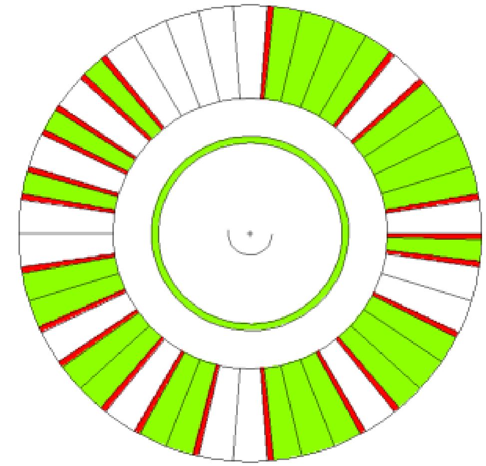
Simulation Designs

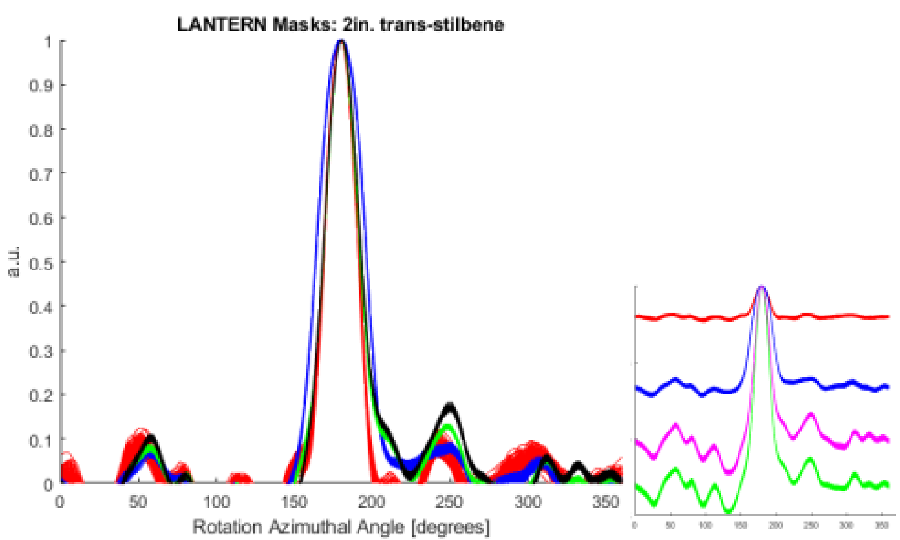
- **First 5 LANTERN design variations with fixed inner/outer diameters**
  - Polycarbonate (green)
  - Tungsten (red)

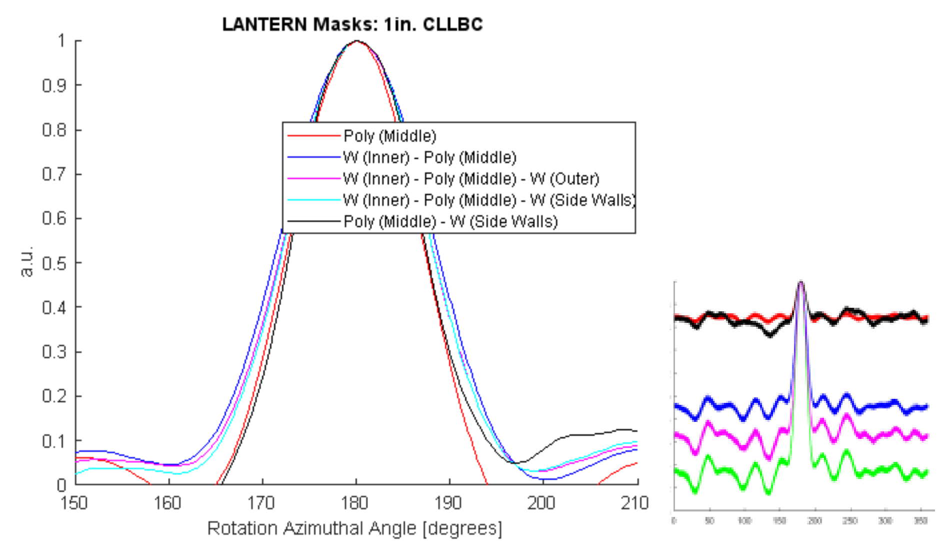


Simulation Results – Angular Resolution

- Simulated angular resolution ranges from 9° - 12°. Larger detectors result in greater side lobe noise.
- Hypothesis: tungsten may only be required on the side of open elements for gamma-rays
  - This design has very low SNR and noise in side lobes is increased.

