CORTEX

Core monitoring techniques and experimental validation and demonstration

Overview of the validation exercises undertaken in CORTEX

Final workshop, June 20th, 2021

M. Hursin (EPFL) on behalf of all partners involved in WP2

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Outline

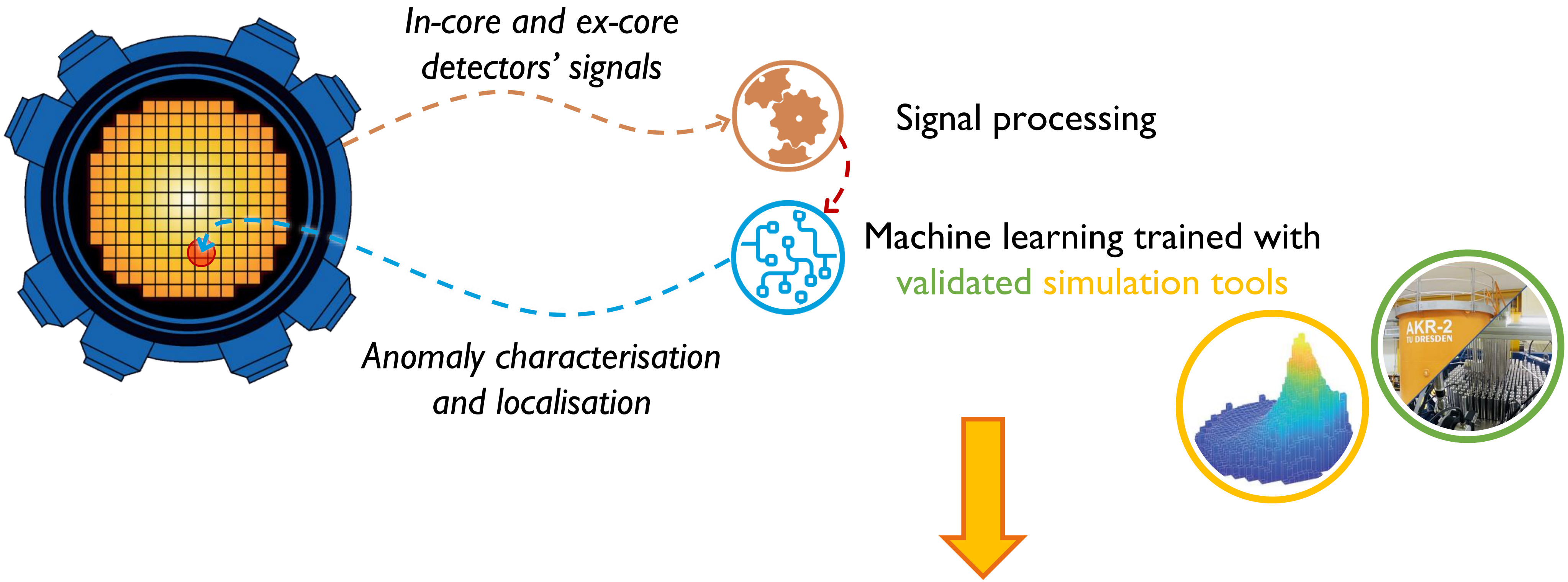
- Noise simulator validation activities within CORTEX (WP2)
  - Interactions between Experimentalists and Modelers
  - “Validation” of a code in the framework of CORTEX
  - Quantities of Interest

- Generation of high quality experimental data at CROCUS and AKR-2
  - Overview of the facilities
  - Processing the time series to produce the QoI
  - Development of fiber based detectors

- Modeling the beasts
  - Overview of the computational models for AKR-2 and CROCUS
  - A word on uncertainty quantification

