



Instrumentation for New Fuel Cycles

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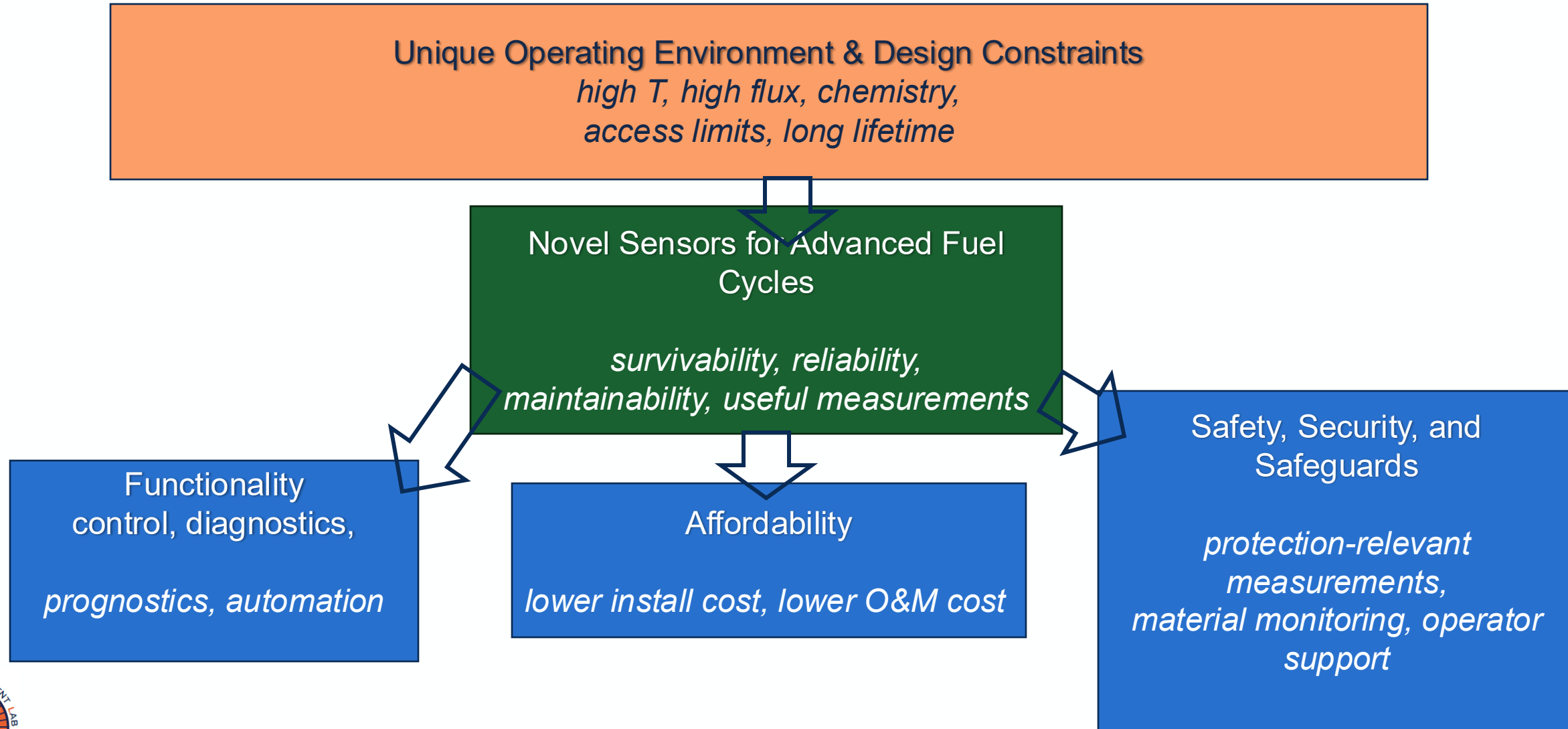
Instrumentation Needs for Advanced Nuclear Fuel Cycles

- Advanced fuel cycles introduce **new reactor configurations, coolants, and operating conditions.**
- **Higher temperatures, harder neutron spectra, and extended operating cycles** challenge conventional instrumentation.
- Reliable measurements are essential for reactor control, safety, diagnostics, and nuclear material monitoring.
- Sensor development must address both the operating environment and the measurement requirements imposed by reactor design.

Economic Drivers for Advanced Instrumentation

- Capital costs
 - Sensor installation, cabling, and associated I&C infrastructure
 - Limited scaling of instrumentation costs with reactor size
 - Increased instrumentation needs for condition monitoring
- Operating and maintenance costs
 - Staffing requirements and maintenance workload
 - Plant availability and unplanned outages
 - Extended intervals between maintenance and refueling
- Cost reduction opportunities
 - Integrated instrumentation architectures
 - Online diagnostics and predictive maintenance
 - Increased automation and remote monitoring

Role of I&C in Advanced Reactors



Instrumentation Challenges in Advanced Reactor Designs

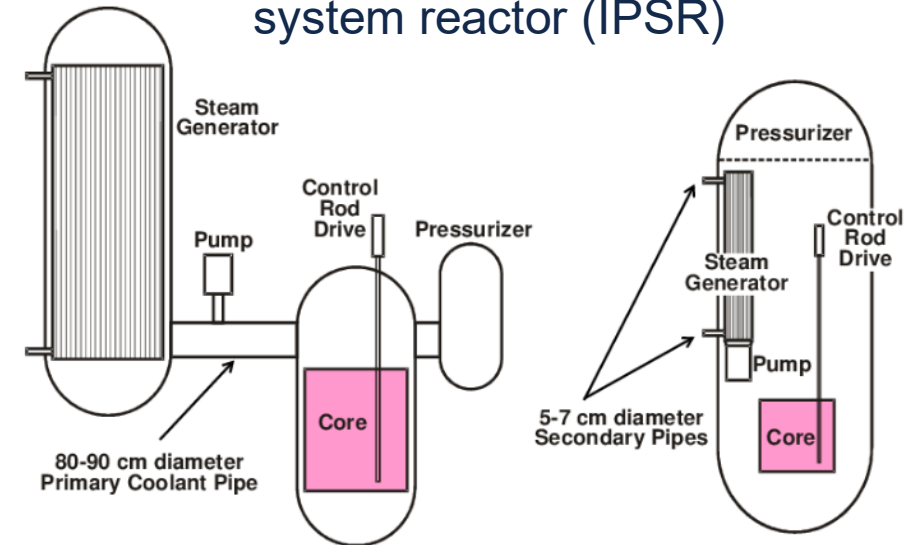
Environment constraints:

- Near-core: high neutron flux and temperature; favorable neutron signal but challenging environmental conditions.
- Intermediate location: reduced environmental stress but potentially less representative measurements.
- Ex-core: more accessible and less severe environment, but reduced sensitivity to some core parameters.

Design-specific constraints:

- Core and steam generators within the same pressure vessel.
- Large water gap between the core and vessel attenuates neutron flux.
- Ex-vessel neutron detectors receive a weaker signal, particularly during startup.
- In-vessel instrumentation faces restricted access, penetrations, and maintenance challenges.

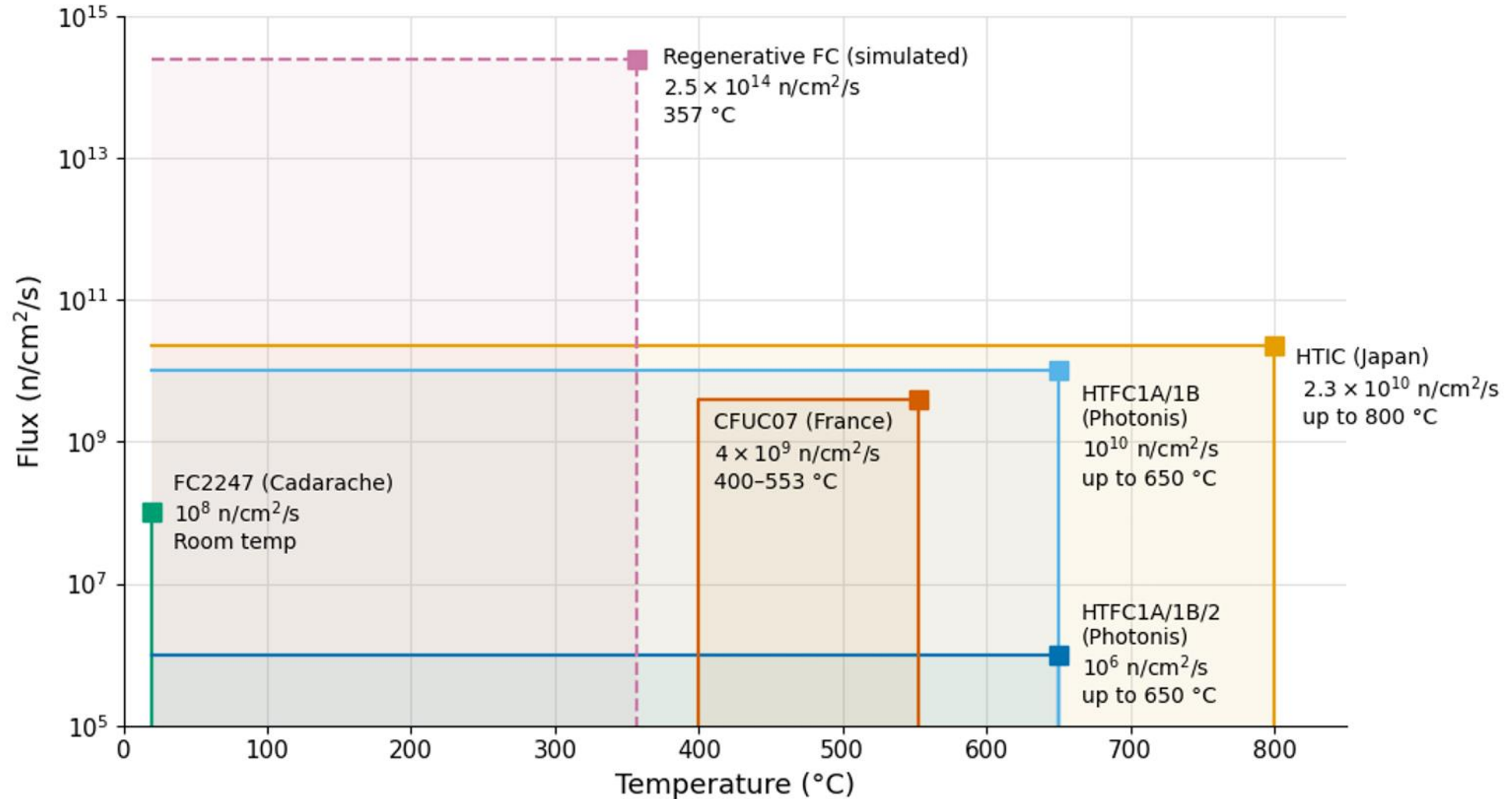
Sensor positioning in an integral primary system reactor (IPSR)



From Reactor Design Features to Sensor Technology Gaps

Design feature	Measurement gap	Candidate technologies or approaches
High temperature and radiation	Neutron flux measurement near the core	High-temperature fission chambers, ruggedized neutron detectors, radiation-hardened electronics
High-temperature operation and extended fuel cycles	Temperature measurement with limited calibration drift	Radiation-resistant thermocouples, RTDs where suitable, Johnson-noise thermometry
Integral reactor geometry	Insufficient neutron signal outside the vessel	In-vessel neutron monitoring
Restricted vessel penetrations	Direct water-level and primary-flow measurement	Alternative level sensing, pump electrical-signature analysis, neutron-noise analysis
Inaccessible internal components	Monitoring vibration and mechanical degradation	Electrical-signature analysis, neutron-noise diagnostics

Fission Chamber Performance Limits in Advanced Reactor Environments

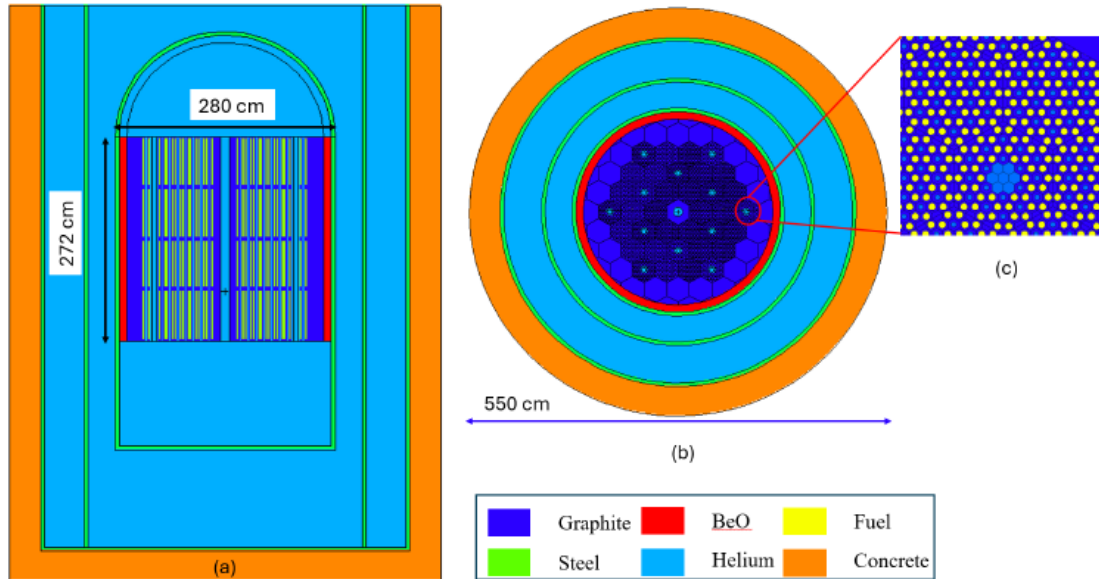


Remote Monitoring

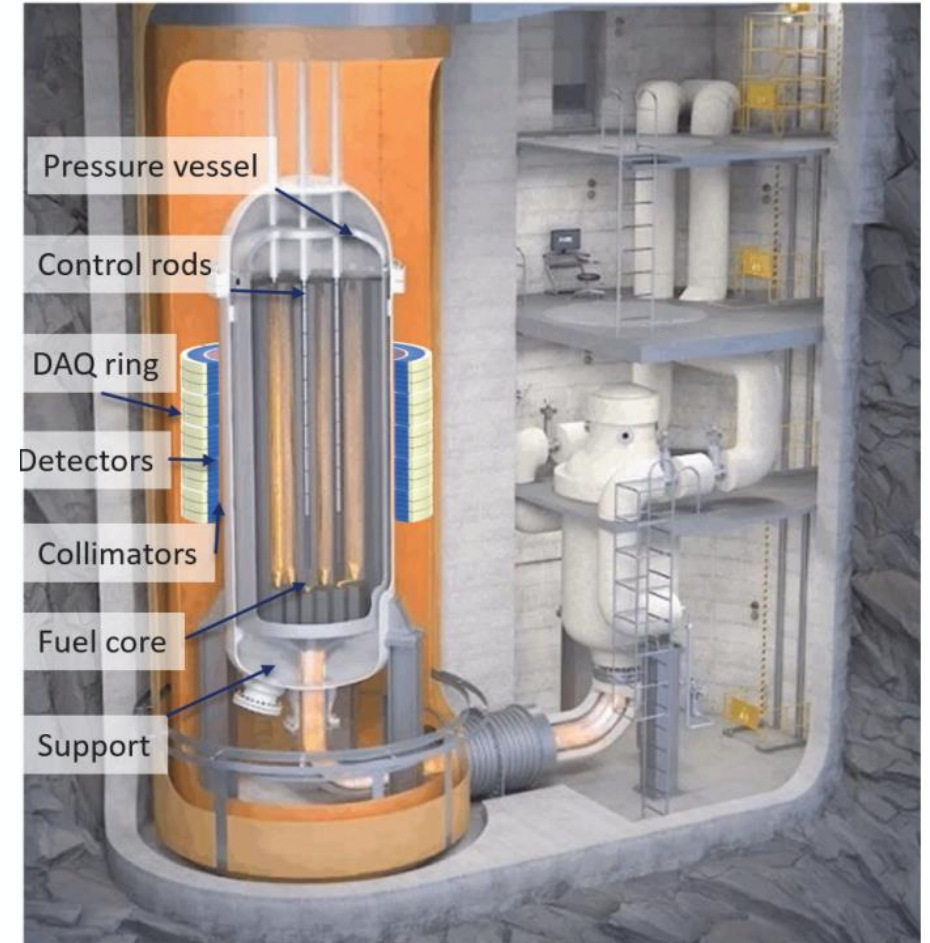
- **Increased automation:** Advanced reactors are being designed with reduced staffing and greater reliance on remote supervision. This creates a need for instrumentation that provides spatial information without direct operator intervention.
- **Safeguards and material tracking:** Advanced fuel cycles can involve repeated transfers of nuclear material between processing, storage, and handling systems. Real-time imaging could provide an additional means of verifying material location and movement.
 - Conventional radiation monitors provide dose-rate or count-rate information but generally cannot identify where activity originates.
 - Radiation imaging can provide localization, but conventional approaches may require extended acquisition times.
- Ex-core flux monitoring system
- Real-time radiation imager

Ex-core Neutron Flux Monitoring System

- Limited core access
- Harsh in-core conditions
- Can we use **ex-core** instrumentation with low maintenance cost for monitoring in-core neutron flux in a microreactor?

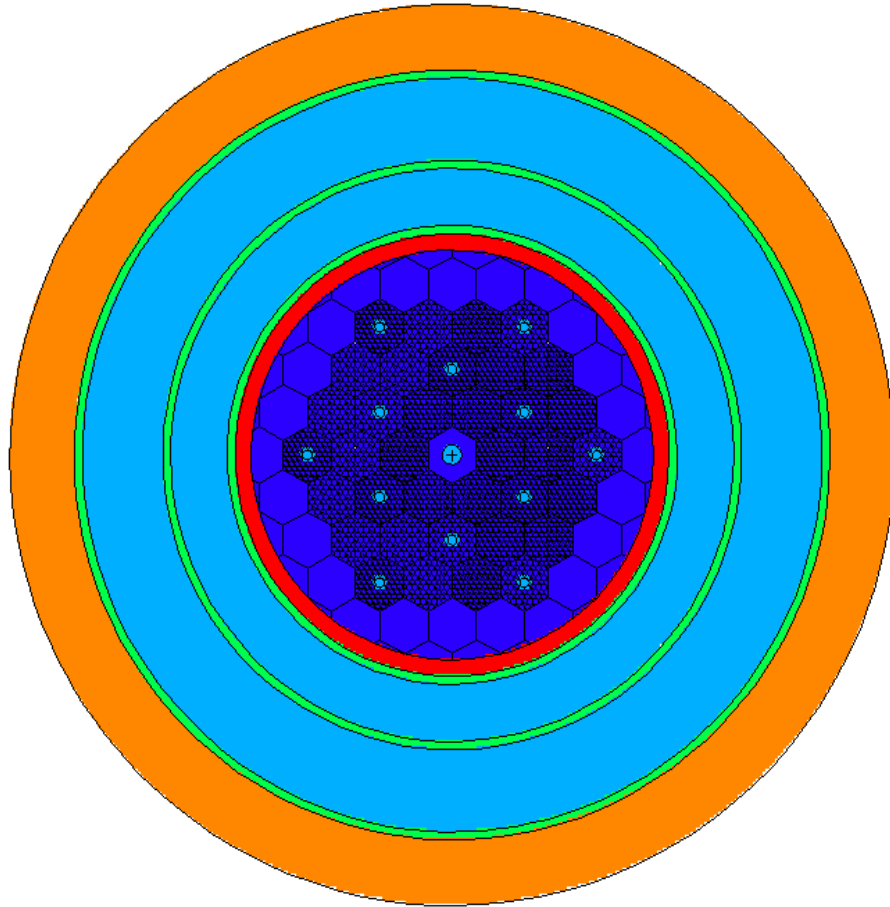


MCNP model of a prototypical Meltdown-Proof Micro Modular Reactor (MDP-MMR). (a) Vertical cross section showing four layers of fuel. (b) Horizontal cross section showing 37 assemblies. (c) Zoomed-in view showing the TRISO pellet-filled fuel rods.