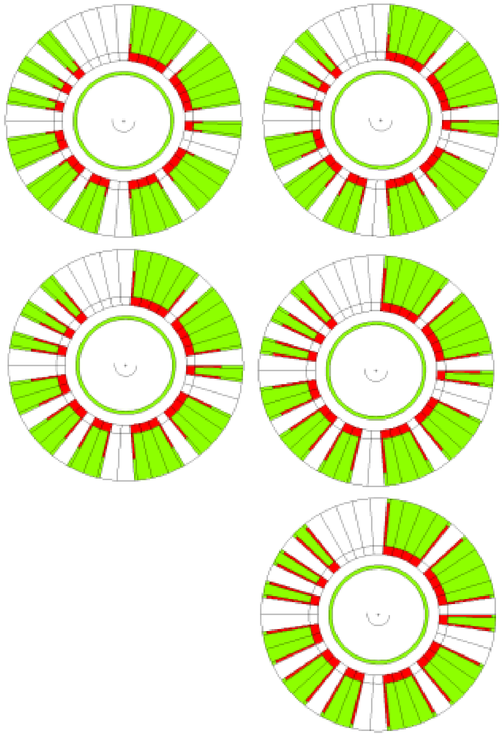


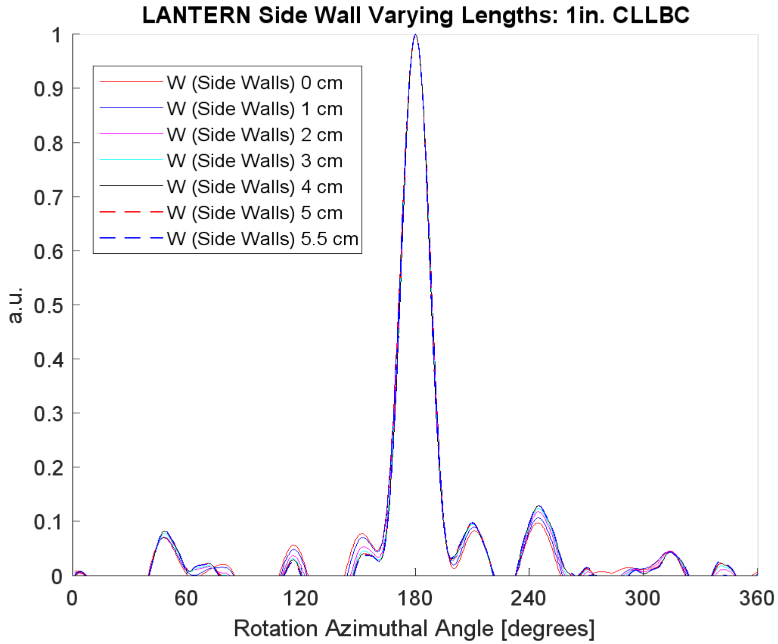


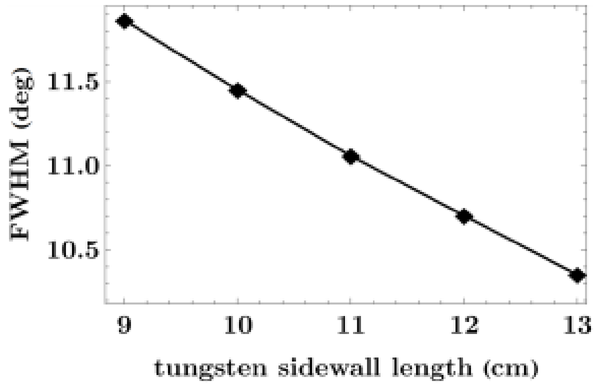


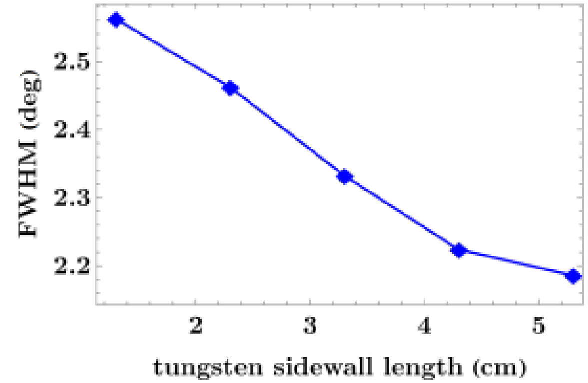
Simulation Results – Tungsten Side Walls