- A selection of results from the “validation” exercises

CORTEX in a picture

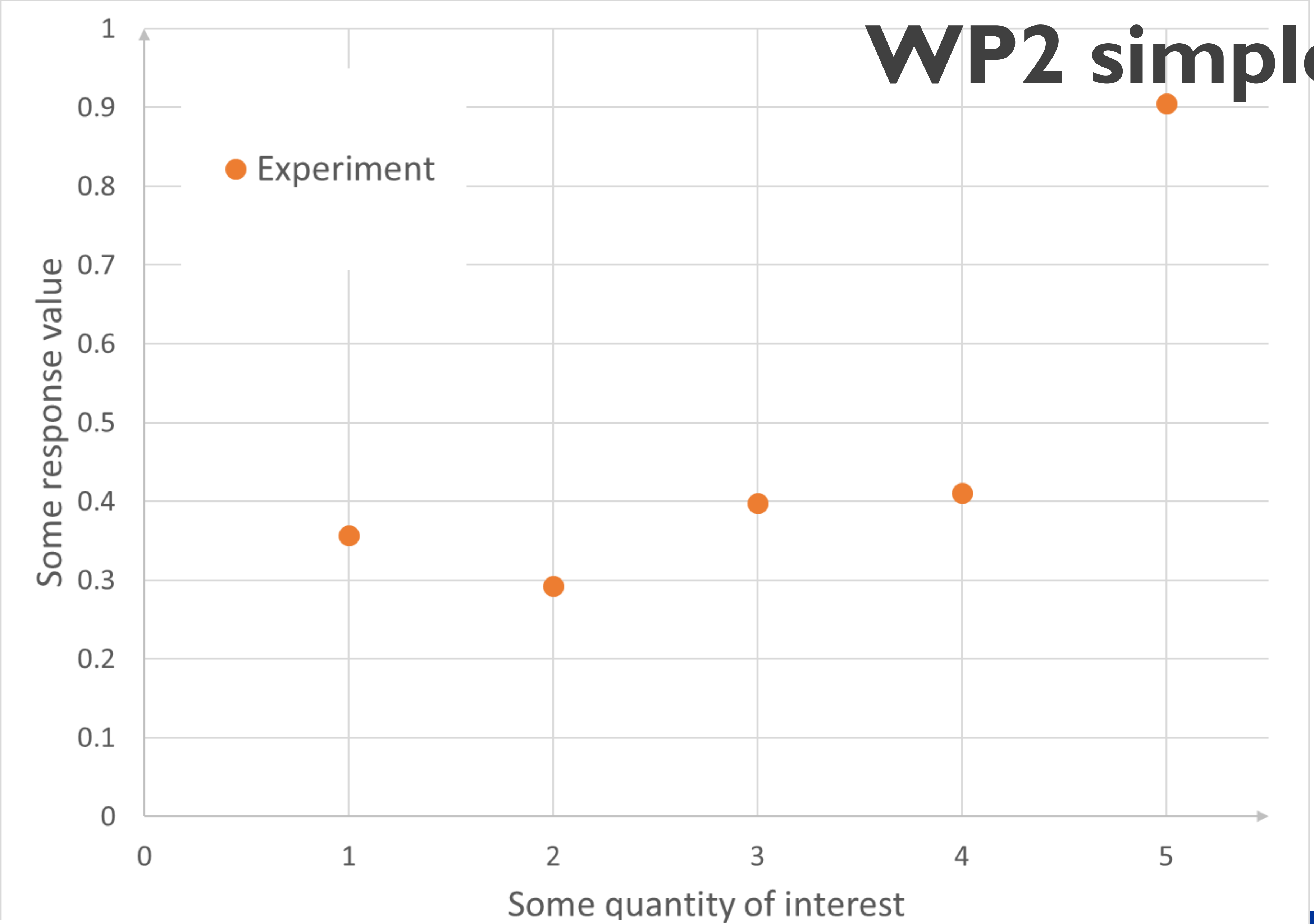


Work package 2 task

WP2 simple life

The data shown in the next few slides is NOT the data produced by measurements and models within CORTEX

