INL/CON-25-84031-Revision-0

# Neutron and X-ray computed tomography of a natural uranium tristructural isotropic (TRISO) fuel compact

June 2025

Changing the World's Energy Future

William C Chuirazzi, Swapnil Kishor Morankar, Yuxuan Zhang

Idaho National Laboratory

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**Idaho National Laboratory**
**Idaho Falls, Idaho 83415**

**http://www.inl.gov**

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**William Chuirazzi[1], Yuxuan Zhang[2], and Swapnil Morankar[1]**

[1]Idaho National Laboratory
[2]Oak Ridge National Laboratory

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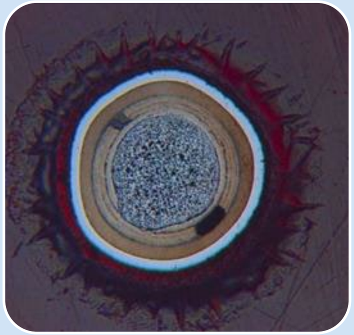
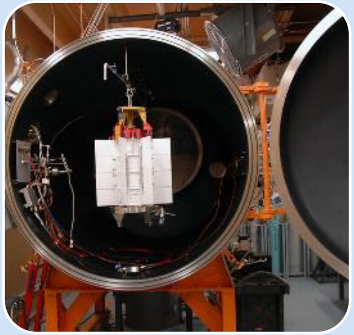
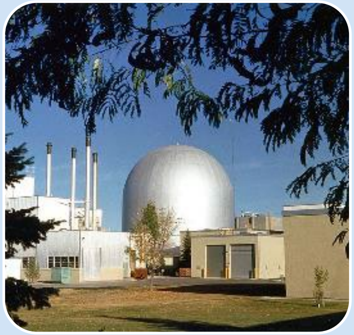
# Introduction

- Idaho National Laboratory's mission is to ***discover, demonstrate*** and ***secure*** innovative ***nuclear energy solutions***, other clean energy options and critical infrastructure
- Nondestructive examination techniques support this mission by:
  - Providing information for ***modeling*** fuel performance
  - Comparing ***pre***- and ***post-irradiation*** effects
  - Informing destructive analysis
  - Saves ***time*** and ***money***
- Quantify material performance in the harsh environment of a reactor to ensure safe commercial operations once deployed
- Ultimately, we aim to ***speed up*** the ***design, development,*** and ***deployment*** of nuclear energy technologies from conceptualization to commercialization

# MFC Nuclear Research, Development & Demonstration Capabilities (*with other connected INL capabilities*)







### Fabrication

- Experimental Fuel Facilities
- Fuels & Applied Science Building
- Fuel Manufacturing Facility
- Zero Power Physics Reactor
- Analytical Laboratory
- Advanced Fuels Facility

### Fresh Fuel Characterization

- Fuels & Applied Science Building
- Analytical Laboratory
- Experimental Fuel Facilities

### Irradiation

- Transient Reactor Experiment & Testing (TREAT)
- Neutron Radiography Reactor (NRAD)
- Advanced Test Reactor (ATR)
- Offsite Reactors

### Post-Irradiation Examination & Characterization

- Hot Fuel Examination Facility
- Irradiated Materials Characterization Lab
- Fuel Conditioning Facility
- Analytical Laboratory
- Fuels & Applied Science Building
- Electron Microscopy Lab
- Neutron Radiography Reactor (NRAD)

### Space Nuclear Power and Isotope Technologies

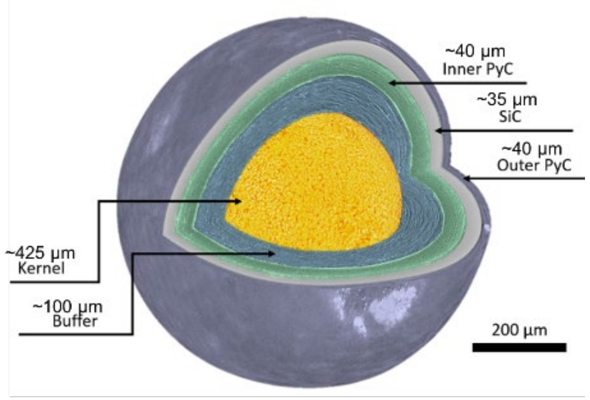
- Space & Security Power Systems Facility
- Engineering Development Lab
- Idaho Nuclear Technology & Engineering Center

### Advanced Reactor Demonstration Test Beds

- TREAT micro-Reactor Experiment Cell
- Laboratory for Operations and Testing in the US
- Demonstration of Microreactor Experiments