- **MCNPX-PoliMi Result: tungsten addition to the side of open elements effectively decreases escape through closed mask elements**
- **Side wall extension improves SNR but does not significantly improve angular resolution and increases side lobe noise.**
- **Using an experimentally derived sensing matrix improves angular resolution.**









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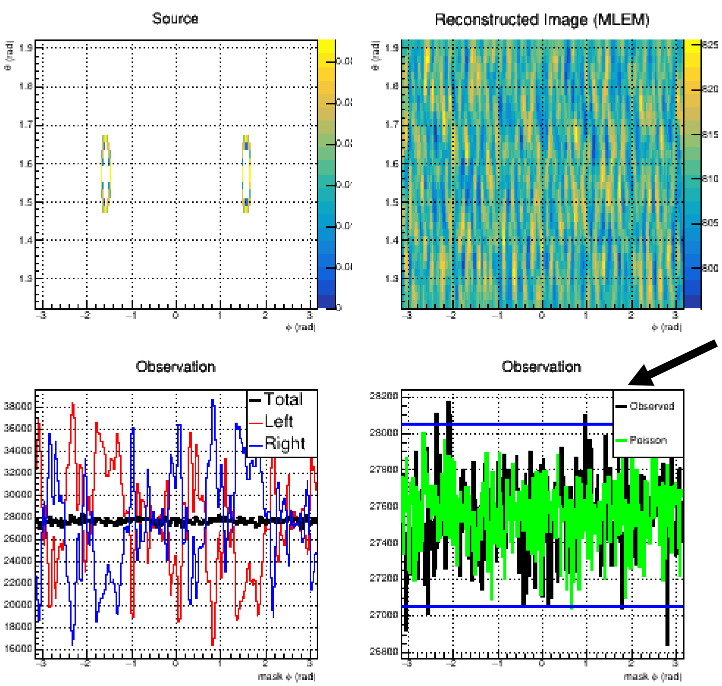
Zero Knowledge Testing of Modified Extended Sources

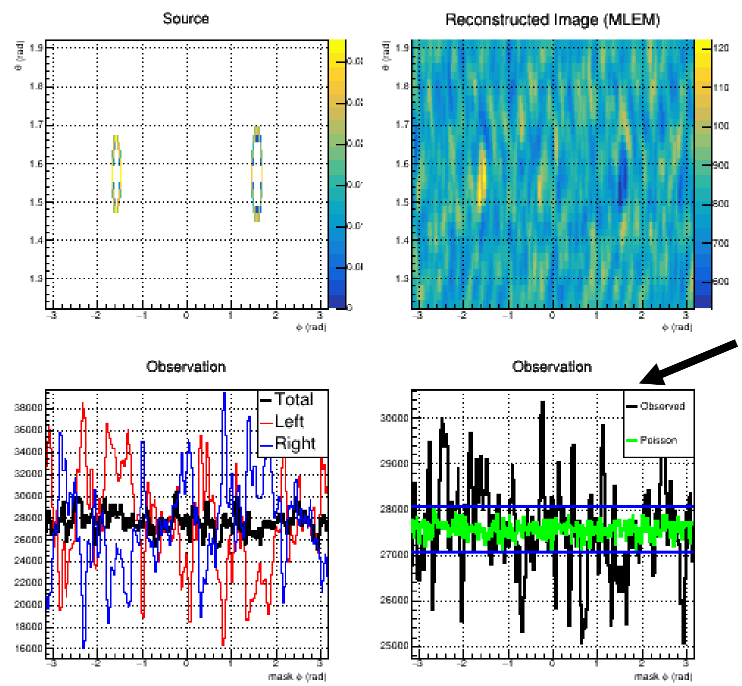
- **An ideal mask anti-mask pattern should view two identical ring sources as Poisson noise**
  - Maximum deviation from Poisson is desired when sources are not identical in ring diameter