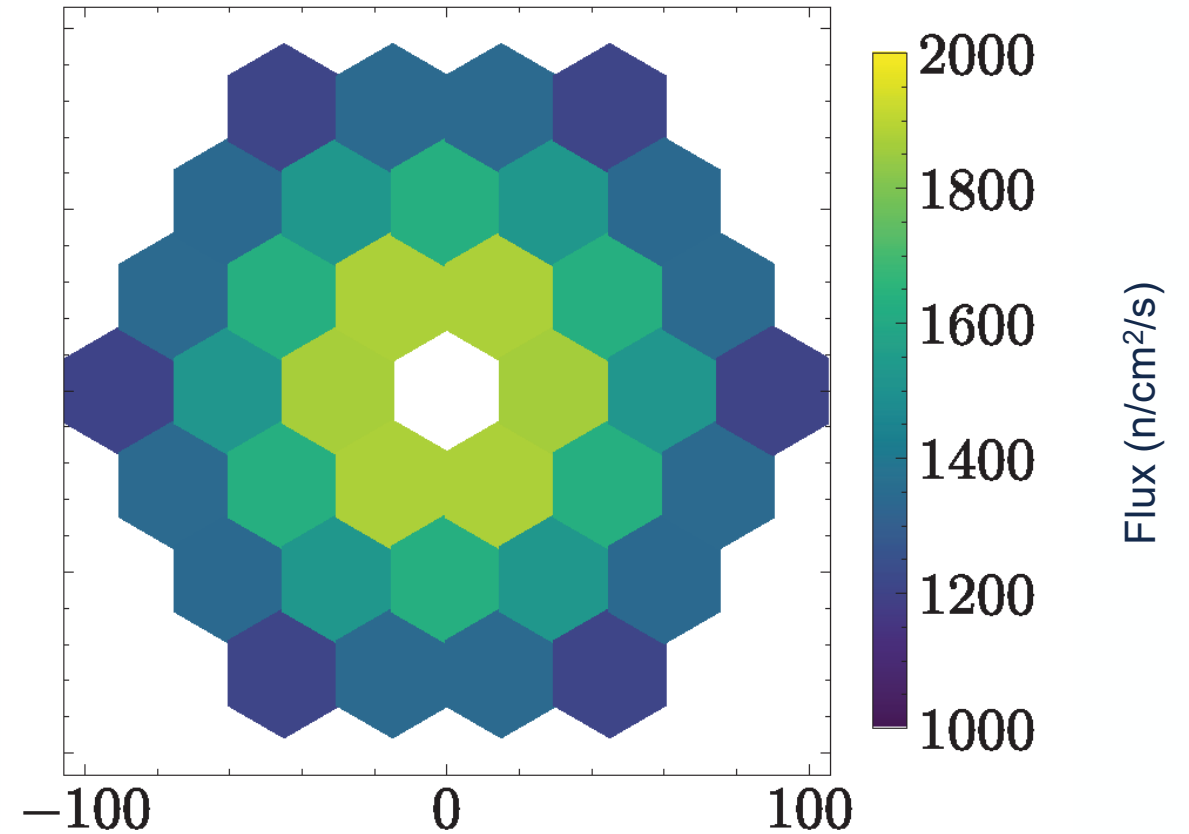


Schematic of a possible configuration of an ex-core measurement system surrounding a micro reactor core.

Proof-of-concept in Simulation



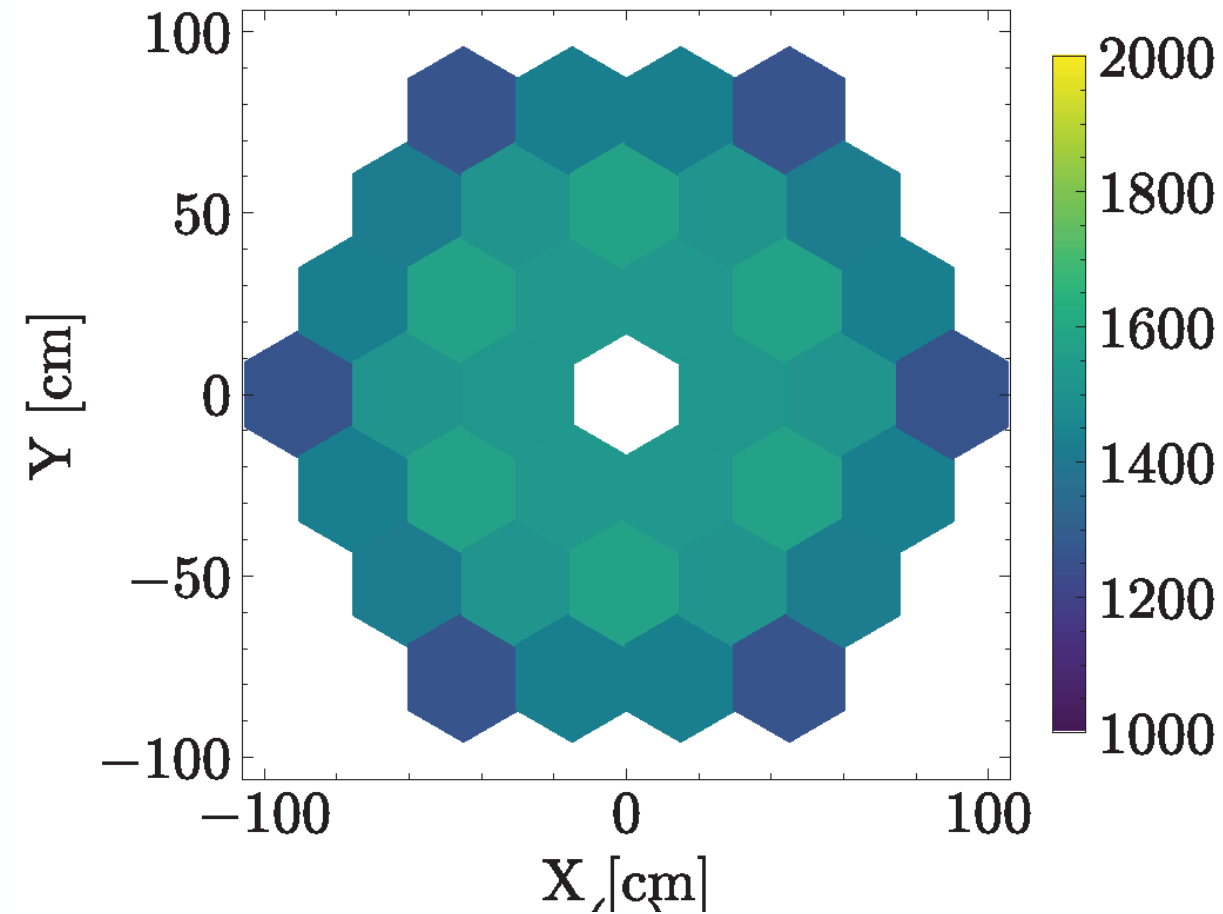
No control rod inserted



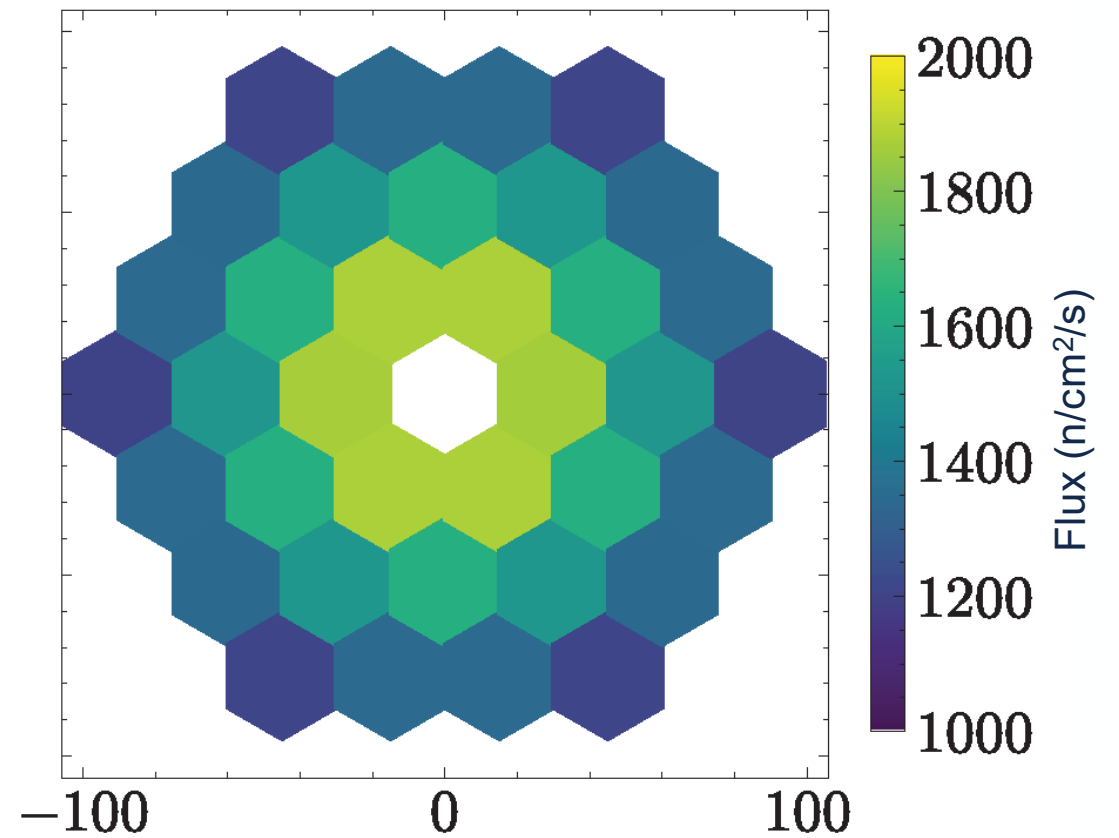
MCNP-simulated flux



Proof-of-concept in Simulation



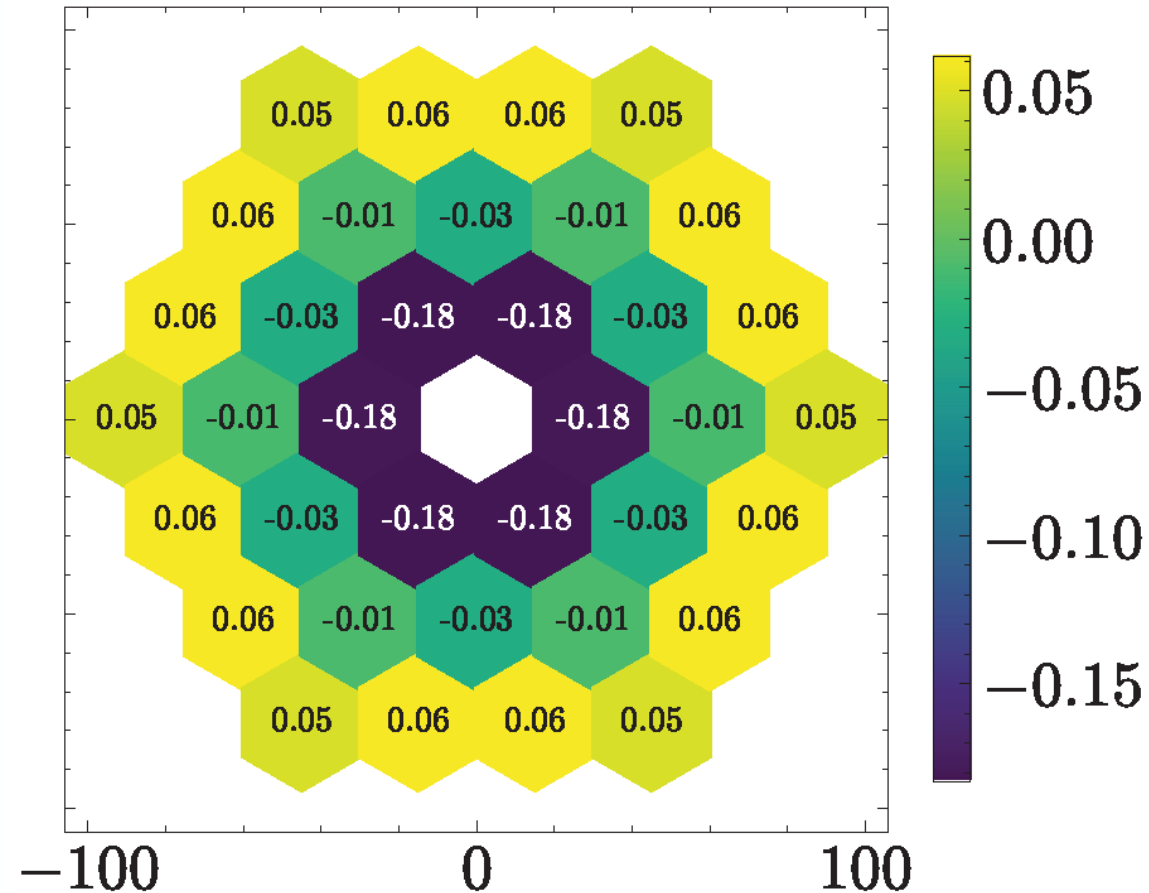
Reconstructed in-core neutron flux



MCNP-simulated flux



Proof-of-concept in Simulation

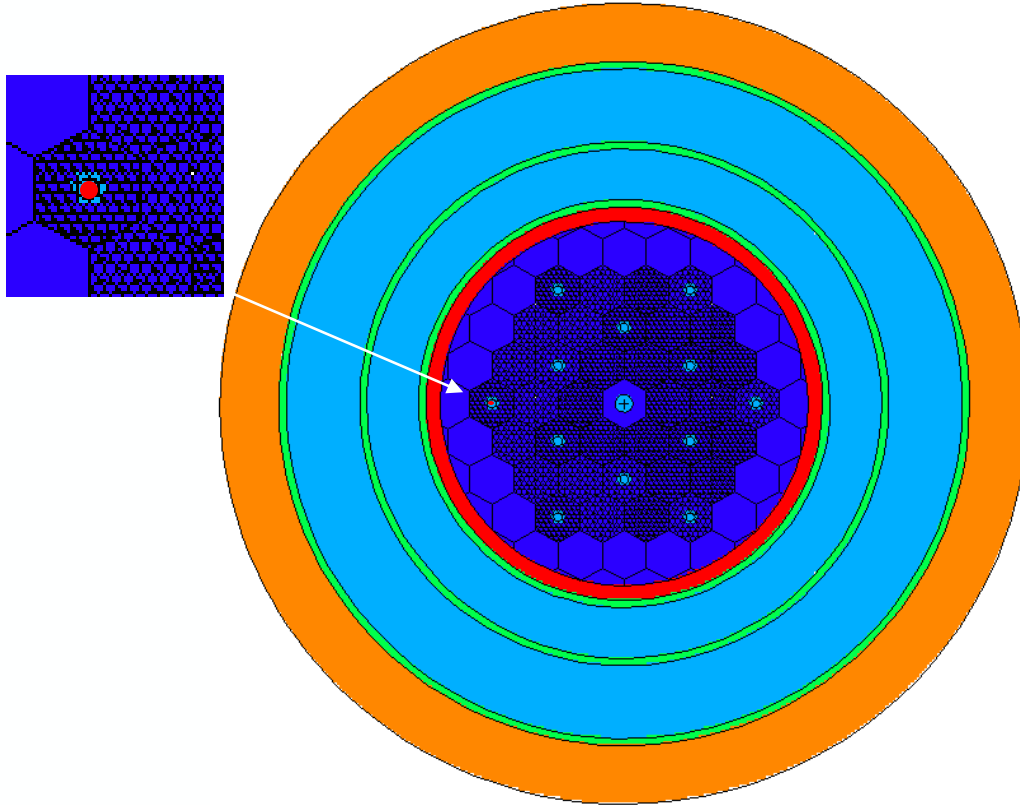


Relative difference between the reconstructed and native neutron flux. **Relative difference in Φ_{tot} is +3%**

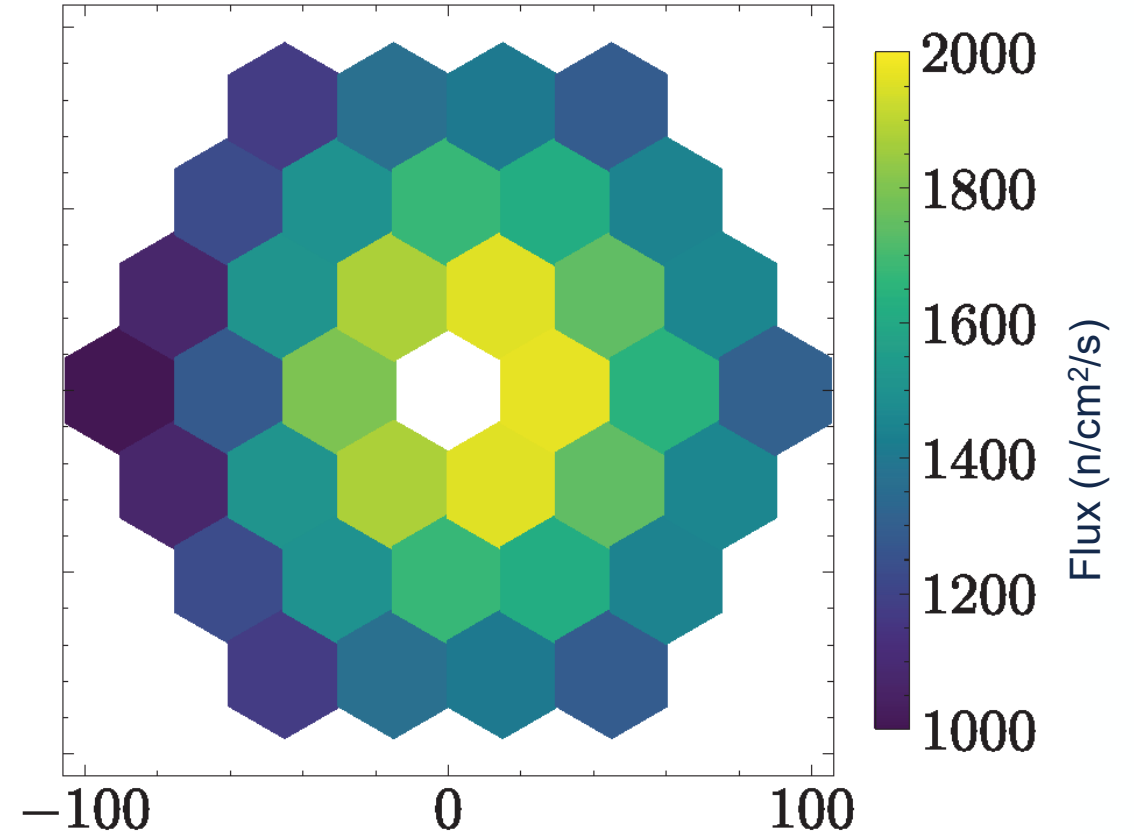
M. Fang, A. Lee, B. Beaumont, A. Chaube, H. Ardiansyah, K. Harvis, T. Grunloh, C. Brooks, T. Kozłowski, and A. Di Fulvio. Enabling reactor monitoring through ex-core neutron detection. In ANS Global 2026, 2026



Proof-of-concept in Simulation

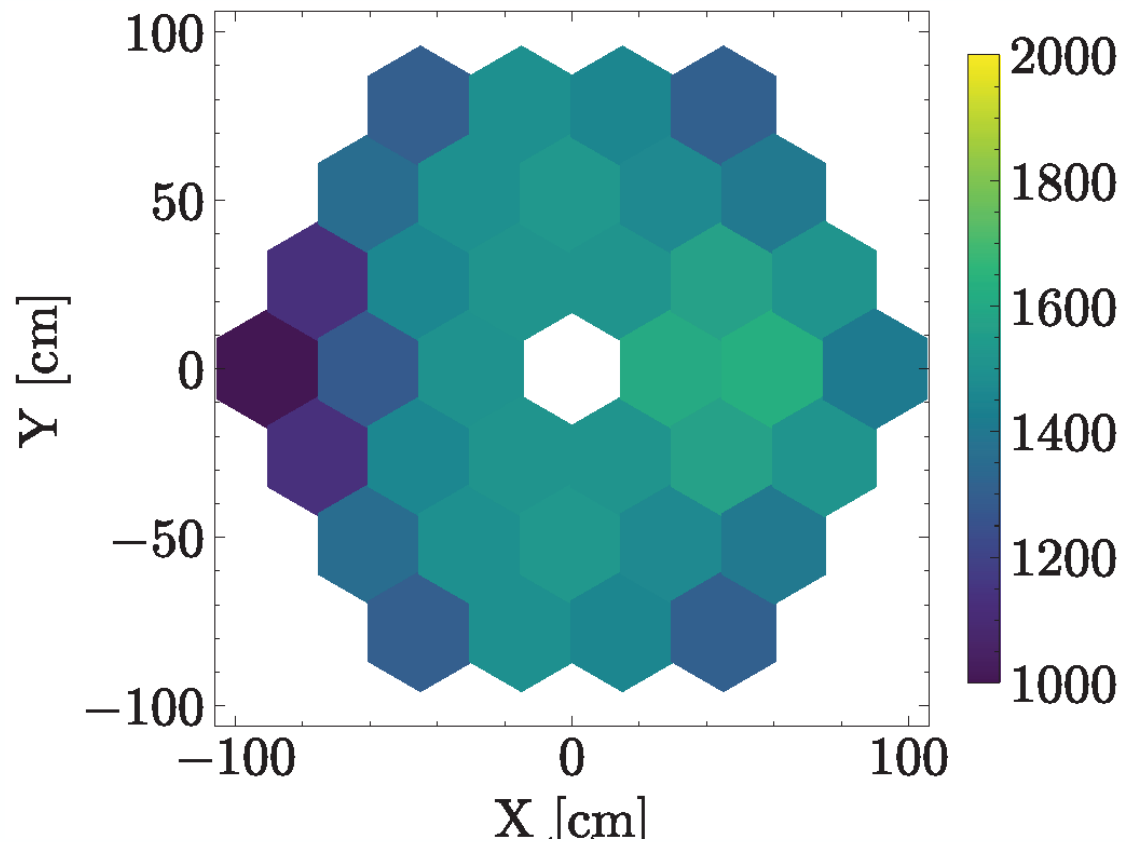


Control rod in an outer assembly fully inserted.

