The Effects of Incorporating Measured Data into a Reconstruction of Spent Fuel Pins

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NSSC Fall Workshop and Advisory Board Review
October 17-18, 2023

Introduction

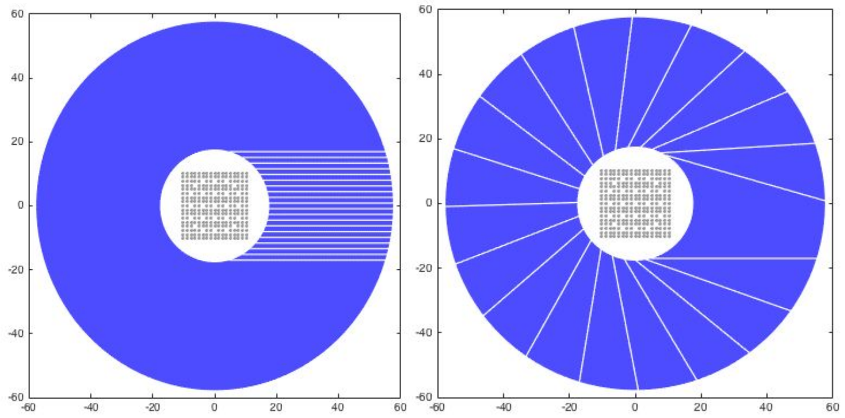
- **6th Year PhD student at UTK**
  - Department of Nuclear Engineering
  - Academic Advisor: Dr. Jason Hayward
  - Detector Development and Characterization
  - Planned Graduation: December 2023
- **National Lab Collaboration with ORNL**
  - Lab Mentor: Dr. Paul Hausladen
- **Focus: Nuclear Nonproliferation**
  - Emphasis on Materials Management and International Safeguards/Nuclear Verification
- **Mission Relevance of Research:**
  - Nuclear nonproliferation principles involve verification of spent fuel. A fast neutron emission tomography system for spent nuclear fuel would allow for imaging of individual fuel pins and quantifications of neutron source strength and burnup, which could help detect when fuel pins have gone outside regulatory control.

