U.S. DEPARTMENT OF ENERGY | Office of NUCLEAR ENERGY

ASI Advanced Sensors and Instrumentation

Advanced Controls - ANL

Advanced Sensors and Instrumentation (ASI)
Annual Program Webinar
November 4, 6-7, 2024

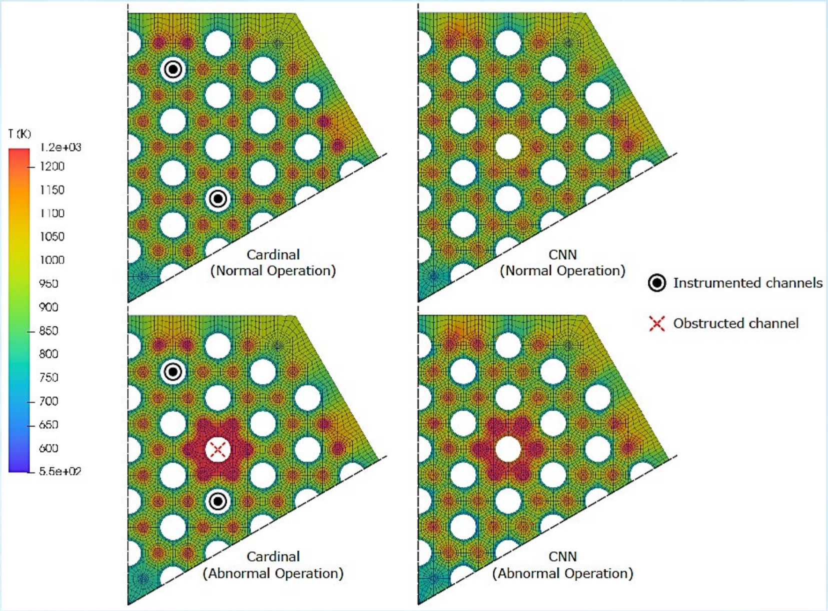
PI: Richard B. Vilim; Co-PI: Haoyu Wang, Roberto Ponciroli

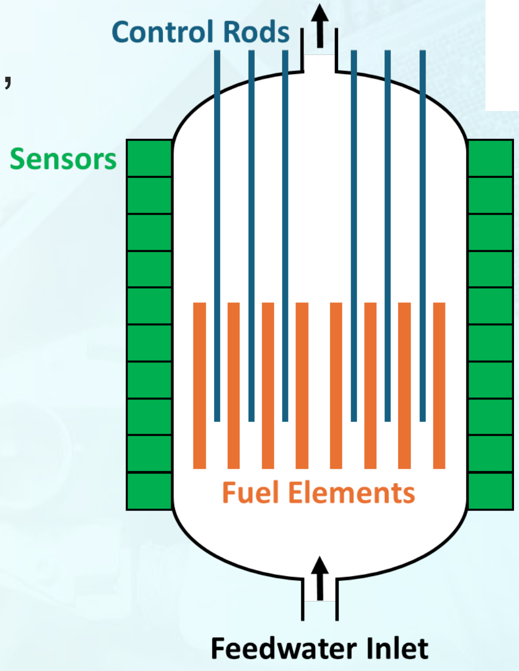
Argonne National Laboratory

Project Overview

Research scope:

- Develop an innovative approach for monitoring and managing core performance for micro reactors and advanced reactors.
- Develop power reconstruction techniques by combining physics-informed machine learning, high-fidelity modeling and real-time ex-core measurements, thereby reducing the dependence on in-core detectors.
- Demonstration in a university reactor (Purdue University Reactor Number One).