Identical Eu Ring Sources of Diameter 5 cm



Very little deviation from Poisson noise

One Eu Source Diameter is Modified to 6 cm

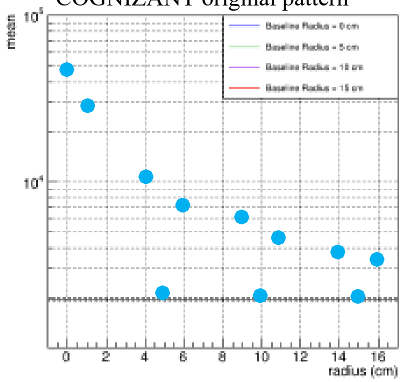


Deviation from Poisson noise

Results - Great Deluge Algorithm

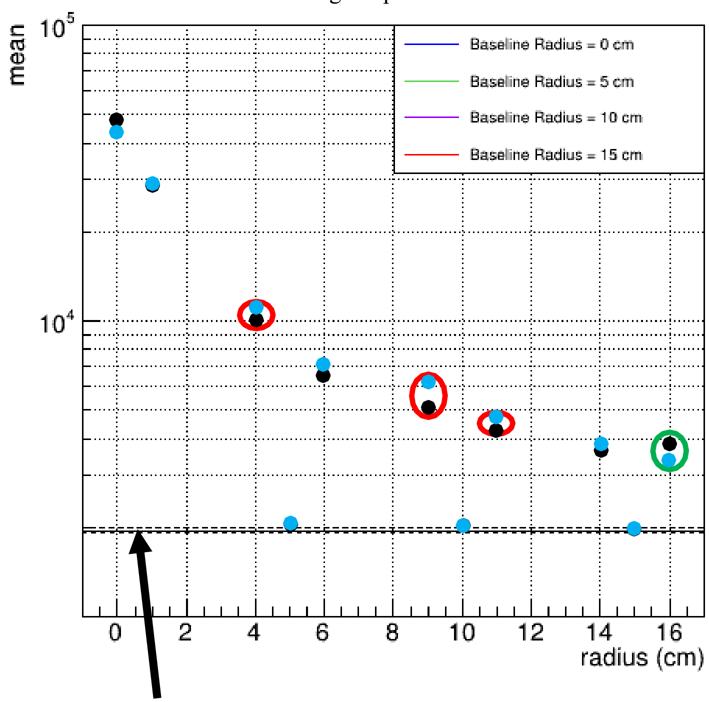
- **Figure of merit - mean of negative log likelihood (NLL)**
- **GDA generated patterns perform worse than COGNIZANT original pattern for smaller sources but better for extended sources**

COGNIZANT original pattern



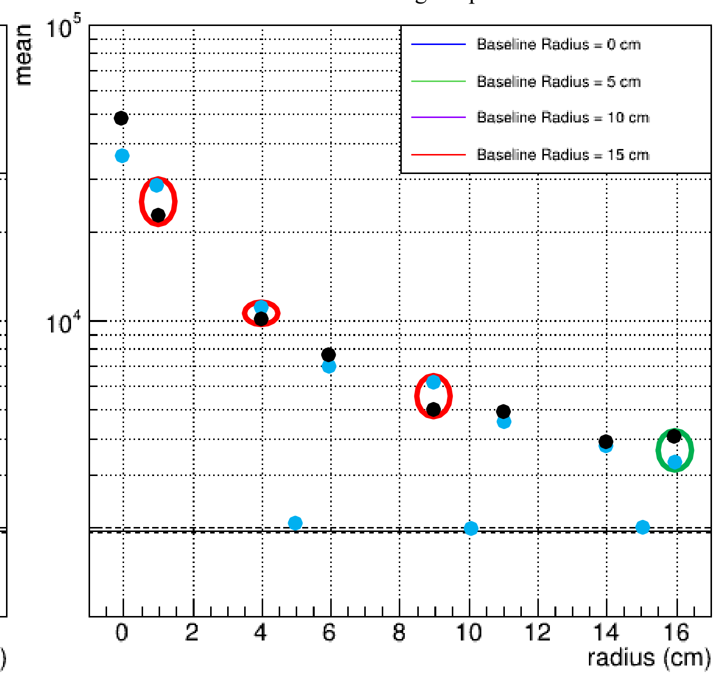
1st Source Radius	Modified Source Radius
0 cm	0 cm
0 cm	1 cm
5 cm	4 cm
5 cm	5 cm
5 cm	6 cm
10 cm	9 cm
10 cm	10 cm
10 cm	11 cm
15 cm	14 cm
15 cm	15 cm
15 cm	16 cm