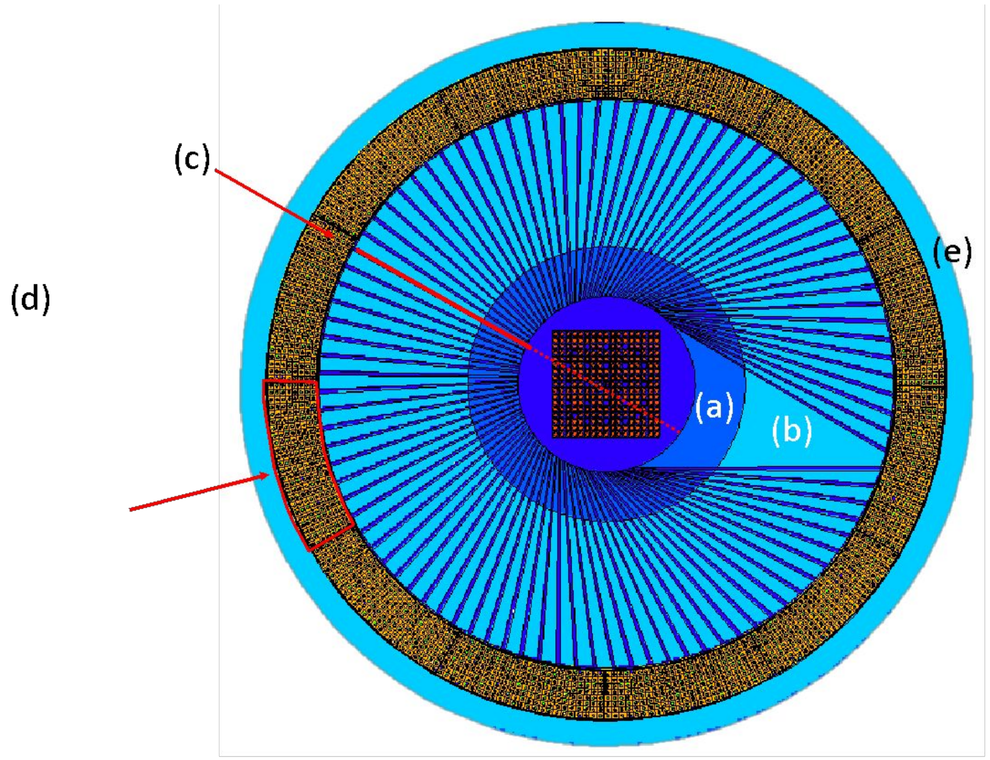
Mission Relevance and Background

- International Atomic Energy Agency (IAEA) has interest in nuclear safeguards and nonproliferation
  - Developing methods for verification of spent nuclear fuel (SNF)
  - Develop containment and surveillance techniques for nuclear materials
  - Pursue the continuity of knowledge over nuclear materials and facilities
- IAEA's goal is to detect diversion of SNF
  - Gross defects: the diversion of full spent fuel assemblies
  - Partial defects: the diversion of single or multiple fuel pins.
- Goal of a Tomography Verification Tool
  - single fuel pin resolution
  - minimally invasive
  - Nondestructive verification

- Passive Gamma Emission Tomography (PGET)
  - Uses ^{137}Cs (661 keV) and a higher energy gamma emitter like ^{154}Eu (1274 keV) in combination to image fuel assemblies
  - Limited research on 17 x 17 fuel assemblies
- Neutron Emission Tomography
  - Less self-shielding potentially allows for imaging 17 x 17 fuel assemblies
  - Potential source strength identification
    - ^{244}Cm buildup is proportional to Pu buildup
    - Burnup determination

