Modelling neutron noise experiments from the second experimental campaign at the AKR-2 reactor

IMORN-31

11-9-2024

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Contents

Motivation

The CORTEX project was originally of interest as a platform to gain experience with 3D neutron kinetics and noise simulation.

NRG participated in the project as part of the End-User Group, allowing us access to the benchmarks developed within the project .

Use experimental benchmarks to determine if our existing operational support tools can:

- Model the response of transient changes in the core at the (ex-core) detectors
- Be used to determine sources of noise

In the past, unexpected (noisy?) behavior has been observed in the nuclear channels at the High Flux Reactor (HFR), and the physics team were involved in trying to determine the possible cause.

We would like to be better prepared for these types of questions in the future.

Current team:

- 2 people from Reactor Analysis and Operational Support Group

- 2 people from HFR Physics (Nuclear Operations)

The OSCAR-5 Platform

Developed at NECSA (South Africa)

Used as operational support tool at a number of research reactors (SAFARI-1, HFR, HOR, MNR).

Latest version includes two major components:

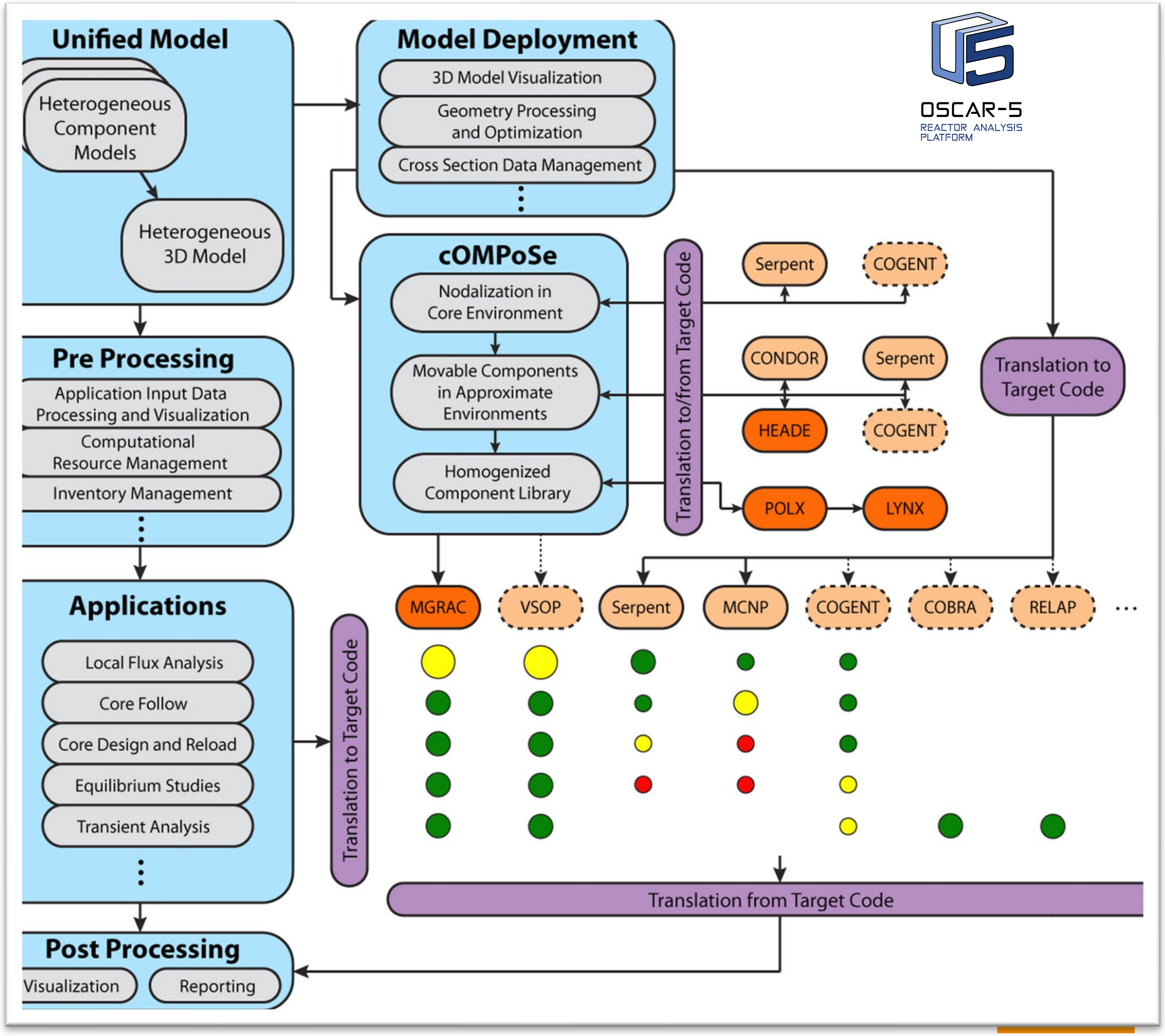
1. Nodal diffusion package: MGRAC (Multi Group Analytic Nodal Method).
2. Python based pre- and post processing tool RAPYDS.

Latest version of MGRAC incorporates 3D spatial kinetics

The RAPYDS platform provides connections to other codes:

- Monte Carlo N-Particle (MCNP)
- Serpent (VTT-Tech)

RAPYDS is used to prepare cross sections for MGRAC and to create the custom application modes used to calculate the detector response functions.