Top: Convolution Neural Network temperature field reconstruction

Left: Schematics showing the ex-core sensors for reactor monitoring

Project Overview

Status of Project: 2nd year of 3-year plan

Fiscal Year	Stage	Deliverable	Status
FY24	Planning	M4CT-24AN0704022: Definition of a strategy to develop a control scheme for core thermal performance optimization (April 30, 2024)	Completed on time
	Modeling	M2CT-24AN0704023: Development of data-driven approach to core power distribution reconstruction in a nuclear reactor (September 30, 2024)	Completed on time
FY25	Modeling	M3CT-25AN0704021: Complete the development of a High-fidelity neutron transport and sensor response model (March 31, 2025)	On Schedule
	Algorithm Development	M3CT-25AN0704022: Complete the development of scoring and optimization system to facilitate improved reactor control (September 30, 2025)	On Schedule
FY26	Optimization & Demonstration	TBD	TBD

Participants:

- PI: Richard B. Vilim (ANL)
- Co-PI: Haoyu Wang (ANL), Roberto Ponciroli (ANL), Tim Nguyen (ANL), Stylianos Chatzidakis (Purdue University)
- Student: Vasileios Theos (Purdue University)

Technology Impact

- Traditional techniques for reconstructing the power distribution in Light Water Reactors need $\sim 10^2$ sensors placed at various positions within the core. This approach cannot be applied to Advanced Reactors (harsh environment) and Microreactors (limited space).

- ANL-Purdue team aim to develop a highly adaptable method by integrating high-fidelity modeling with data-driven techniques, thereby reducing the dependence on in-core sensors.

- This work paves a way for a non-intrusive core monitoring approach that only needs ex-core sensors. It will enhance the reactor economic performance via the following benefits:
  - Reduced fuel cycle cost through improved fuel utilization and Improved outage scheduling by better predicting reactivity loss over a cycle;
  - Increased energy production by recovering thermal margin; and
  - Increased radioisotope production efficiency

Results and Accomplishments

In FY24, the following items are accomplished by ANL-Purdue team:

1. High Fidelity model development of PUR-1 reactor in MCNP6 and OpenMC 0.15.0
2. Validation of neutronics models using neutron flux measured in PUR-1 reactor
3. Theoretical Formulation and Sensor requirements assessment

Results and Accomplishments: High-fidelity model development

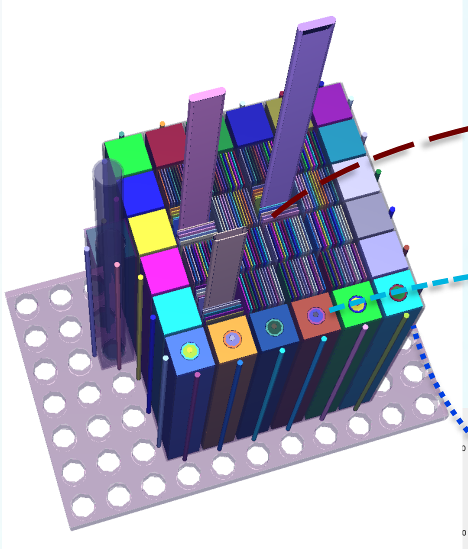
PUR-1 reactor models in MCNP6 and OpenMC 0.15.0

Key components:

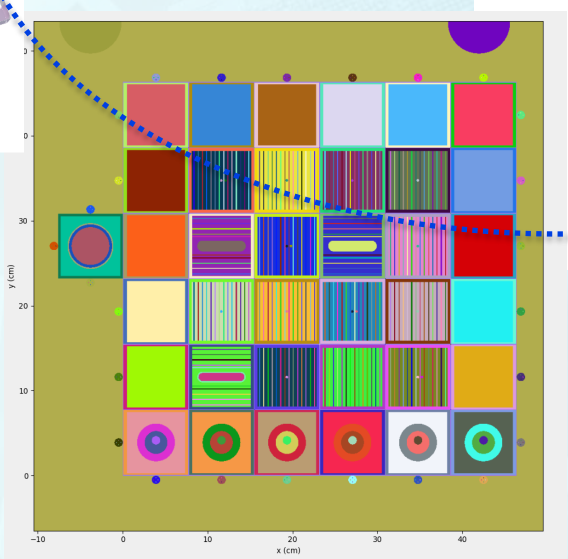
- 16 Fuel Assemblies (FAs) with 16 Dummy plates
- 3 Control Rods
- 20 Graphite Bricks constituting the core reflector with 6 irradiation ports