WP2 simple life

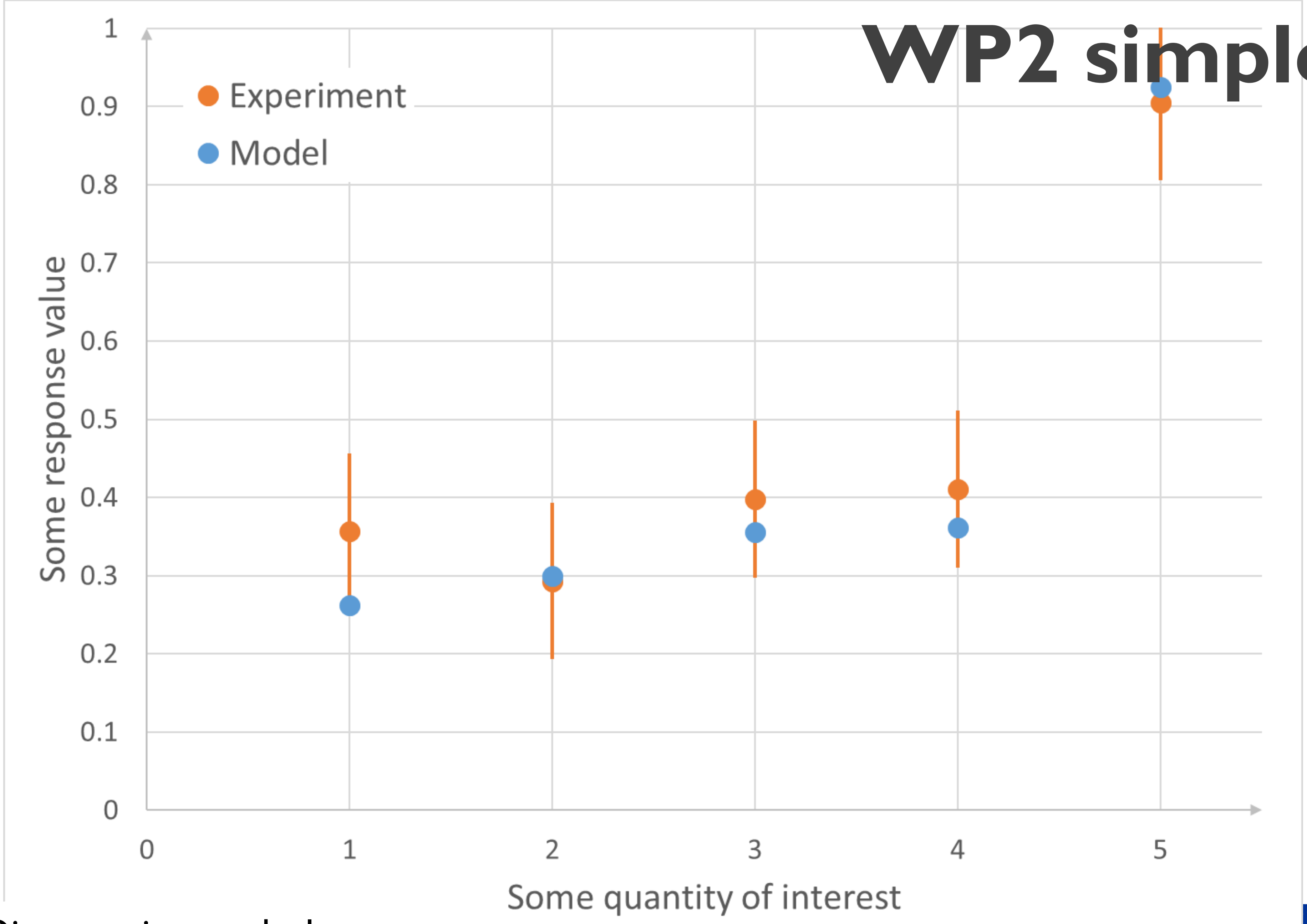


Early in the project according to the Gantt Diagram

WP2 simple life

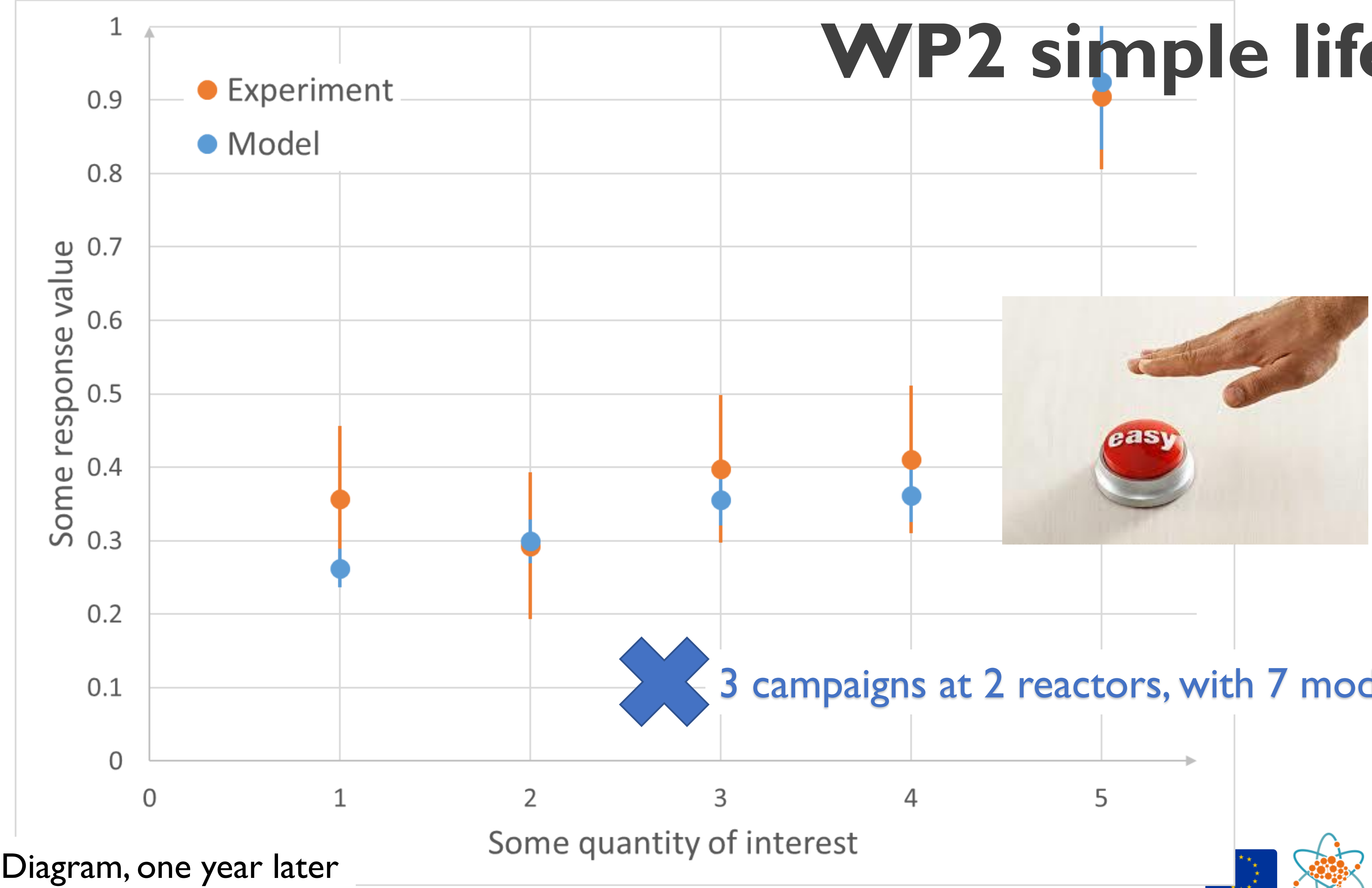
Gantt Diagram, one month later

WP2 simple life



Gantt Diagram, six months later

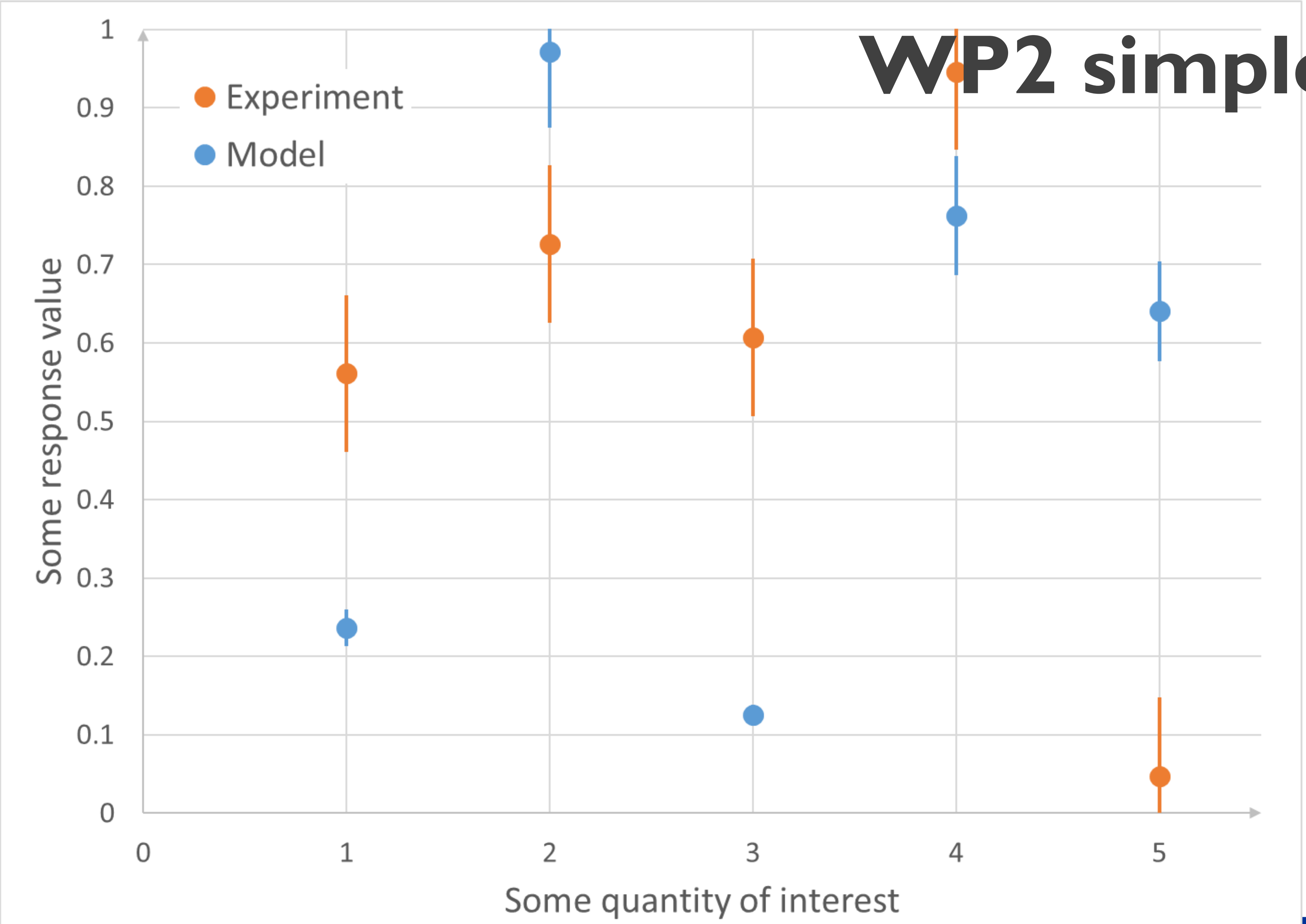
WP2 simple life



3 campaigns at 2 reactors, with 7 models