AKR-2 Experiments

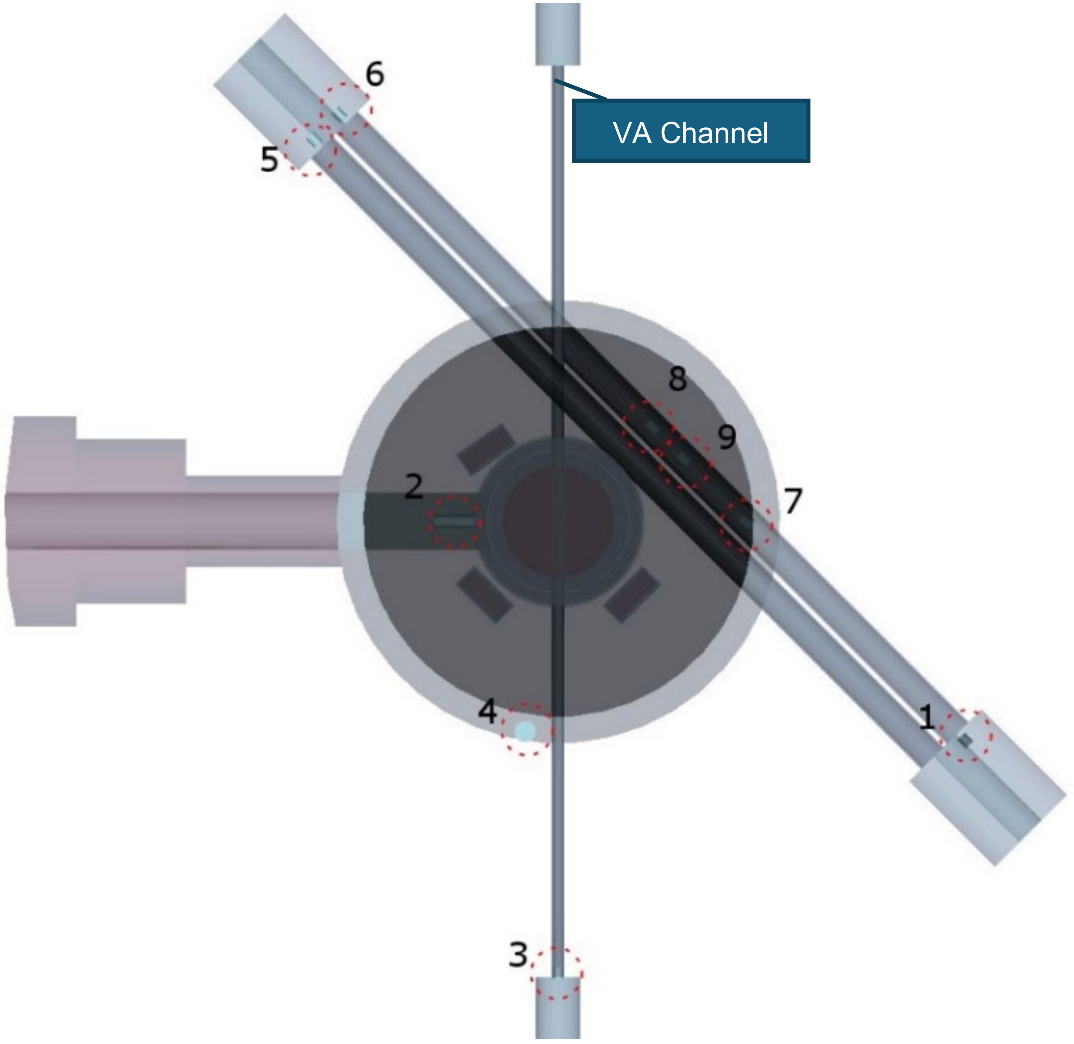
AKR-2 is a thermal zero-power experimental facility at the TU Dresden:

- Homogeneous uranium-oxide, polyethylene core
- Graphite reflector

Reactor characteristics obtained from the MCNP model (with the permission of TU Dresden).

Use the detector configuration of the second experimental campaign.[1]

Consider experiments in which only the Variable Absorber (VA) was perturbed.



[1] V. Lamirand, F. Vitullo and O. Pakari, "Experimental report of the 2nd campaign at AKR-2 and CROCUS", EPFL Report D2.2, 2020

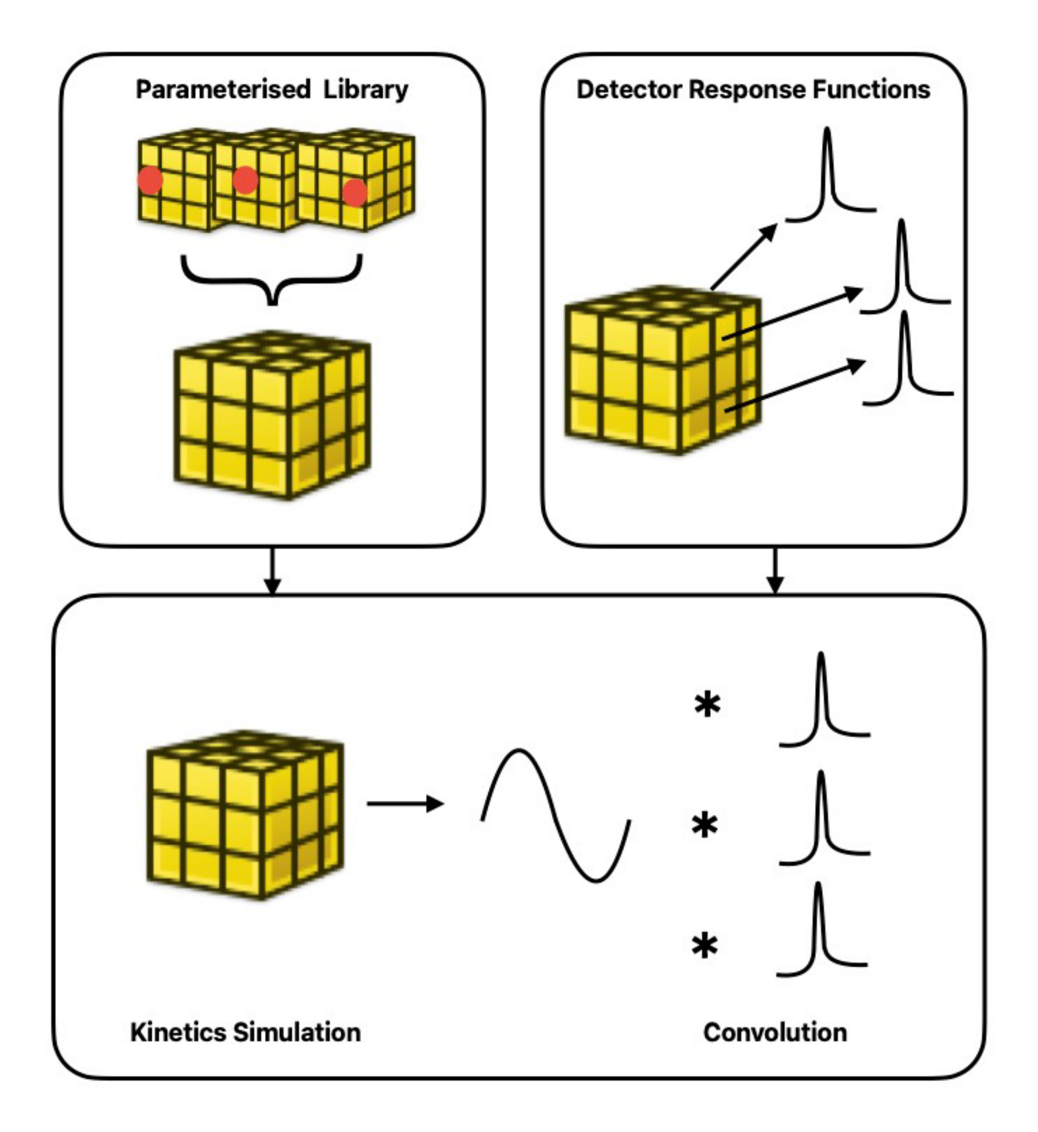
Modelling Approach

Kinetics simulation performed with the nodal diffusion solver is restricted to the core region (fuel with reflector)