Virtual sensors:

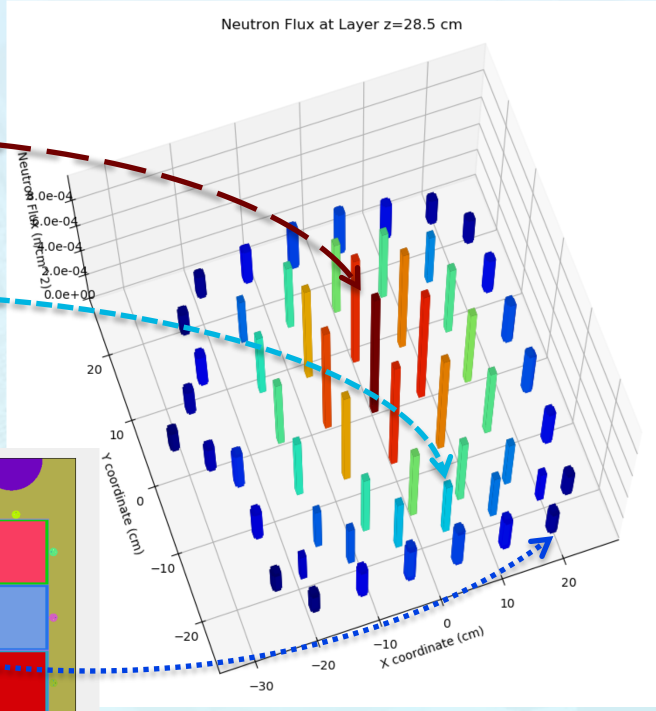
- 25 in-core sensors between FAs for neutron flux
- 16 in-core sensors on Dummy plates
- 26 out-core sensors for neutron flux and neutron current



PUR-1 core geometry in MCNP6.



PUR-1 OpenMC model.



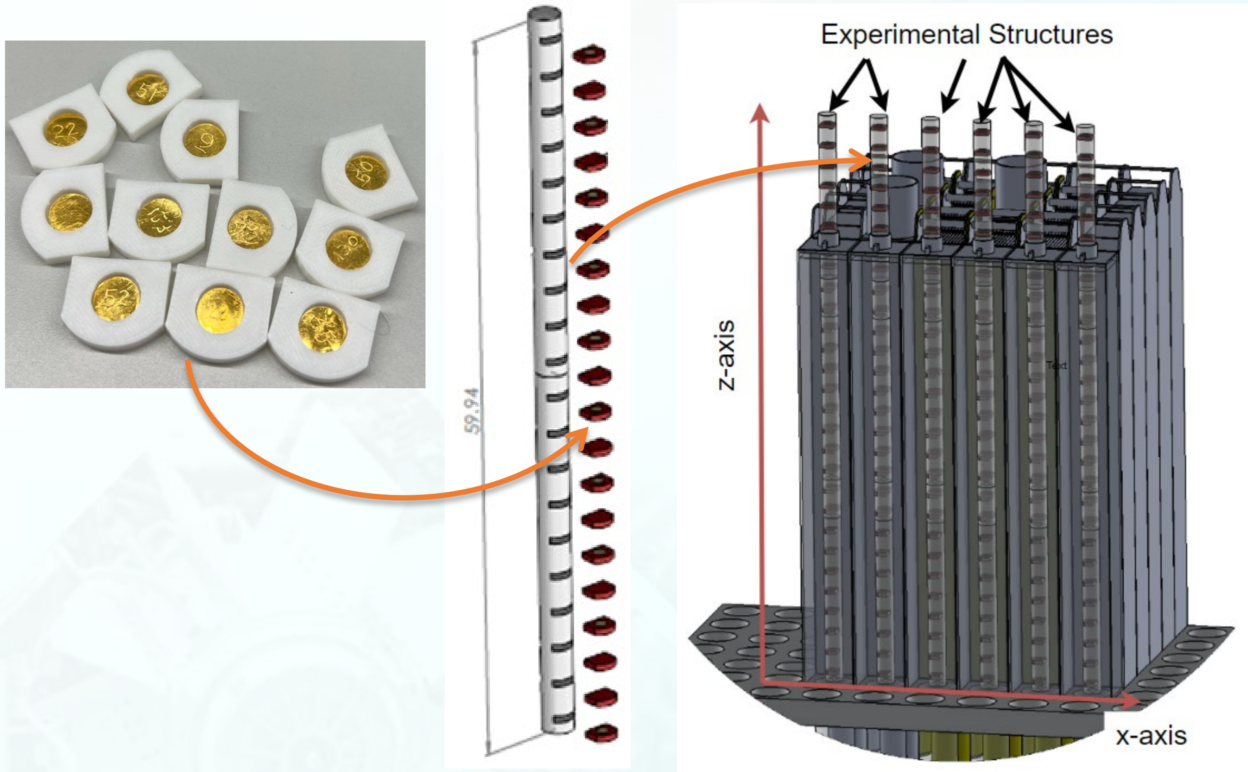
Simulated Neutron Flux Spatial Distribution.