GDA Optimized FOM Pattern overlapping COGNIZANT original pattern



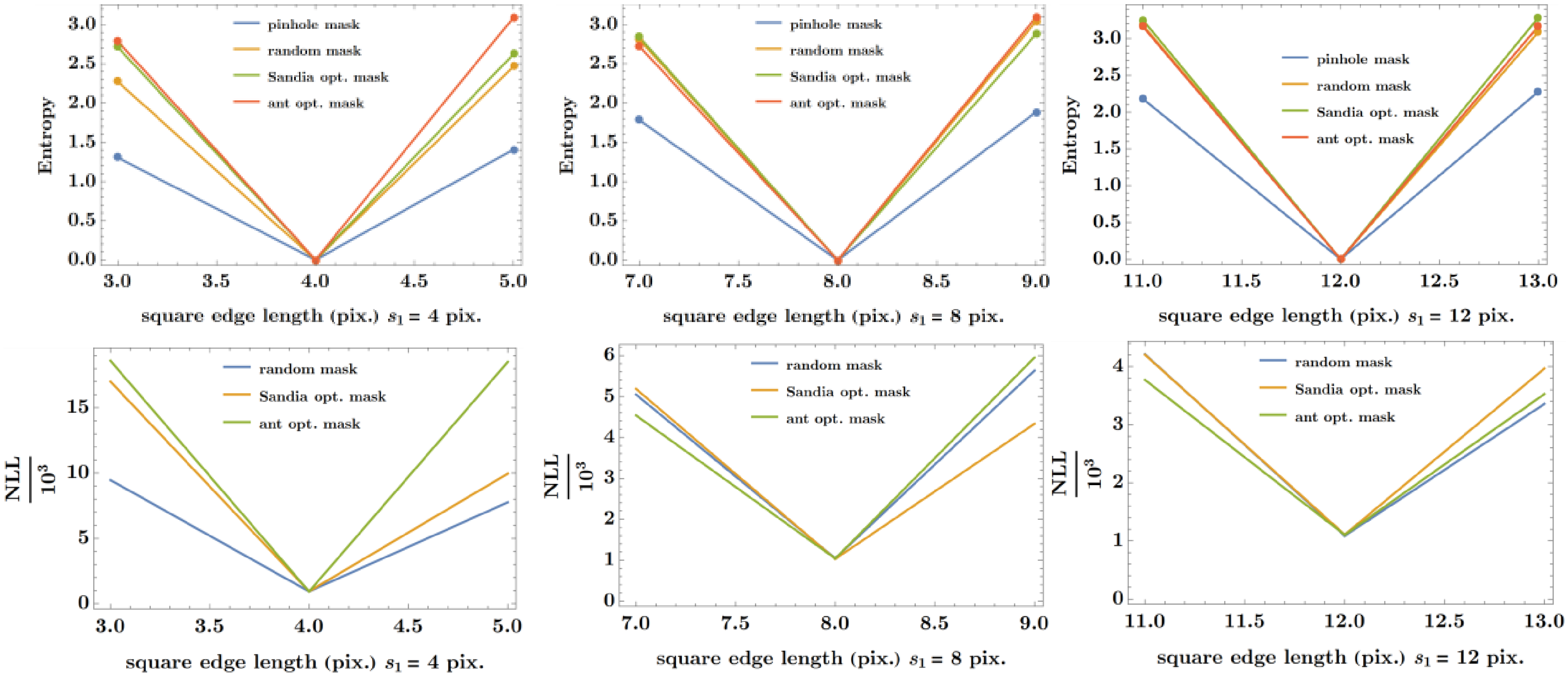
Poisson noise (3 sigma)