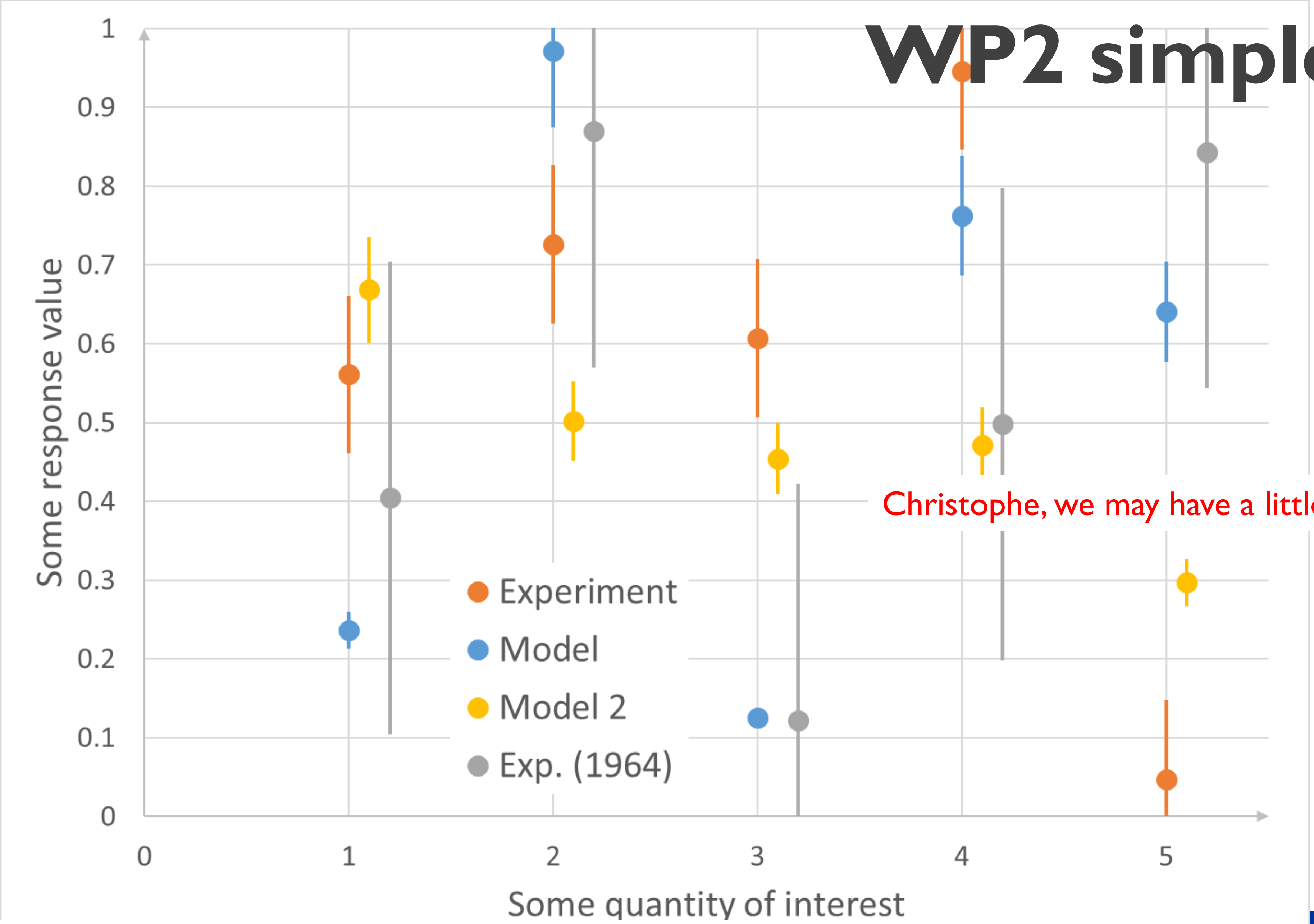
Gantt Diagram, one year later

WP2 simple life



What you see, one week before the workshop …

WP2 simple life



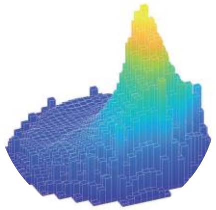
Christophe, we may have a little problem…

What you see, one week before the workshop …

Validation of Noise Simulators

Computer Code System

- Input Data
- Calculation (C)
- Uncertainty σ(C)