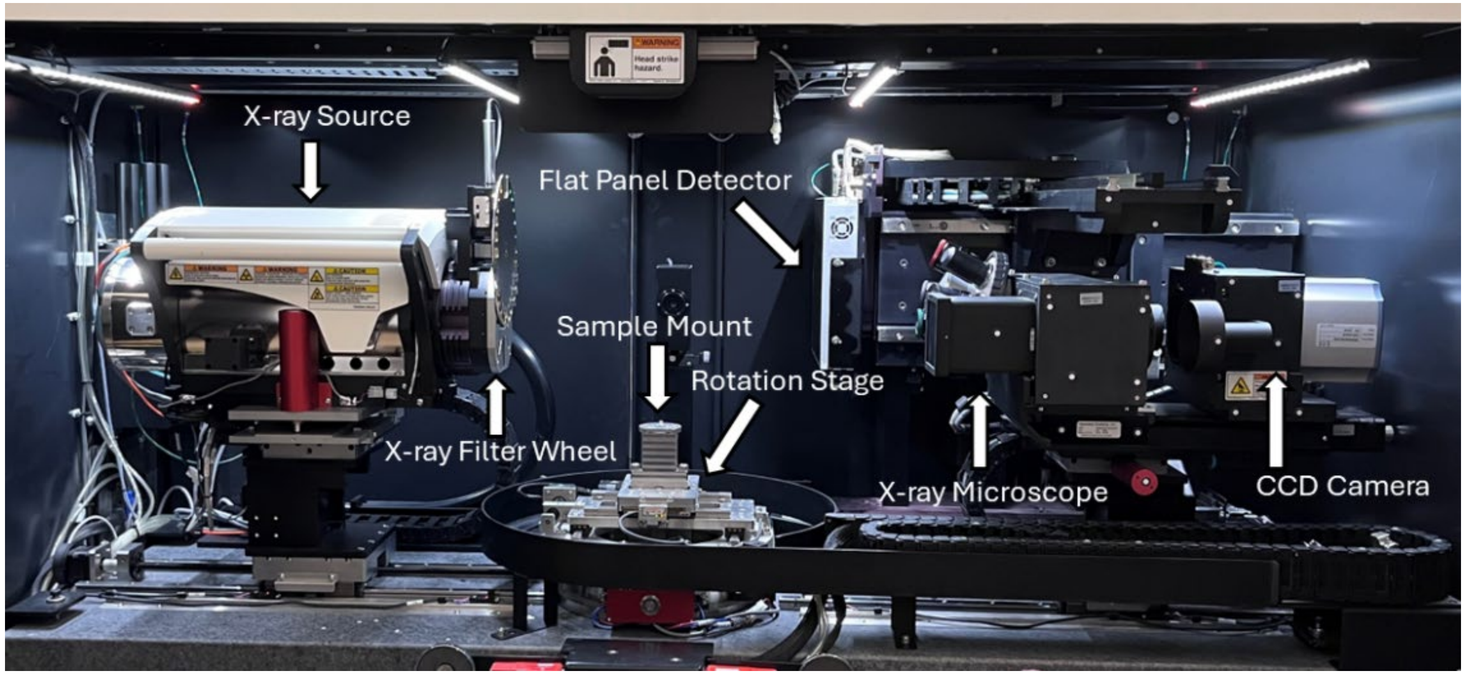
# TRISO Fuel and Compacts

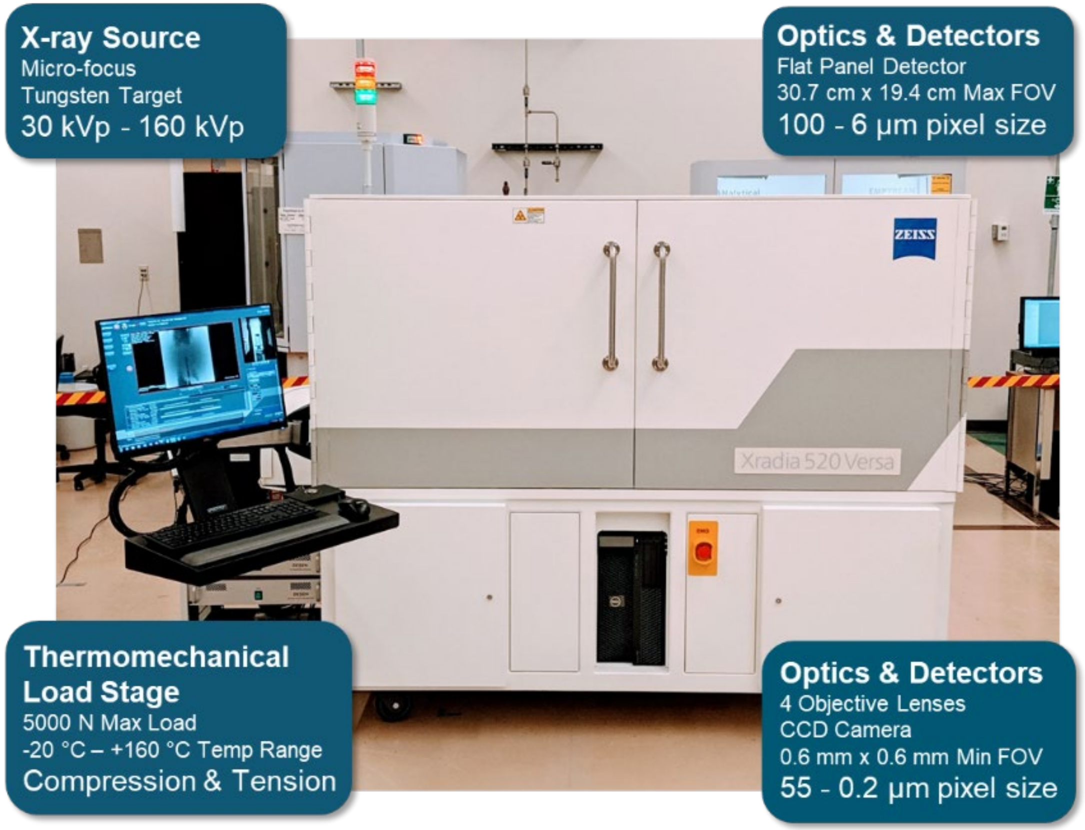
- TRISO- TRi-structural ISOtropic particle fuel
- PIE of individual particles investigates changes in individual particles layers
  - Thickness changes, buffer delamination, etc.
  - Kernel porosity and fission product migration
- PIE XCT of intact fuel compacts and loose particles yields different information. Fuel compact examination provides:
  - Kernel morphology
  - Variations morphology as a function of spatial position
  - Quantification of the buffer fracture frequency
  - Preservers compact for additional exams
    - Impossible following traditional examinations



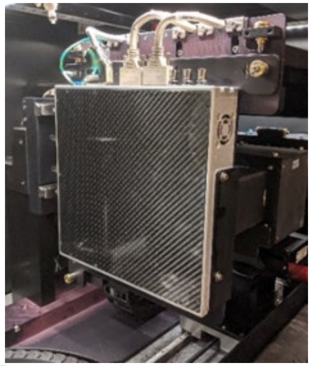
AGR Program TRISO Particle ~855 µm Diameter

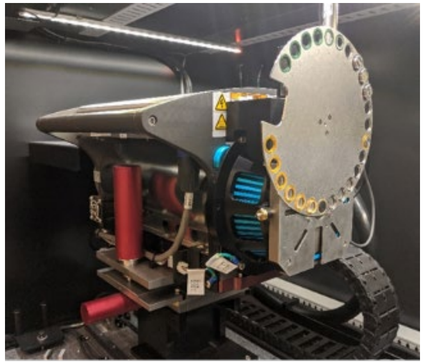
# ZEISS Xradia 620 Versa at IMCL



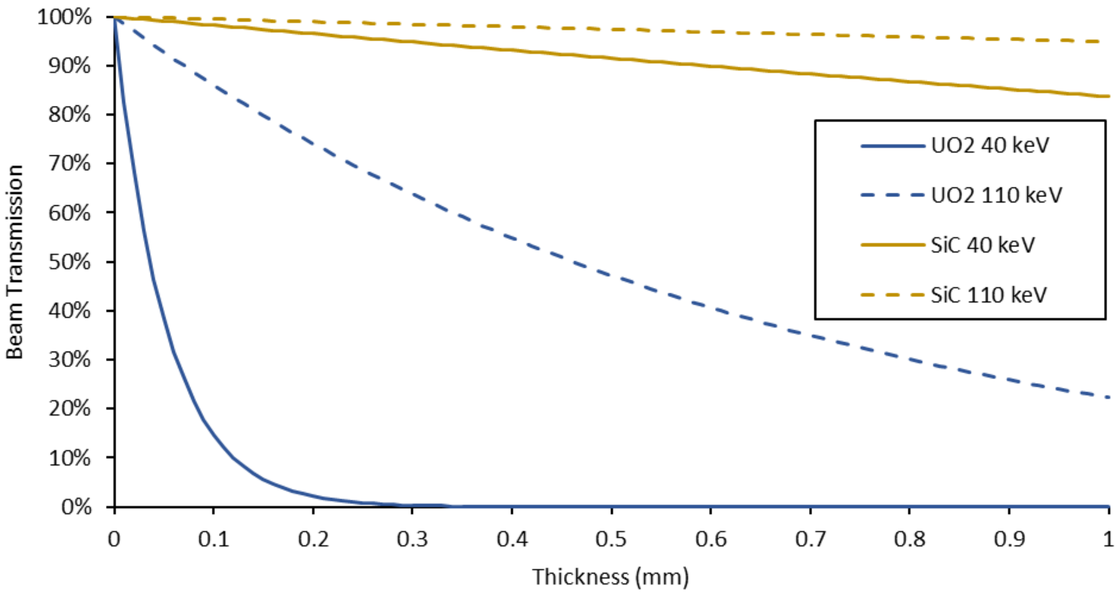



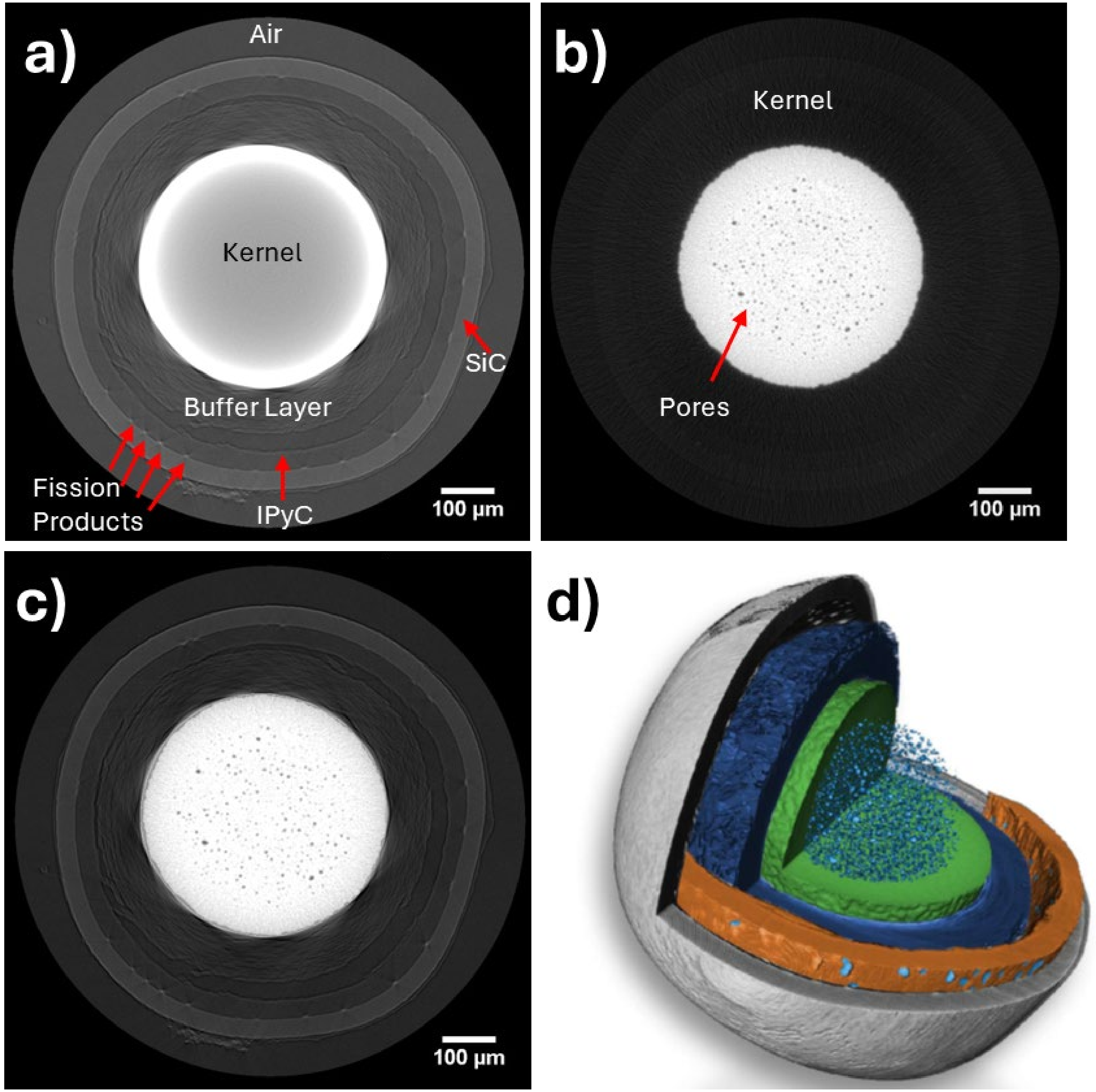

- Best spatial resolution to date: **270 nm/voxel**
- Hottest sample to date: **120 R/hr on contact**
- Instrument is maintained as **radiologically clean**