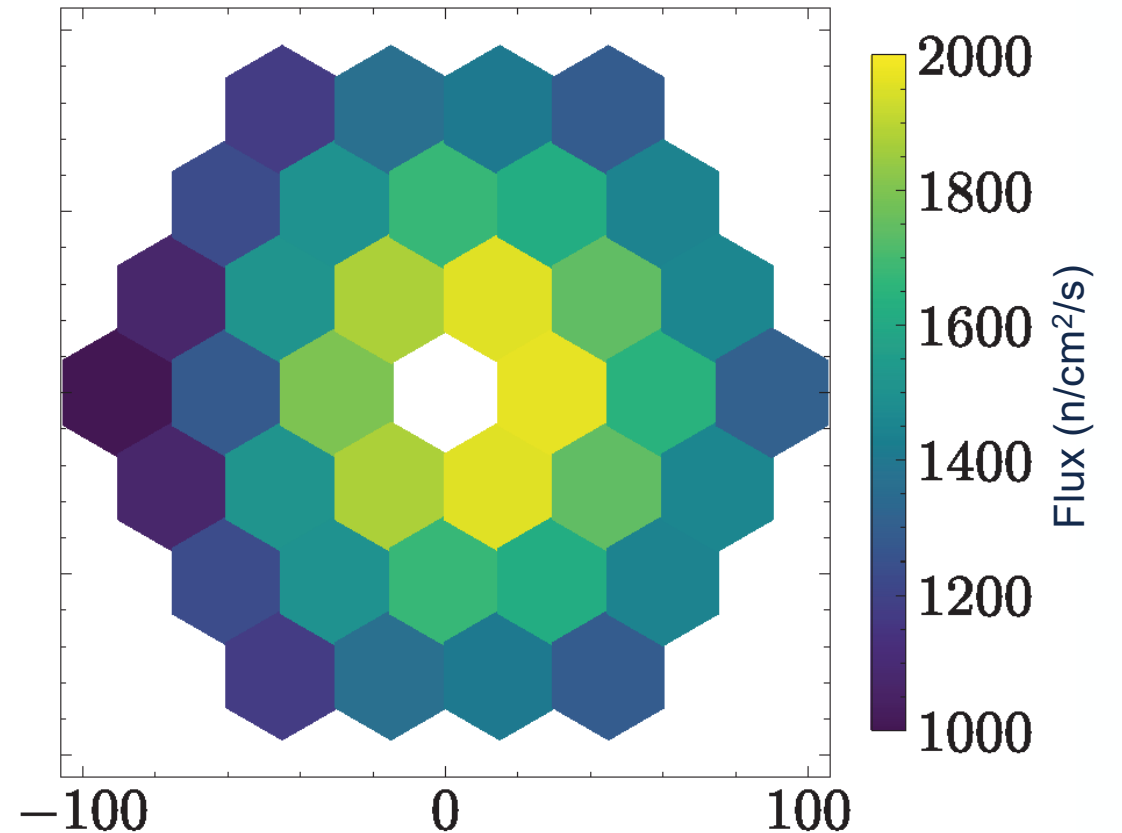


MCNP-simulated flux

Proof-of-concept in Simulation



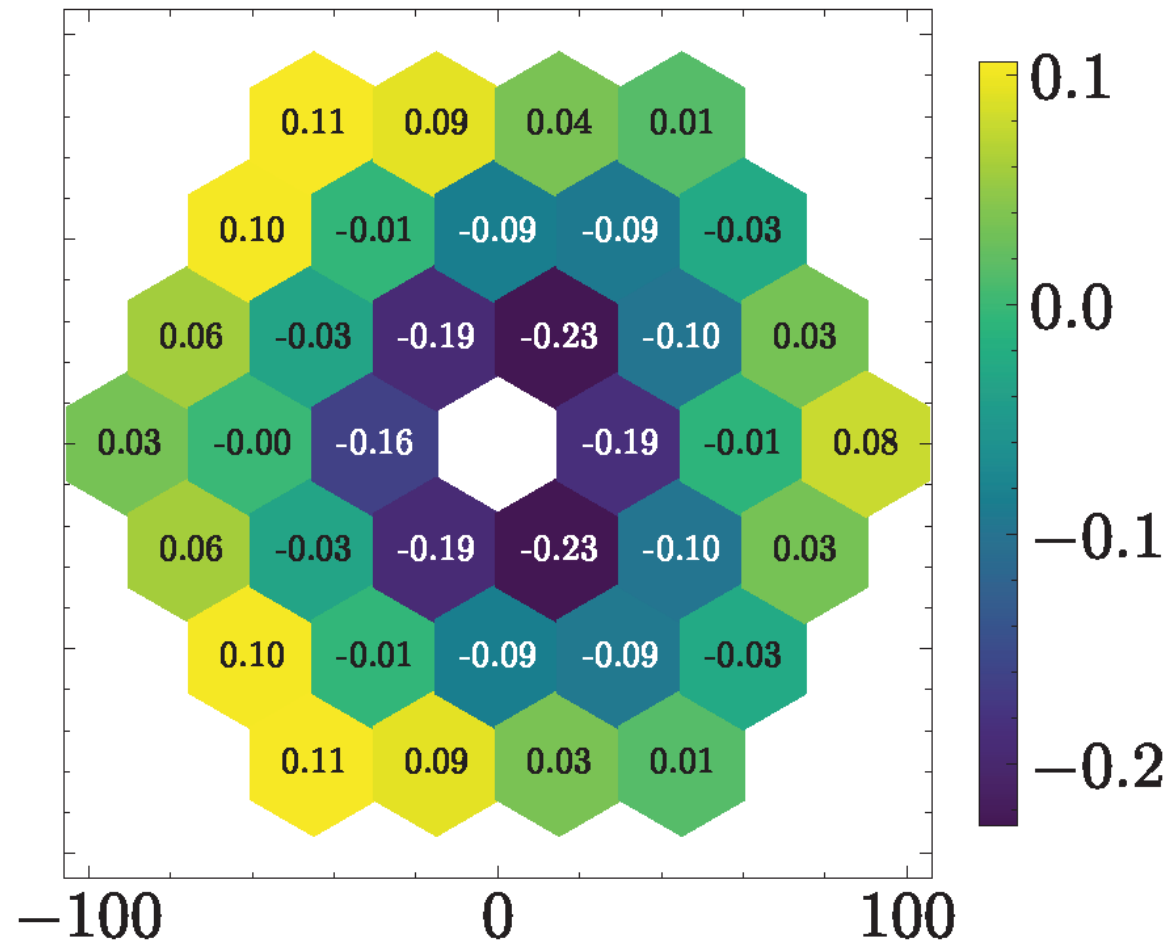
Reconstructed in-core neutron flux



MCNP-simulated flux



Proof-of-concept in Simulation



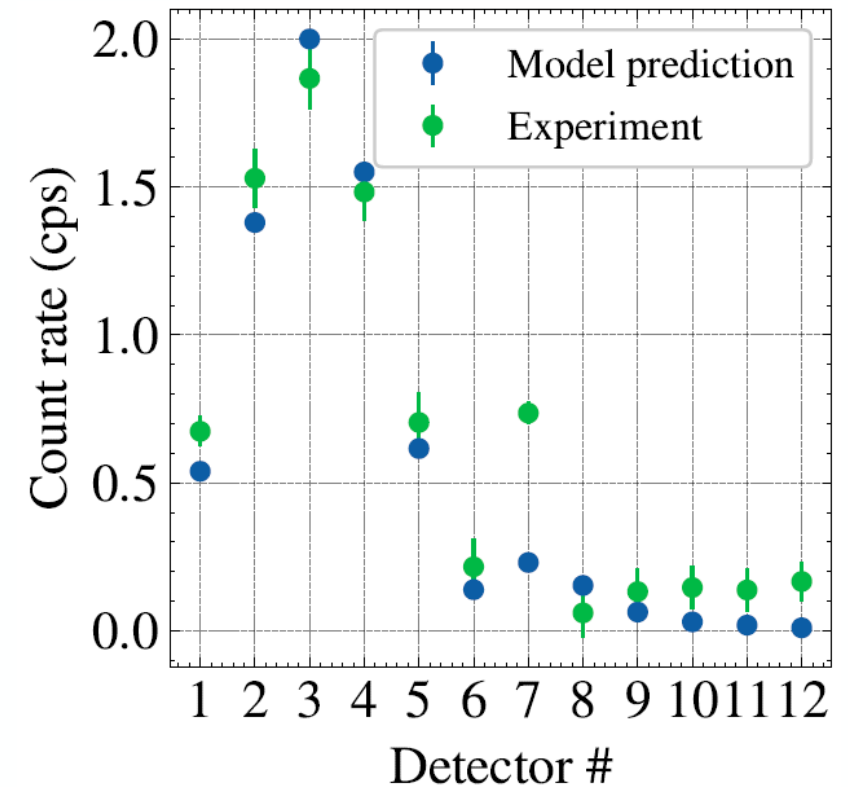
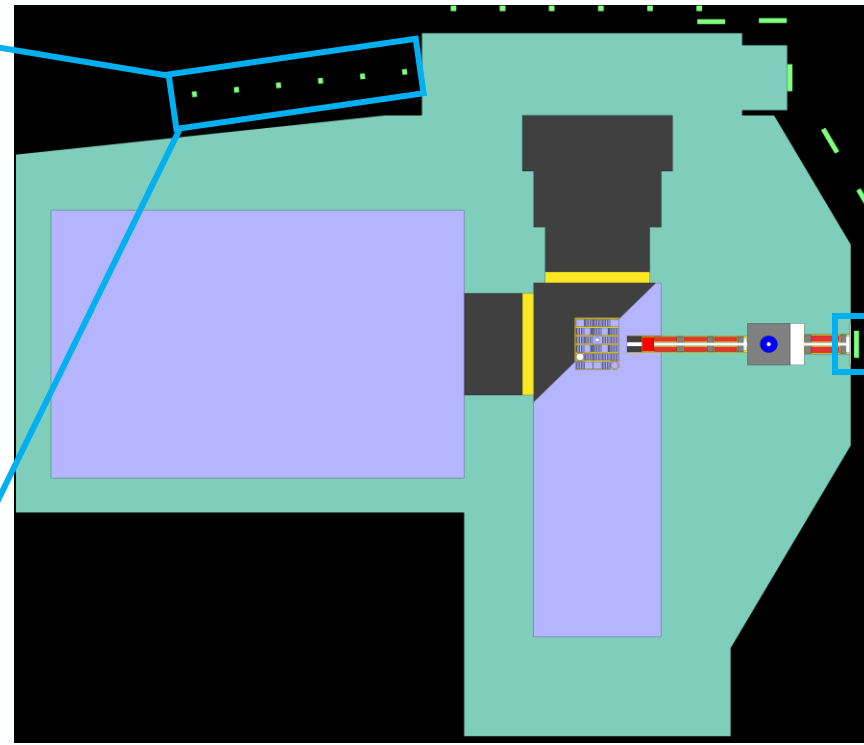
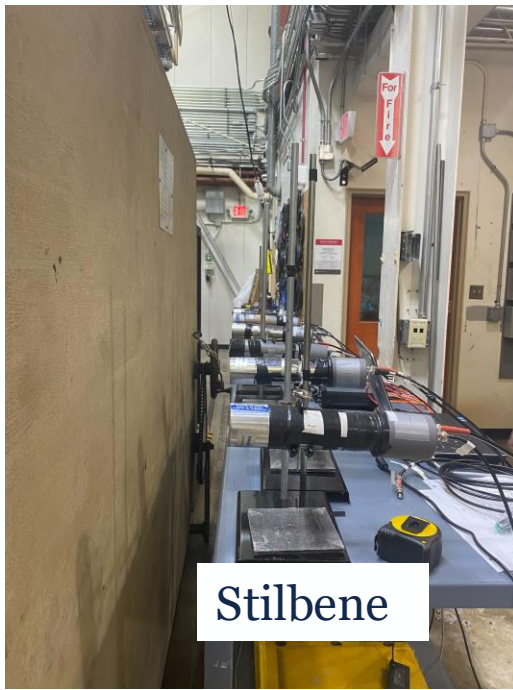
Relative difference between the reconstructed and native neutron flux. **Relative difference in Φ_{tot} is +10%**

M. Fang, A. Lee, B. Beaumont, A. Chaube, H. Ardiansyah, K. Harvis, T. Grunloh, C. Brooks, T. Kozłowski, and A. Di Fulvio. Enabling reactor monitoring through ex-core neutron detection. In ANS Global 2026, 2026

Experimental Campaign at Ohio State University Research Reactor (OSURR)

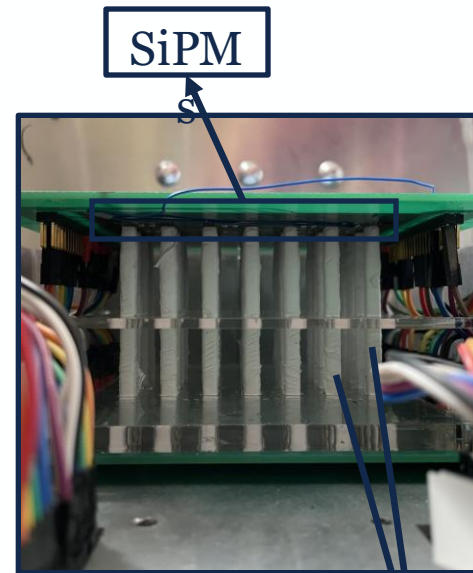
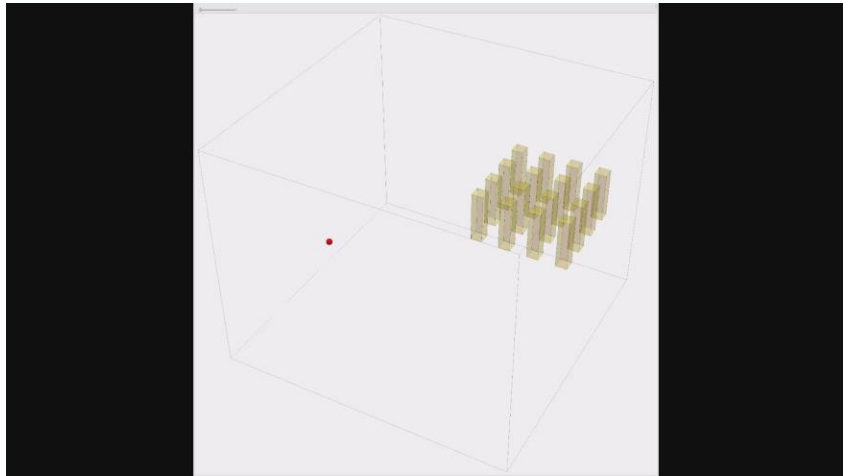
- 12 stilbene and 6 Boron-Coated Straw (BCS) detectors were used in the measurement
- Upcoming demonstration at MARVEL INL facility

■ 18 detectors



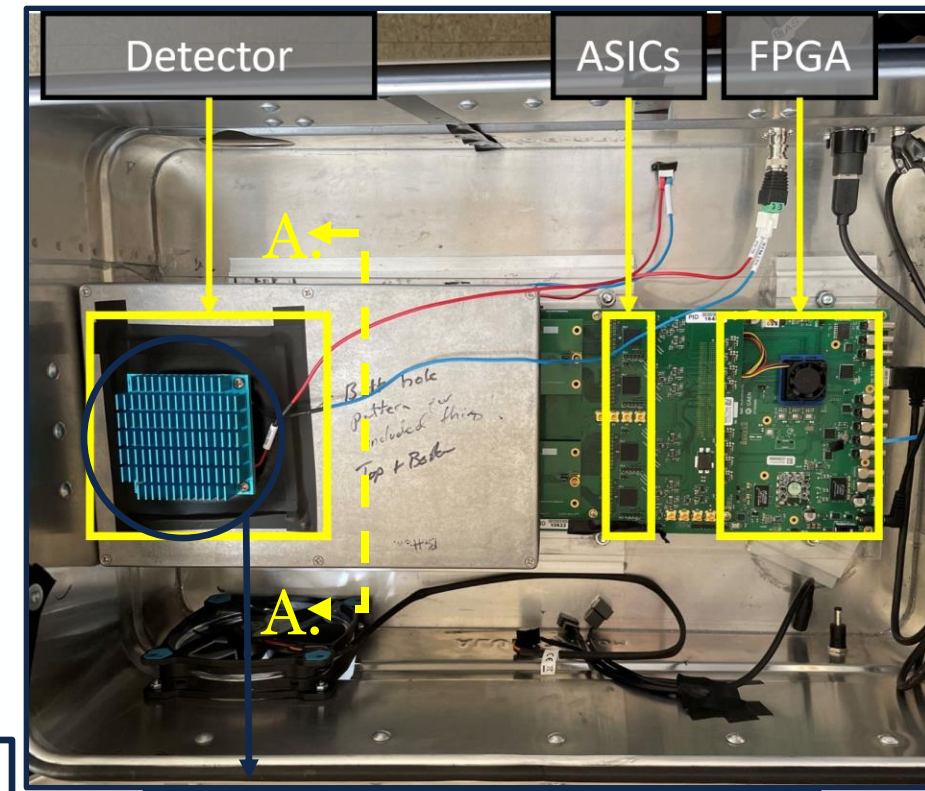
Real-time Stand-Off Imaging for Remote Monitoring

- Continuous monitoring of changing radiation distributions
- Remote measurements without direct access to radioactive materials
- Potential applications in fuel handling, hot-cell operations, and nuclear material monitoring



Cross section A-A

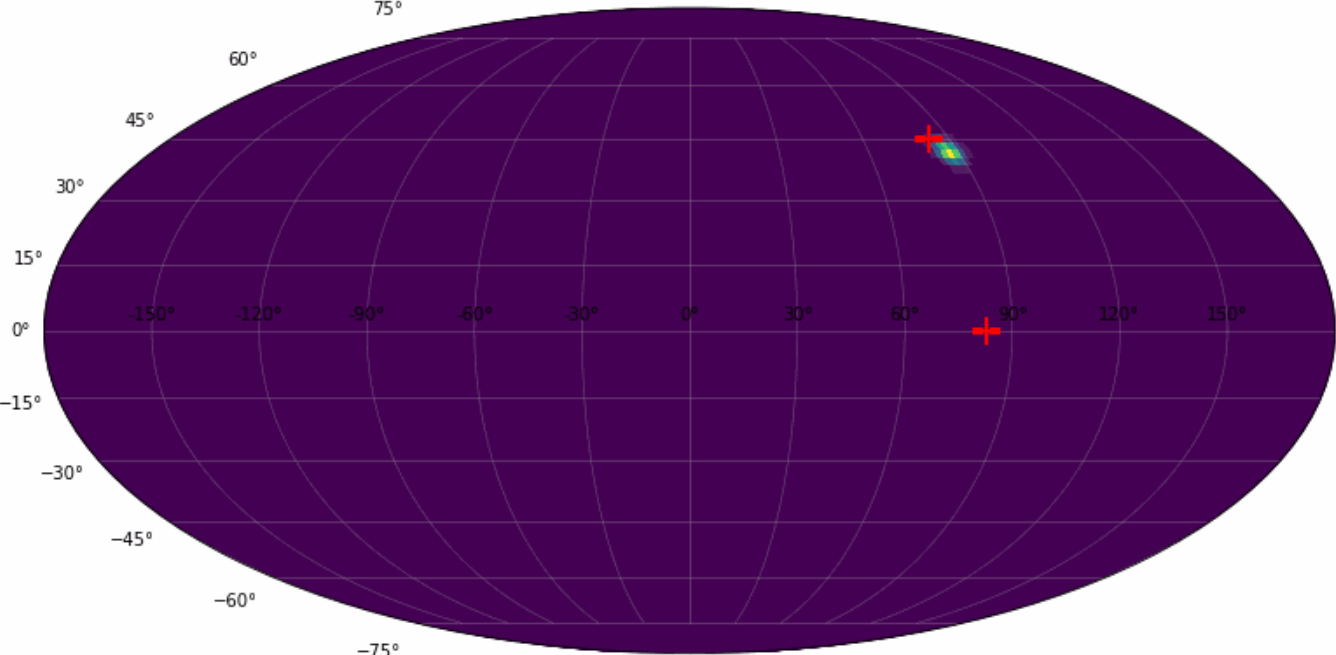
Scintillation
Crystals



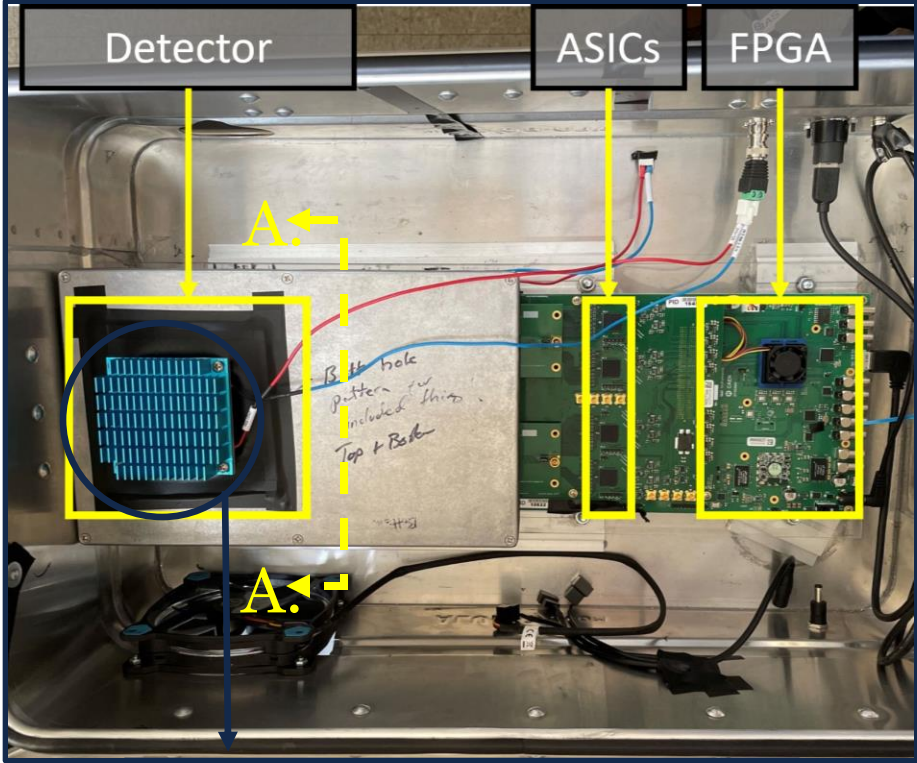
Peltier cooling unit used to cool
the top and bottom SiPMs.