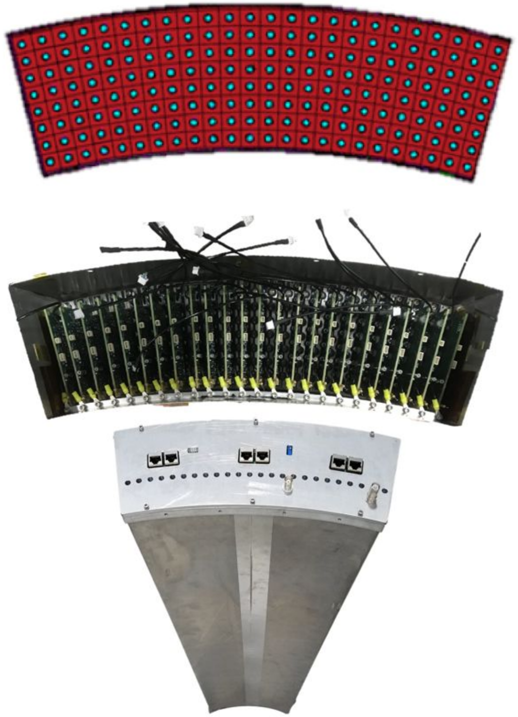
Initial Imager Design

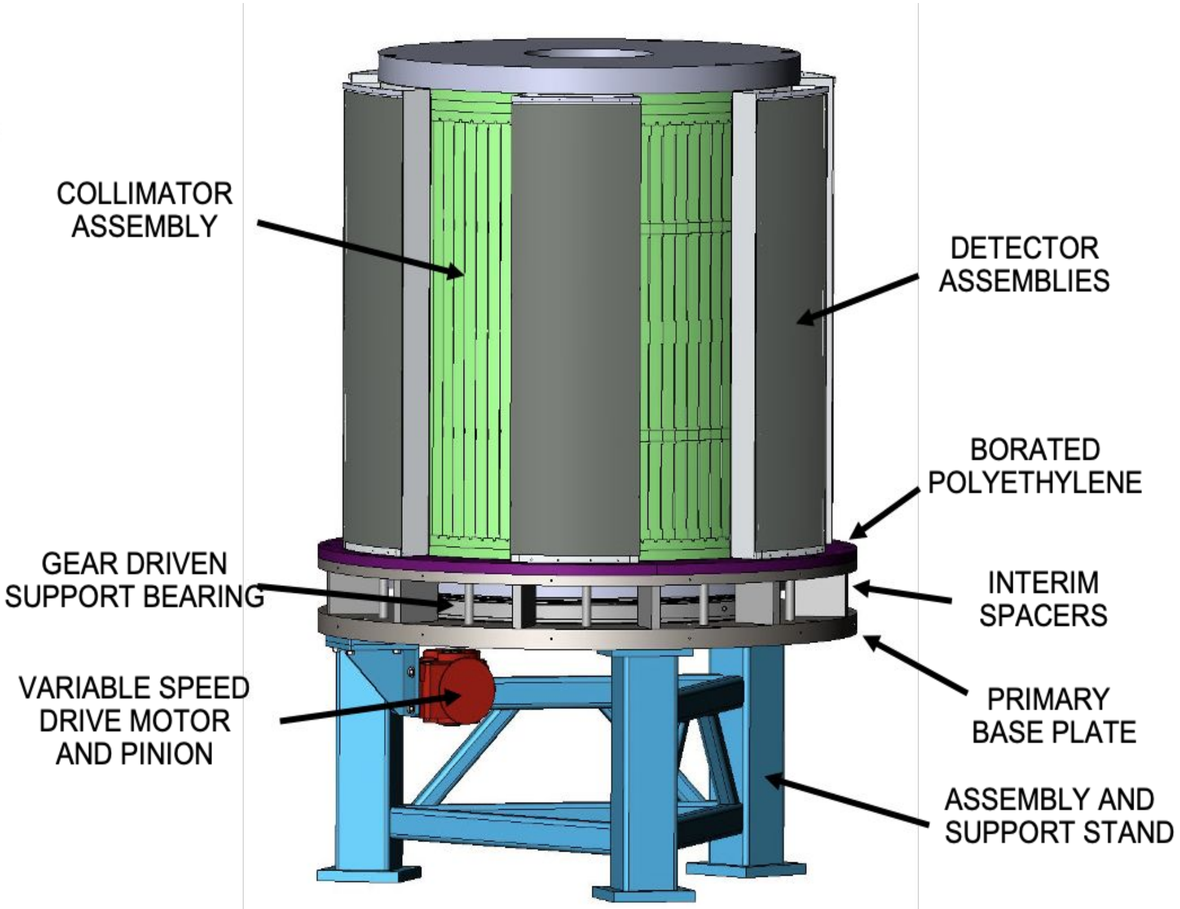




- Collimator annulus
  - (a) inner stainless steel
  - (b) outer borated polyethylene ring
  - (c) 96 slits - define lines of response across the field of view.
- Neutron detection
  - (d) 12 detector modules - 24 rows of 8 boron straws each and inner and outer edges lined with Cd