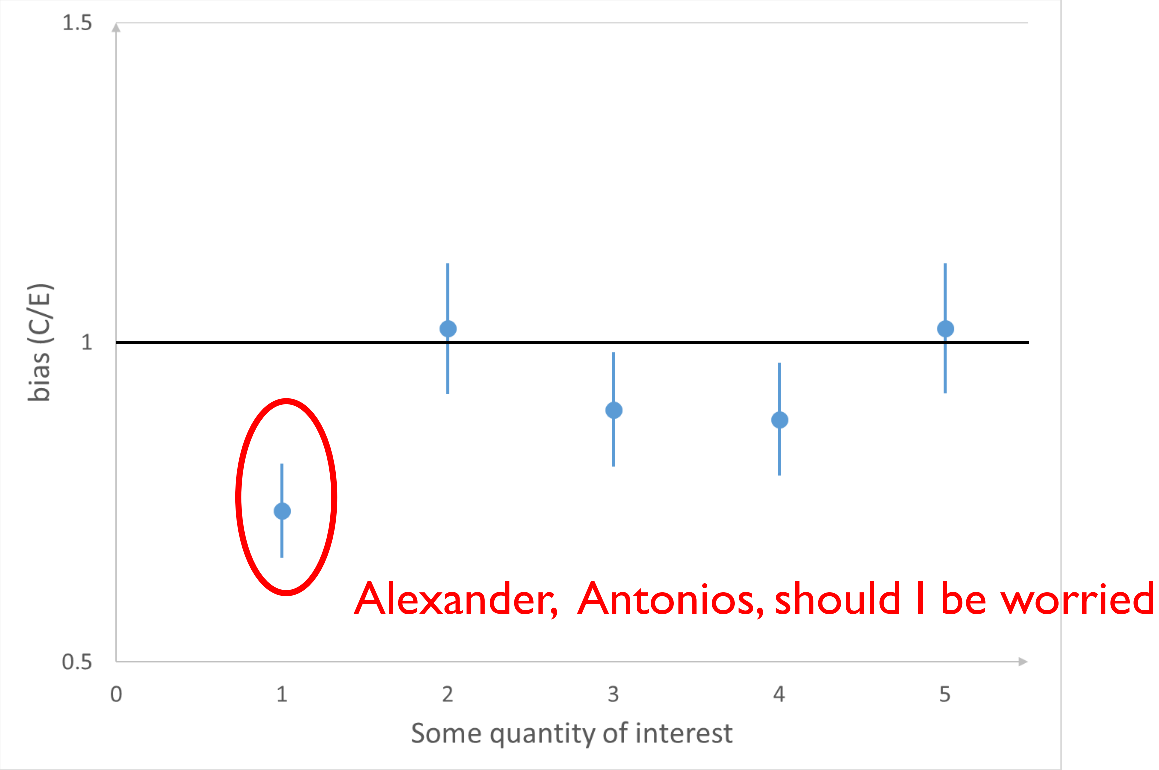
Validation

C/E+σ(C/E)

$$\sigma(C/E)=\sqrt{\sigma_E^2+\sigma_C^2}$$

Experimental Facility

- Measurements (E)
- Uncertainty σ(E)



WP1/WP2 “virtuous” loop

I measure apples, I
call them “bananas”

I compute oranges, I
call them “bananas”

John the experimentalist

Countless number of
meetings / videoconferences

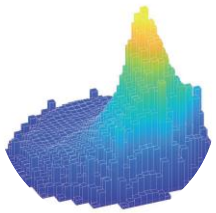
Jim the modeler

We both determine
“bananas”; we can do a
meaningful comparison

Validation of Noise Simulators

Computer Code System

- Input Data
- Calculation (C)
- Uncertainty σ(C)



Validation

C/E+σ(C/E)

$$\sigma\left(C/E\right)=\sqrt{\sigma_E^2+\sigma_C^2}$$

Experimental Facility

- Measurements (E)
- Uncertainty σ(E)

1) Reliable Predictive Tool?

2) Useful Experiment?

NPP Design and Safety

Bias Estimation

Q: How wrong can my code be for the envisioned application?

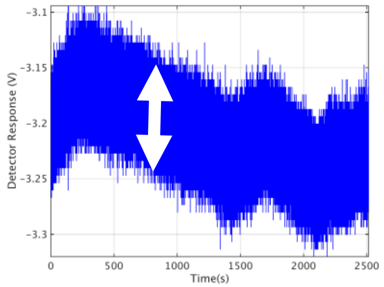
Representativity Analysis

Q: Is my experiment suitable to demonstrate the performance of my code?