Perturbation is modelled using a parametrized library

For each facet (and energy group) on the boundary of the nodal mesh, a detector response function for each detector is pre calculated (using MCNP)

Detector response during transient is then the convolution of the pre-computed response functions and the time dependent leakage produced by the nodal diffusion solver



Detector Response in Time and Frequency Domain

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For each detector *d*, a suitable response function $R_{fg}^{d}(t)$ is computed, which captures the effect that one neutron leaving the facet *f* and with energy in group *g* at time 0 would have on the detector at time *t.*

Let $C_{fg}(t)$ denote the time dependent outwards current for each sub-facet *f* and energy group *g.*

The final time dependent response on the detector is

$$R^{d}(t) = \sum_{f} \sum_{g} A_{f} \int_{0}^{t} dt' C_{fg}(t') R_{fg}^{d}(t - t'),$$

where A_f is the area of facet *f.*

In the frequency domain, we can use the convolution theorem to obtain the expression:

$$\widehat{R^{d}}(\omega) = \int dt R^{d}(t) e^{-i2\pi\omega t} = \sum_{f} \sum_{g} A_{f} \widehat{C_{fg}}(\omega) \cdot \widehat{R_{fg}^{d}}(\omega) .$$

Preparing the Nodal Diffusion Model

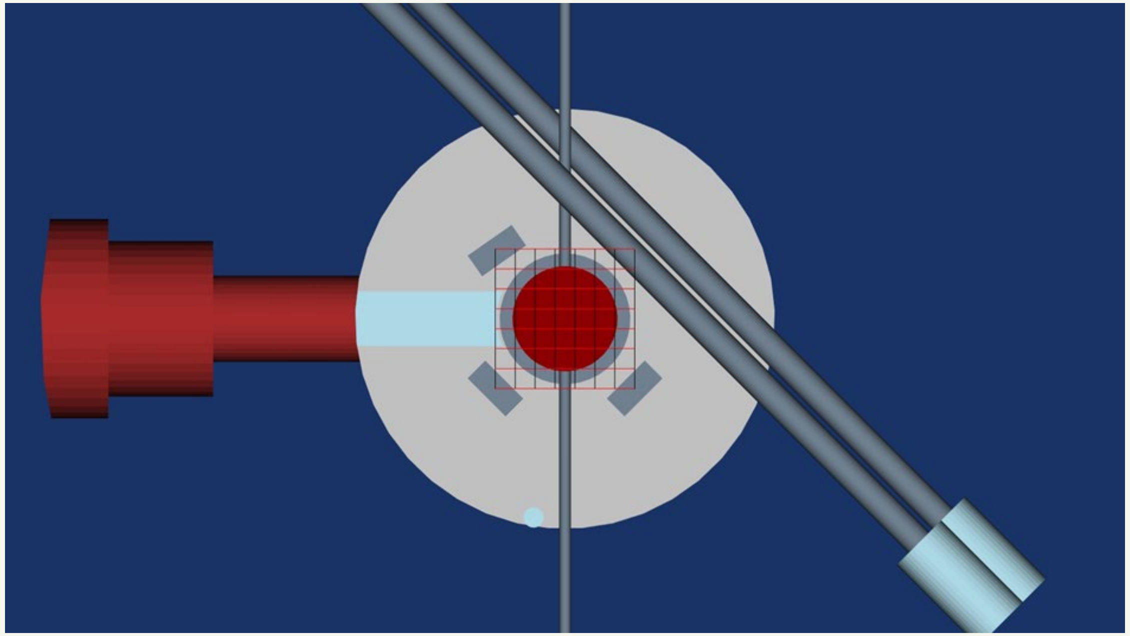
Diffusion model contains a (coarse) 7x7 radial mesh and 8 axial material zones. Energy was condensed to a seven groups.

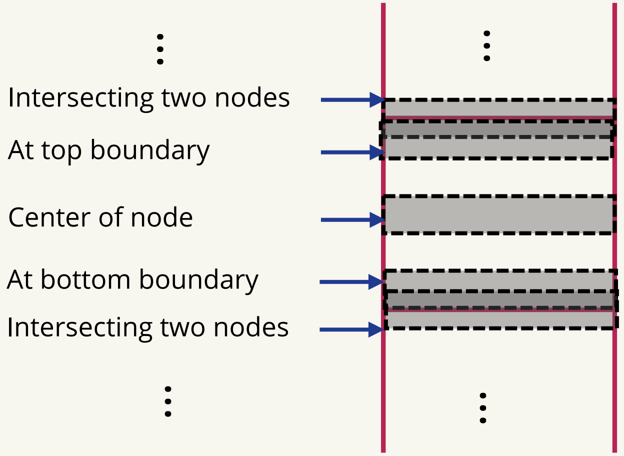
Group constants and radial discontinuity factors were calculated using Serpent.

Albedo boundary conditions were also calculated for the radial plane.

In the axial region which contains the VA absorber, a parametrized set of cross sections were made, with the absorber at different positions.

Group	Lower Bound (MeV)	Upper Bound (MeV)
1	8.208E-01	2.000E+01
2	5.531E-03	8.208E-01
3	4.000E-06	5.531E-03
4	6.250E-07	4.000E-06
5	2.480E-07	6.250E-07
6	5.800E-08	2.480E-07
7	1.000E-11	5.800E-08





Validation of Reactivity Effect

The tabulated cross sections were mapped to a state parameter so that it can be easily perturbed during static and transient simulations in MGRAC.

Check that the tabulated cross sections produce the correct reactivity effect when the absorber is moved:

Position w.r.t reactor center (cm)	Amplitude around position (cm)	Measured (cents)	MGRAC (cents)
5.5	±3	3.35 (±0.05)	3.28
4.5	±1	1.10 (±0.05)	0.91

Reactivity effect is captured reasonably well (but underestimated, especially for small perturbations)