  - (e) 5-cm-thick ring of borated polyethylene shielding

As-Built Imager Construction





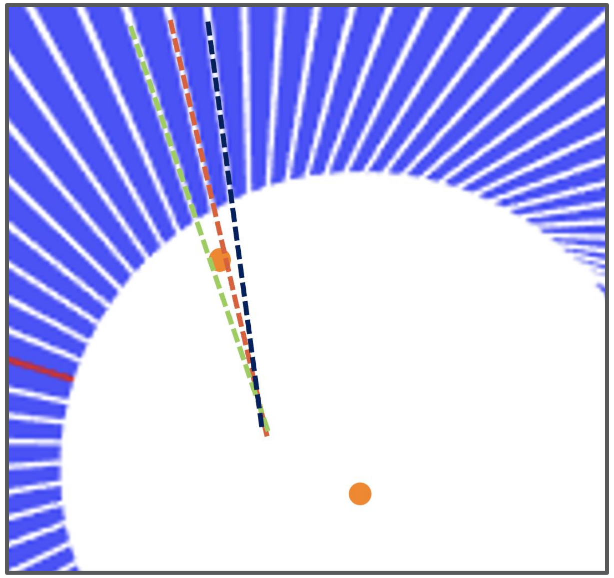
Measurements

Neutron Source: Cf-252 source - 3,173,000 n/s

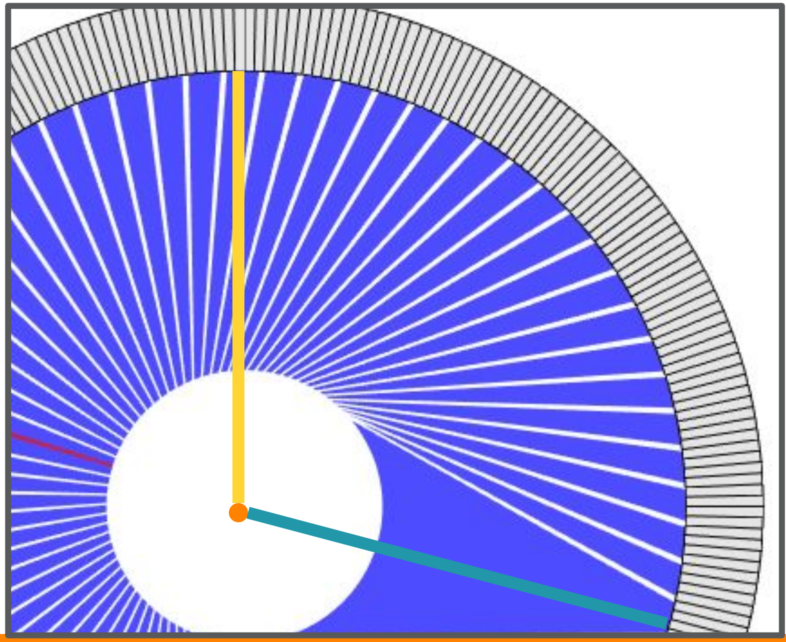
- Spent fuel: ~250,000 n/s per meter of fuel pin for 40 GWd/MTU
  - Cf-252 source is equivalent to about 3.1 fuel pins ~4m in length each