Results and Accomplishments: Validation of neutronics models (1/3)

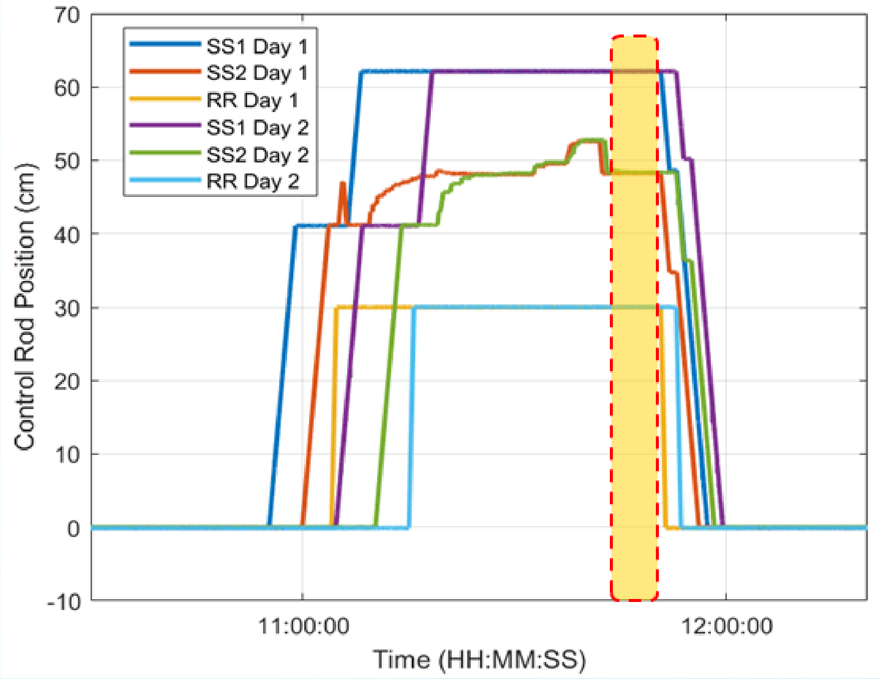
Neutron Activation Analysis (NAA) in PUR-1 core using Gold foils

$$^{197}Au + n \rightarrow {}^{198}Au + \gamma$$

- Experiment conducted in 2 days to collect measurements in all the Irradiation Ports