Imaging system with FPGA-based readout.

Standoff imaging for source localization and characterization



- We have developed a scintillator-based Compton imager consisting of a 4×7 array of scintillation crystals with an FPGA-based readout.
- We have developed a reconstruction algo capable of multi-source localization and tracking, in real time.



Peltier cooling unit used to cool the top and bottom SiPMs.

Imaging system with FPGA-based readout.

John Leland, Grant Roche, Ming Fang, Angela Di Fulvio, Optimizing Depth-of-Interaction and Energy Resolution Through Surface Treatment for Compton Imaging, submitted to Radiation Measurements

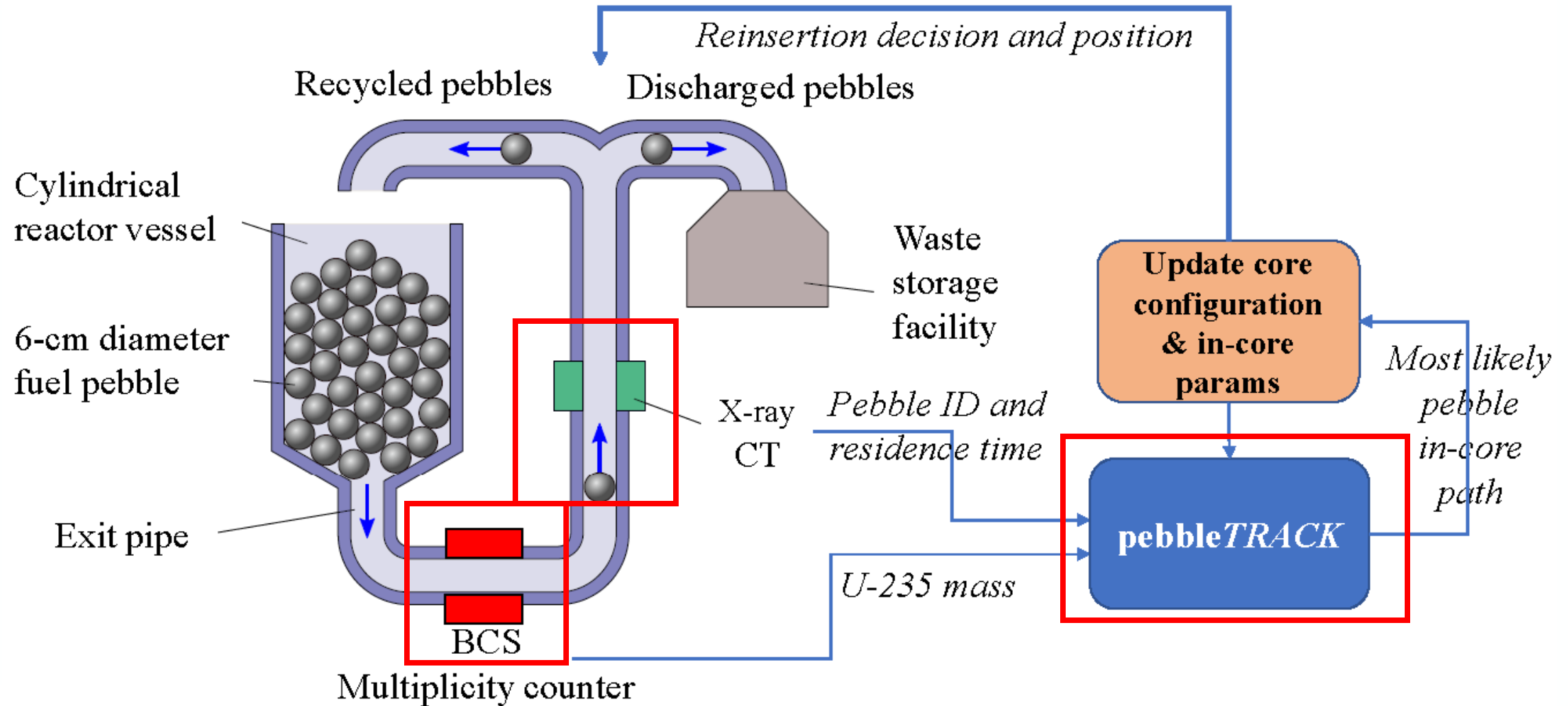


Instrumentation for Advanced Reactor Operations

- Innovative sensing and monitoring systems to:
 - Enable control and diagnostics: Real-time monitoring of reactor conditions and performance
 - Support plant operations: Improve reliability, safety, and operational awareness
 - Enhance plant functionality: Enable new capabilities, automation, and operational flexibility

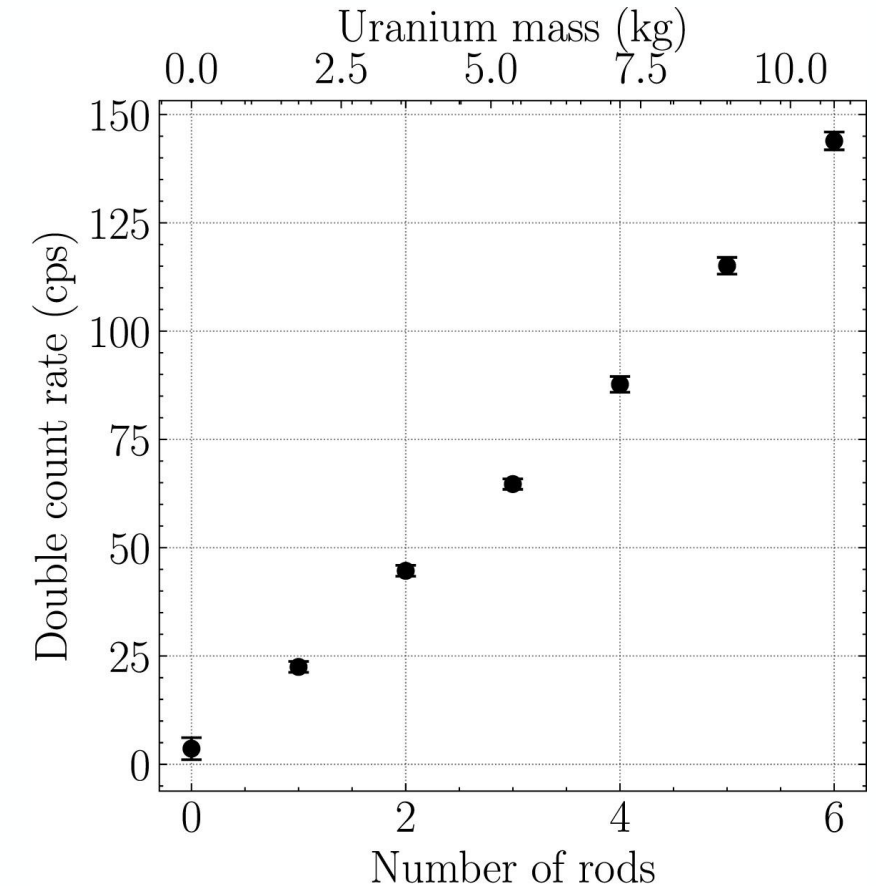
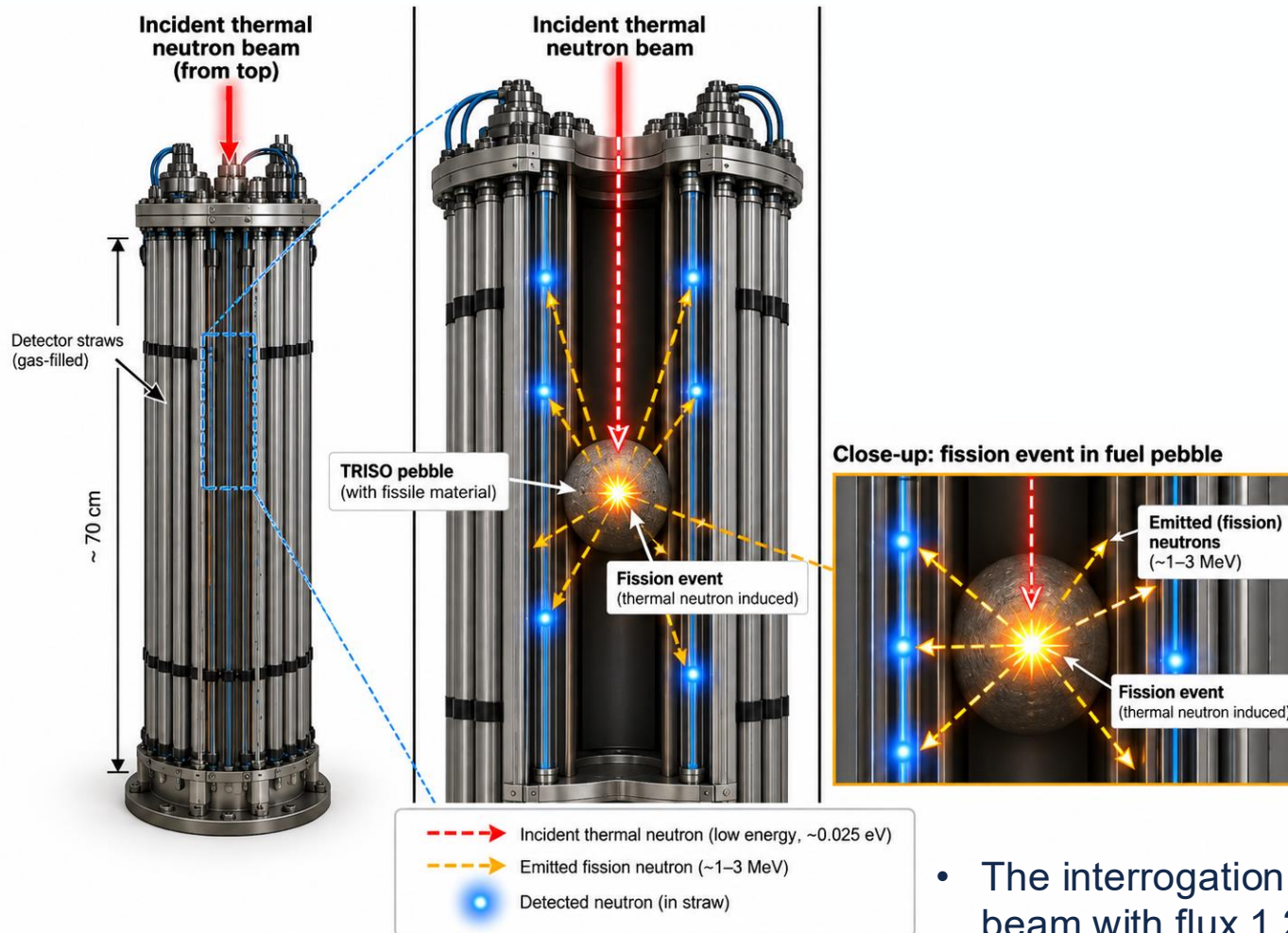


Enabling Advanced Reactor Operation Through Pebble Tracking in PBRs



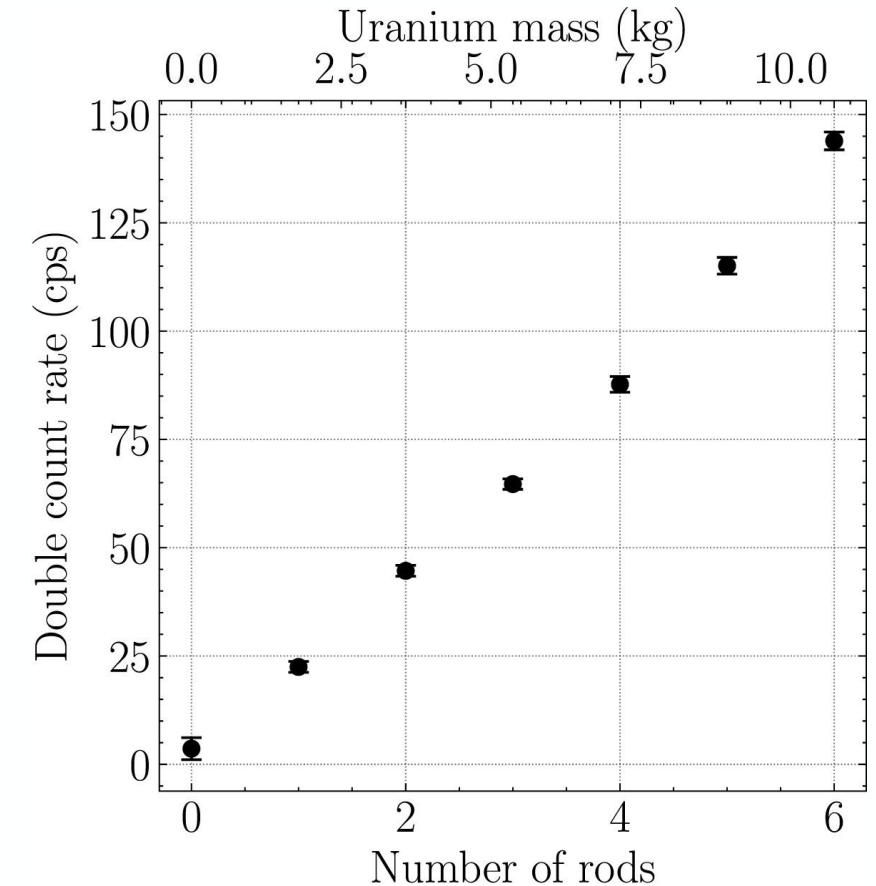
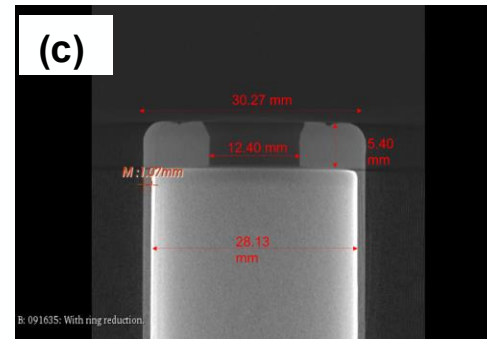
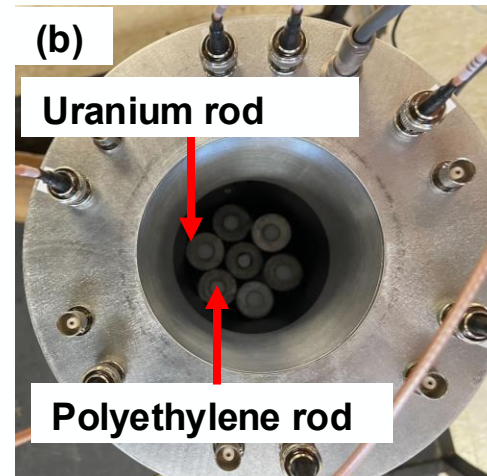
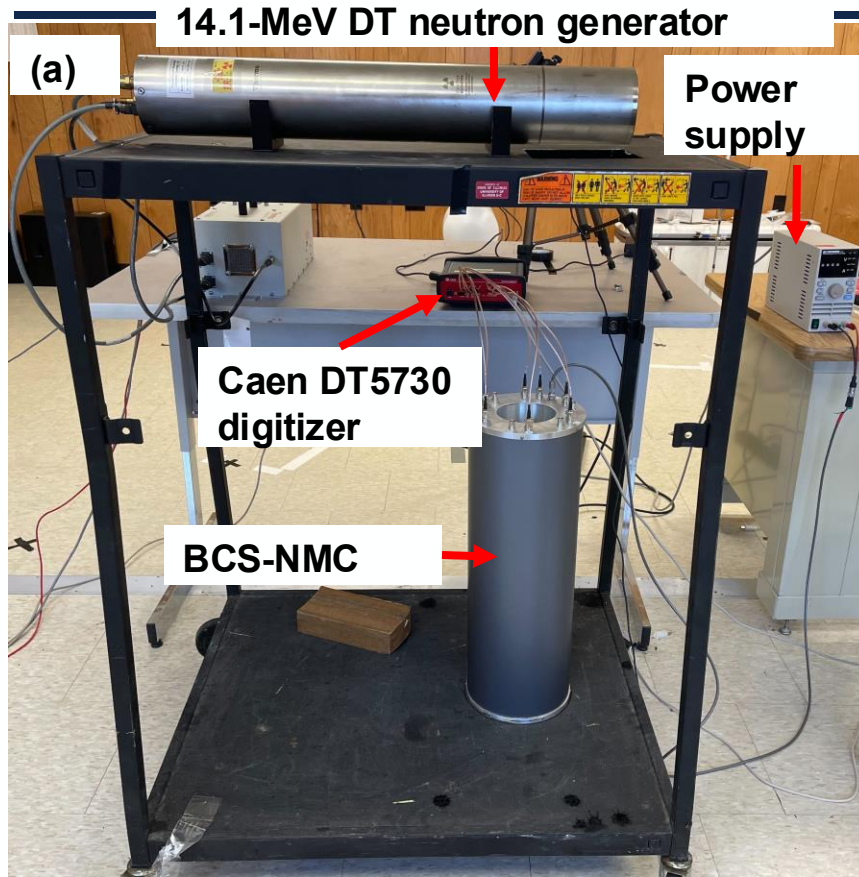
Block diagram of an example reactor core including a pebble-flow control loop

Pebble Identification 1: Quantify U-235



- The interrogation source was a collimated thermal neutron beam with flux 1.27×10^6 n/cm²/s.
- Linear relationship between the neutron doubles and ²³⁵U mass.
- <2.5% relative uncertainty and relative error in 100 s.