# AGR TRISO Fuel

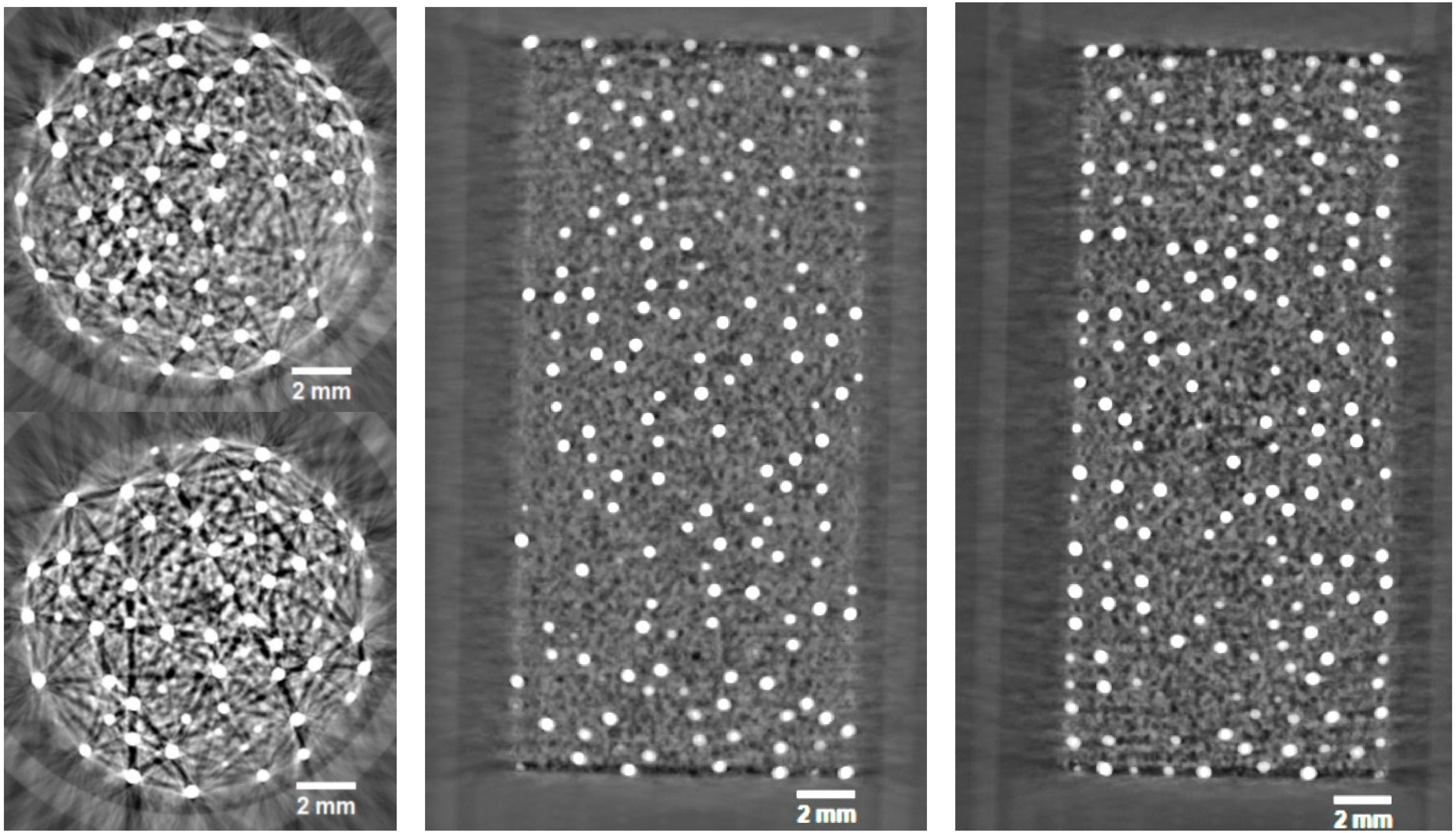


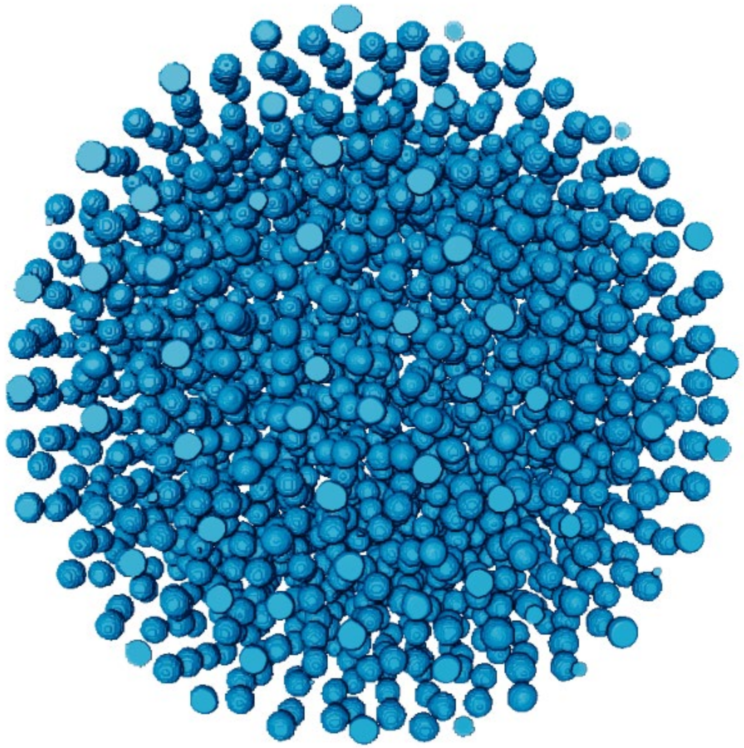

2D slices of a 3D reconstructed volume showing a) a low-energy (40 keV) scan on an irradiated AGR-2 TRISO particle, b) the corresponding high-energy (110 keV) scan of the same particle, c) the images fused together, and d) a 3D rendering of the particle using information from both datasets.

William Chuirazzi, Joshua J. Kane, Nikolaus L. Cordes, John D. Stempien, Rahul R. Kancharla, and Fei Xu. "Seeing the whole picture: Methods for getting the most from micro X-ray computed tomography of TRISO nuclear fuel particles." *Tomography of Materials and Structures* 2 (2023): 100005.