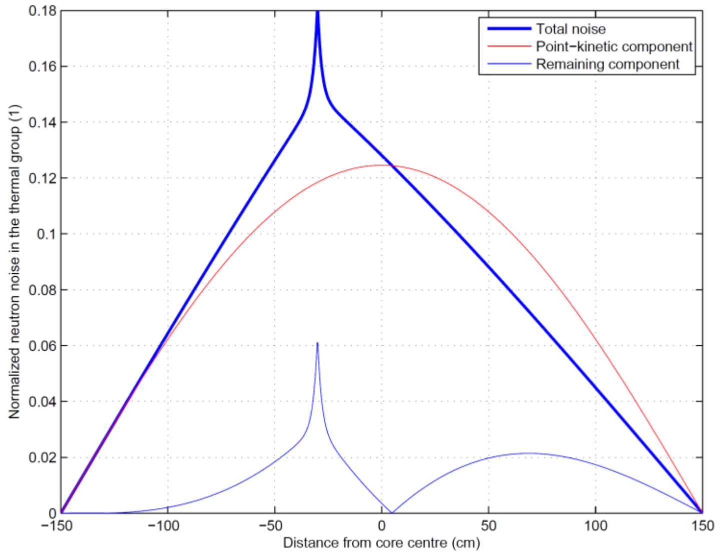
Not this project

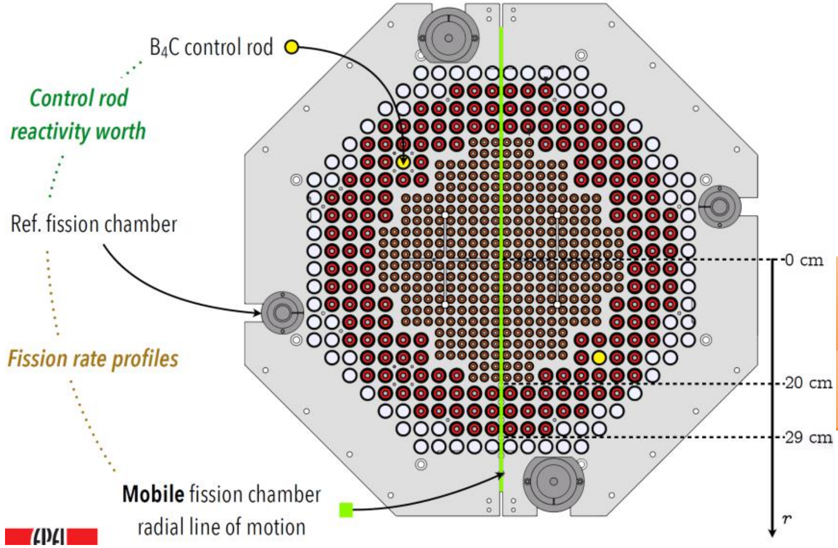
A useful experiment?

Absolute noise amplitude



- We want to use small research reactors to demonstrate that our codes can determine a spatially dependent noise distribution
- Zero power reactors tend to behave like points (small deviations)

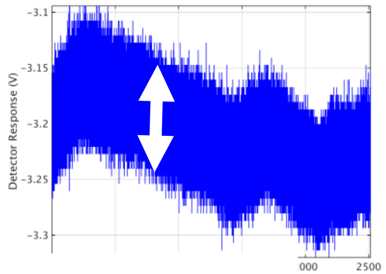


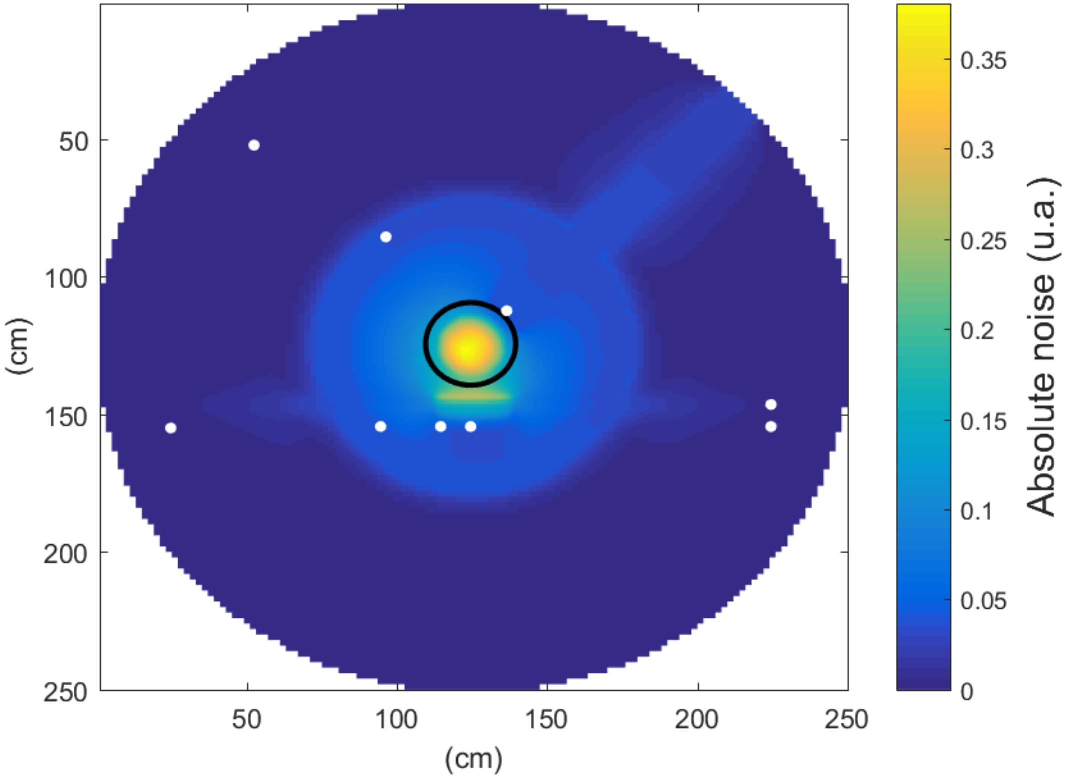


- Looking at the relative noise (relative to the fundamental flux distribution), allows to “filter out” the unwanted point kinetic component