Pebble Identification 1: Quantify U-235



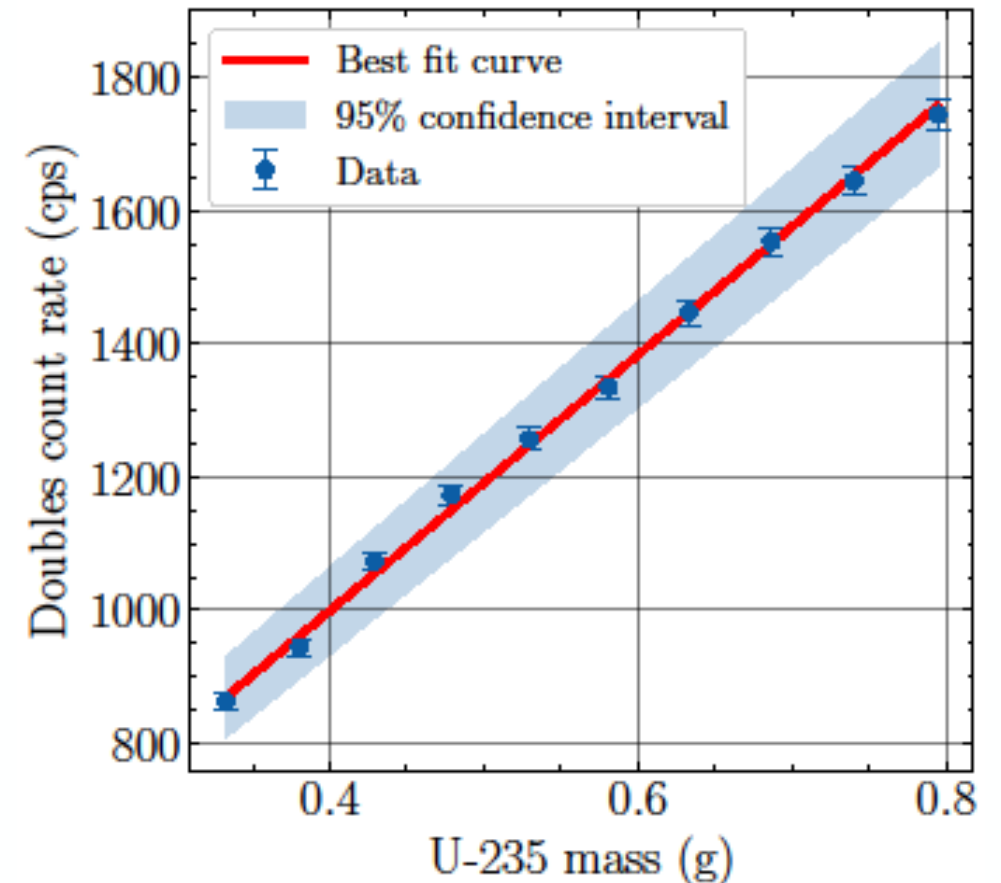
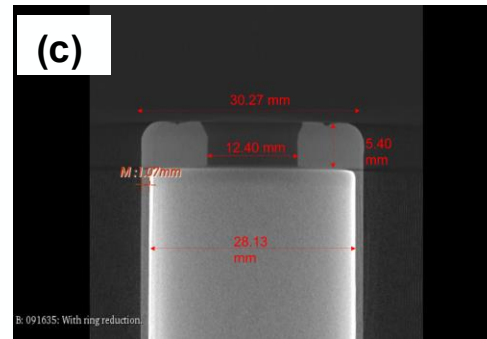
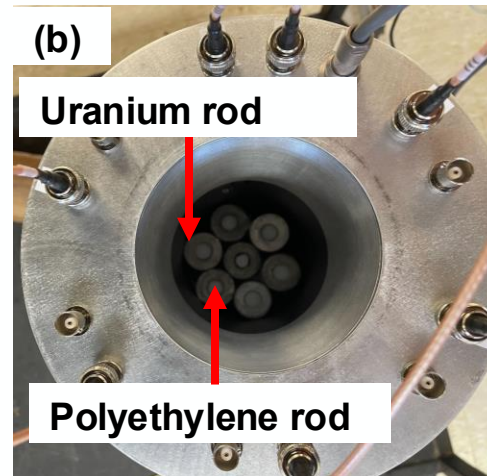
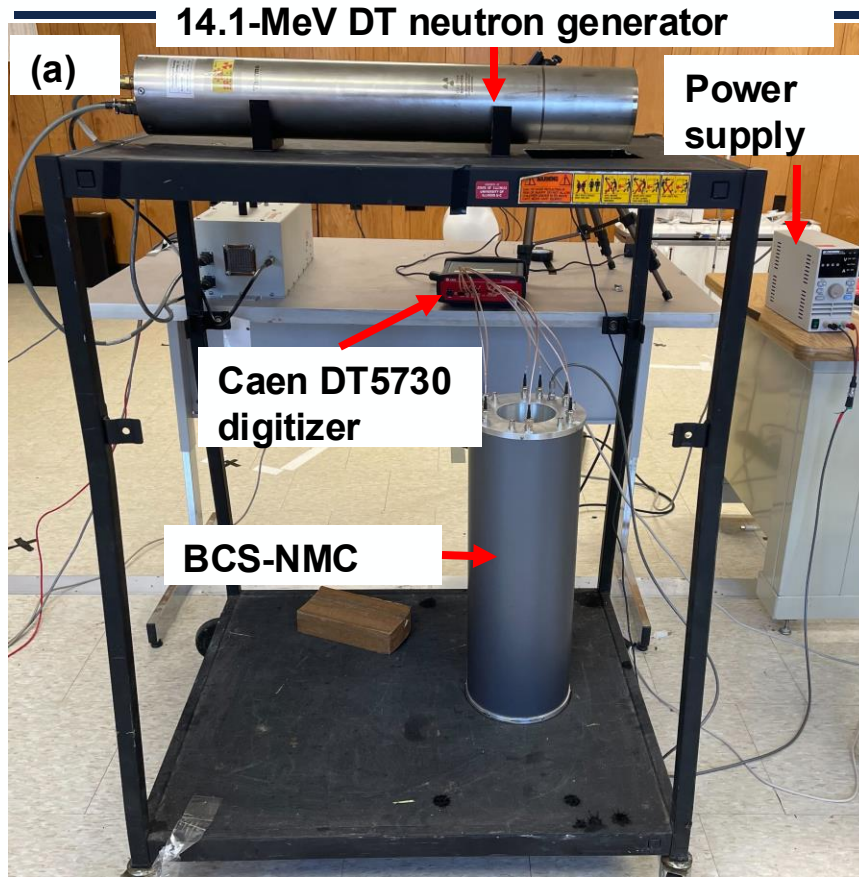
(a): Overview of the experimental setup.

(b): Top view of the NMC with seven uranium rods inside.

(c): Computed tomography cross section of a uranium rod. Each rod contains 1789 g uranium (approx. 1g of ^{235}U in each rod) and 93 g aluminum coating.

- The interrogation source was a collimated thermal neutron beam with flux $1.27 \times 10^6 \text{ n/cm}^2/\text{s}$.
- Linear relationship between the neutron doubles and ^{235}U mass.
- **<2.5% relative uncertainty and relative error in 100 s.**

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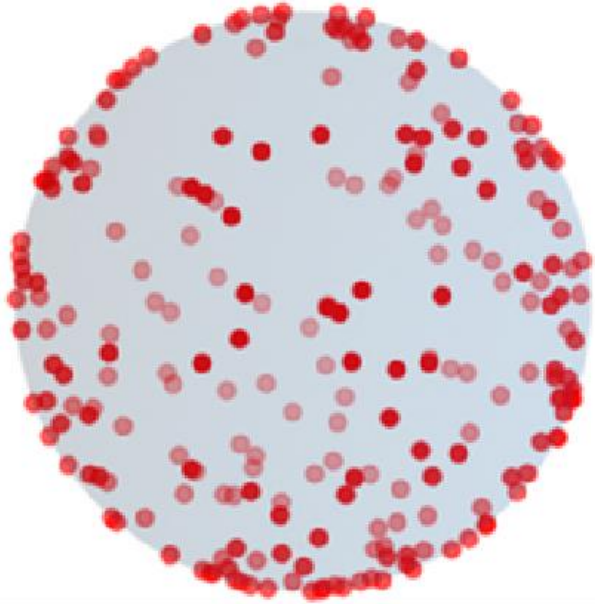
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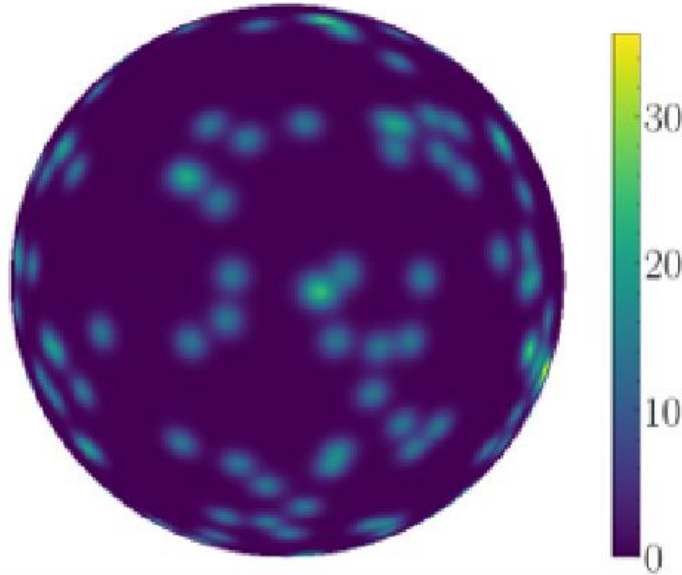
(c): Computed tomography cross section of a uranium rod. Each rod contains 1789 g uranium (approx. 1g of ^{235}U in each rod) and 93 g aluminum coating.

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Pebble Identification 2: Rotation Invariant Feature

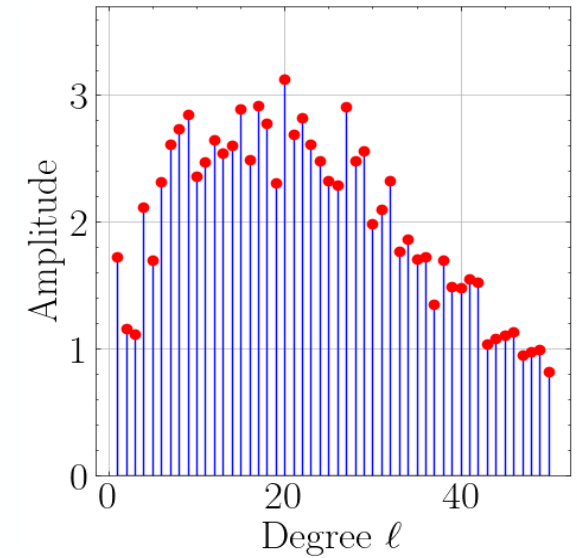


Definition of a point cloud



Initialization of a spherical function $f(\theta, \phi)$ by Gaussian blurring the point cloud

Decompose $f(\theta, \phi)$ into a series of spherical harmonics



The rotation-invariant feature is h

$$h = \{h_0, h_1, \dots\}, h_l := \sqrt{\sum_{m=-l}^l |a_{lm}|^2}$$

With a_{lm} weights of the spherical harmonics

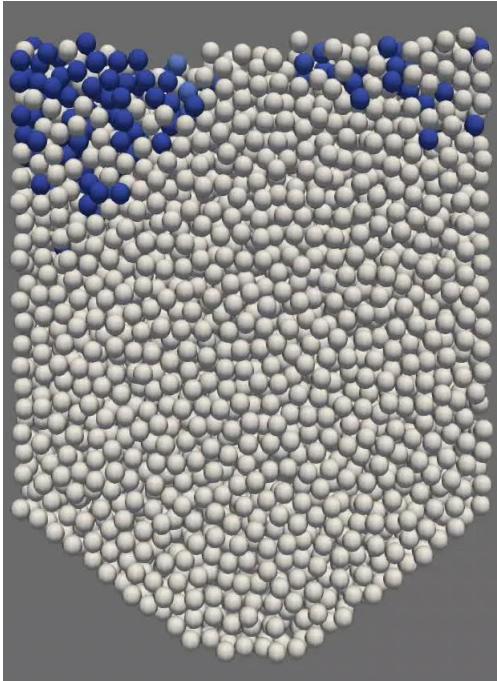
Performance of Neutron and Gamma-ray-based Assays Combined

- The developed NMC can estimate the ^{235}U mass in a TRISO-fueled pebble with **2.5% relative uncertainty in 100 s**, which reduces the fraction of candidate pebbles to 16%.
- The combination of the two approaches will enable the identification of a single discharged TRISO-fueled pebble from a PBR encompassing 625,000 pebbles in 150 s.

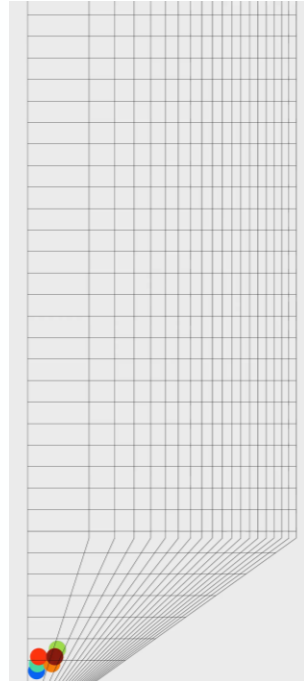


M. Fang and A. Di Fulvio. Rotation-invariant rapid TRISO-fueled pebble identification based on feature matching and point cloud registration. Annals of Nuclear Energy, 203:110527, 2024. ISSN 0306-4549.doi:<https://doi.org/10.1016/j.anucene.2024.11052>

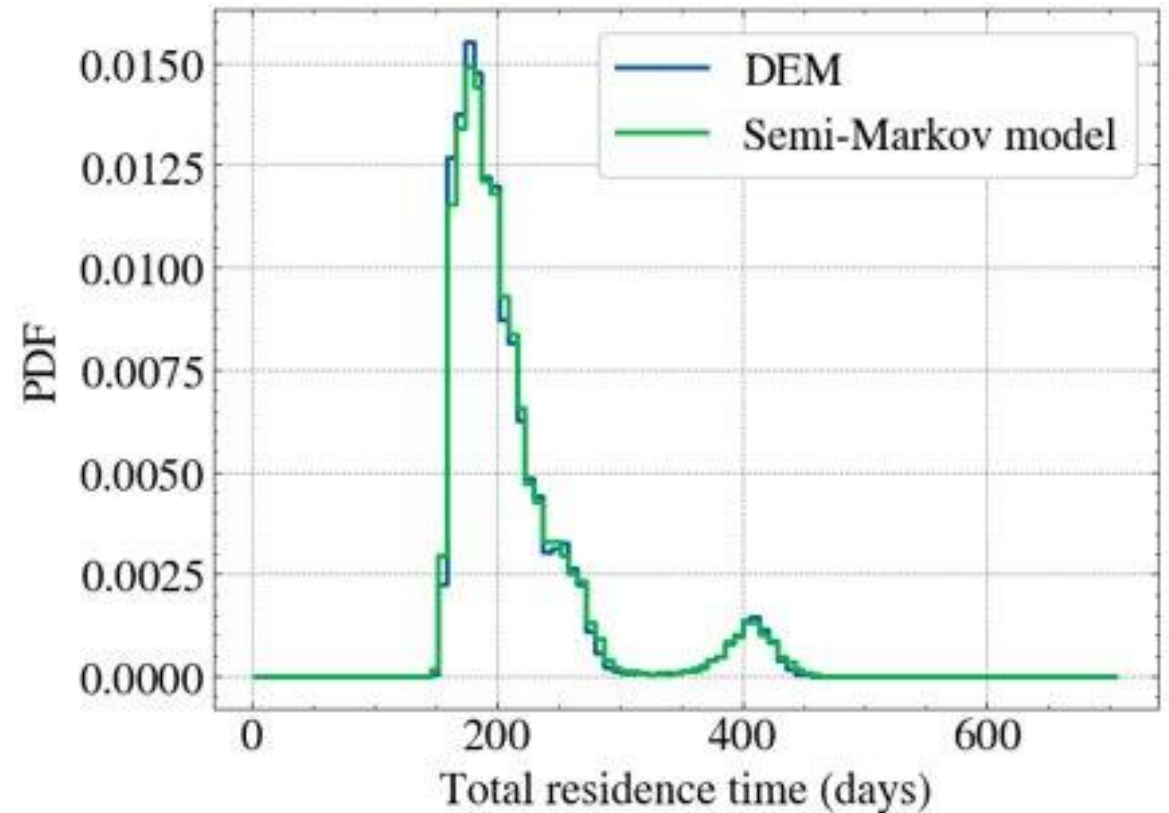
PebbleTRACK - Statistical Analysis



Discrete element simulation of pebble flow. ~350 hours.



Pebble flow path sampled from the statistical model. ~2 min.

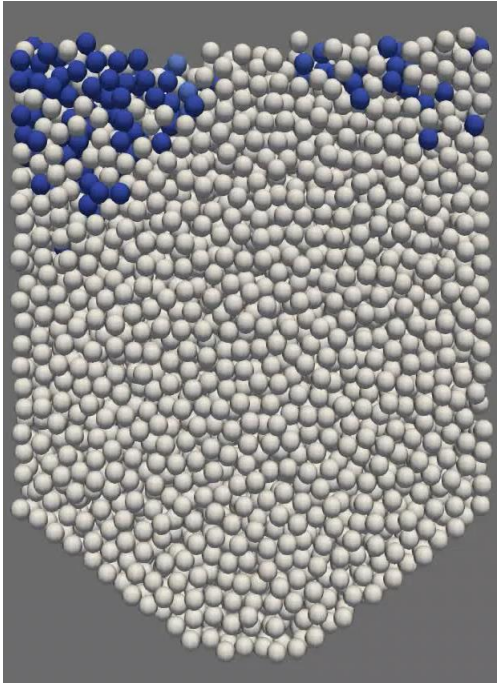


Comparison of model predictions to DEM simulation of the probability density function of residence time.

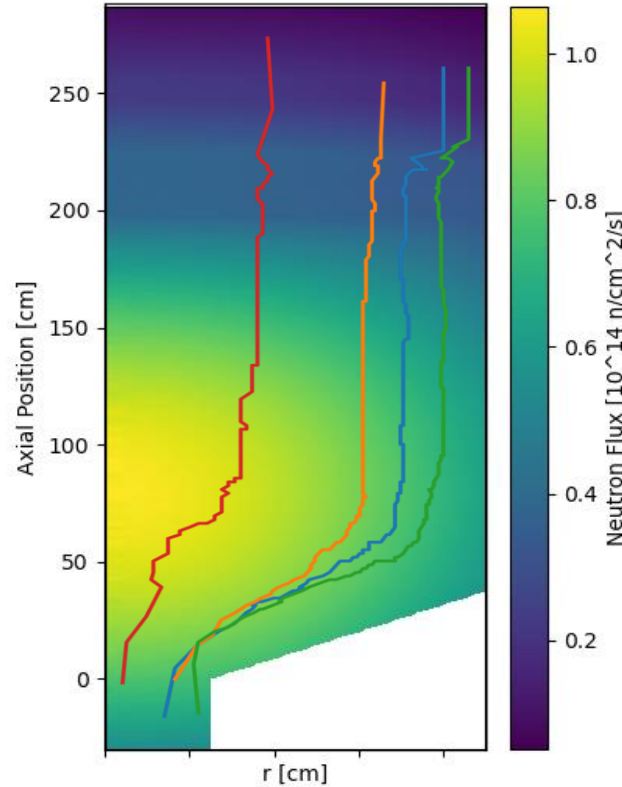
HTR-10 used as a model.

With the statistical model, for a pebble inserted at any position, we can calculate the probability distribution of burnup increase when it exits

PebbleTRACK - Statistical Analysis

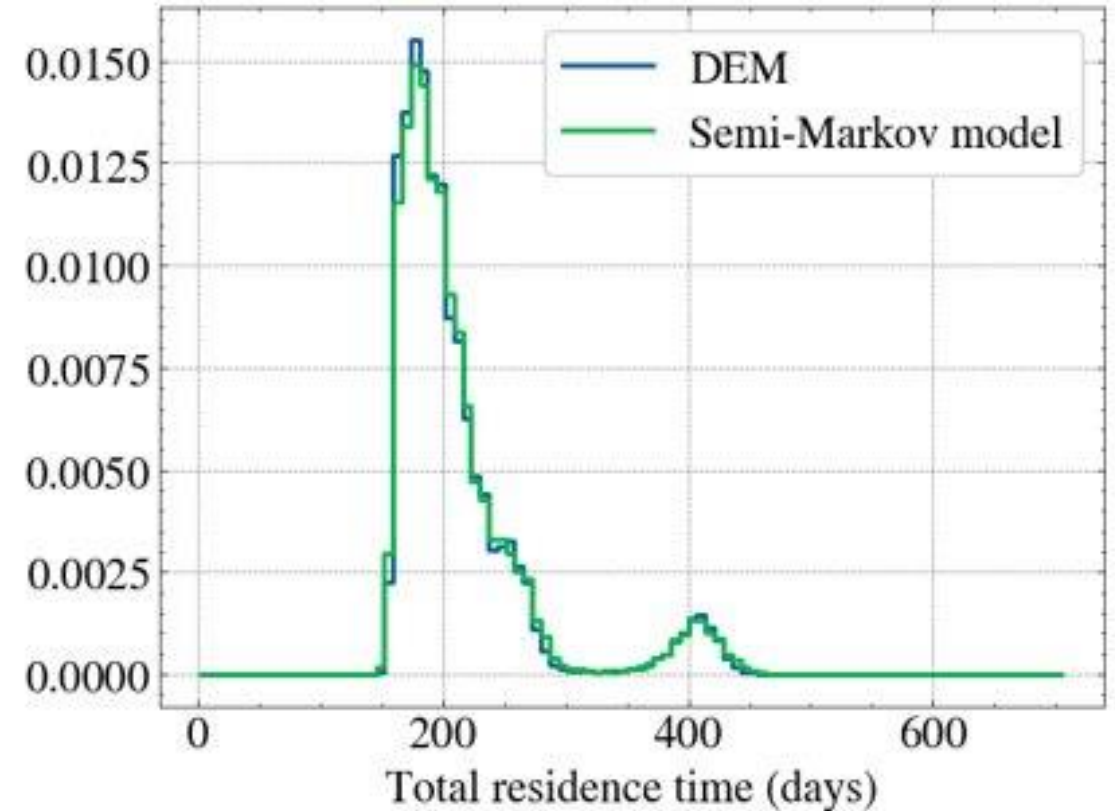


Discrete element simulation of pebble flow. ~350 hours.



Neutron flux distribution and paths of a pebble with four passes before discharge

- Pass 1
- Pass 2
- Pass 3
- Pass 4



Comparison of model predictions to DEM simulation of the probability density function of residence time.

HTR-10 used as a model.