# TRISO Compact Examination

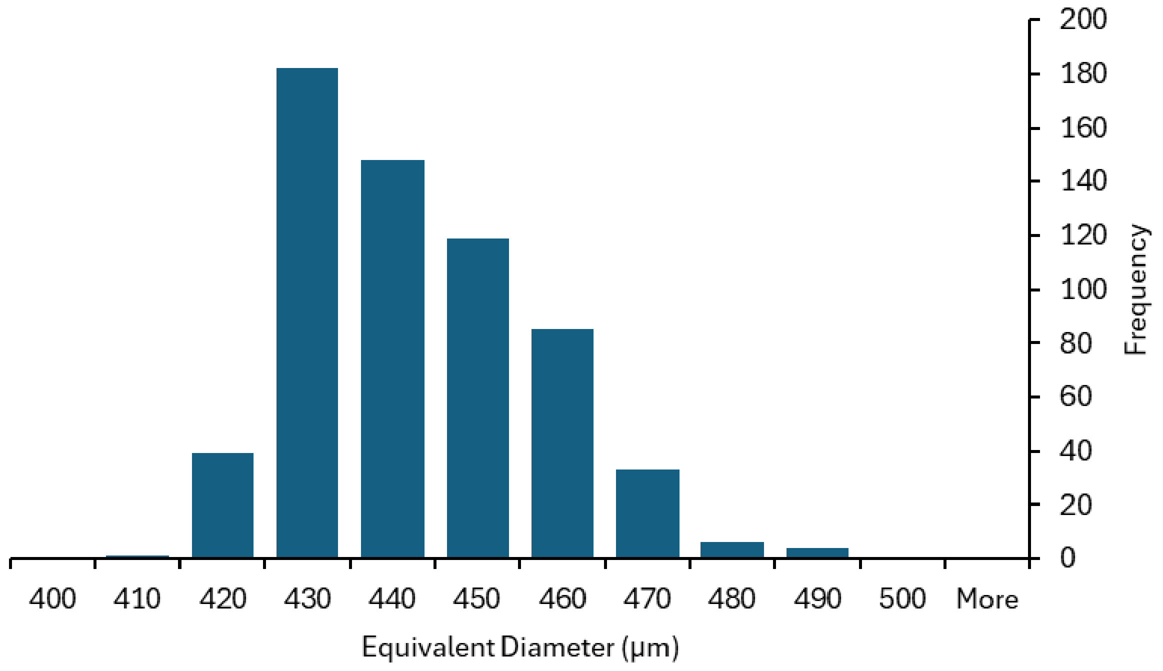


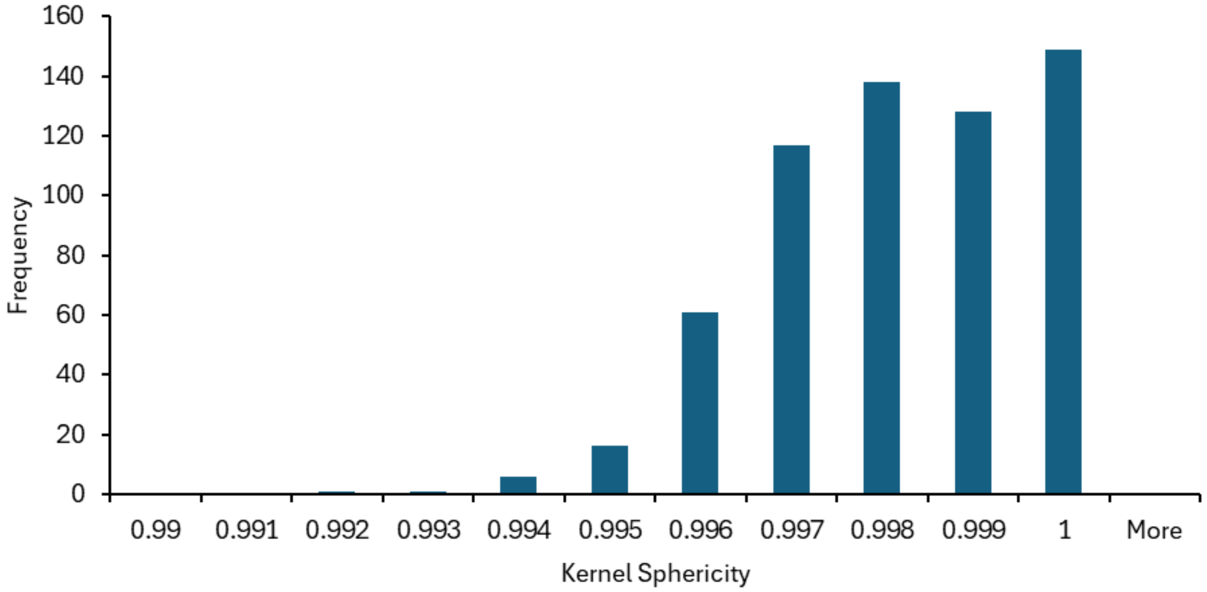
# XCT Renderings



# Quantitative Results

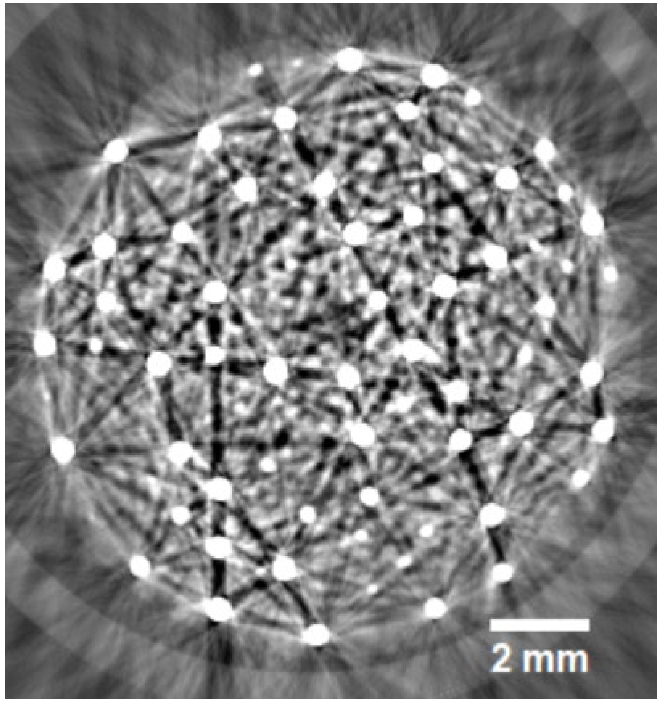
- Quantify kernel information
  - Equivalent diameter
  - Sphericity
  - Kernel position
  - Packing fraction
- Useful to compare pre- and post-irradiation to examine changes
  - Kernel swelling
  - Aspherical particles

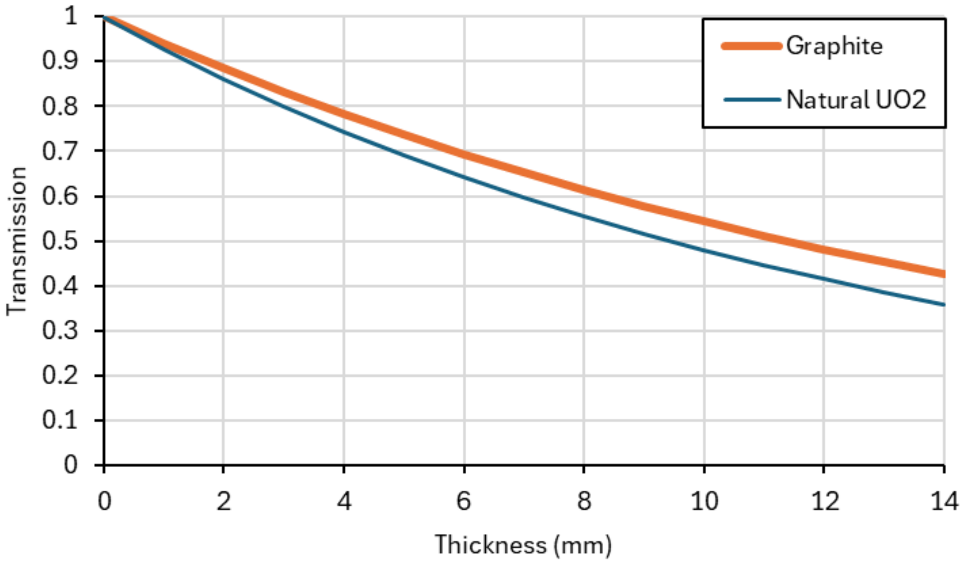


# Need for Neutron CT

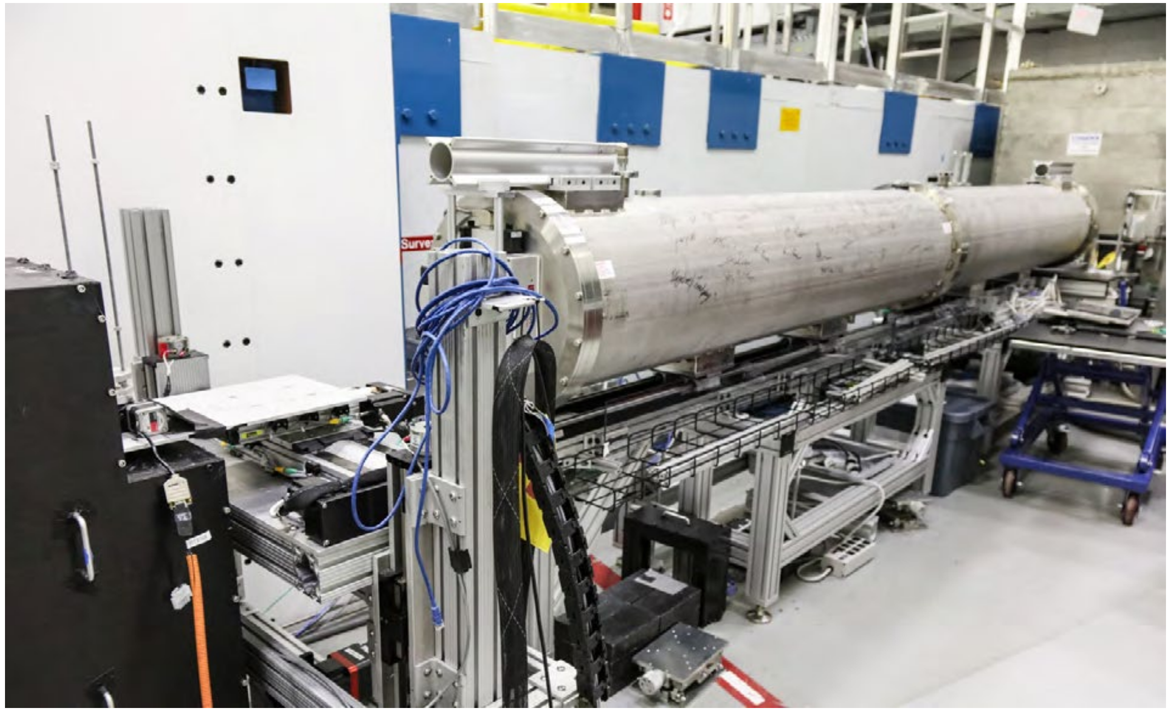
- Can we see defects in the matrix of the compacts nondestructively?
- **Informs structural integrity** of the compact before and after irradiation
- If features of interest (i.e. cracks) are found, their location can be used to determine potential causes
- X-ray attenuation introduces too much noise for matrix examination
  - Advanced reconstruction and artifact reduction techniques cannot sufficiently resolve features in the matrix
- Neutrons may offer a solution
- Used an unirradiated, natural Uranium compact as a proof-of-principal