214 Total Measurements

- Characterization – measurement data used to improve the reconstruction model
  - Efficiency Characterization
  - Collimator Penetration Characterization
  - Direct and Edge Transmission Characterization
- Full Fuel Assembly
  - Source rod mockup with no shielding rods
  - Source mockup with shielding rods



Edge and Direct Scattering:
Red – line of response includes main portion of source (direct)
Green – line of response includes edge of source
Black – line of response does not include source

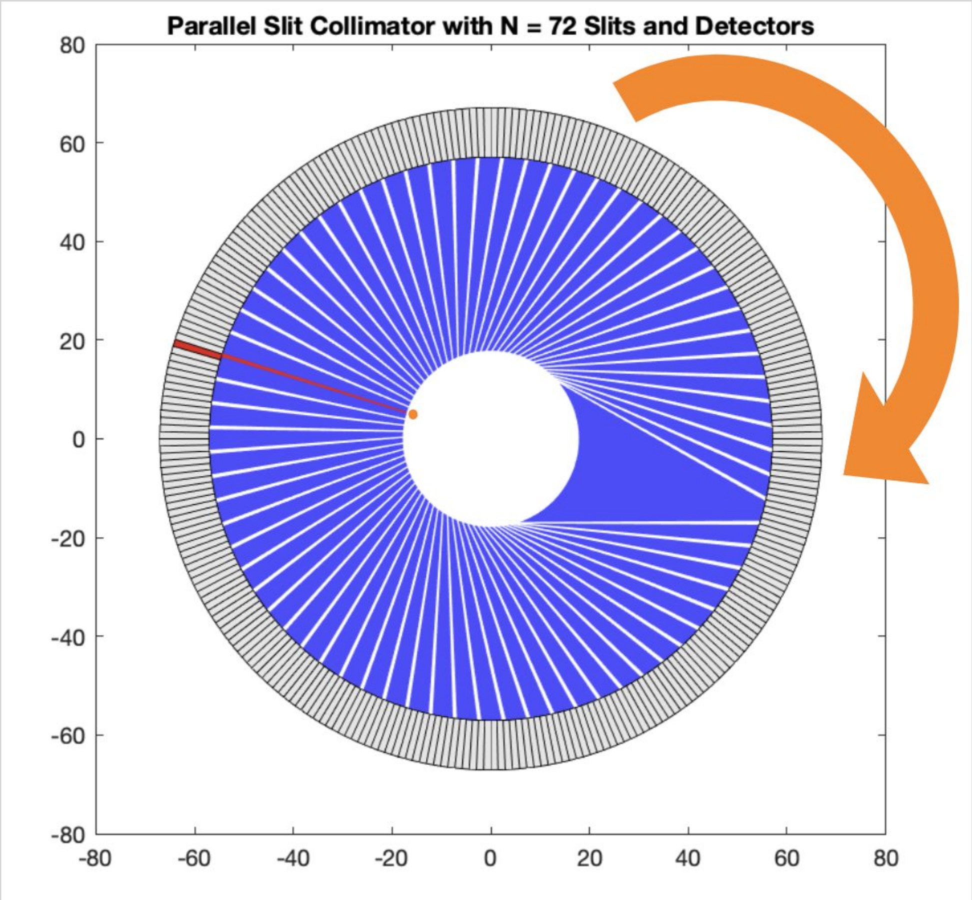


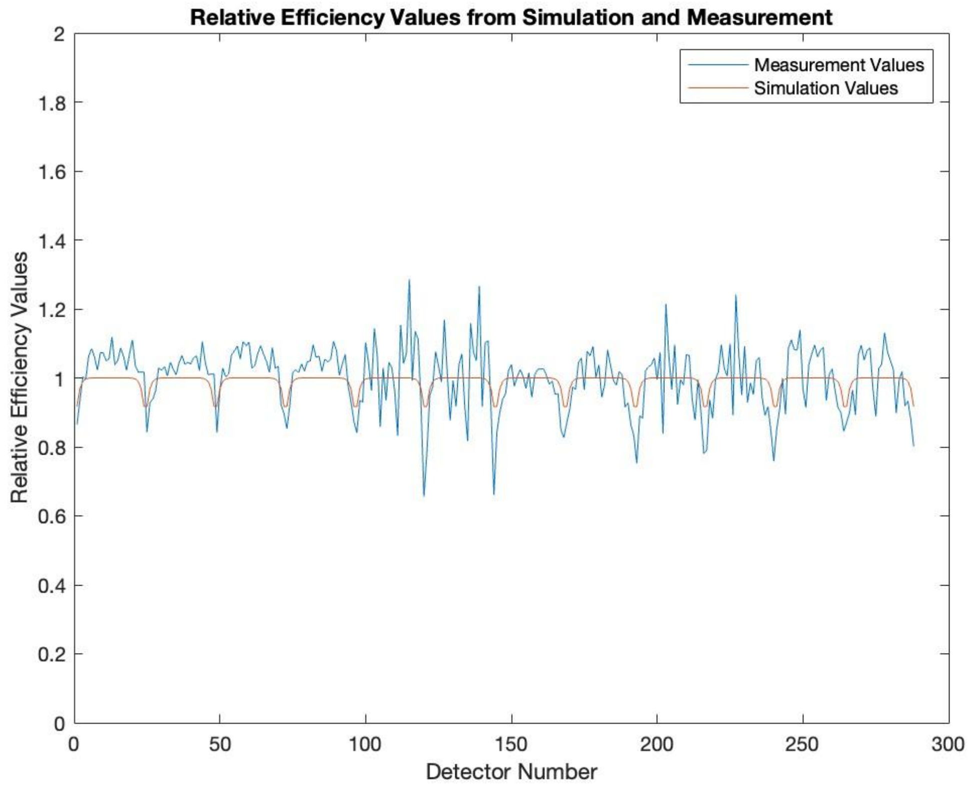
Collimator Penetration:
Yellow – less collimator material
Blue – thickest part of collimator

Efficiency Calibration

Efficiency Measurement

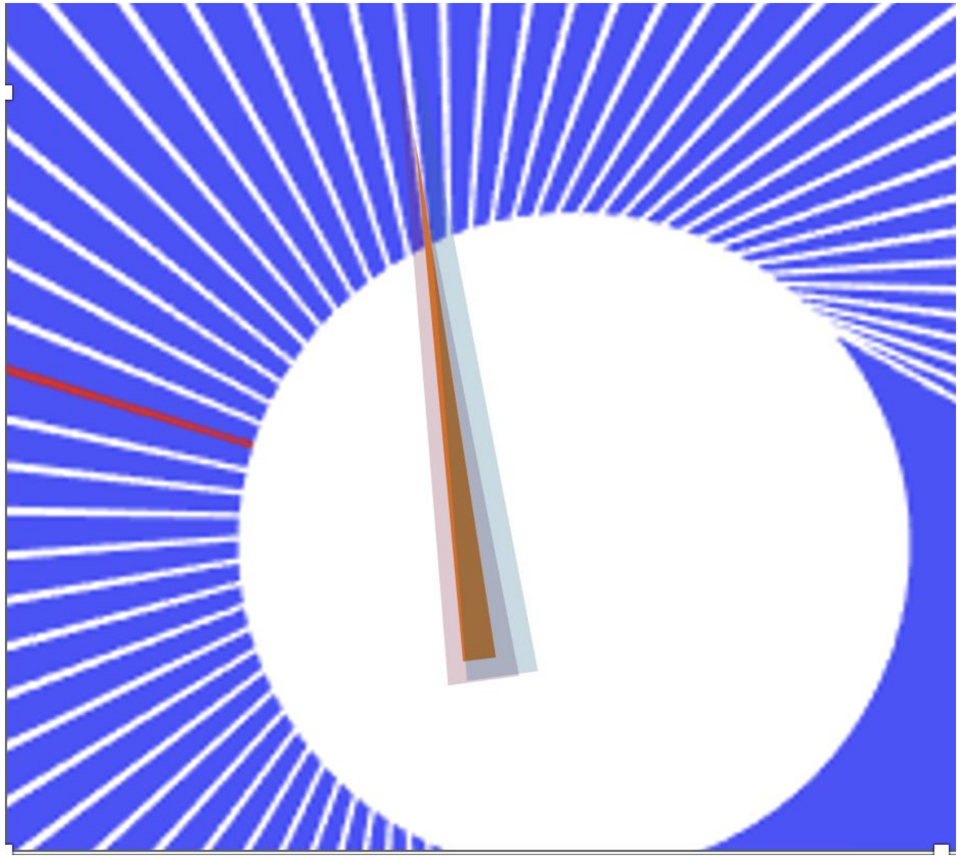
- Placed Cf-252 source along the perpendicular collimator slit and rotated the collimator to highlight each detector