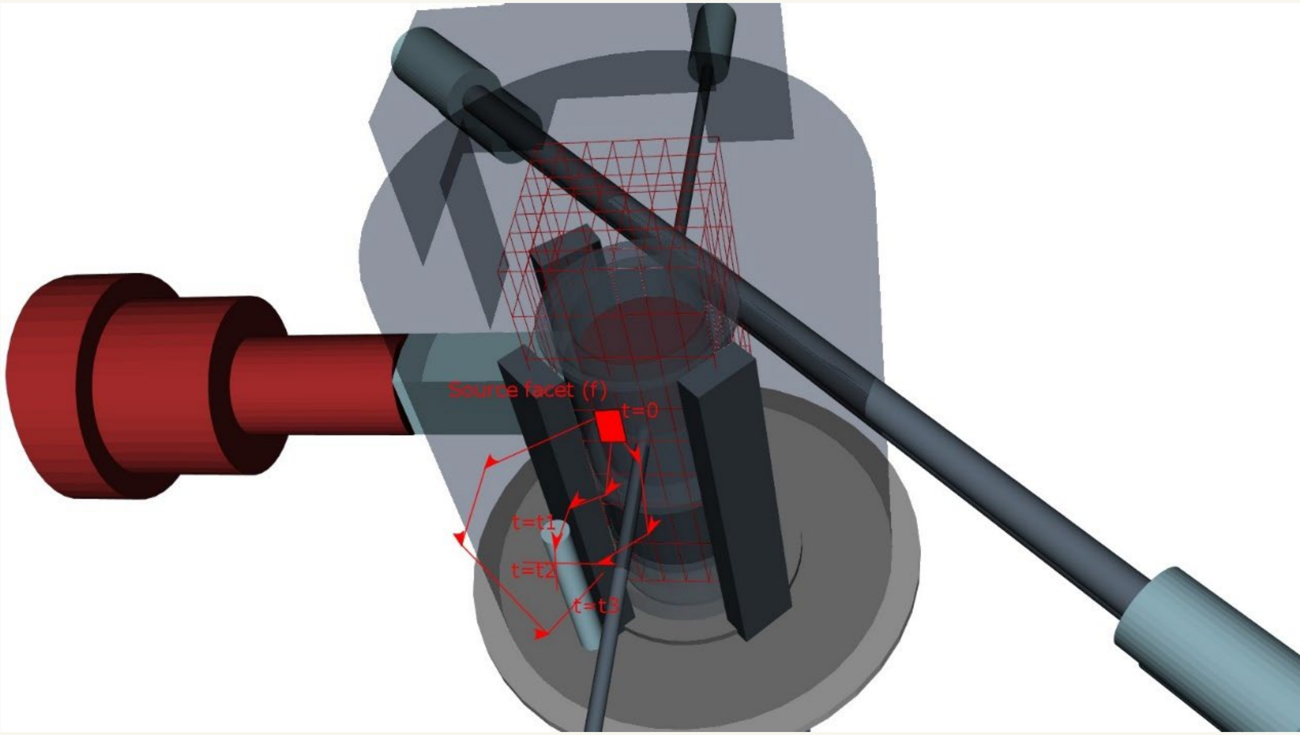
Calculation of Response Functions (1)

For each detector *d*, estimate a response function $R^{d}_{fg}(t)$, which captures the effect that one neutron leaving the facet *f* and with energy in group *g* at time 0 would have on detector *d* at time *t.*

Use (multiple) MCNP calculations, with suitable source and detector definitions.

A time bin structure is used at the detector to represent the time dependence.

Three different approaches were identified and tested for the source definition



Calculation of Response Functions (2)

1. Direct fixed source calculations:
    - Uniform surface source over the facet area (standard SDEF card)
    - Isotropic angular distribution on the facet is assumed
2. Adjoint Fixed source calculations:
    - Detector regions now act as source
    - Values at facets are detected using a meshed tally
3. Explicit surface source:
    - Calculate explicit surface source (WSSA) in MCNP from KCODE calculation
    - Response calculations are then performed using this explicit source
    - Use detector flagging option to determine from which facet a scoring particle originated
    - Weights must be normalized for each facet and energy group (requires processing of the WSSA file)

Advantages and Disadvantages

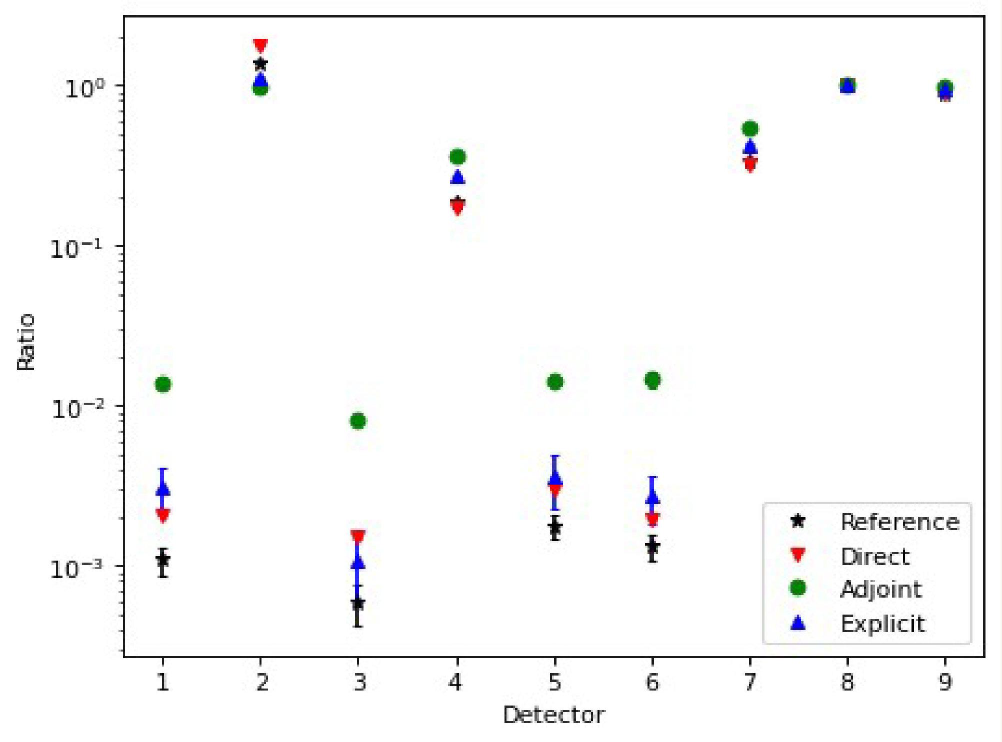
Method	Advantages	Disadvantages	Minimum number of MCNP calculations required
Direct Source	Easy to implement with existing tools. For a given facet and group, all detector responses can be calculated in a single run. Efficient sampling of the source	Isotropic source is assumed. Large energy range to sample from at the source. Poor convergence at certain detectors (depending upon the source region being considered). A large number of fixed source simulations are required!	Number of facets X number of groups
Adjoint Source	Fairly easy to implement with existing tools. For a given detector, the response function for all facets and groups can be calculated in a single run. Improved statistics.	Isotropic source is assumed. A multi-group approximation is required. Use of an overlay volume mesh can cause contributions to be double counted, and also produces large tally files containing mainly zeros.	One for each detector
Explicit Source	Angular distribution of the surface source is explicitly taken into consideration. Energy distribution of source is also better represented.	Low resolution of the source per surface segment. Complicated to implement using existing tools (uses advanced MCNP tally features, requires access to and editing of the binary particle source files). Poor statistics on the detector responses functions.	One for each energy group

Verification of Response Functions

Check the response functions in equilibrium setting.