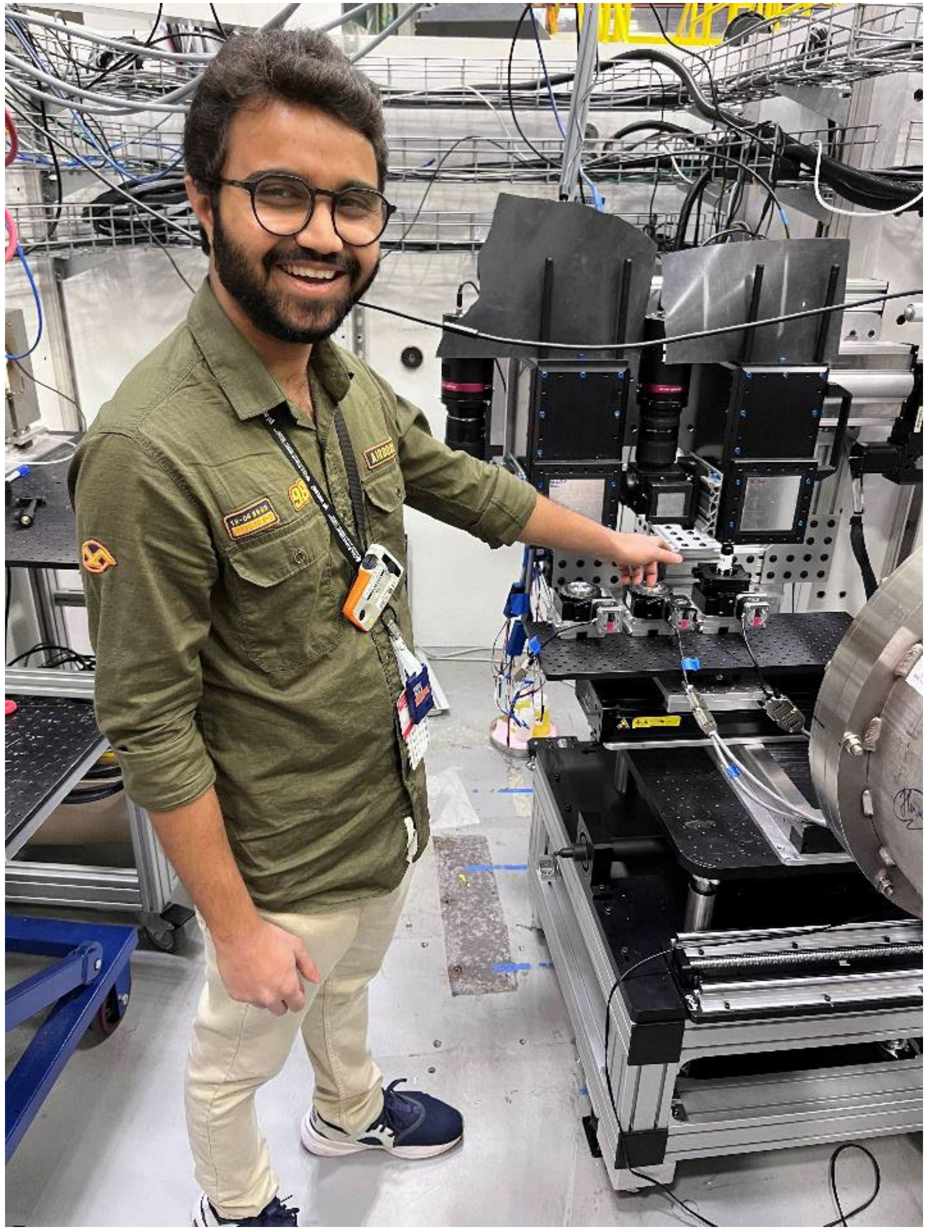


# MARS Beamline

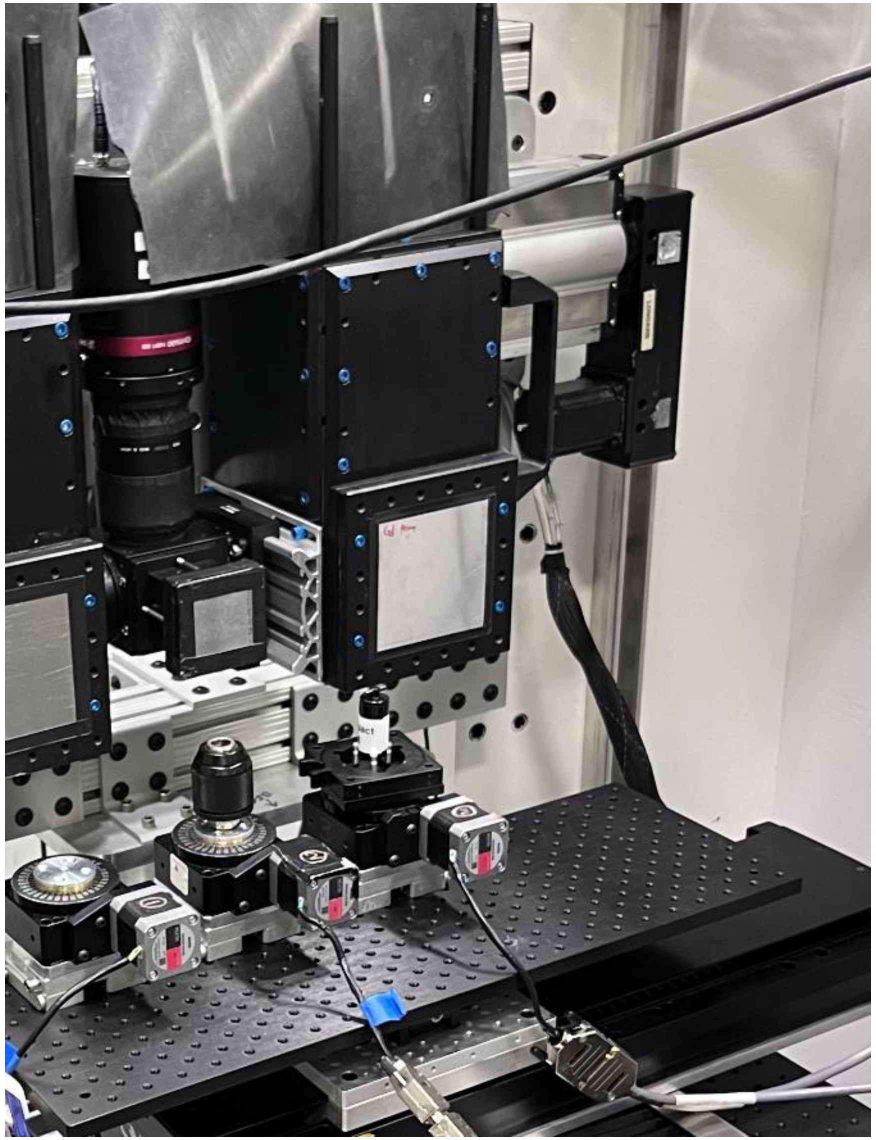
- Multimodal Advanced Radiography Station at HFIR's CG-1D Beamline
- Polychromatic beam of cold neutrons (peak wavelength 2.6 Å)