Edge and Direct Scattering Changes

- Analytic code doesn't truly account for collimator rotation
  - Point and shoot vs constant rotation
    - In constant rotation the data is 'binned' to create the projection
    - In the analytic code each projection is an exact point, so no bins needed
  - Lines of Response need to be expanded
    - Solid orange triangle is how code defines a single projection
    - Pink translucent triangle accounts for response as the collimator rotates **away** from the projection point
    - Blue translucent triangle accounts for response as the collimator rotates **toward** from the projection point



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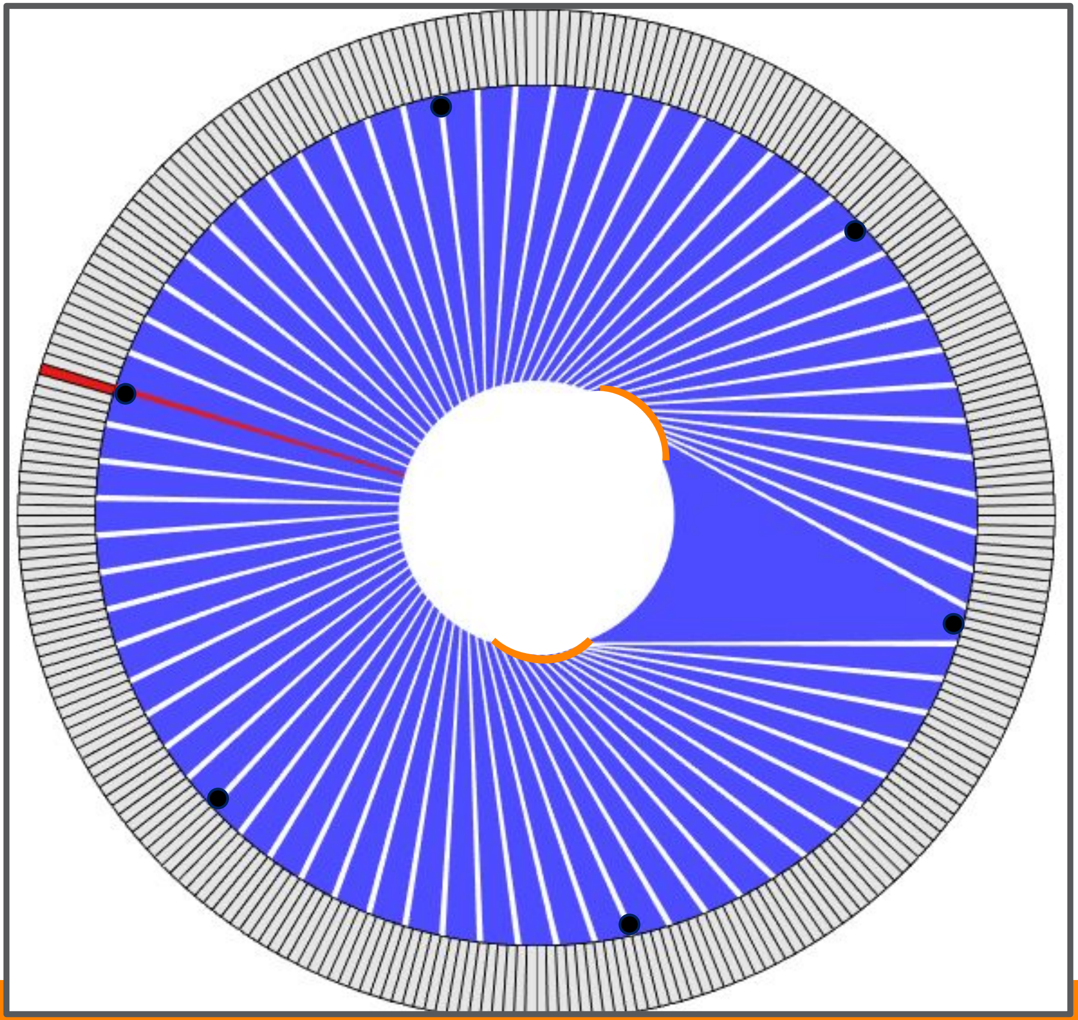
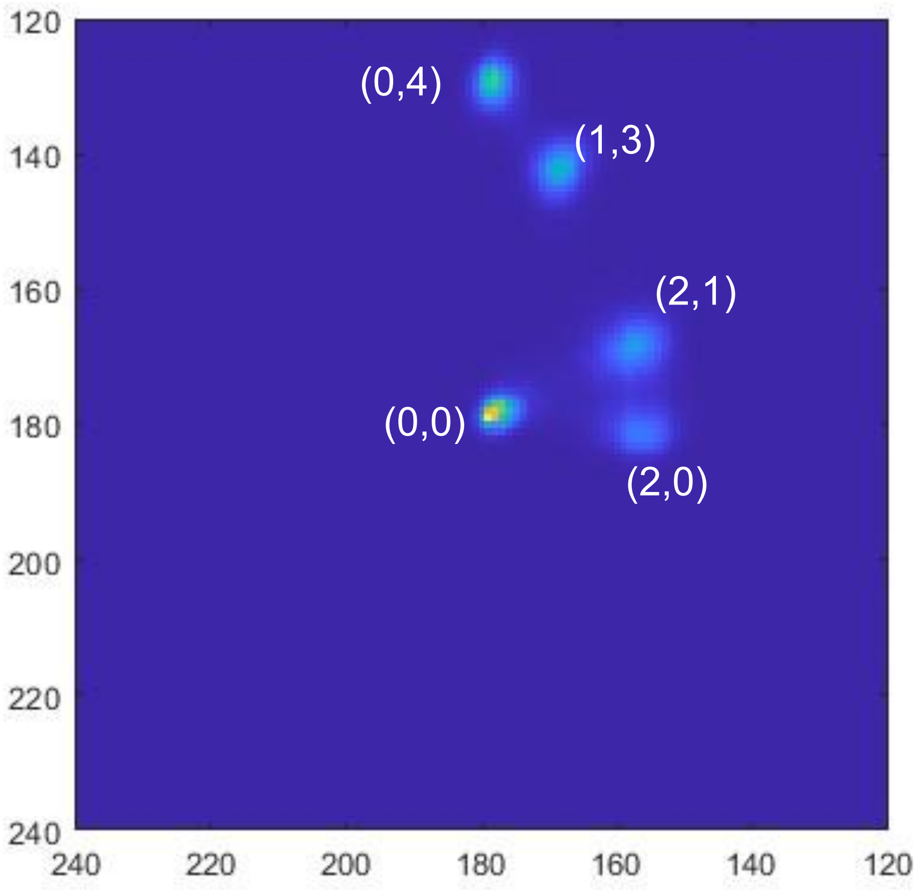
Collimator Penetration Changes



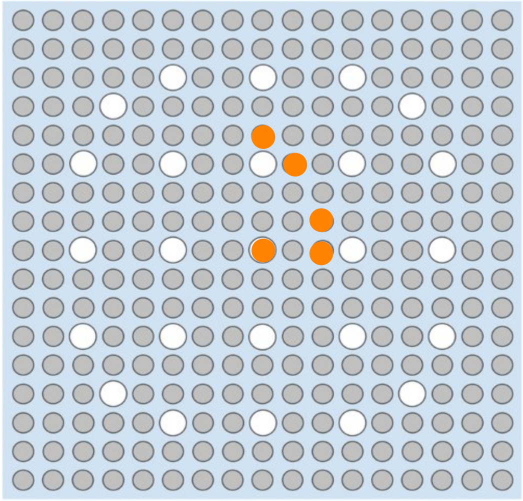
- Due to building challenges some sections of the collimator are thinner than originally designed
  - Collimator cannot reach the inspection volume (orange curves)
  - Tie rods make collimator shorter (black dots)
  - There are more neutrons interacting with detectors at these points because they are not being as attenuated