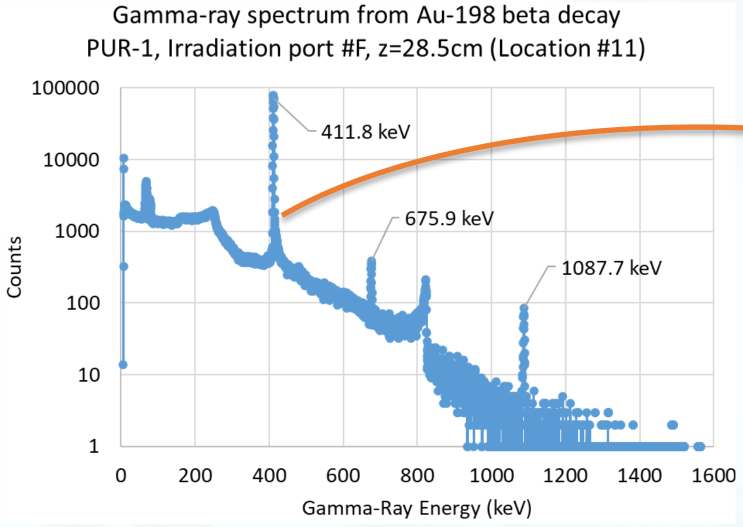
Experimental setup with 30 gold foils, sample positioner and Irradiation Ports in PUR-1 core.

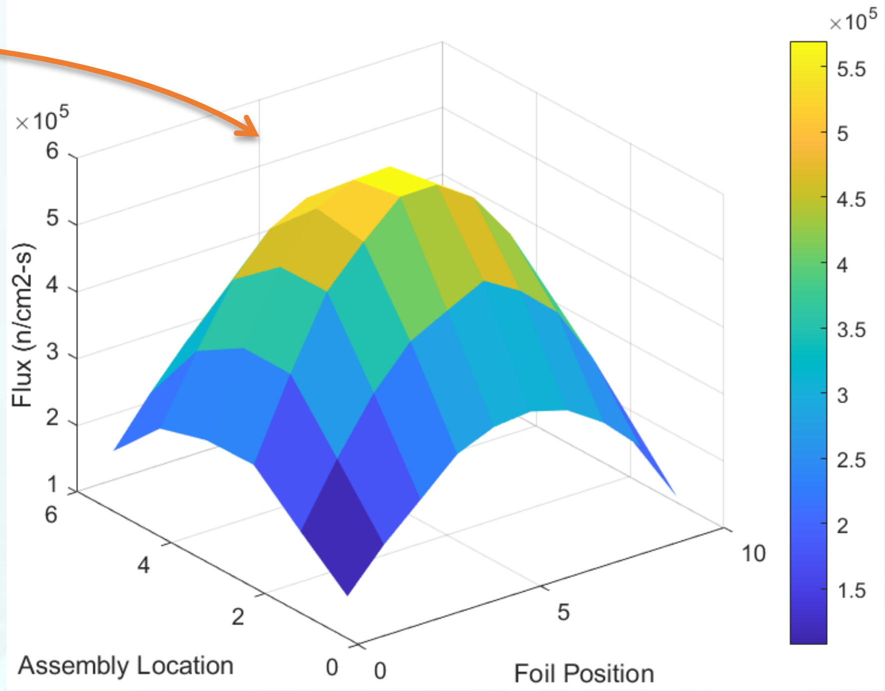


Control rod pattern during experimental campaign (at-power periods are highlighted).

Results and Accomplishments: Validation of neutronics models (2/3)