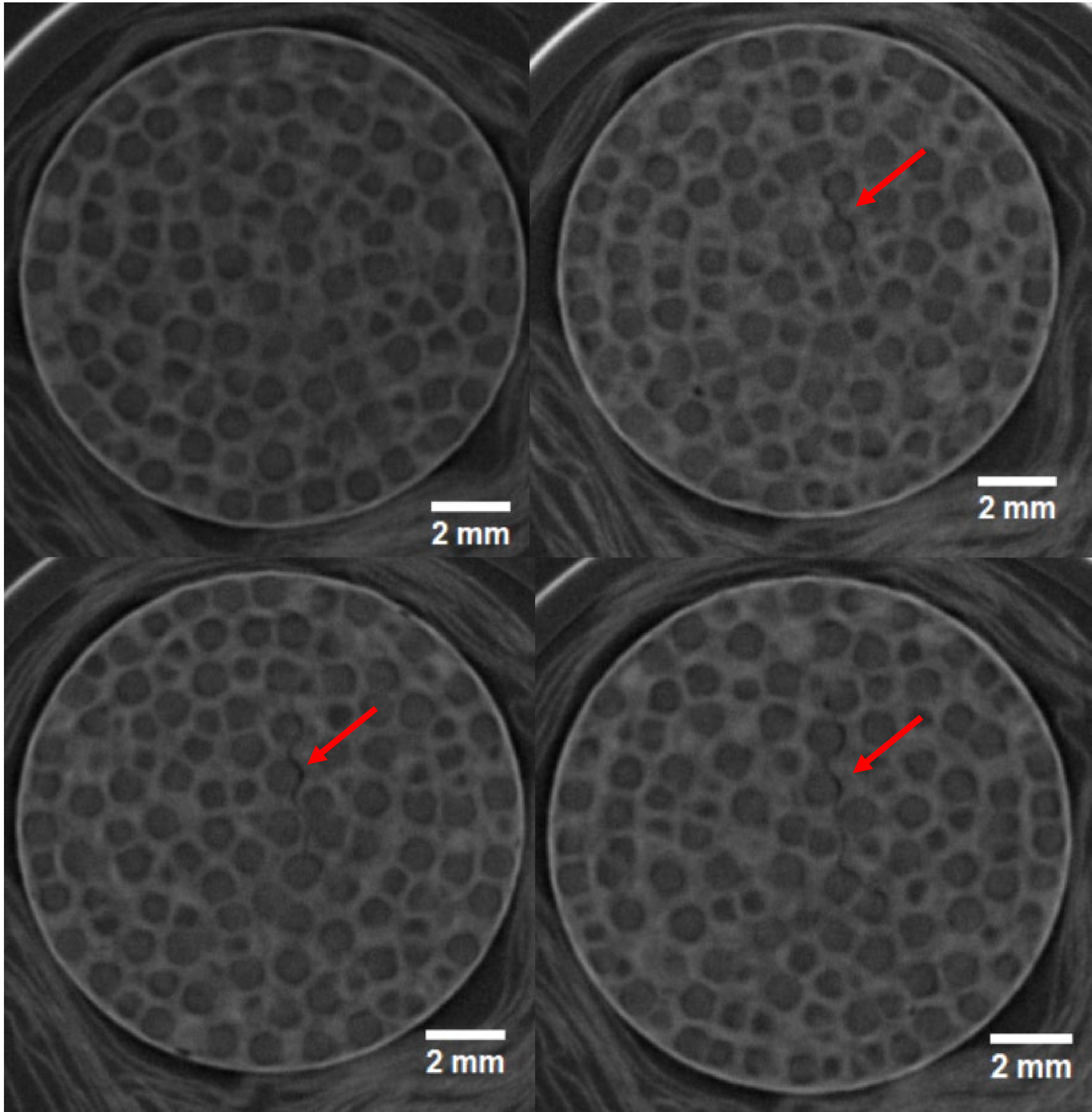
# MARS Imaging Conditions

- Absolute neutron flux was ~$5x10^6$ n/$cm^2$/s
- Pixel size is ~16 um/pixel
  - Spatial resolution is ~48 um
- L/D ~600
- sCMOS camera
- 1091 Radiographs captured
- SIRT Reconstruction algorithm
- Ring artifact removal but otherwise no image processing
  - bm3d ring removal

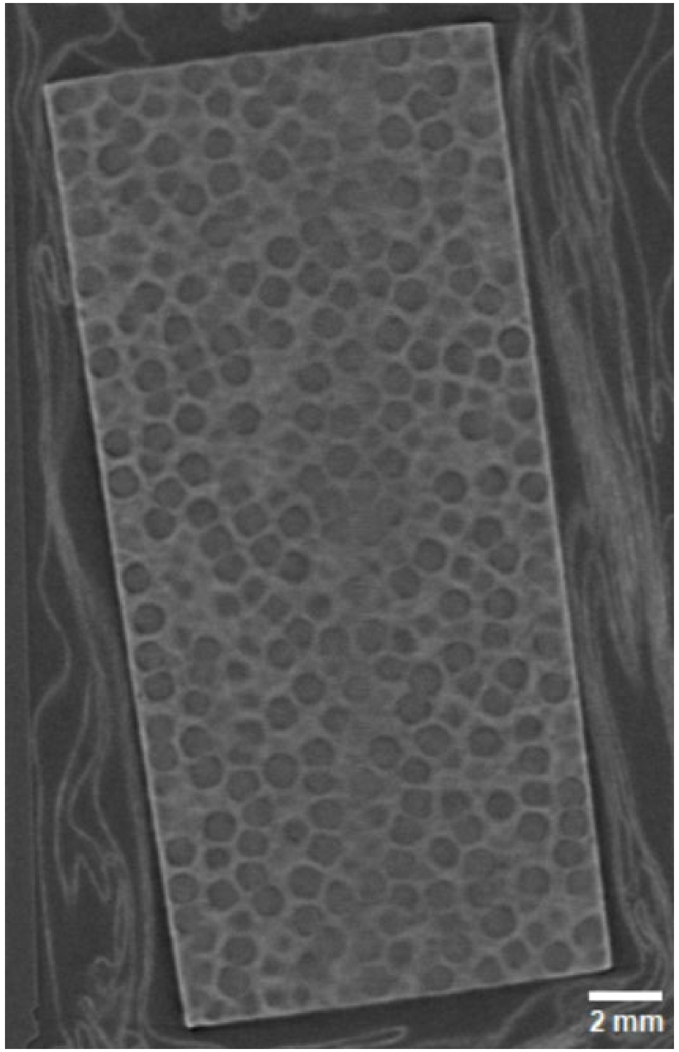


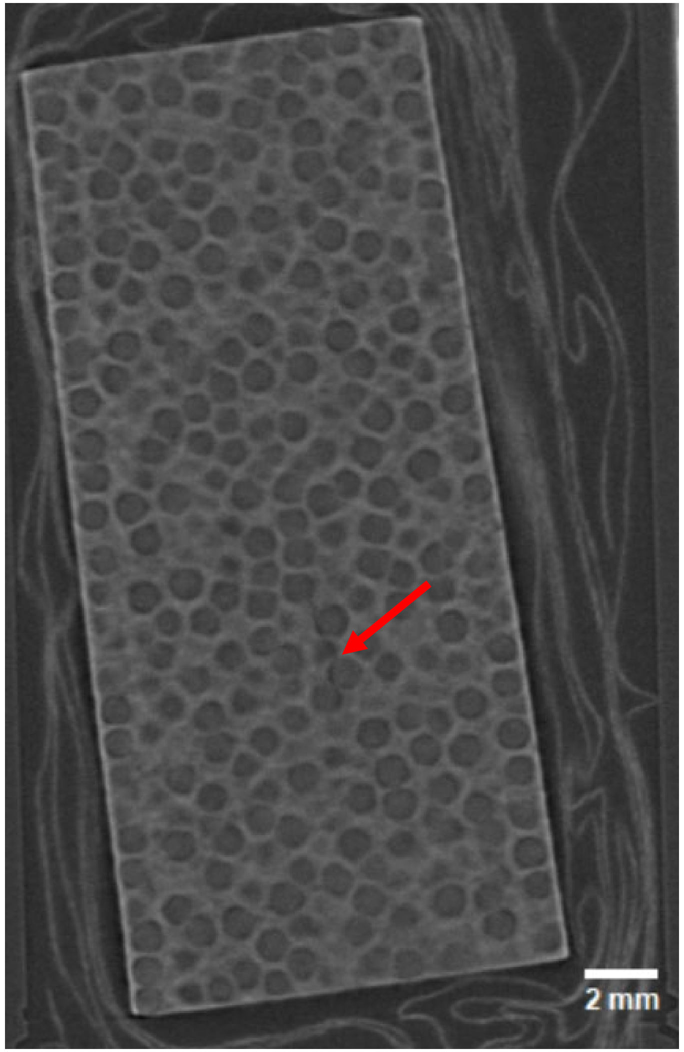
# nCT Results

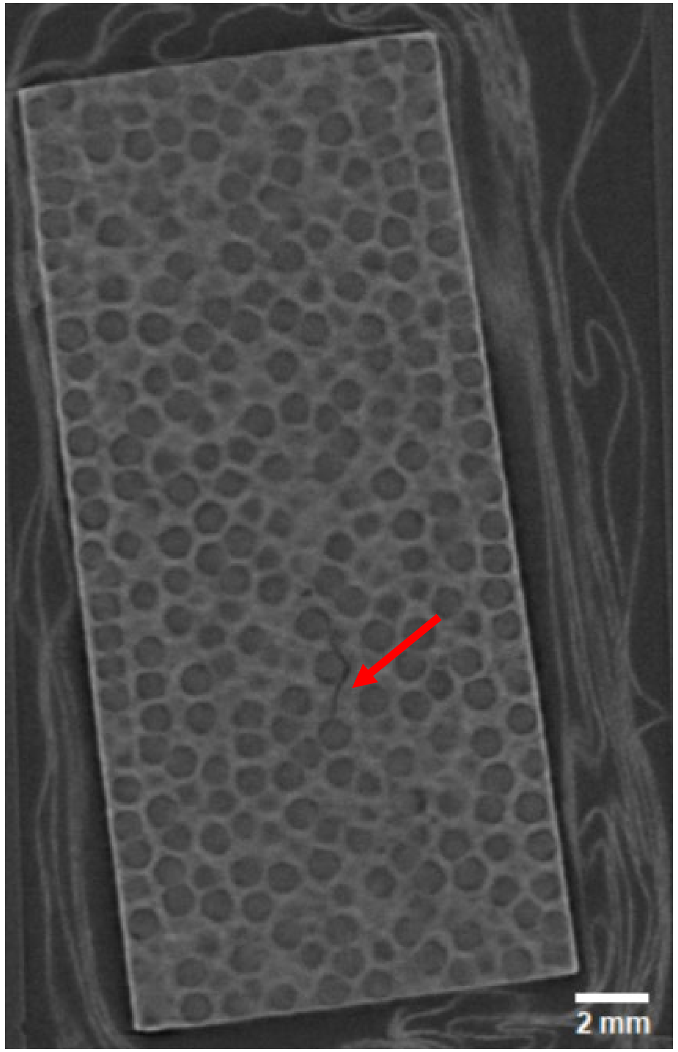
- Difficult to get information about individual particles
- **Crack** within matrix can **clearly** be **seen** across multiple slices
- Can provide useful method for matrix inspection