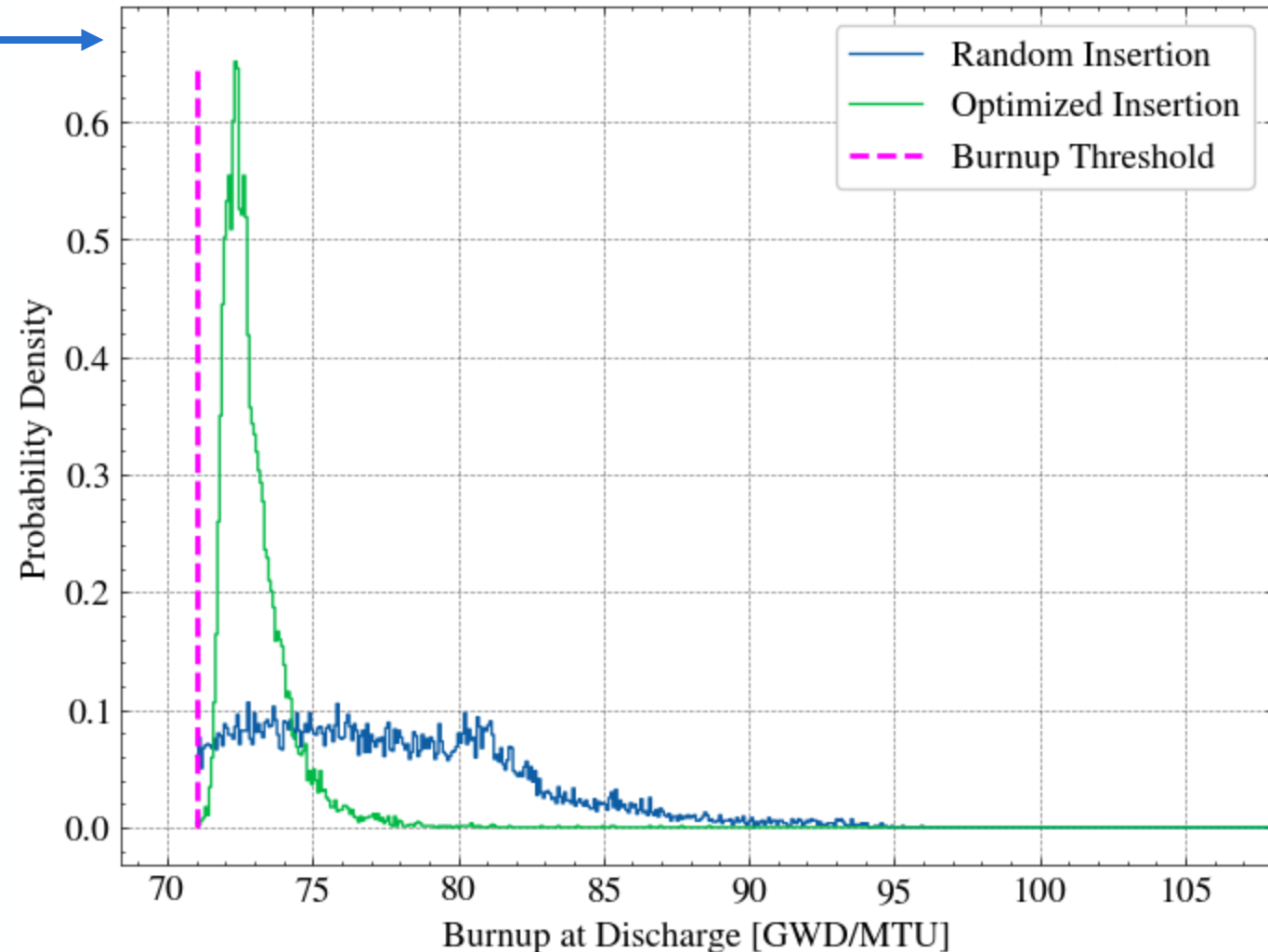
With the statistical model, for a pebble inserted at any position, we can calculate the probability distribution of burnup increase when it exits.

From external measurements to knowledge of the internal reactor state *without direct in-core access*

Burnup distribution at discharge. →

12000 pebbles were recirculated with either random or optimized reinsertion scheme until the fluence exceeds a preset threshold of 71 GWd/t.

- **Nonintrusive monitoring:**
Estimates pebble trajectories without requiring sensors inside the reactor core.
- **Reduced computational cost:**
Uses a DEM-informed statistical model instead of computationally expensive full-scale particle tracking.

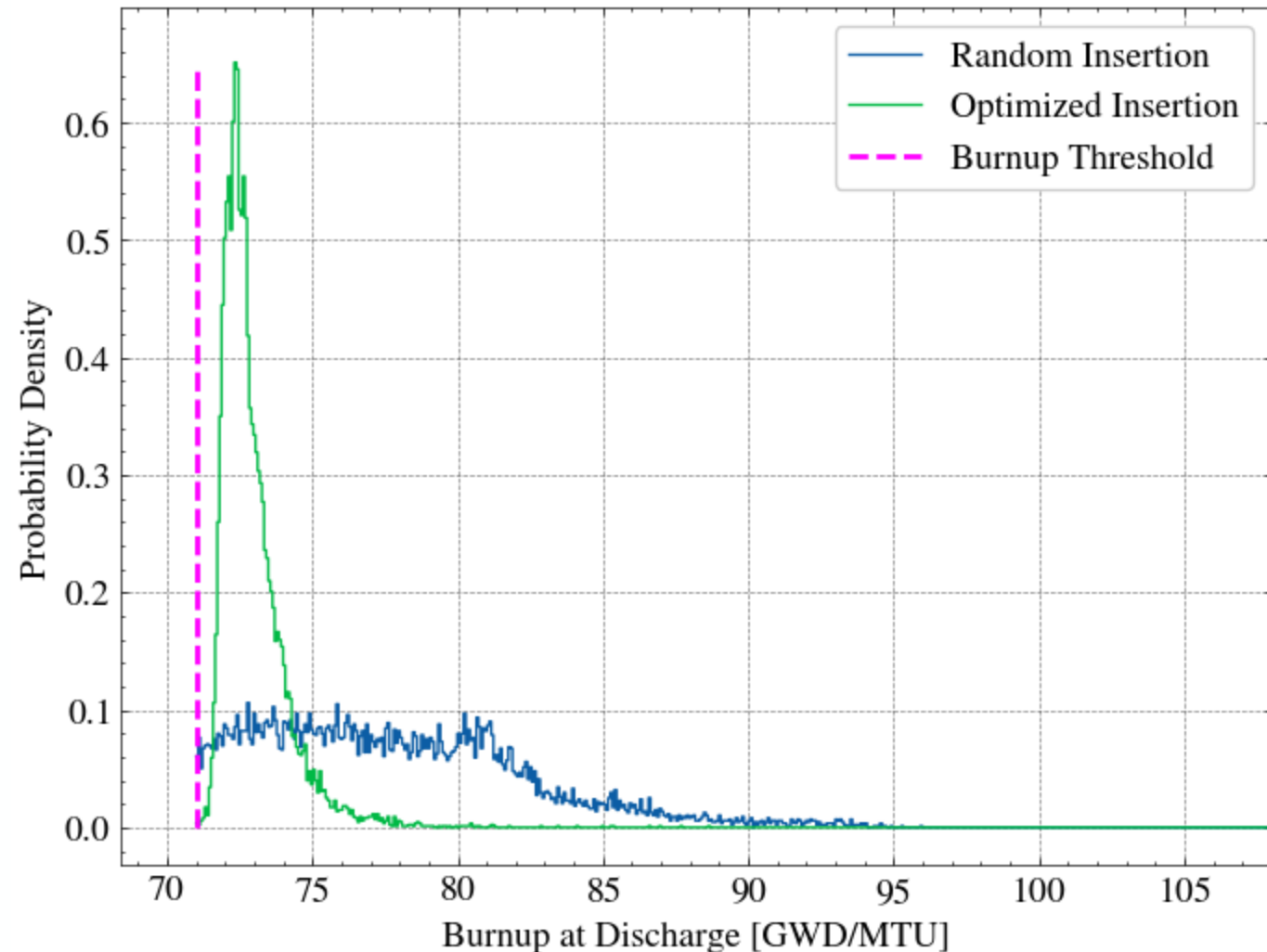


From external measurements to knowledge of the internal reactor state *without direct in-core access*

Individual fuel tracking: Combines pebble identification, residence time, and fissile-content measurements to estimate individual fuel histories.

Improved operational margins: Reduces uncertainty in fuel distribution and burnup, potentially enabling more efficient use of fuel while maintaining safety margins.

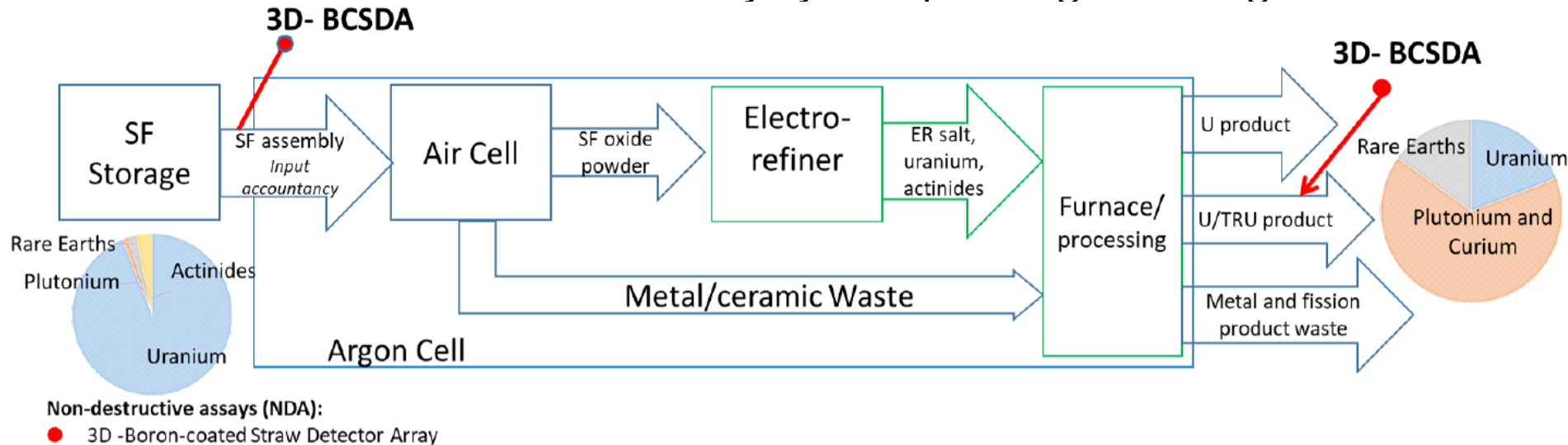
Enhanced plant functionality: Supports informed fuel reinsertion, discharge decisions, and automated fuel management.



E. Nicolls, T. Grunloh, S. Pemberton, M. Fang, S. Malik, W. Dick, C. Brooks, and A. Di Fulvio. Statistical analyses of granular flows in pebble bed reactors. *Annals of Nuclear Energy*, 240:112722, 2027. ISSN 0306-4549. doi:<https://doi.org/10.1016/j.anucene.2026.112722>

Form-factor-agnostic Multiplicity Counting for Fissile Quantification

- There is a need to assess plutonium mass, including bulk materials in pyroprocessing and fuel streams in molten salt-based fuels
 - The IAEA International Target Value for plutonium mass uncertainty is 5.4% [1].
 - Current uncertainty can exceed 500% [2], due to the point model assumption.
- The proposed method aims to demonstrate neutron tomography with double-sided readout detectors and reduces the uncertainty by incorporating knowledge of the material's form factor.



Prototypical pyroprocessing facility with 3D-BCS assay points.



Active Well Coincidence Counter based on 48 ^3He tubes [3].



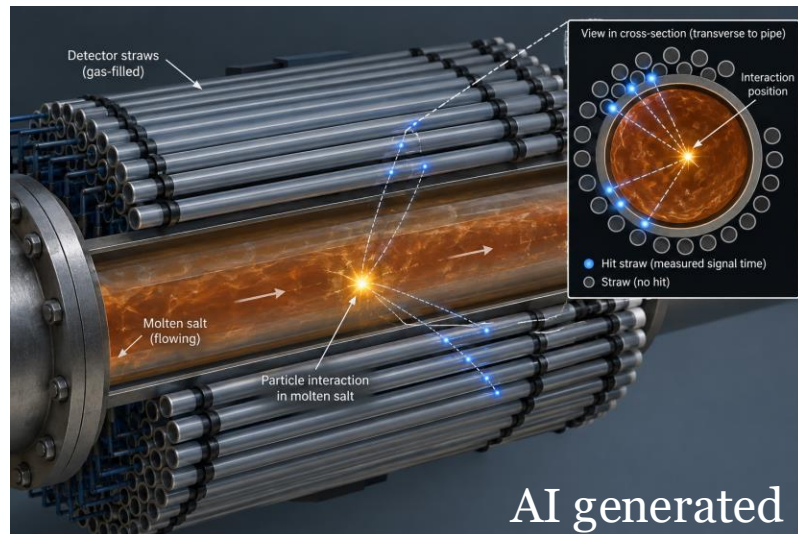
[1] Joint Research Centre, "International target values for measurement uncertainties in safeguarding nuclear materials," IAEA, Vienna, Austria, Tech. Rep. STR – 368, Feb. 2022

[2] N. Miura and H. O. Menlove, "The use of curium neutrons to verify plutonium in spent fuel and reprocessing wastes," Tech. Rep. LA-12774-MS, 1994.

[3] M. Lockhart, et al. "Neutron Coincidence Measurements of Uranium-233 Oxide". Oak Ridge National Laboratory (ORNL), Oak Ridge, TN (United States), 2023.

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3D multiplicity counter surrounding a molten-salt pipe, ability to reconstruct the flux profile can enable real-time fissile estimate regardless of the fuel form factor.



Active Well Coincidence Counter based on 48 ^3He tubes [3].



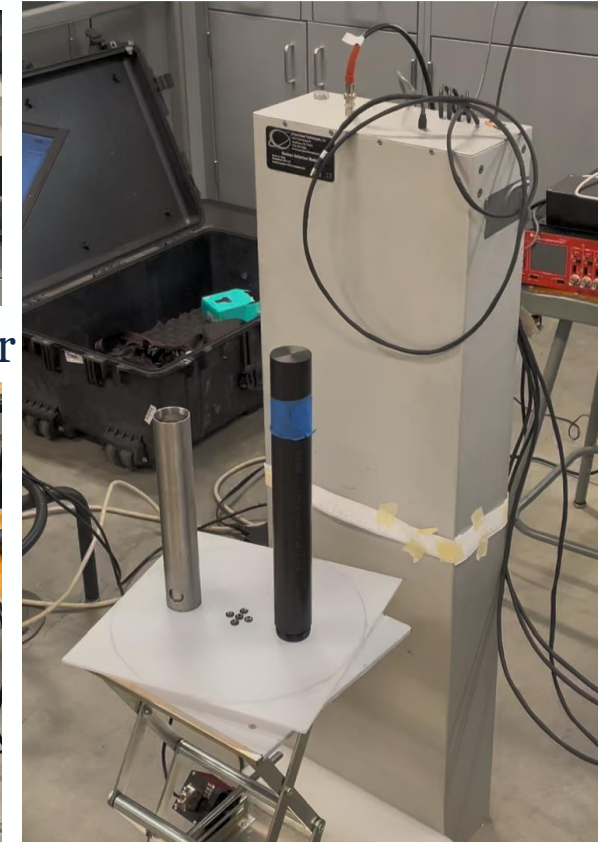
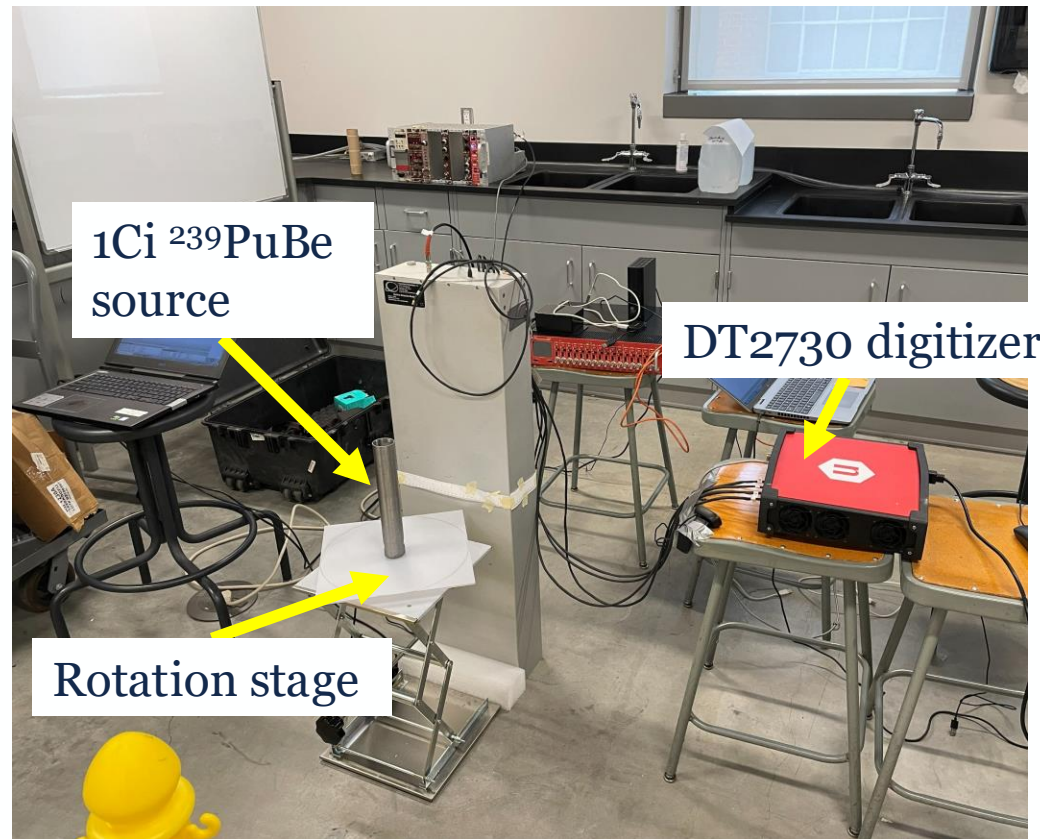
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Form-factor-agnostic Multiplicity Counting for Fissile Quantification

- We developed a boron-coated straw detector array (BCSDA) comprising 30 straws with individual dual-ended readout for neutron emission tomography.
- We performed neutron emission tomography of a PuBe source at *centered* and *off-centered* positions, using 4° angular increments and measurement times of 3 s and 19 s per increment respectively.



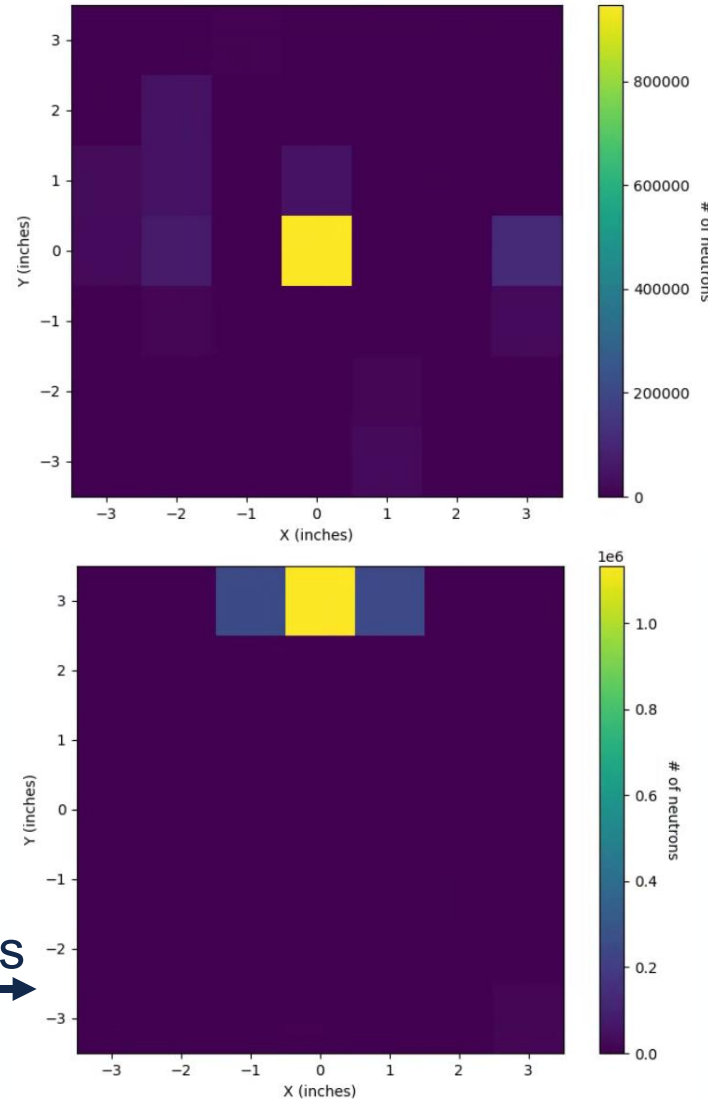
Experimental Setup

Form-factor-agnostic Multiplicity Counting for Fissile Quantification

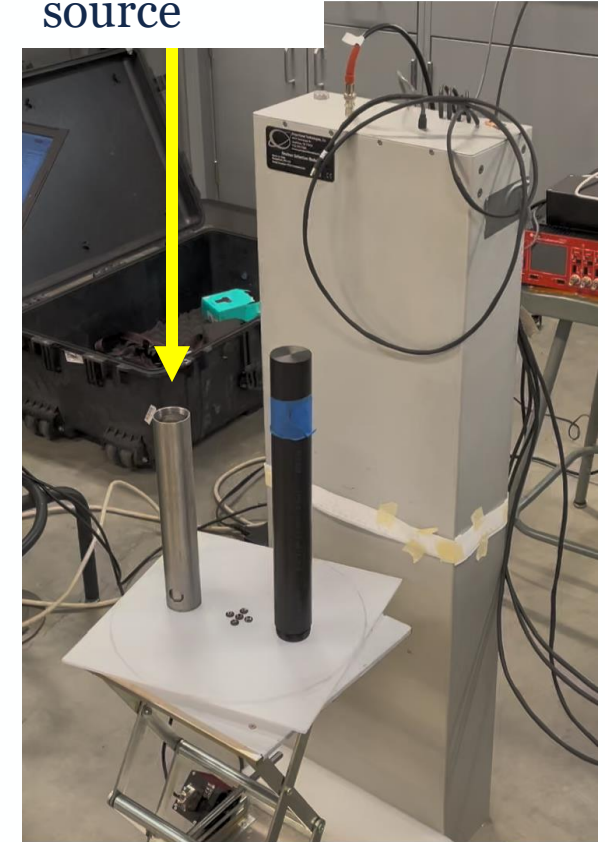
Dual-purpose technology for process diagnostics and nuclear material accountancy.