Neutron Activation Analysis (NAA) in PUR-1 core using Gold foils

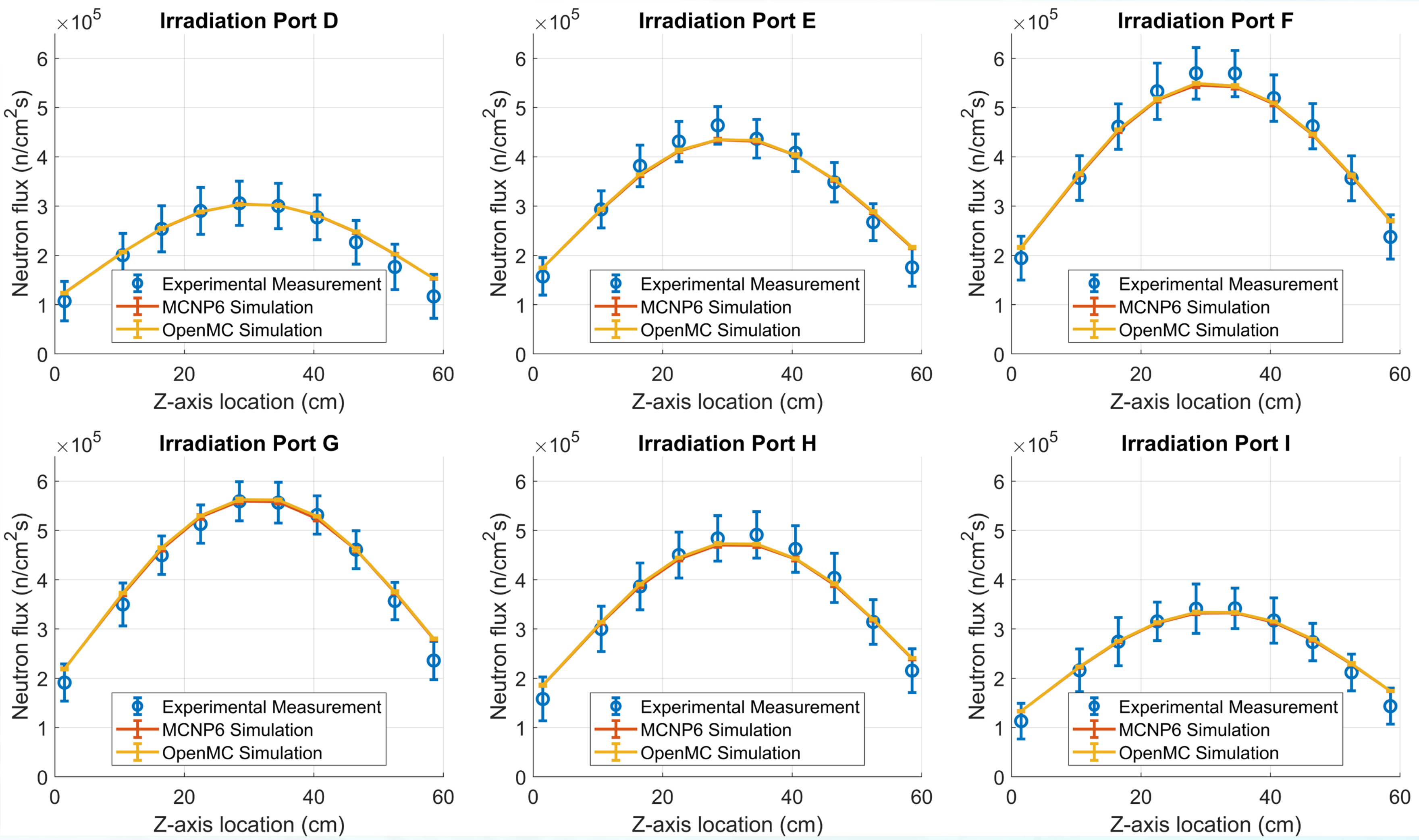




Distribution of neutron flux (10 axial positions, 6 irradiation ports) of PUR-1 reactor.

- Neutron flux evaluated in each location via:
  - Measuring the activity of Au-198 after neutron capture.
  - Corrected by the reactor power, irradiation time, decay time before measurement, and sample mass.

Results and Accomplishments: Validation of neutronics models (3/3)



- Spatial distribution of neutron flux from MCNP6 and OpenMC simulation is validated by NAA results.
- Results from two simulation frameworks agree with the experimental measurement within 1 error bar.