Null transient was run in MGRAC (no perturbation) and flux at detector was calculated using the convolution with detector response functions.

Compared to reference flux at detector values computed using a MCNP KCODE calculation.

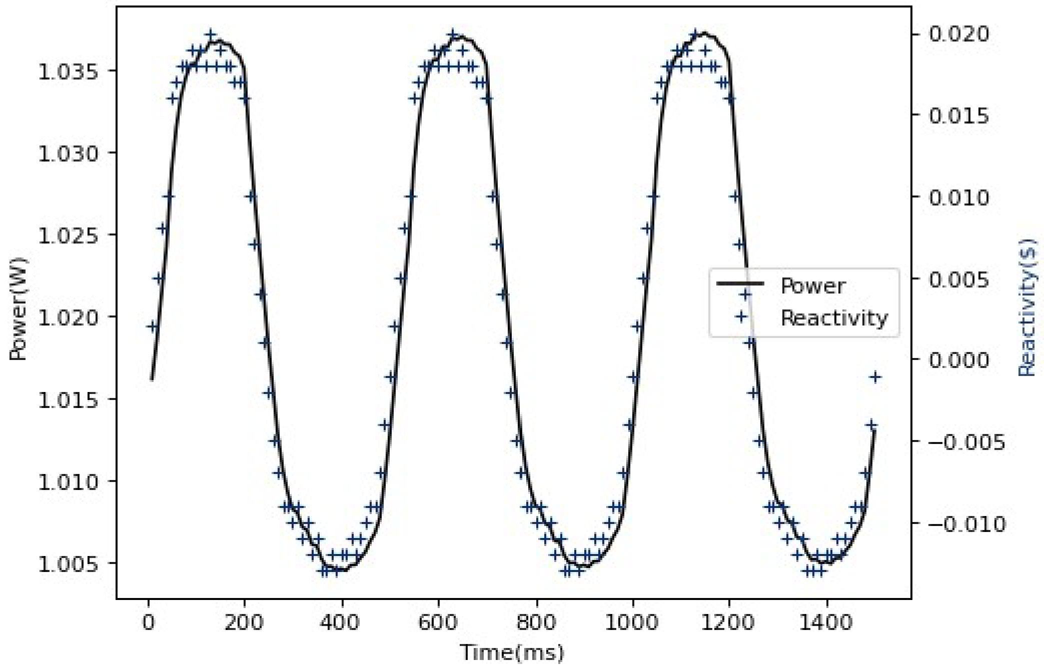


Comparison of detector ratios relative to detector 8

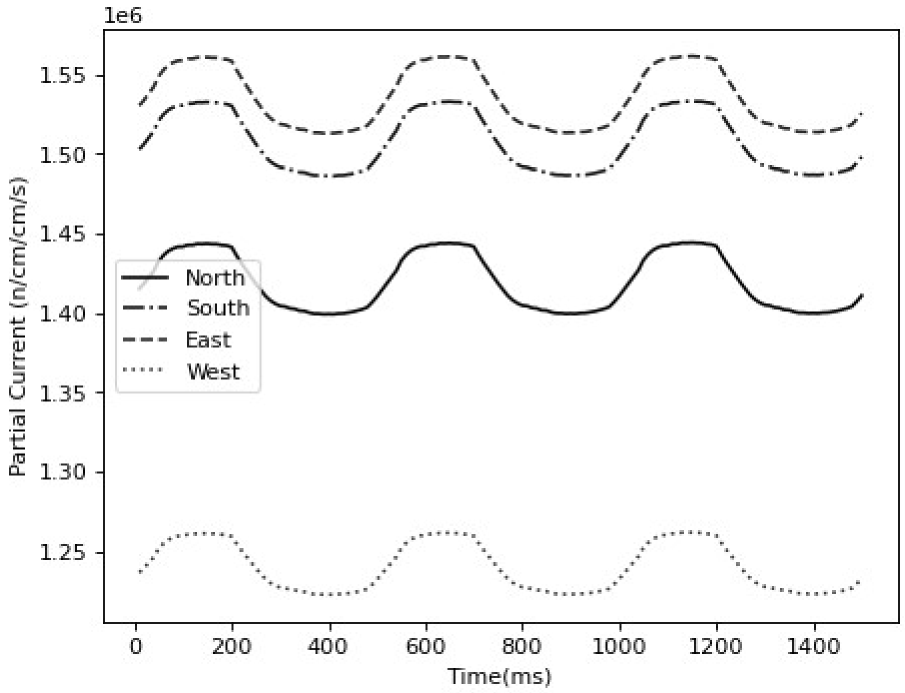
Results: Transient Simulation

Experiment 20 (perturbation of VA absorber only):

Parameter	Value	Unit
Frequency	2	Hz
Amplitude	3	cm
Center (relative to core center)	5.5	cm



Total power and reactivity during transient



Partial current through the central facet in the thermal energy group

Detector Responses: Amplitudes and Phases

Relative noise:

$$N^d(t) = \frac{R^d(t) - R^d(0)}{R^d(0)}$$

In frequency domain:

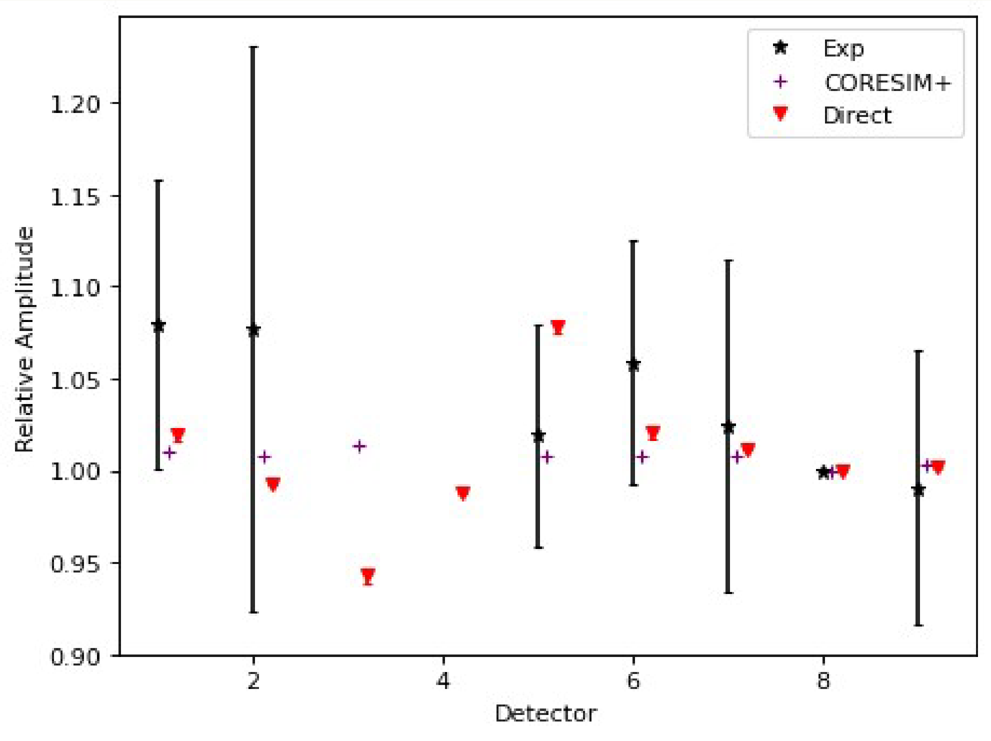
$$\widehat{N^d}(\omega) = \frac{\widehat{R^d}(\omega)}{R^d(0)}$$