- Enables accurate material accountancy and safeguards in high-radiation environments for samples of non-standard form factors.
- Nonintrusive monitoring could decrease reliance on destructive chemical sampling and associated handling.
- External neutron detectors could **monitor circulating fuel salt without placing instrumentation in the chemically aggressive, high-temperature fluid.**

Reconstructed images



$^{1}\text{Ci } ^{239}\text{PuBe}$
source



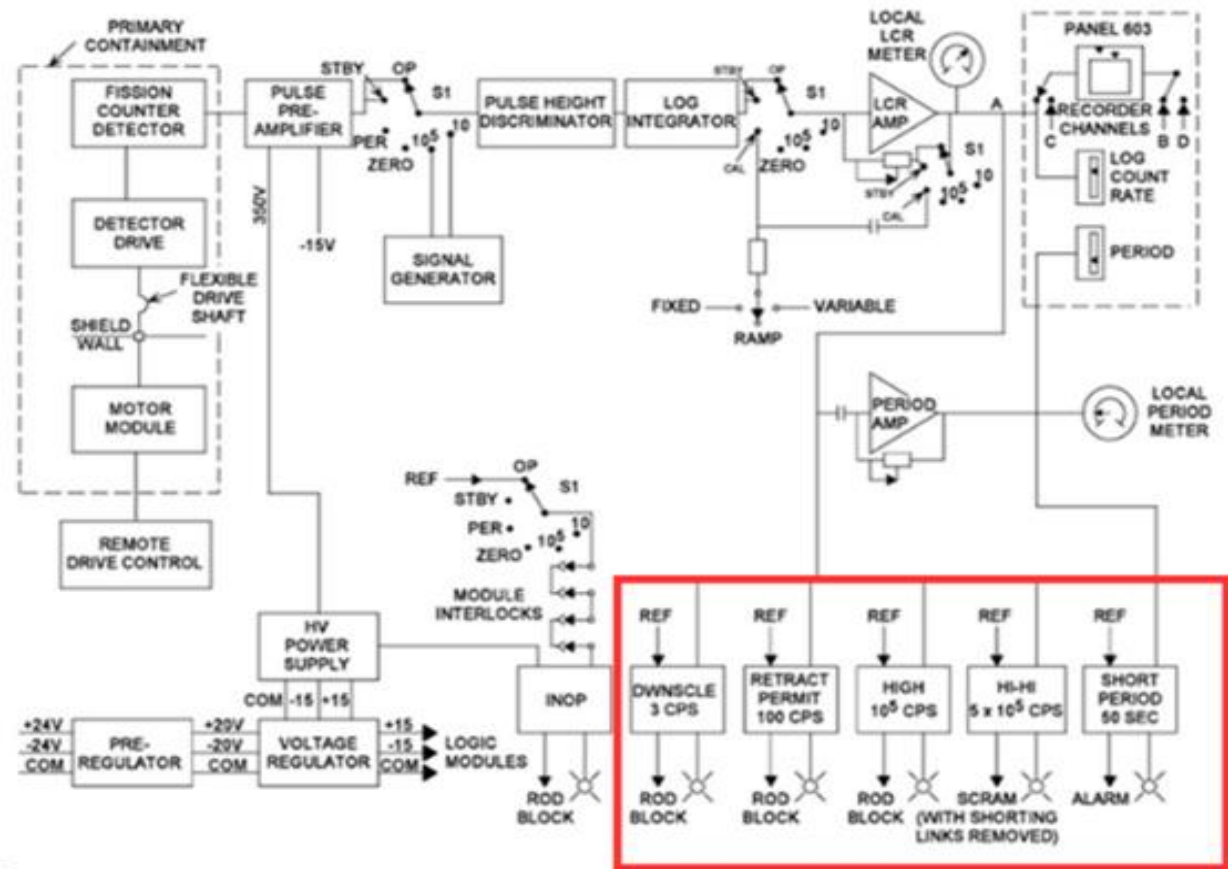
Experimental Setup

Gain-adaptive Fission Chamber

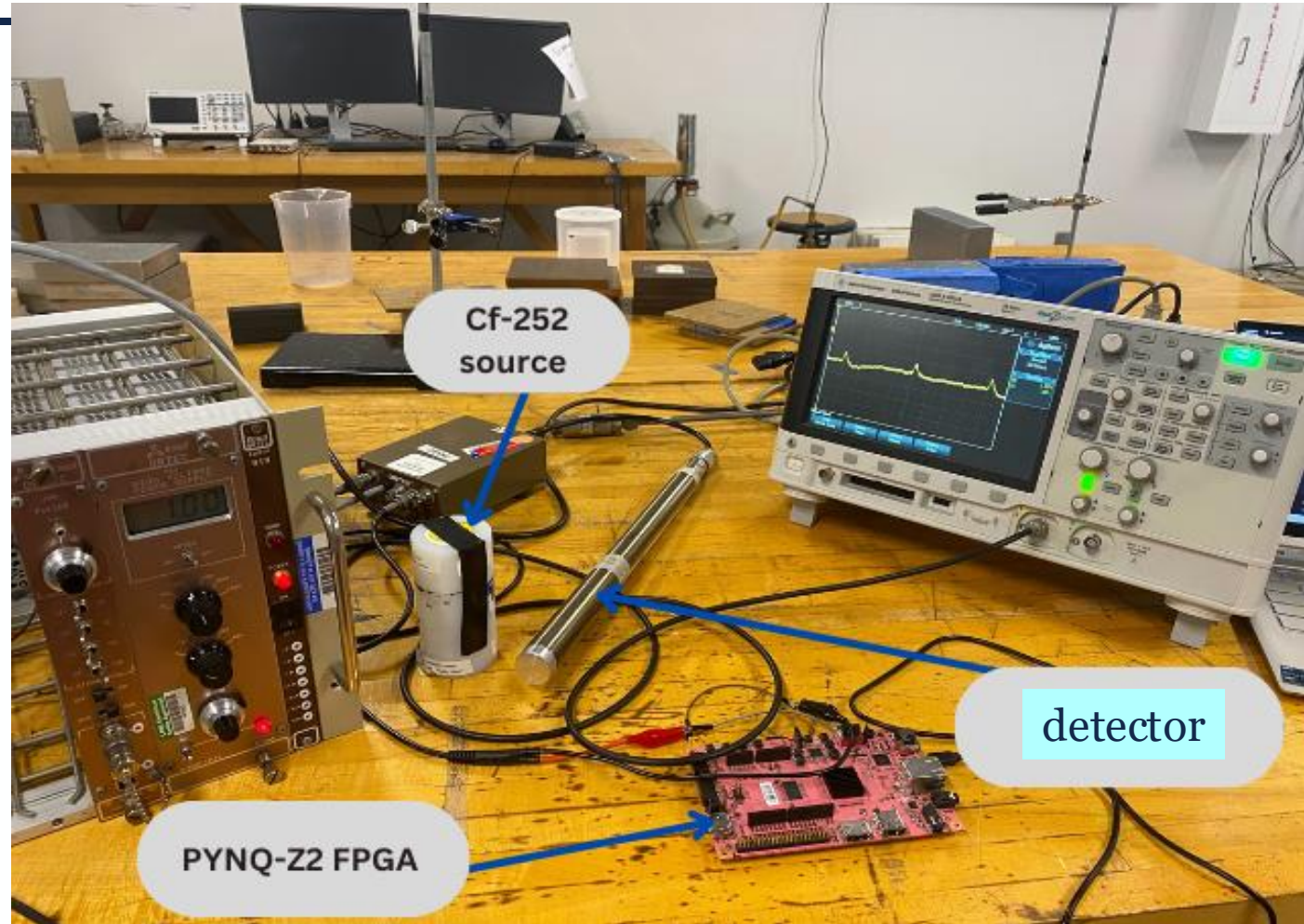
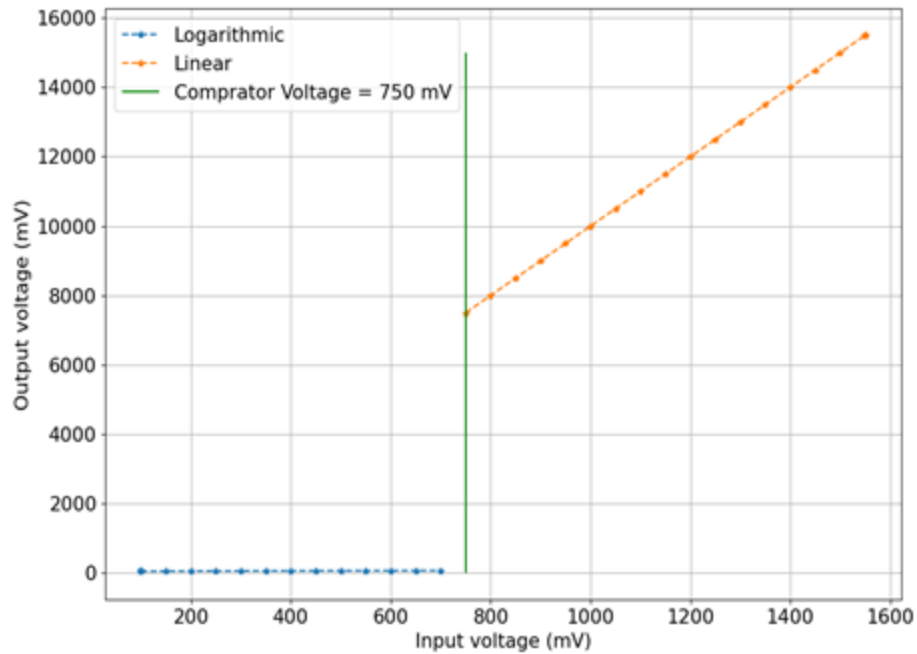
- Conventional fission chambers require transitions between pulse, fluctuation (Campbelling), and current modes to cover the wide neutron flux range of advanced reactors.

Gain-adaptive Fission Chamber

- Seamless mode transitions:** Adaptive gain and readout enable reliable measurements across changing neutron flux levels.
- Improved automation:** FPGA-based processing enables autonomous mode selection and gain adjustment without operator intervention.

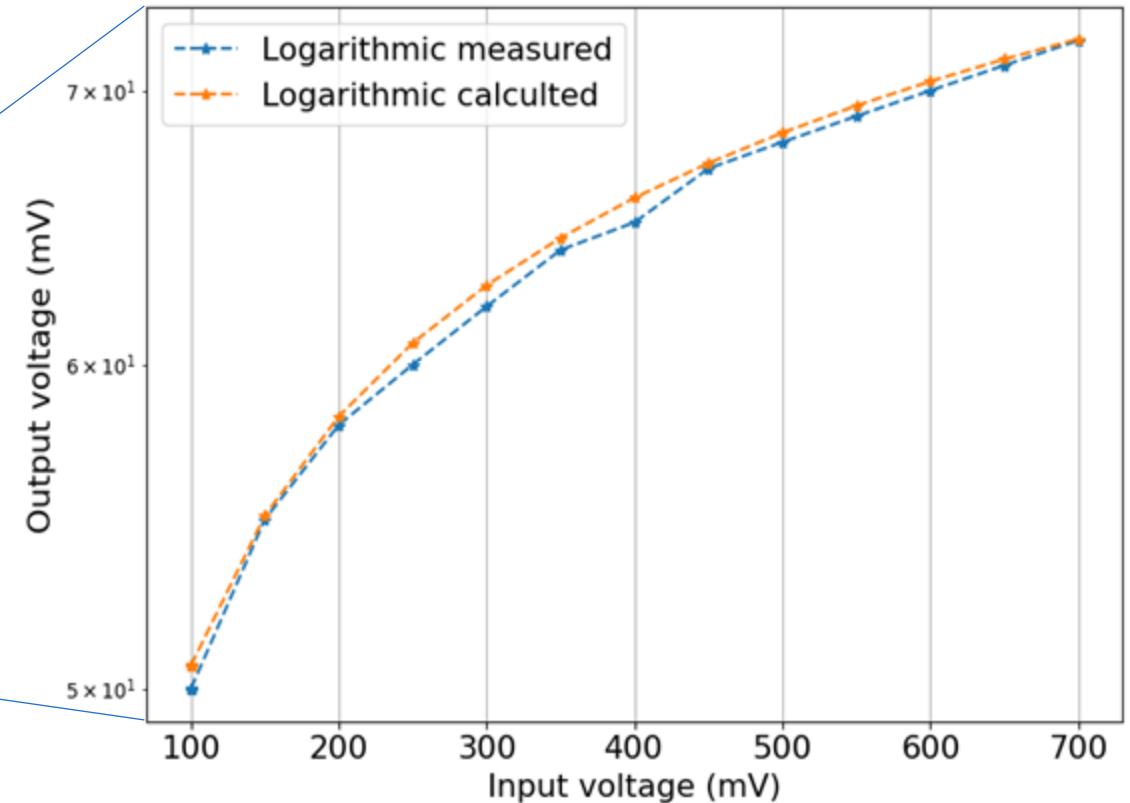
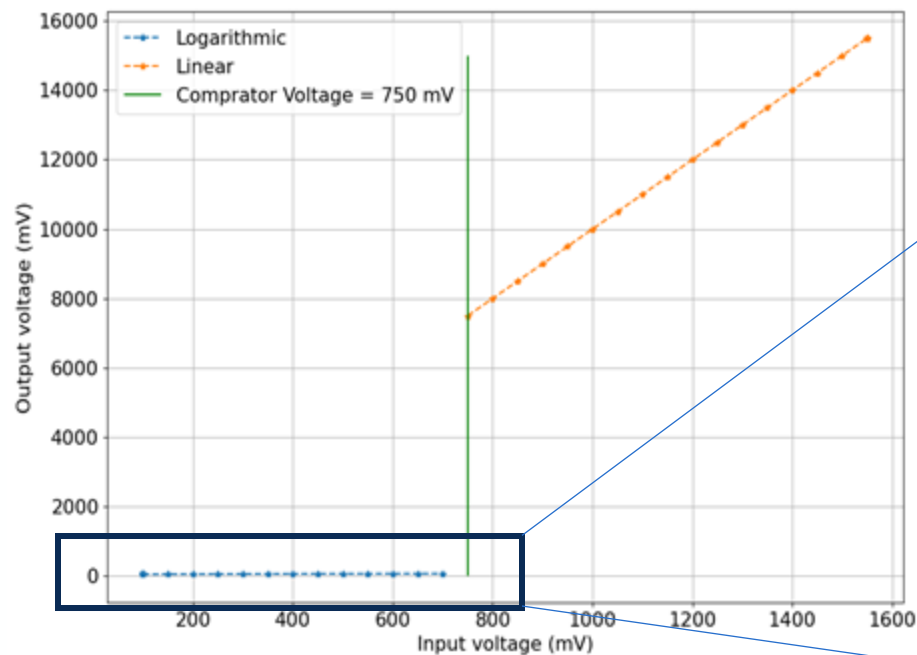


Gain-adaptive Fission Chamber



PYNQ-Z2 is an open-source development board based on the Xilinx ZYNQ XC7Z020 System on Chip (SoC), featuring a combination of a dual-core ARM Cortex-A9 processor and programmable logic (FPGA).

Gain-adaptive Fission Chamber



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Gain-Adaptive Fission Chamber for Autonomous Reactor Monitoring

- **Wide dynamic range:** Extends neutron monitoring from startup through full-power operation.
- **Reduced instrumentation complexity:** Integrated digital processing supports more compact, versatile monitoring systems.
- **Enhanced reliability:** FPGA redundancy and fault-tolerant architectures mitigate single-event upsets (SEUs).

Conclusions - Role of I&C in Advanced Reactors

Unique Operating Environment & Design Constraints
*high T, high flux, chemistry,
access limits, long lifetime*

Novel Sensors for Advanced Fuel
Cycles

*survivability, reliability,
maintainability, useful measurements*

Functionality
control, diagnostics,

- *3D BCS / multiplicity*
- *Fuel residence and reinsertion decision support*
- *Real-time stand-off imaging*

Affordability

- *External neutron / gamma sensing*
- *FPGA-adaptive readout*

Safety, Security, and
Safeguards

- *3D neutron multiplicity counting*
- *Prospective in-line MSR monitoring*
- *PebbleTRACK burnup estimates*



Conclusions

- We have developed innovative sensing and monitoring systems to address the unique challenges of advanced reactors and fuel cycles. We have leveraged computational methods and digital technologies to enhance sensor functionality, enable automation, and reduce computational and operational costs.
- **We recommend introducing novel instrumentation initially in non-safety-rated systems**, building operational experience and establishing pathways toward safety qualification.
- **Leverage digital technologies and automation:** Integrate adaptive sensing, FPGA-based processing, and computational methods to improve diagnostics, control, and operational efficiency.



Nuclear Measurement Lab Contributors

Main contributors

- Dr. Ming Fang, Research Scientist, UIUC
- John Leland, graduate student, NML, UIUC
- Ethan Nicholls, Naval Reactors Engineer at the Office of Naval Reactors

Current and past NML students involved in these projects

- Undergraduate Students: Kennedy Dempsey, Justin Dorman, Justin Jia, Arnav Goyal
- Graduate Students: Kaixin Xue, Kholod Mahmood

Collaborators:

Prof. Yoann Altmann, Herriot Watt University (UK), Prof. Caleb Brooks (UIUC), Dr. Timothy Grunloh (UIUC), Prof. Raffaele Giordano (UniNa), Dr. Jianwei Hu (ORNL), Prof. Sara Pozzi (UM).



Thank you for your attention!

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This work was also supported by **the U.S. Department of Energy, Office of Nuclear Energy under DOE Idaho Operations Office Contract DE-AC07-05ID14517 as part of a Nuclear Science User Facilities experiment**. We would like to acknowledge the support of The **Ohio State University Nuclear Reactor Laboratory** and the assistance of the reactor staff members Dr. Raymond Cao, Dr. Susan White, and Dr. Kevin Herminghuysen for the irradiation services provided.

This material is based upon work supported in part by the Department of Energy **National Nuclear Security Administration** through the Nuclear Science and Security Consortium under Award Number DE-NA0003996.