Comparison between simulation results and collected neutron flux measurements in PUR-1 core

Results and Accomplishments: Problem setting (1/2)

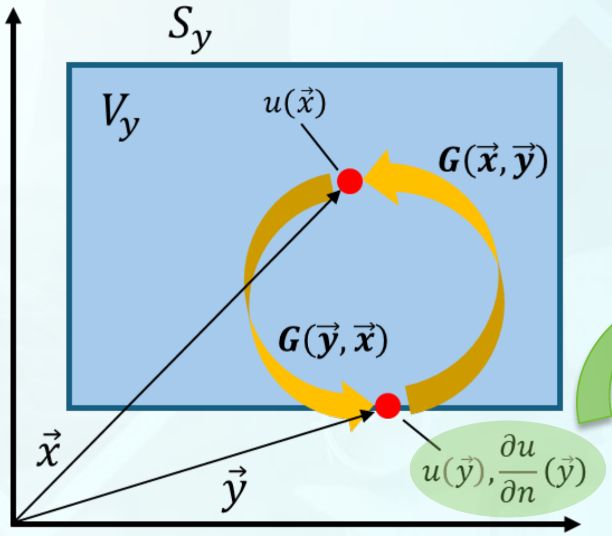
Theoretical formulation: Kirchhoff-Helmholtz (K-H) Integral Equation

Developed for acoustics applications, it could be used for neutron field reconstruction

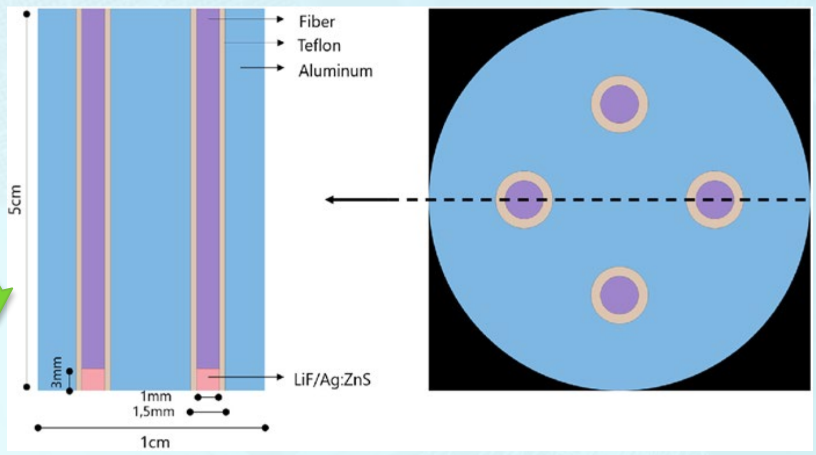
$$\underbrace{u(\vec{x})}_{\text{Field value}} = \int_{S_y} \underbrace{G(\vec{x},\vec{y})\frac{\partial u}{\partial n}(\vec{y})}_{\text{Neumann BC}}\, dS_y - \int_{S_y} \underbrace{u(\vec{y})\frac{\partial G(\vec{x},\vec{y})}{\partial n}}_{\text{Dirichlet BC}}\, dS_y + \int_{V_y} \underbrace{Q(\vec{y})G(\vec{x},\vec{y})}_{\text{Source term}}\, dV_y$$

$$\begin{cases} u(\vec{y}) \longrightarrow \phi(\vec{y}) \\ \dfrac{\partial u}{\partial n}(\vec{y}) \longrightarrow \nabla\phi(\vec{y})\cdot\vec{n} \\ Q(\vec{y}) \longrightarrow \text{CR position} \end{cases}$$

- Green's function is the **key ingredient** for reconstructing neutron flux distribution (derived from **high-fidelity simulations**).
- Dedicated sensor measuring **neutron current** is necessary (consultation with ORNL experts).



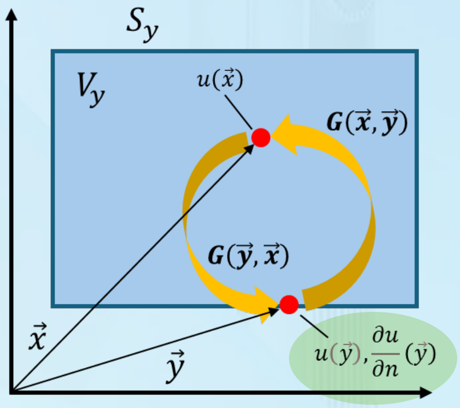
Green's function concept and K-H equation input data