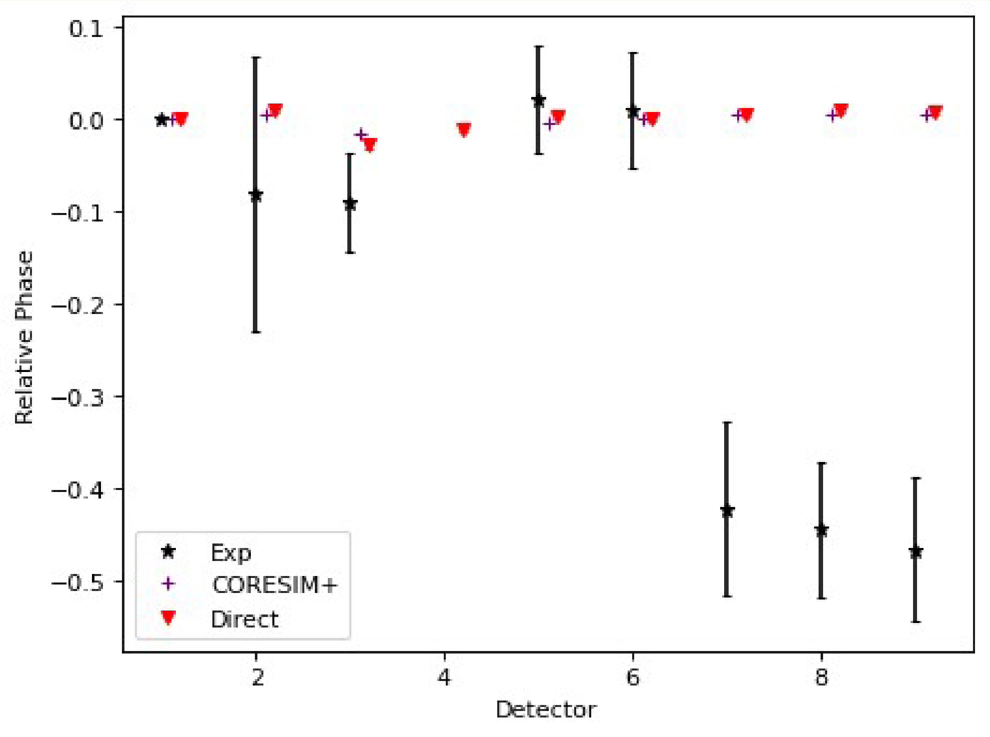
Setting $\widehat{N^d}(2) = a_d + ib_d$, the frequency amplitude α_d, and phase ϕ_d, for each detector *d* are defined as:

$$\alpha_d = \sqrt{a_d^2 + b_d^2} \qquad \phi_d = \text{atan}(b_d/a_d)$$

Detector Responses: Direct Source RF

Relative (to detector 8) amplitudes and phases. Published results from CORE SIM+ is also shown.