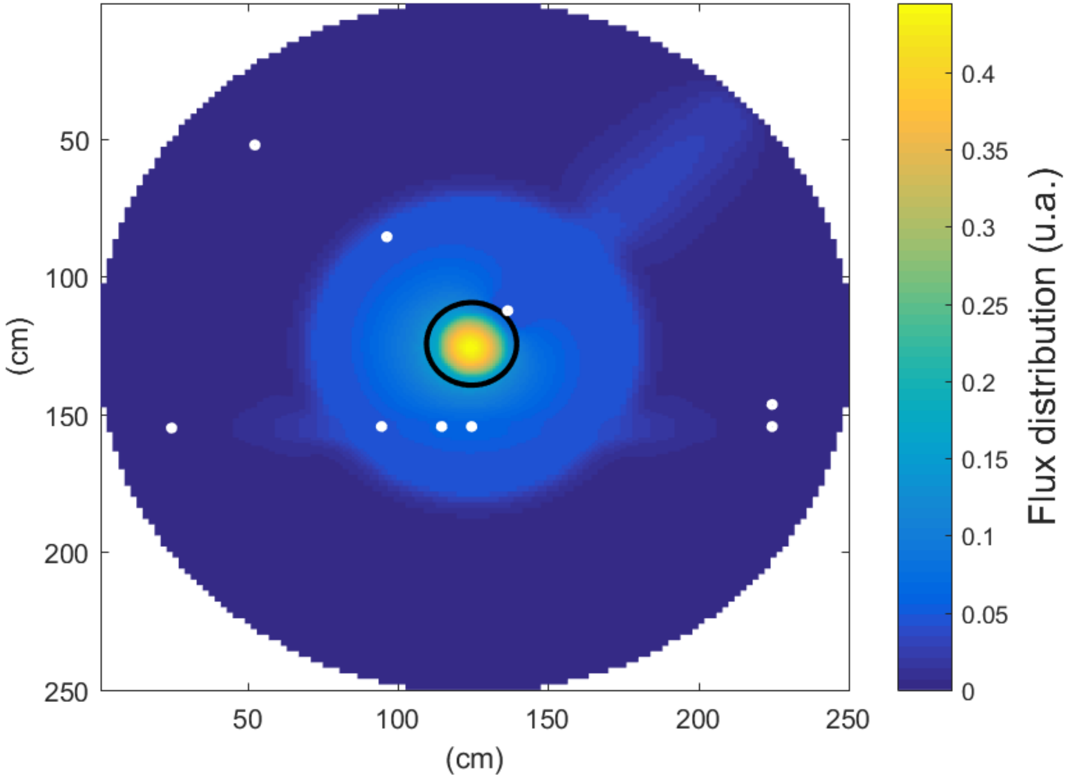
Absolute vs Relative noise amplitude

Absolute noise amplitude





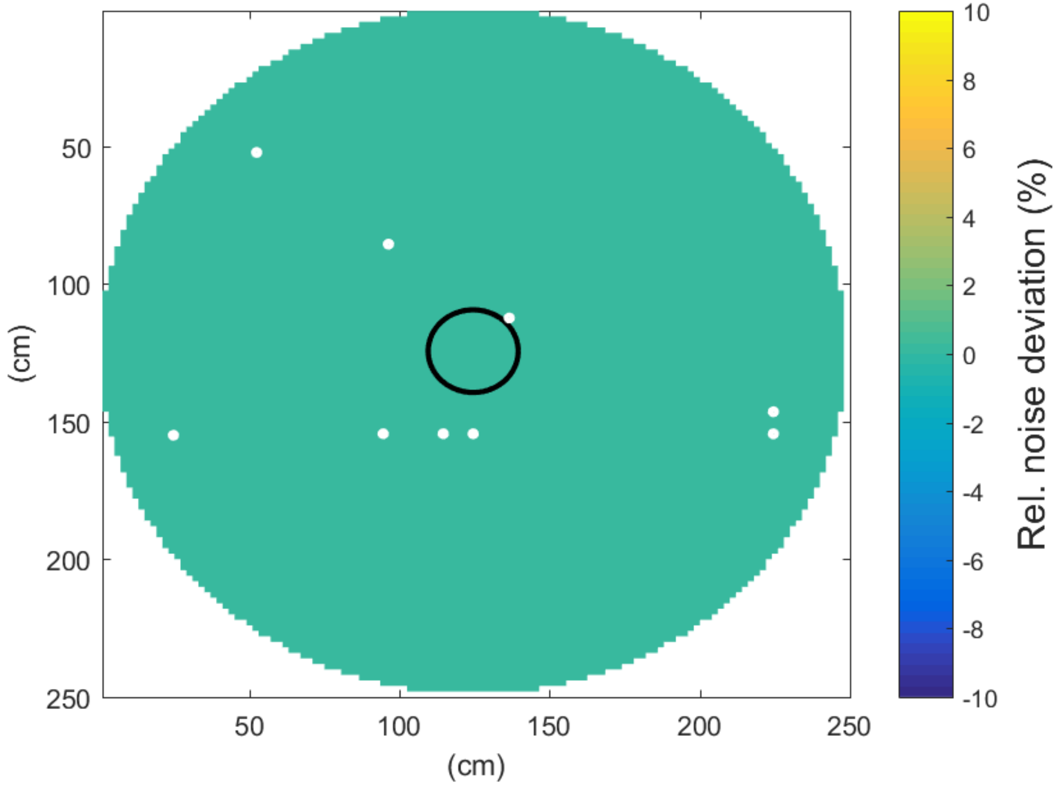
Absolute noise map at AKR-2



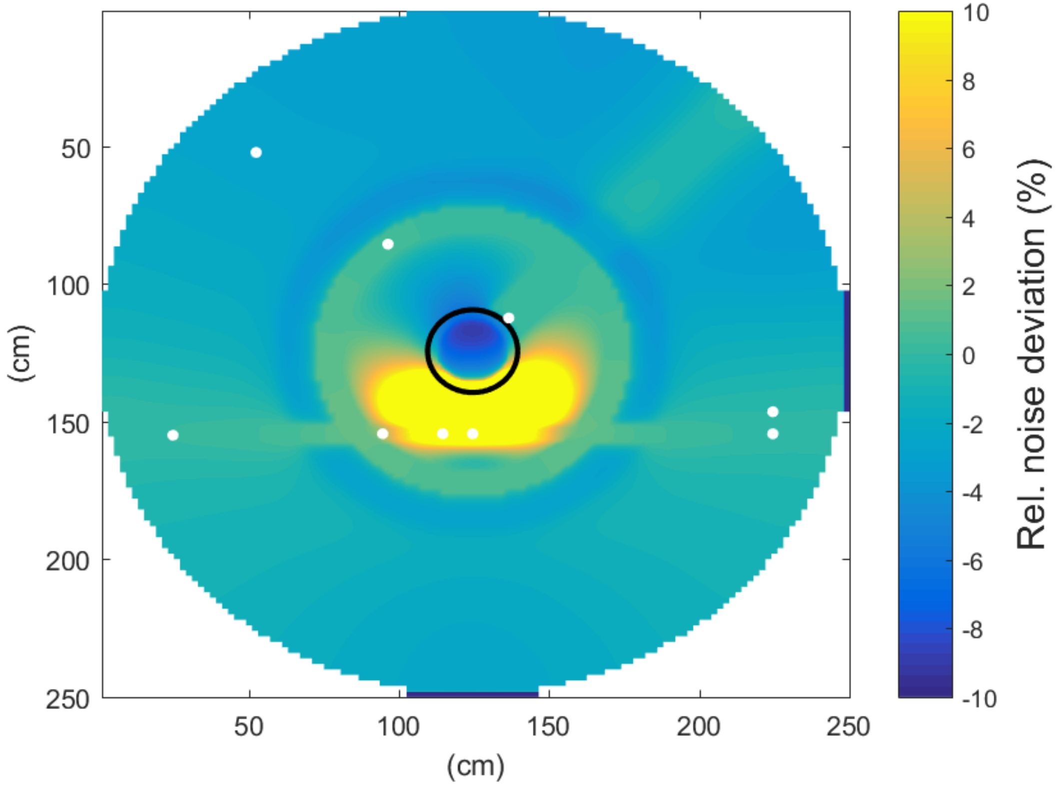
Fundamental flux map at AKR-2

Absolute noise looks like fundamental flux distribution

Absolute vs Relative noise amplitude



Relative noise map (perfect point reactor)



Relative noise map at AKR-2

- Relative noise magnifies the spatial component of the noise
- Only small deviations are expected due to the core size
- Small experimental uncertainties are required to “see” deviations

Noise analysis in the frequency domain

- Time series for detector *i* + Fast Fourrier Transform

$$F_i(f) = \int_{-\infty}^{\infty} \mathrm{TS}_i\,(t) e^{-2\pi i t} dt$$

- Power spectral density (PSD) at frequency *f*:

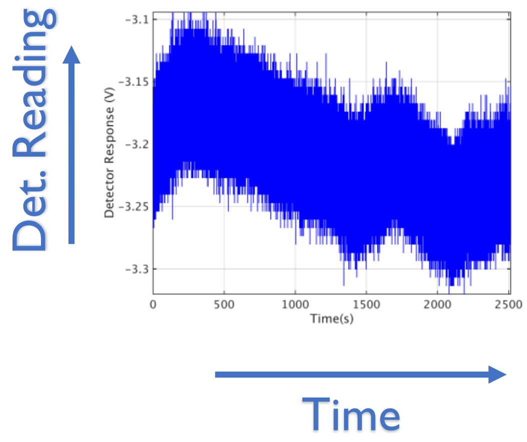
$$PSD_{i,j}(f) = \left| conj\big(F_i(f)\big) \cdot F_j(f) \right|$$

- Phase at frequency *f* :

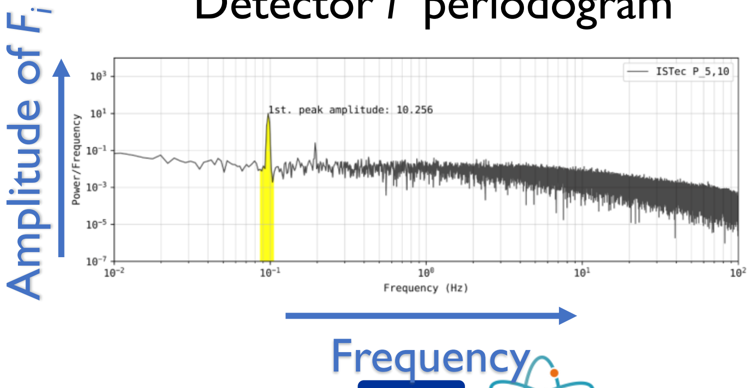