5 Points Reconstruction



5 Separate Measurements

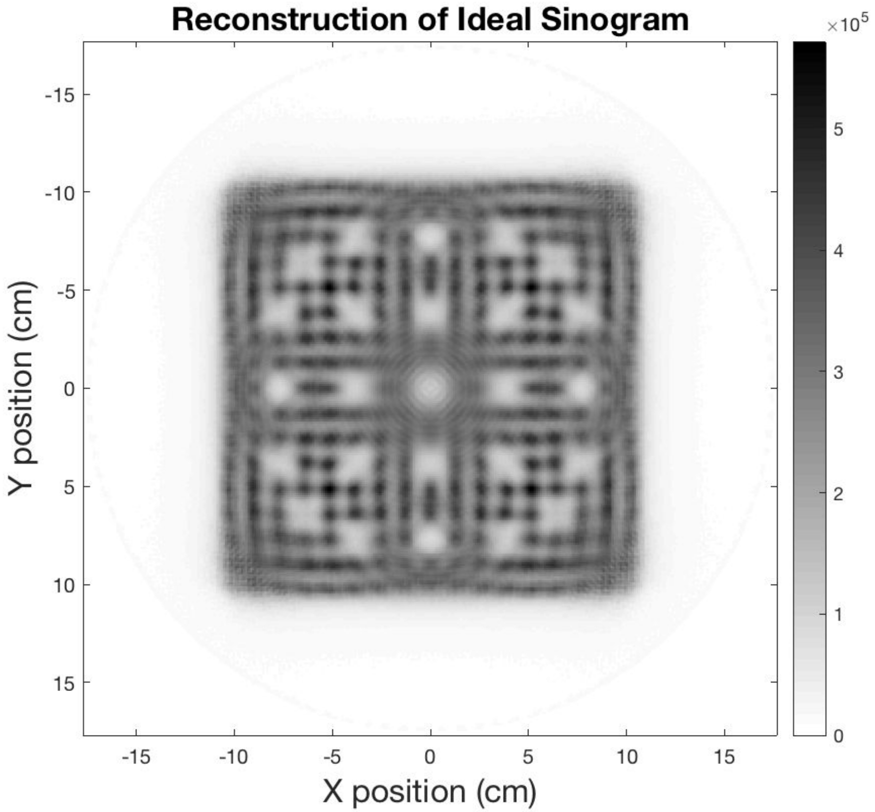
- (0,0), (2,0), (0,4), (2,1), (3,1)
- (2,1) and (2,0) are 0.5 in apart
- 0.5” < Fuel Pin Gap



Point	Distance from Expected Pixel
(0,0)	0 mm
(2,0)	3.94 mm
(2,1)	3.80 mm
(3,1)	2.92 mm
(0,4)	1.28 mm

Conclusions and Moving Forward

- Experimental data has been analyzed to incorporate into an analytic neutron response model
  - Relative Efficiency
  - Collimator Penetration
- Moving forward:
  - Reconstruct a full fuel assembly
    - Add pins slowly starting from the corner and working in



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The NSSC Experience

- **NSSC Graduate Fellow 2020-Present**
  - IEEE NSS/MIC
    - Poster Presentation – Nov. 2023
    - Oral Presentation – Nov. 2022
    - Oral Presentation – Nov. 2020
  - NSSC Presentations
    - UPR Oral Presentation – June 2023
    - UPR Oral Presentation – Sept. 2021
    - Kickoff Meeting Poster Presentation – April 2022
    - Virtual Scholar Showcase – June 2020
  - Workshops
    - GWU's Nuclear Security Bootcamp – June 2021
    - PNNL's Intro to Arms Control – July 2023
    - PNNL's Radiation Detection for Nuclear Security – June 2022
- **NSSC Undergraduate Affiliate 2017-2018**
  - Academic Advisor: Bethany Goldblum
  - Lab Mentor: Dr. Darren Bleuel at LBNL

Acknowledgements

This material is based upon work supported by the Department of Energy National Nuclear Security Administration under Award Number **DE-NA0003996.** This work is supported by the US Department of Energy, Office of Defense Nuclear Nonproliferation Research and Development in the National Nuclear Security Administration (NA-22).

Questions