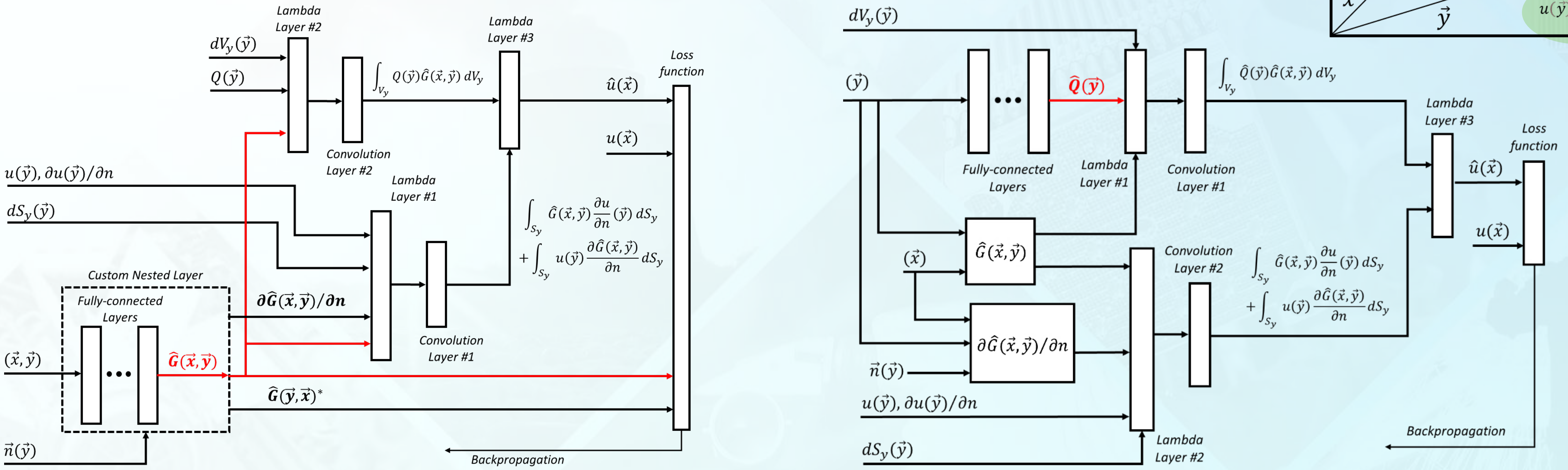


M. Aldbissi et al., "Conceptual design and initial evaluation of a neutron flux gradient detector", NIM-A, 1026 (2022).

Results and Accomplishments: Problem setting (2/2)

- However, analytical solution of Green’s function may not exist for complicated geometry.
- The good news is, Green’s function can be represented by the parameters in CNN.
- With Green Function as the core of physics-informed machine learning, we don’t need to interpolate within huge data set. It allows saving the computational burden and avoid the risks of extrapolation.





Configuration of the proposed CNNs during (Left) training and (Right) testing. Green’s function and Source spatial distribution are defined by the weights/biases of the corresponding sets of “Fully-connected Layers” (outlined in red).

Concluding Remarks

In FY24, the following items are accomplished by ANL-Purdue team:

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In FY25, ANL-Purdue team will focus on:

1. Reconstruction algorithm development
   a) Start with the development of Diffusion-based algorithm, and apply it to a 2D test case;
   b) If the result is promising, we will improve it with Transport-based algorithm.
2. Further experimental validation of the neutronics model.

Concluding Remarks

Planned Presentations and Publications:

- "High-fidelity neutronic modeling for PUR-1 reactor with experimental validation", Digital Engineering Conference 2025, Idaho Falls, ID, May 20-21, 2025
- "A data-driven approach to core power distribution reconstruction in a nuclear reactor", 14th International Topical Meeting on Nuclear Plant Instrumentation, Control & Human-Machine Interface Technologies (NPIC&HMIT 2025), Chicago, IL, June 15-18, 2025

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Thank You