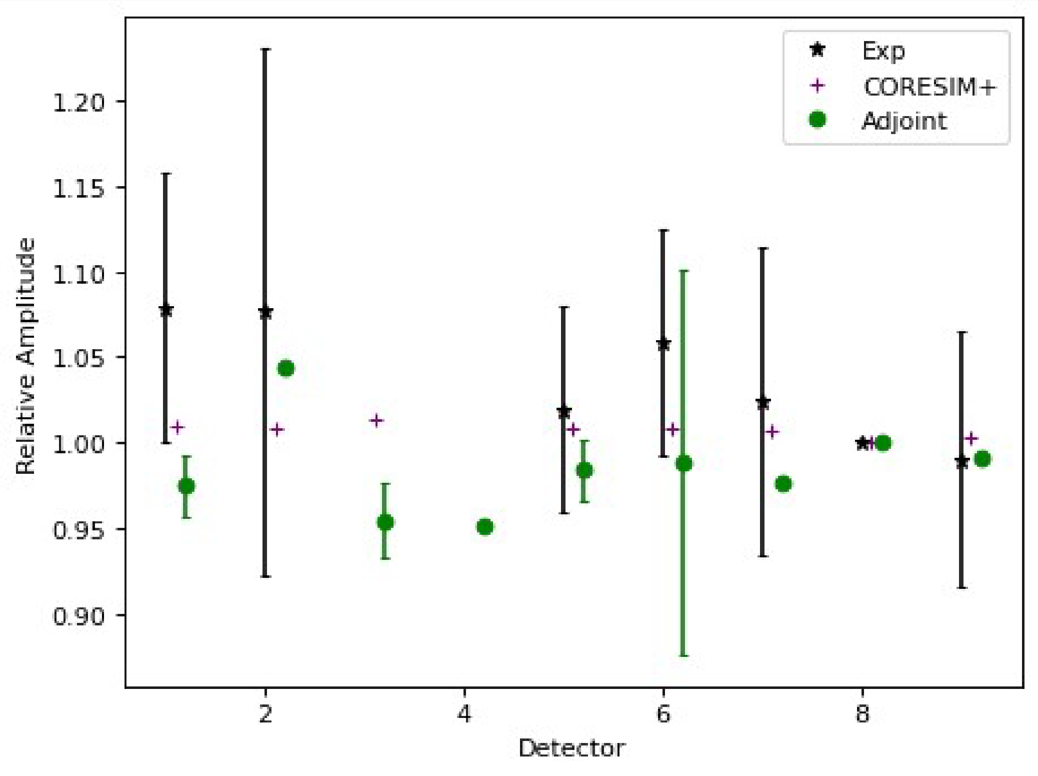


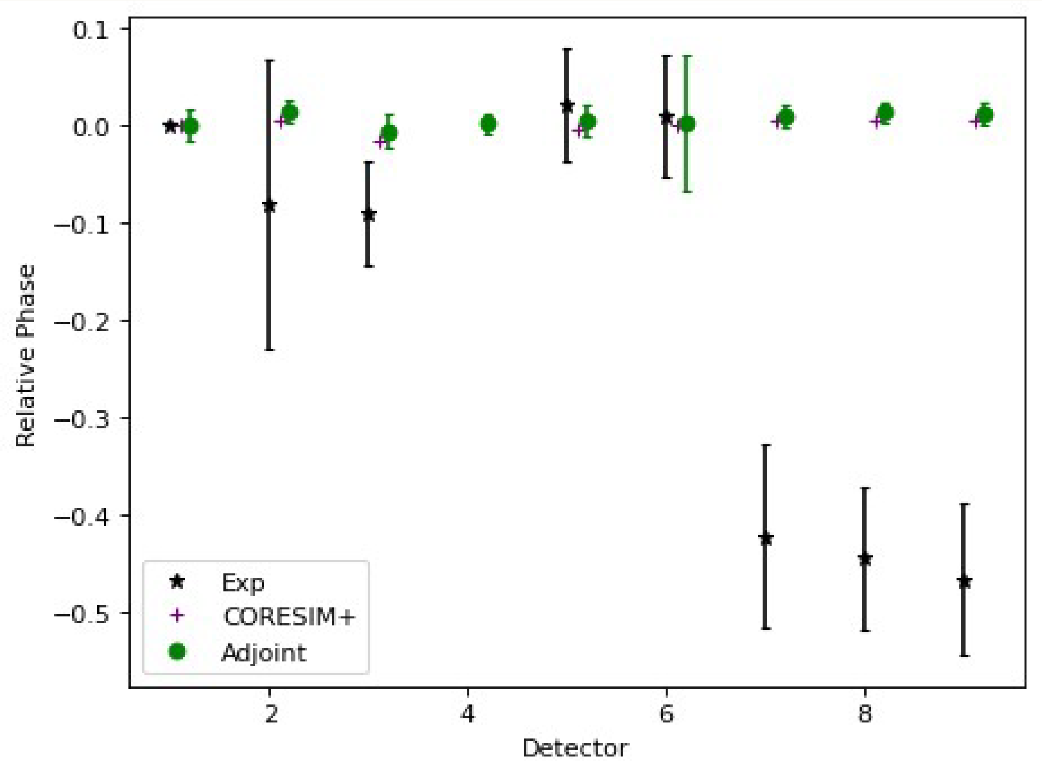
Measured amplitude ratio at detector was 3 (not shown)

Detector 4 was not uses

Detector Responses: Adjoint Source RF

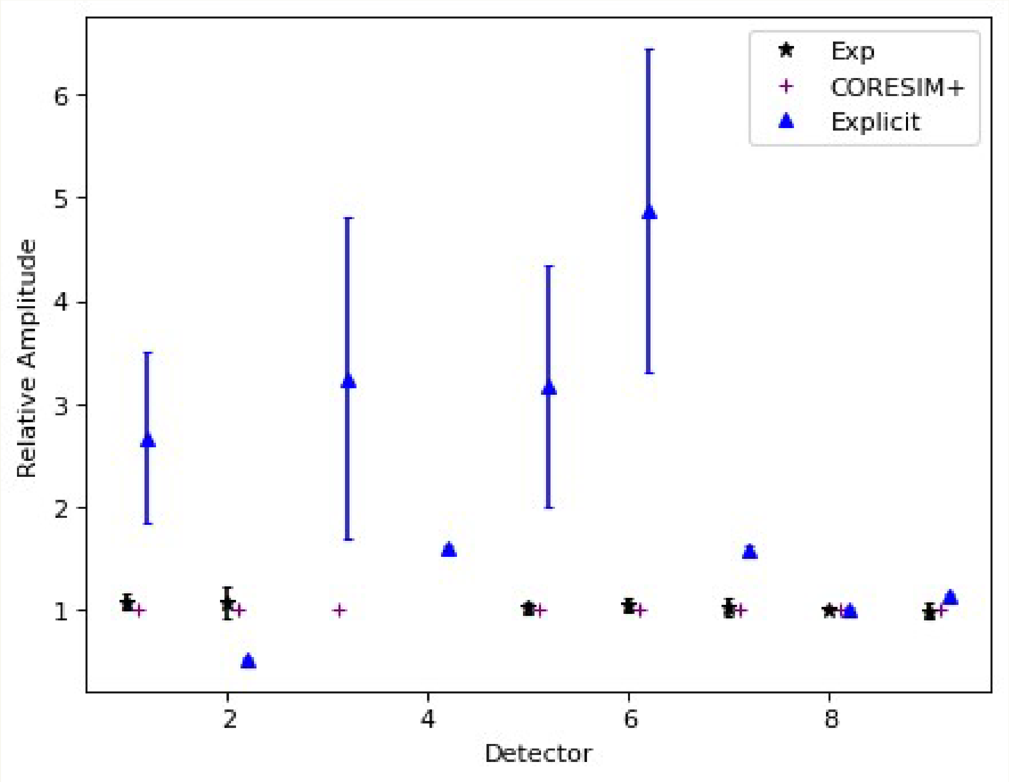
Relative (to detector 8) amplitudes and phases

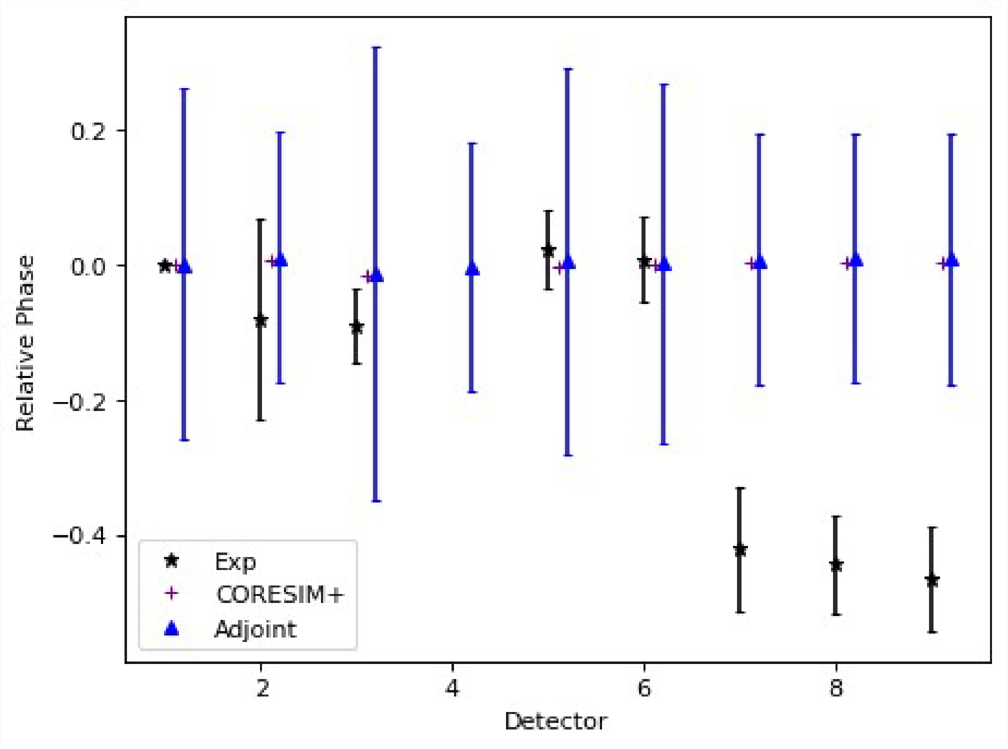




Detector Responses: Explicit Source RF

Relative (to detector 8) amplitudes and phases





Uncertainty on response functions too high!