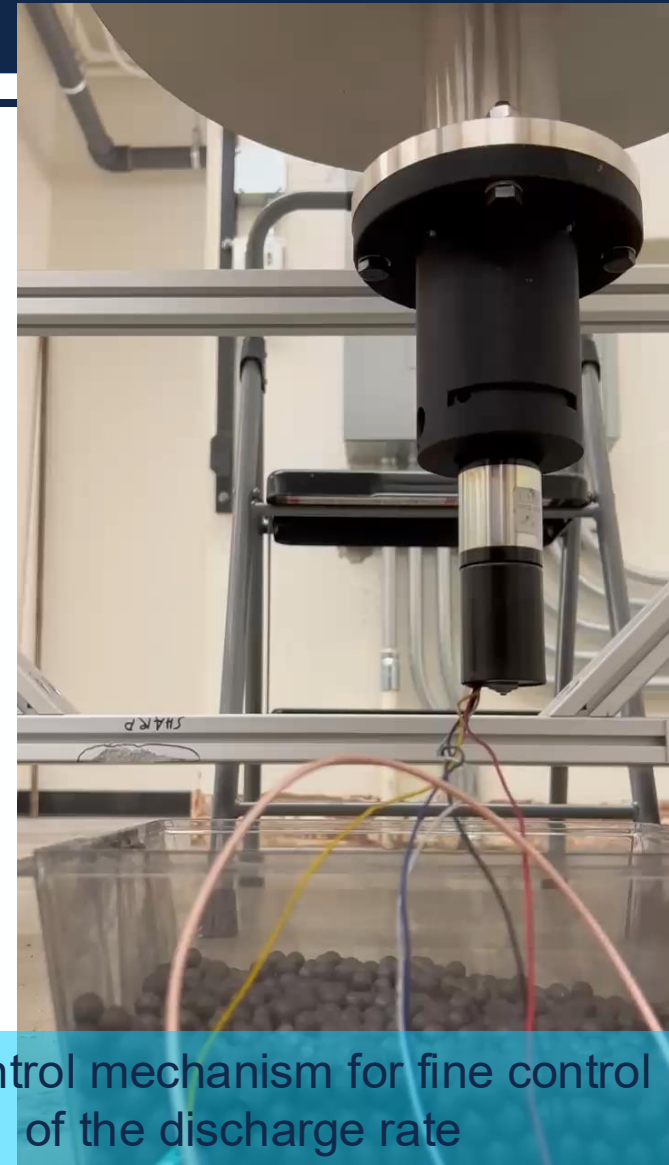
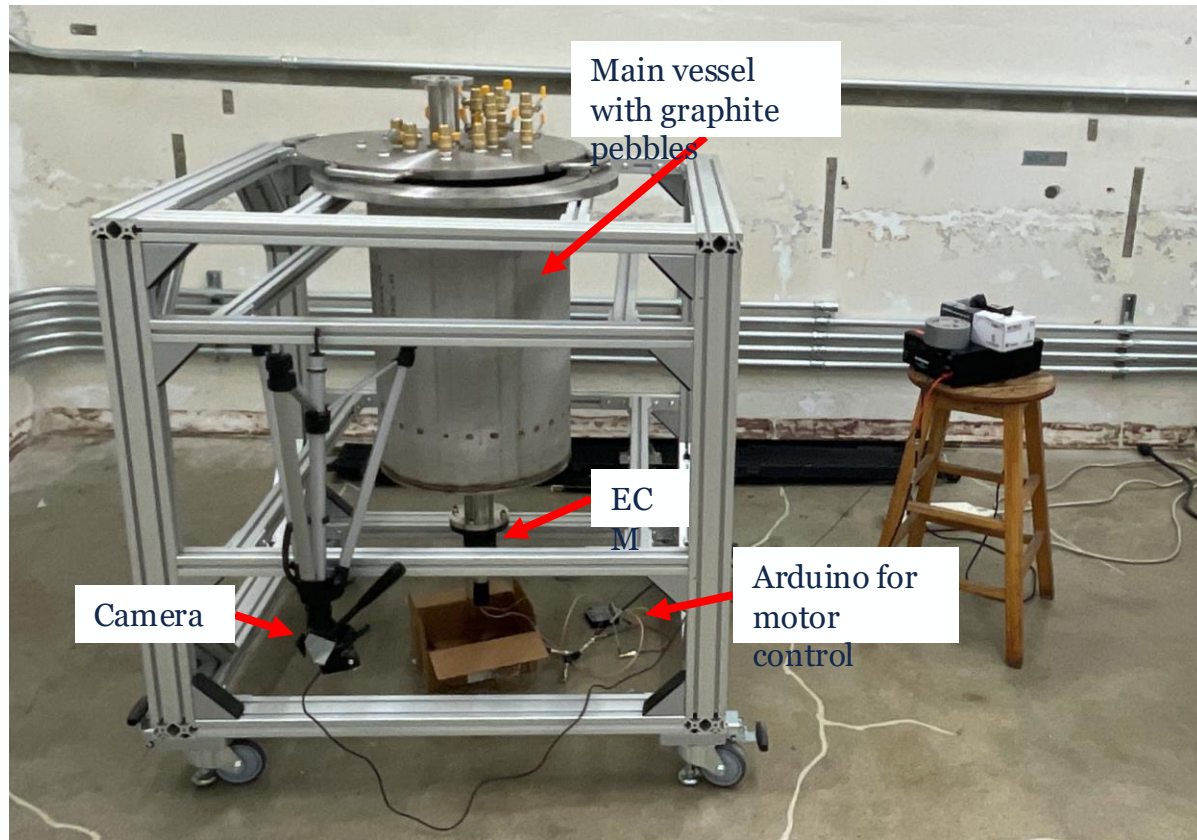
This material is based upon work supported by the **Department of Energy under Award Number DE-NE0009478**. Thank you to X-Energy Collaborators for their feedback on PBR technology.

This material is based upon work supported by the Department of Energy **ARPA-E NEWTON** program under Award Number DE-AR0002080.



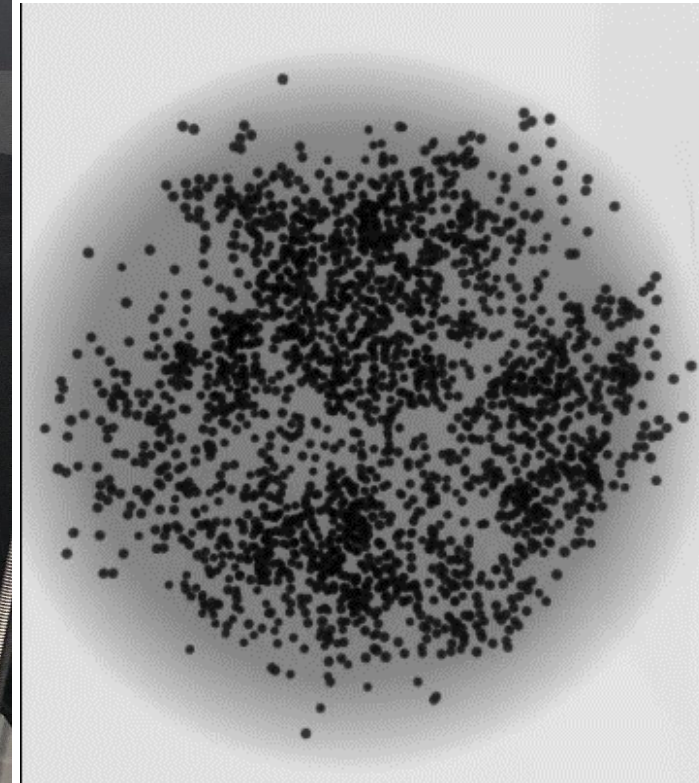
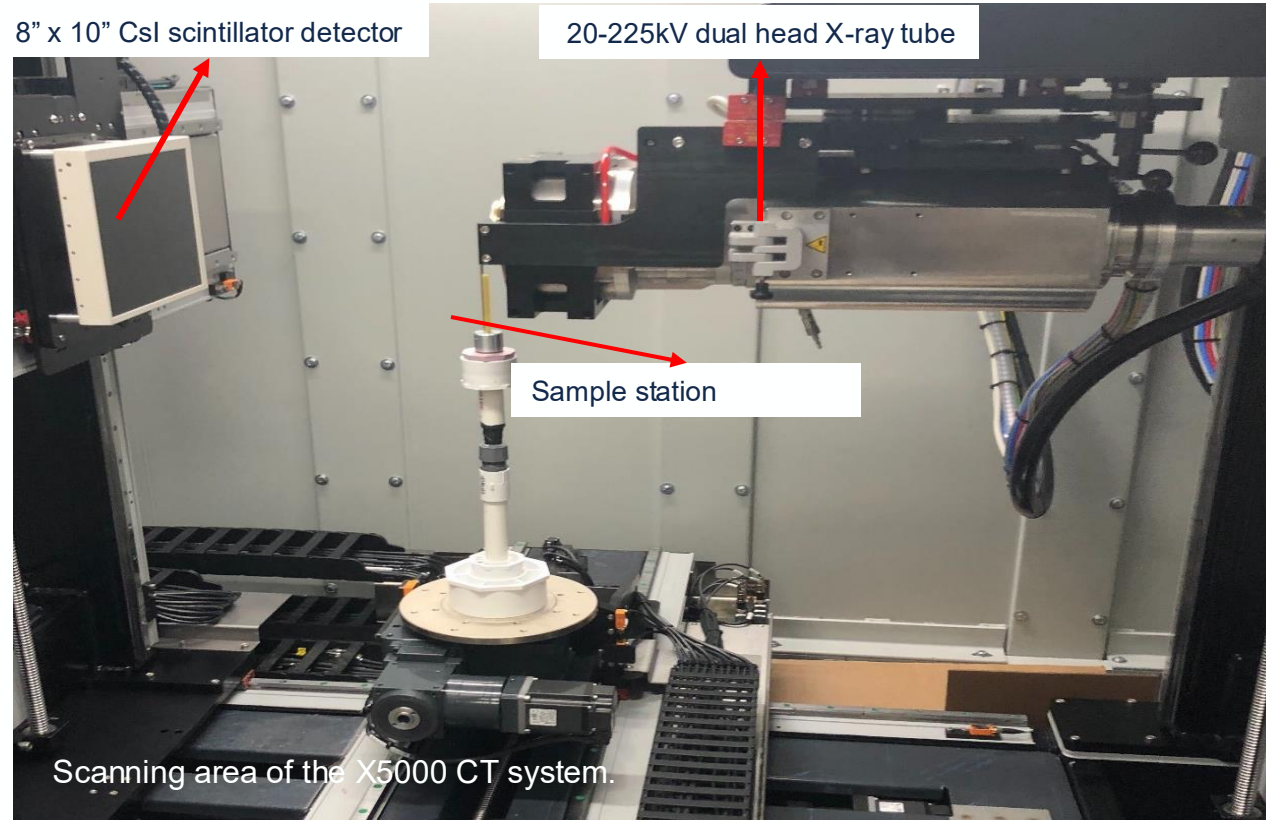
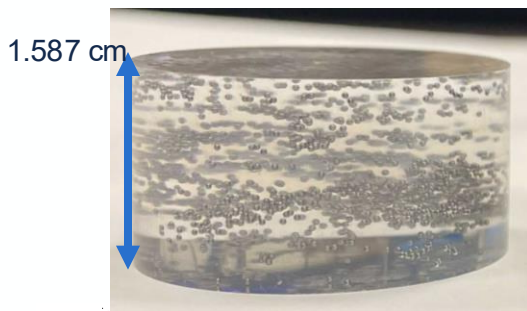
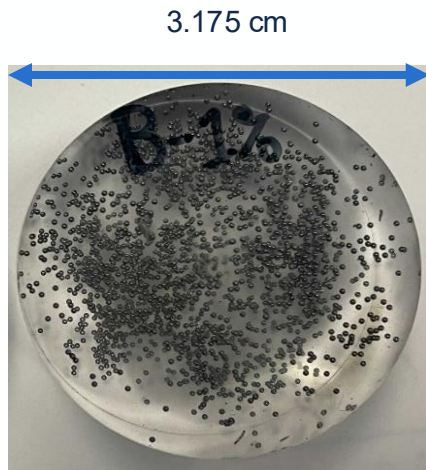
Extra Slides

Experimental Pebble Testbed



X-Ray CT Scan of Mockup Fuel Samples

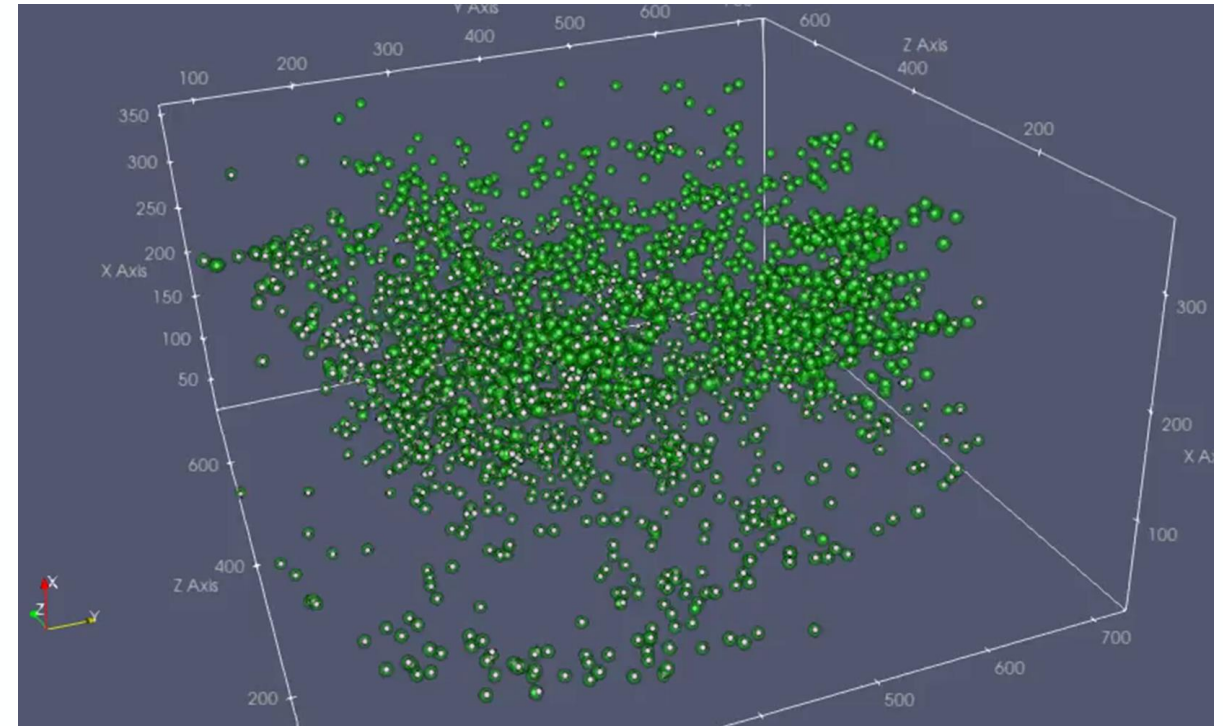
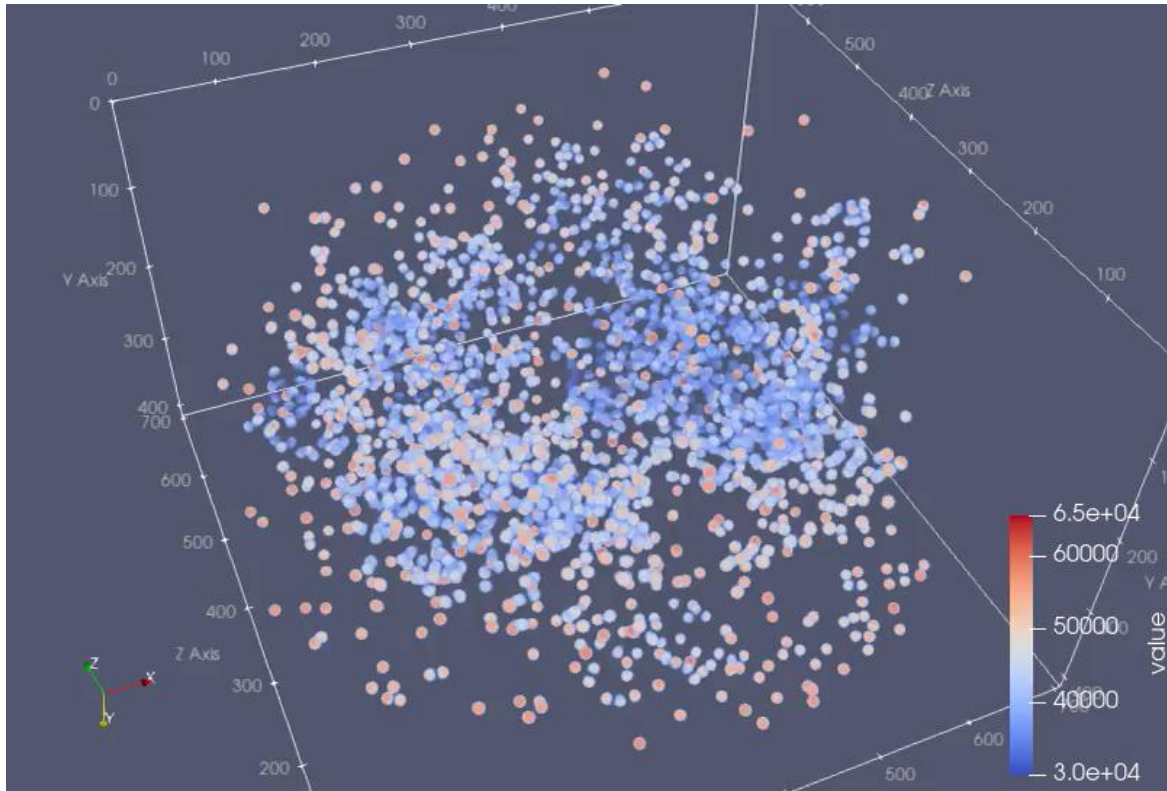
- A 200kVp cone-beam X-ray CT scan of a mockup fuel sample was performed using a *North Star Imaging X5000* industrial CT scanner.



X-ray projections (video)

Mockup fuel compact sample provided by BWXT made of 1920 500-um diameter tungsten-carbide (WC) particles (black) and lucite plastic (transparent). The total attenuation is comparable to a TRISO fuel compact with 17% particle loading.

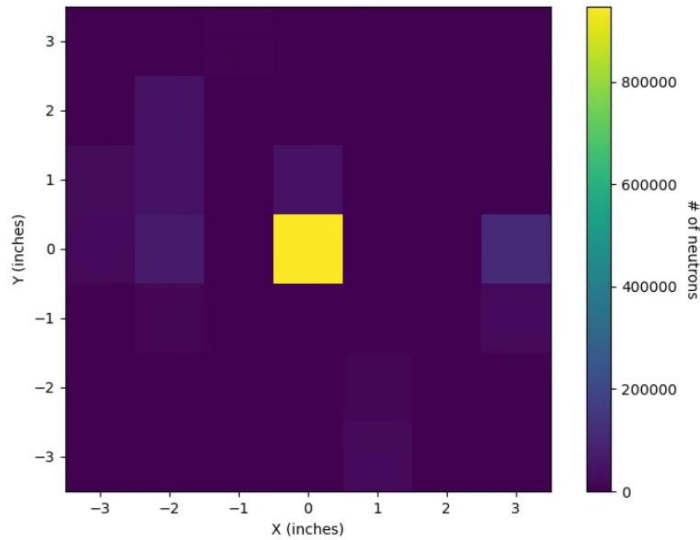
3D Reconstruction and Segmentation of the CT image



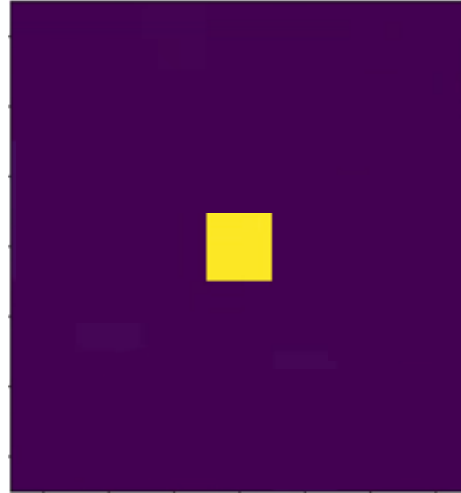
Segmented image (video), identify the kernels and retrieve their location^[1]

^[1] M. Fang and A. Di Fulvio. Rotation-invariant rapid TRISO-fueled pebble identification based on feature matching and point cloud registration. Annals of Nuclear Energy, 203:110527, 2024. ISSN 0306-4549. doi:<https://doi.org/10.1016/j.anucene.2024.110527>

Form-factor Agnostic Multiplicity Counting

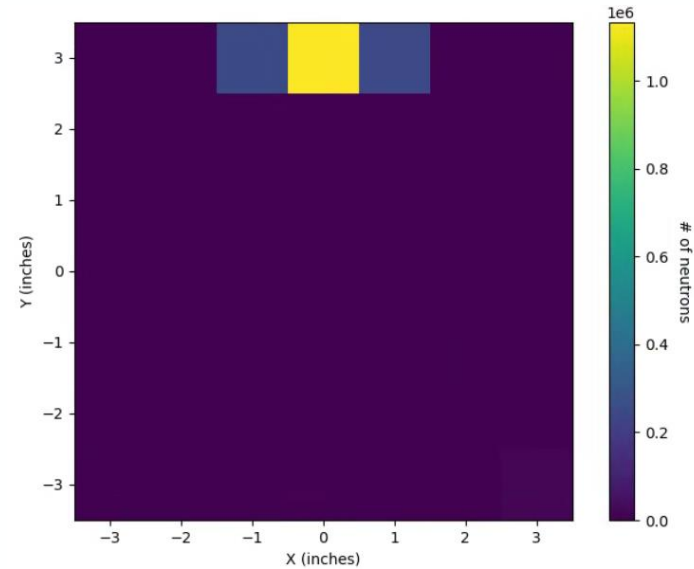


Reconstructed
image

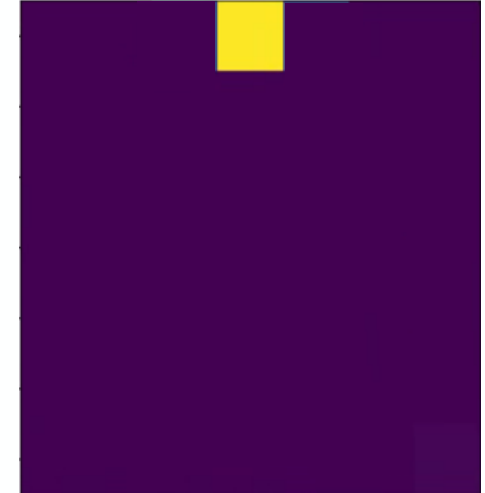


Ground
truth

PuBe source centered



Reconstructed
image



Ground
truth

PuBe source off-centered