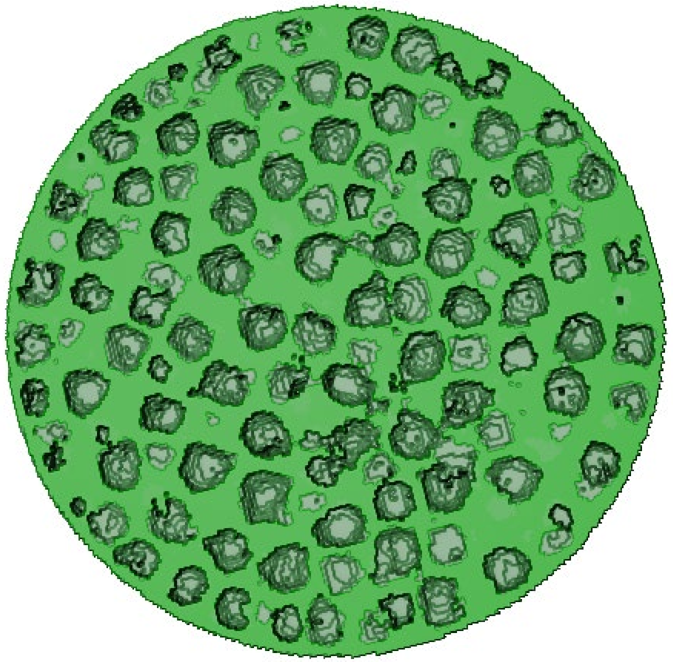
# nCT Results



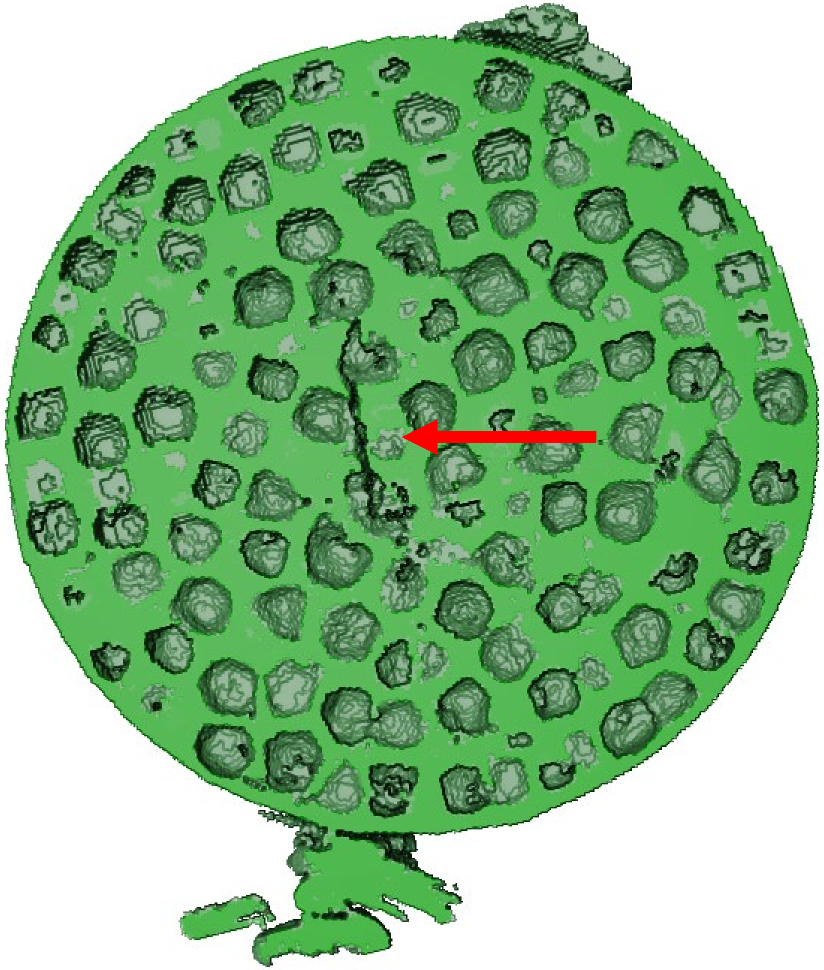



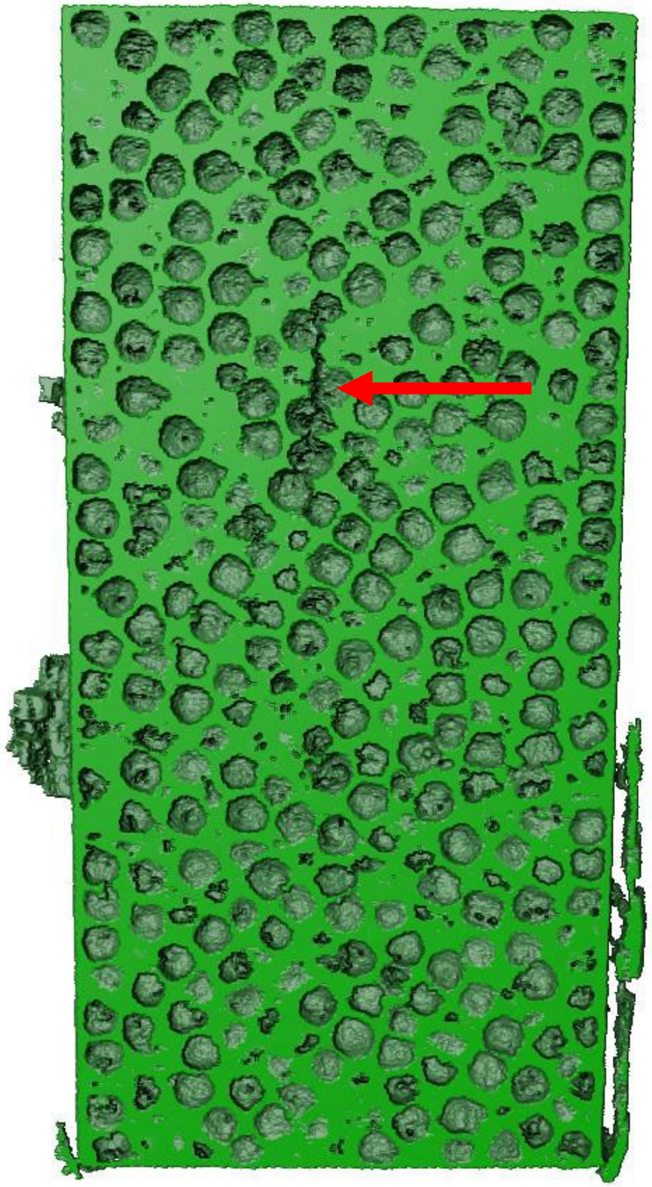



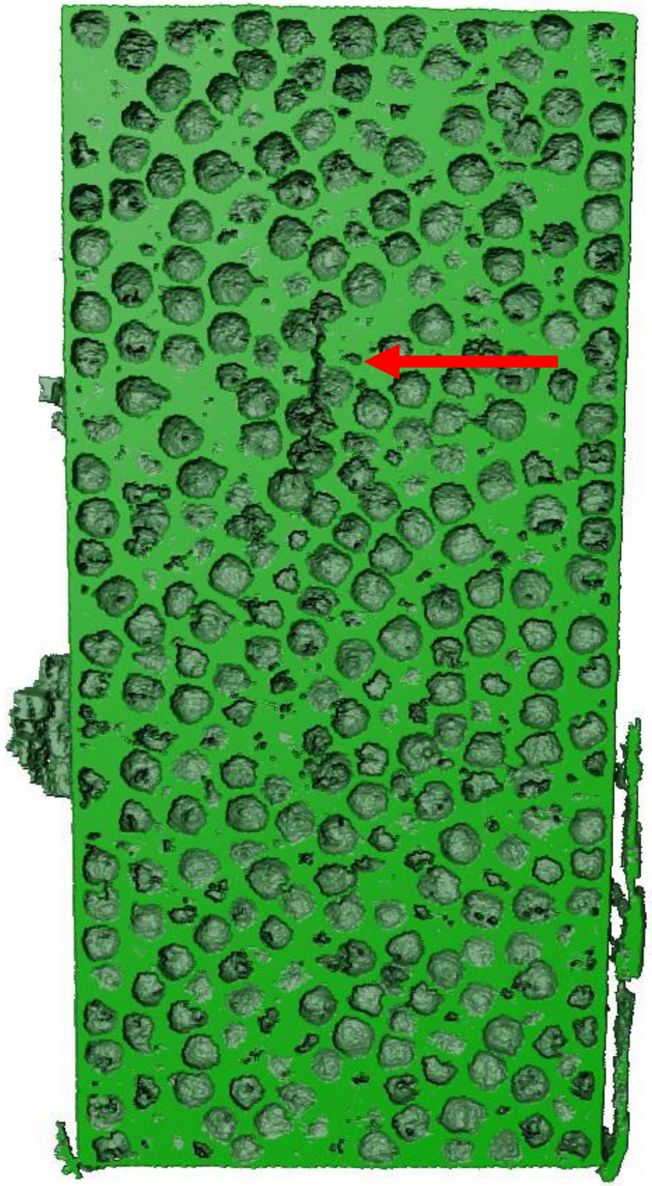
# nCT Renderings



# Crack Identification

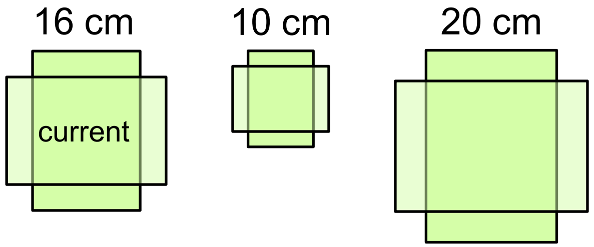


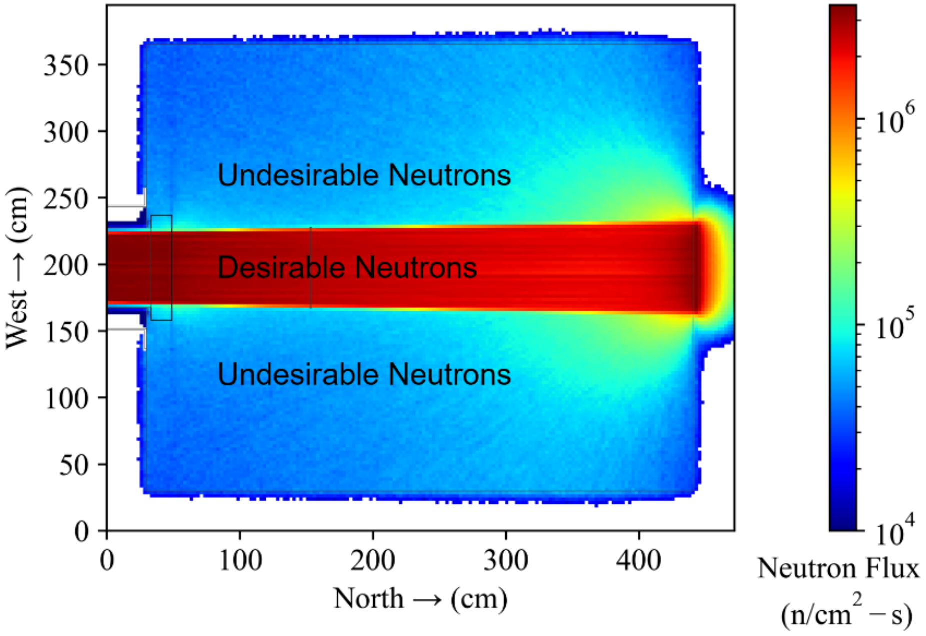


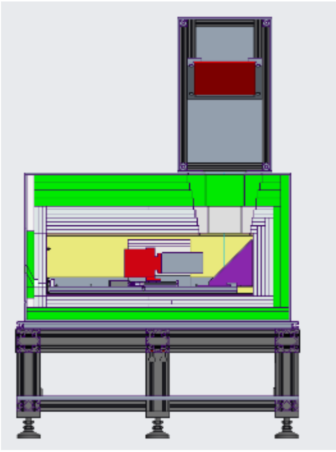


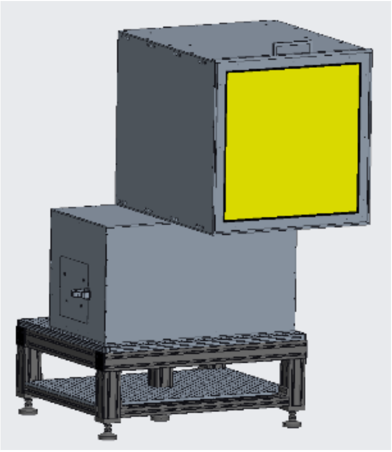
# Future Capabilities – nCT for Multiple FOV’s

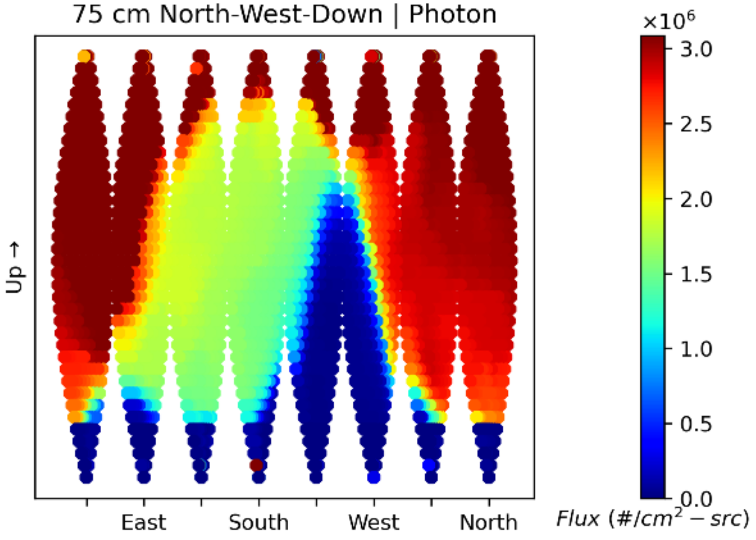
- Different applications require different FOV’s
- A multi-FOV imaging system would cover all applications possible in the NRS beam
- Targeting ~20 μm effective spatial resolution (7 μm pixel)

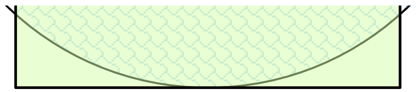






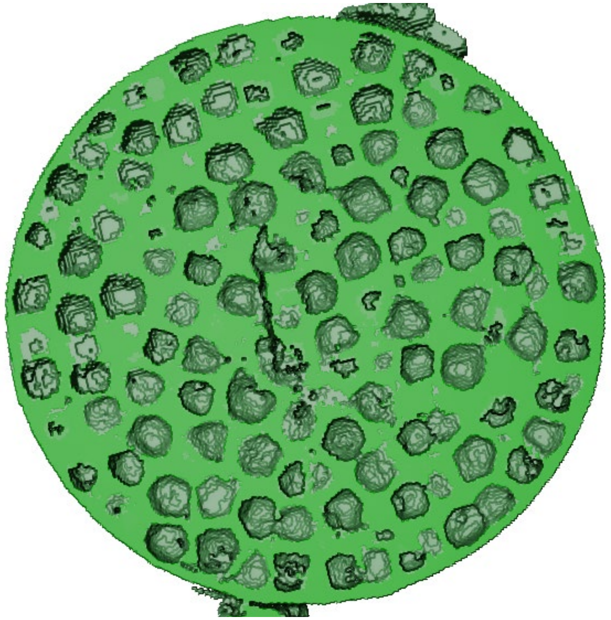



tteries, biofuels)

  - Model V&V using realistic geometry

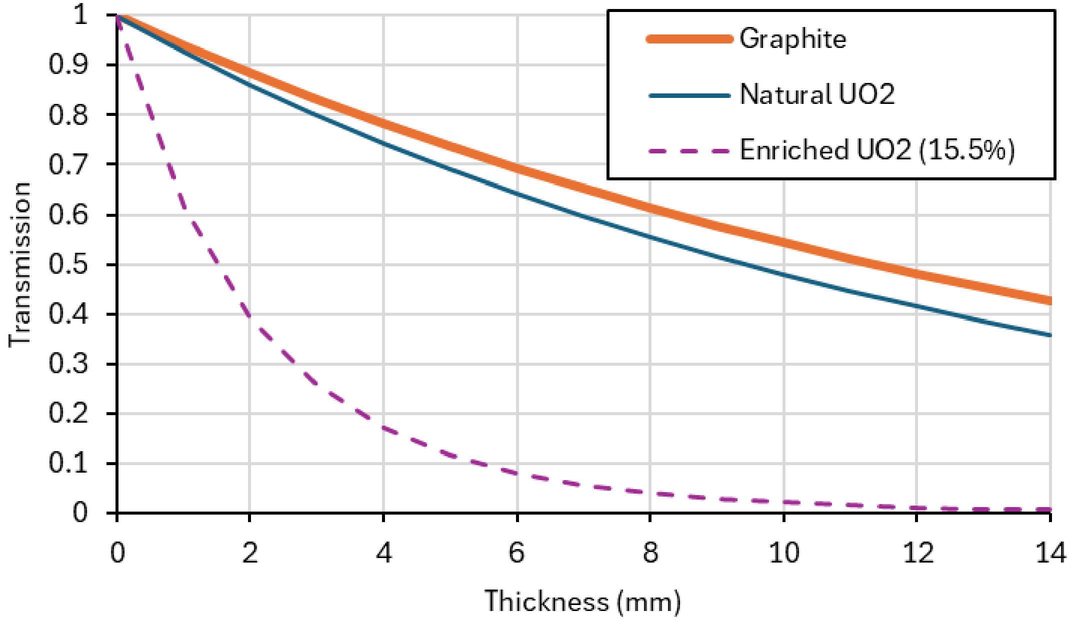
# Conclusions

- Neutron CT successfully identified cracking in the graphite matrix
- X-ray and neutron CT perform complementary examinations of fuel compacts
  - **XCT**: Kernel information
  - **nCT**: Matrix information



**Potential Future Work:**

- nCT of irradiated compact
- XCT/nCT data registration
- Isotopic fission product mapping (nGI/ToF)




Calculations performed with ORNL's NEUIT tool: https://neuit.ornl.gov/transmission

# Acknowledgements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- This research used resources at the High Flux Isotope Reactor a DOE Office of Science User Facility operated by the Oak Ridge National Laboratory. The beam time was allocated to MARS (CG-1D) on proposal number IPTS-34736.

Idaho National Laboratory

*Battelle Energy Alliance manages INL for the U.S. Department of Energy's Office of Nuclear Energy. INL is the nation's center for nuclear energy research and development, and also performs research in each of DOE's strategic goal areas: energy, national security, science and the environment.*