GDA Pattern #3 overlapping COGNIZANT original pattern



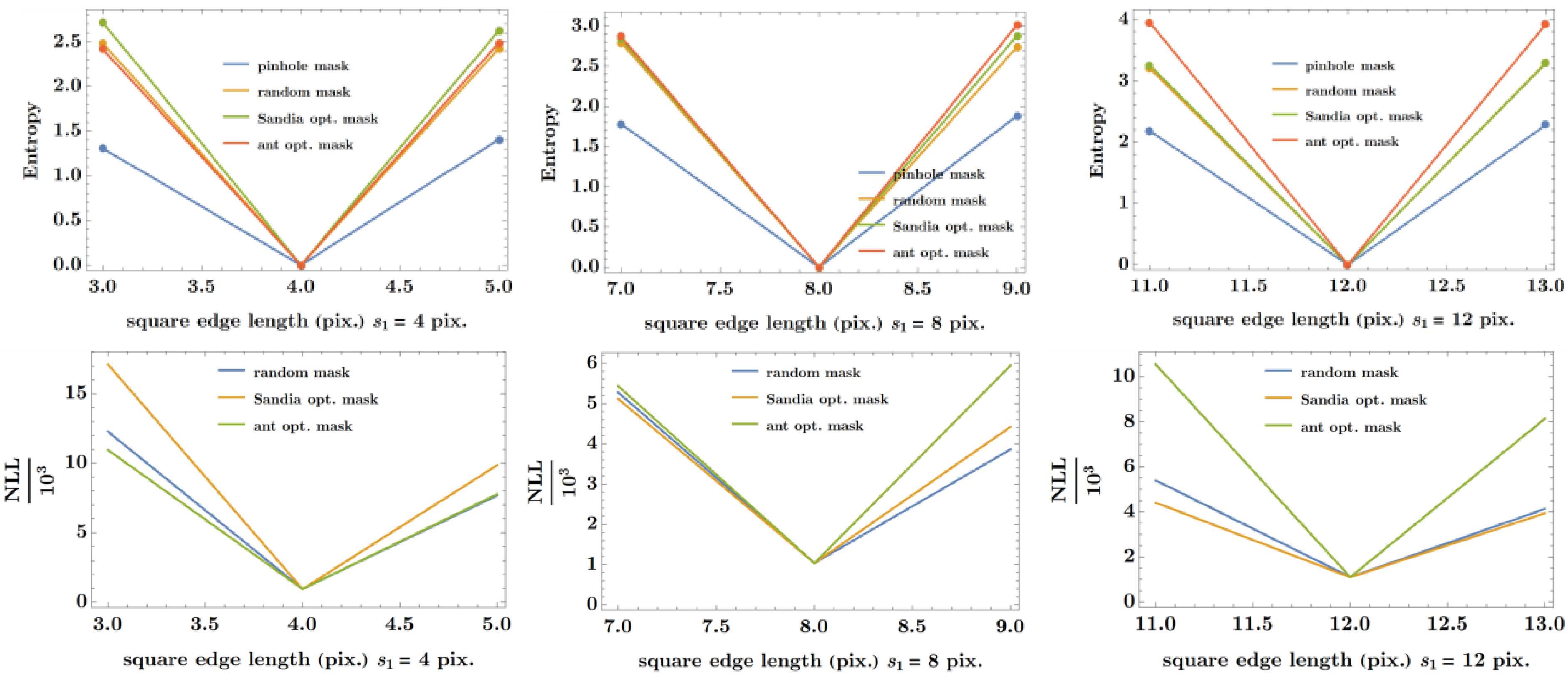
Results - Ant Colony Optimization

- **Optimization Focus: 4 cm radius square source**
- **Optimizing at small square source sizes shows improvement over current Sandia mask pattern for smaller sizes but not for larger sized sources.**



Results - Ant Colony Optimization

- **Optimization Focus: 12 cm radius square source**
- **Optimizing at large square source sizes shows improvement over current Sandia mask pattern for larger sizes but not for smaller sized sources.**



Conclusions

- **PHASE 1: design and implement initial system**
  - coded aperture optimization methods for LANTERN and COGNIZANT have been developed
  - pulse shape discrimination code needs to be optimized for finalizing of current LANTERN results and more initial designs need to be implemented
- **PHASE 2: simulate and implement complex designs**
  - tungsten side walls are useful in decreasing escape through closed mask elements
  - weight, SNR, and image resolution still need to be optimized as mask thickness and other detectors still need to be tested
- **PHASE 3: project validation and advancement**
  - advanced imaging techniques using sparse reconstruction algorithms and experimental sensing matrices can greatly improve image quality

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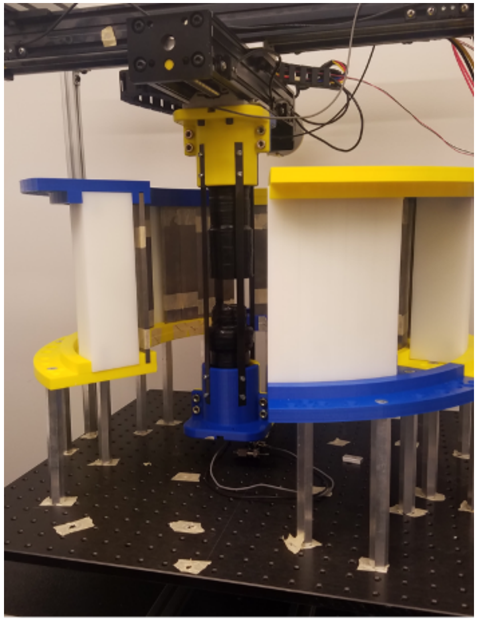
Extra Slides

System Comparisons

CONFIDANTE (Sandia)