Future Work

- Continue to look at other benchmark problems developed in the CORTEX project:
  - COLIBRI oscillation experiment performed in the CROCUS reactor

- Possible improvements to the current modelling of detector responses:
  - Use partial currents from the nodal diffusion code closer to the fueled region?
  - Take detector active material into consideration.
  - Improve the estimation of the time dependent shape function:
    - What is the optimal binning structure?
    - Avoid binning altogether by extracting dumping events (using PTRAC option) and creating a regression (e.g. polynomial) fit offline.
    - OR just use these track events to estimate the Fourier transform directly.

Thank you!

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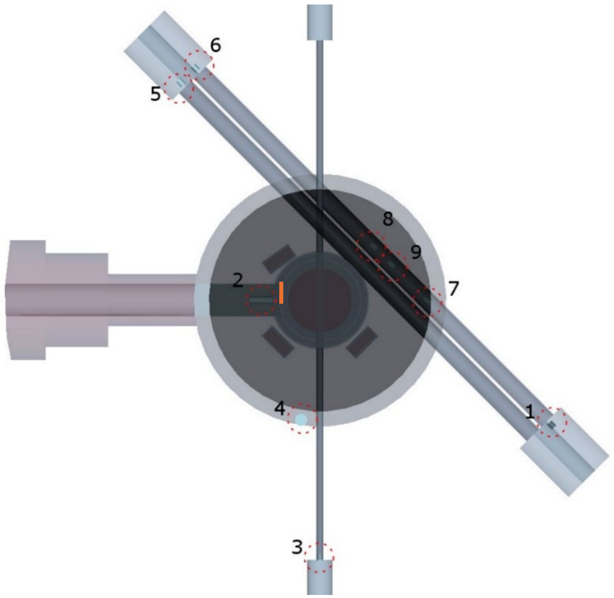
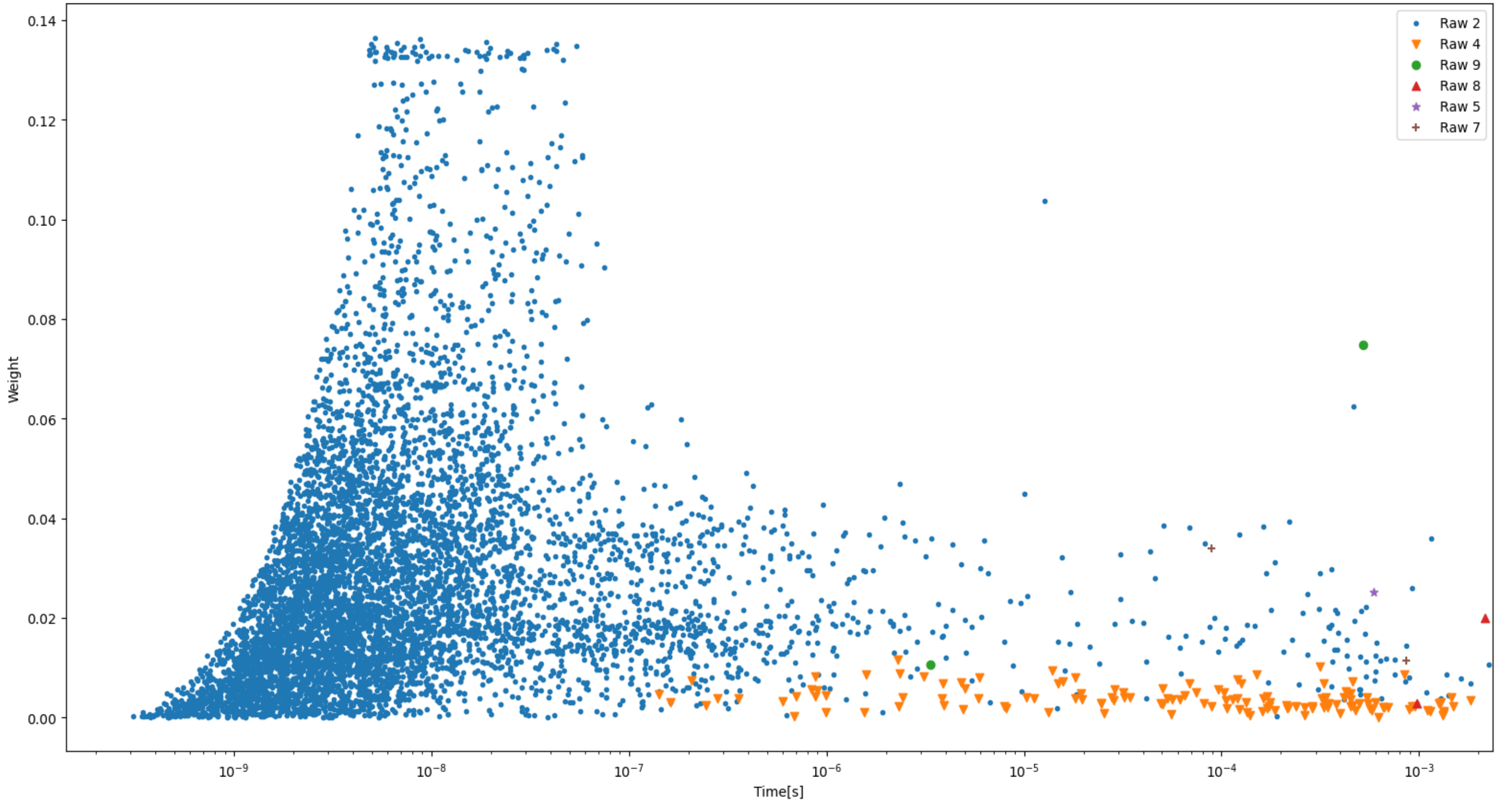
Time Distribution at Detector (1)





Time Distribution at Detector (2)