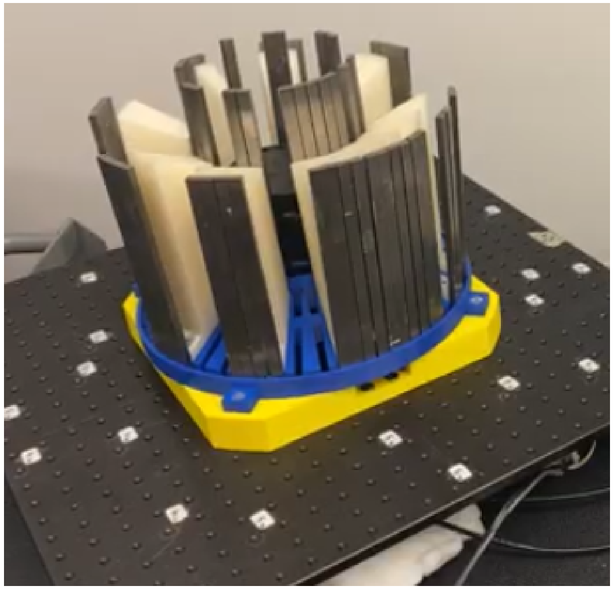
Outer Diameter: 66.6 cm
Inner Diameter: 56.6 cm

MATADOR (Michigan)



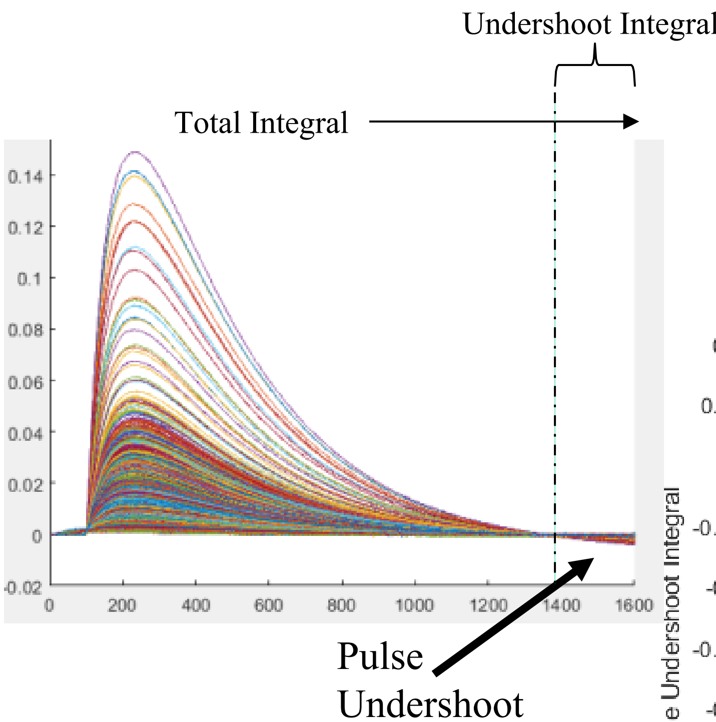
Outer Diameter: 51.4 cm
Inner Diameter: ~25 cm

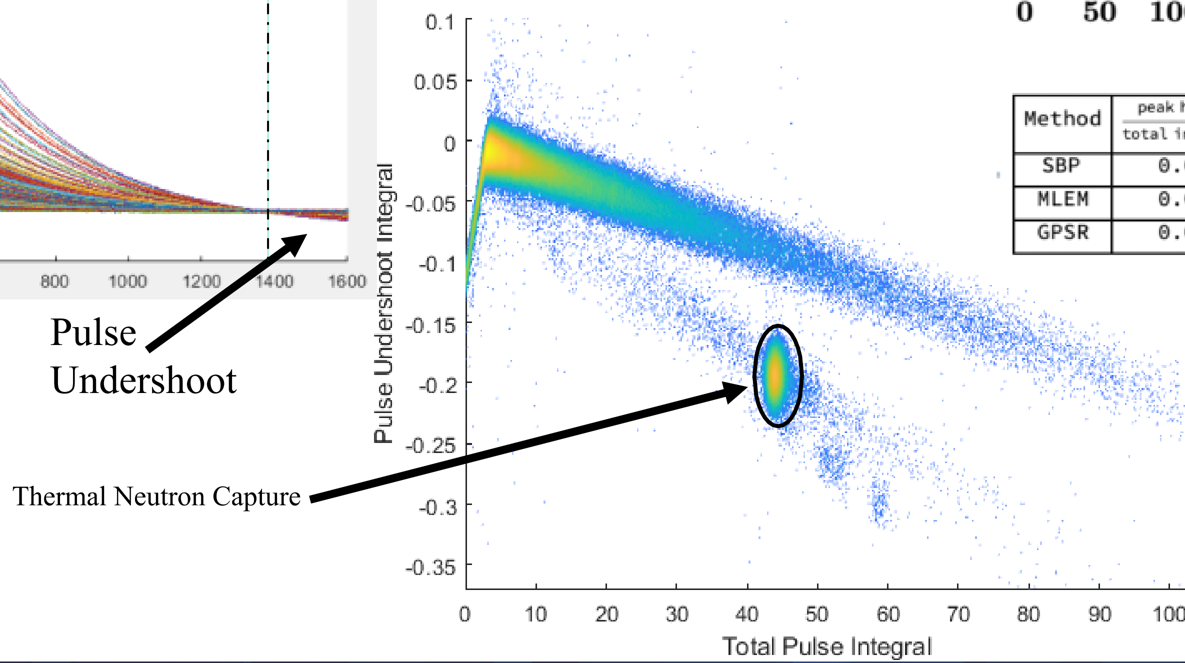
lanTErn (Michigan)

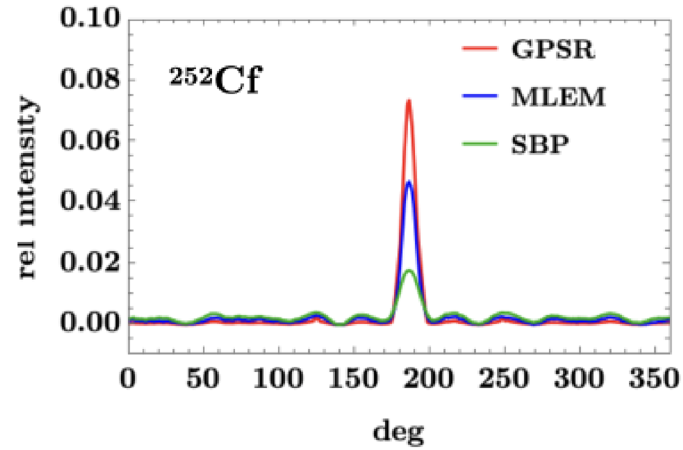


Outer Diameter: 30.635 cm
Inner Diameter: ~12 cm

- **Measured an 883 µCi Cf-252 S.F. source with poly & tungsten mask & 1” CLLBC**
- **Prominent pulse undershoot in most waveforms**







Method	peak height / total intensity	FWHM (deg)	peak height / σ (sidelobes)
SBP	0.018	15.8	19.1
MLEM	0.047	11.1	69.8
GPSR	0.074	10.	225.6

Coded Aperture Optimization - Sandia

- Point spread function
  - “square” spread function
  - “circle” spread function

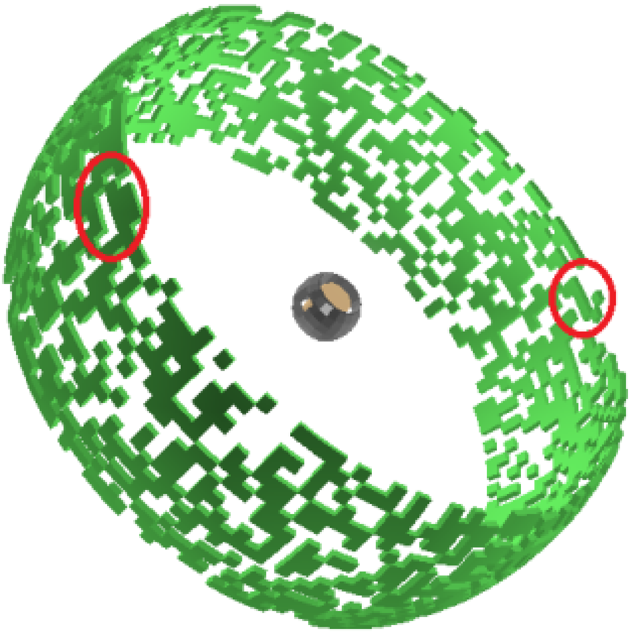
  Better representation for extended sources

- Great Deluge Algorithm
  - random patterns

$$Q = \left[\left(\left[\frac{1}{NxNy} * \sum_{i,j} a(i,j)\right] + \frac{b}{I_T}\right)\frac{1}{NxNy} * \sum_{i,j} \frac{1}{|A(i,j)|^2}\right]^{-1}$$

  - Nx and Ny are the dimensions of the coded aperture pattern and a and A are the pattern and the Fast Fourier Transform of the pattern, respectively

- Ant Colony Optimization



Sandia COGNIZANT mask-antimask cTEI configuration

Ant Colony Optimization