$$\phi_{i,j}(f) = arg\left(conj\big(F_i(f)\big) \cdot F_j(f)\right)$$

- Auto PSD when *i=j*, Cross PSD otherwise

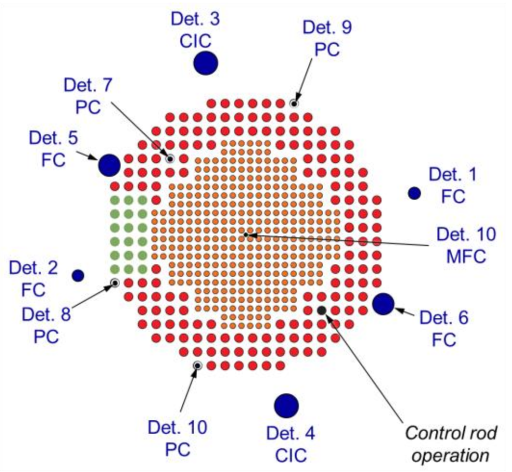
Detector *i* time series



Detector *i* periodogram

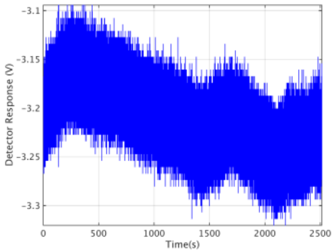


Quantities of Interest for validation



"Amplitude and Phase of the neutron population fluctuations relative to the fundamental mode distribution" at the detectors location

measurement and time-domain simulation

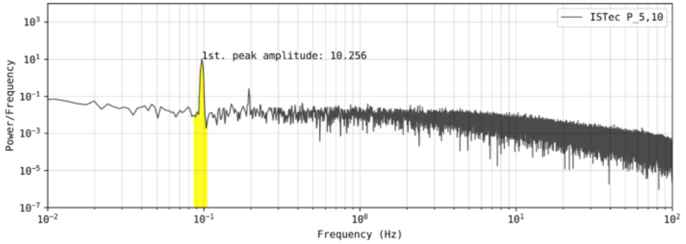


Make it relative

Time series + FFT

Amplitude → Relative peak power

Cross/Auto Power Spectral Density



Phase → Phase at fundamental frequency

Frequency domain calculations

For a set of detectors

$F_i(f)$

Quantities of Interest for validation

- Comparing APSD or CPSD is not straight forward (FFT normalization issues)

- Additional normalization to the PSD of a "reference" detector
  - "**Power Ratios P_i**" (amplitude)

$$P_i = \sqrt{\frac{APSD_i}{APSD_{ref}}} \approx \sum_j w_j \frac{CPSD_{j,i}}{CPSD_{j,ref}}$$

measurements

codes

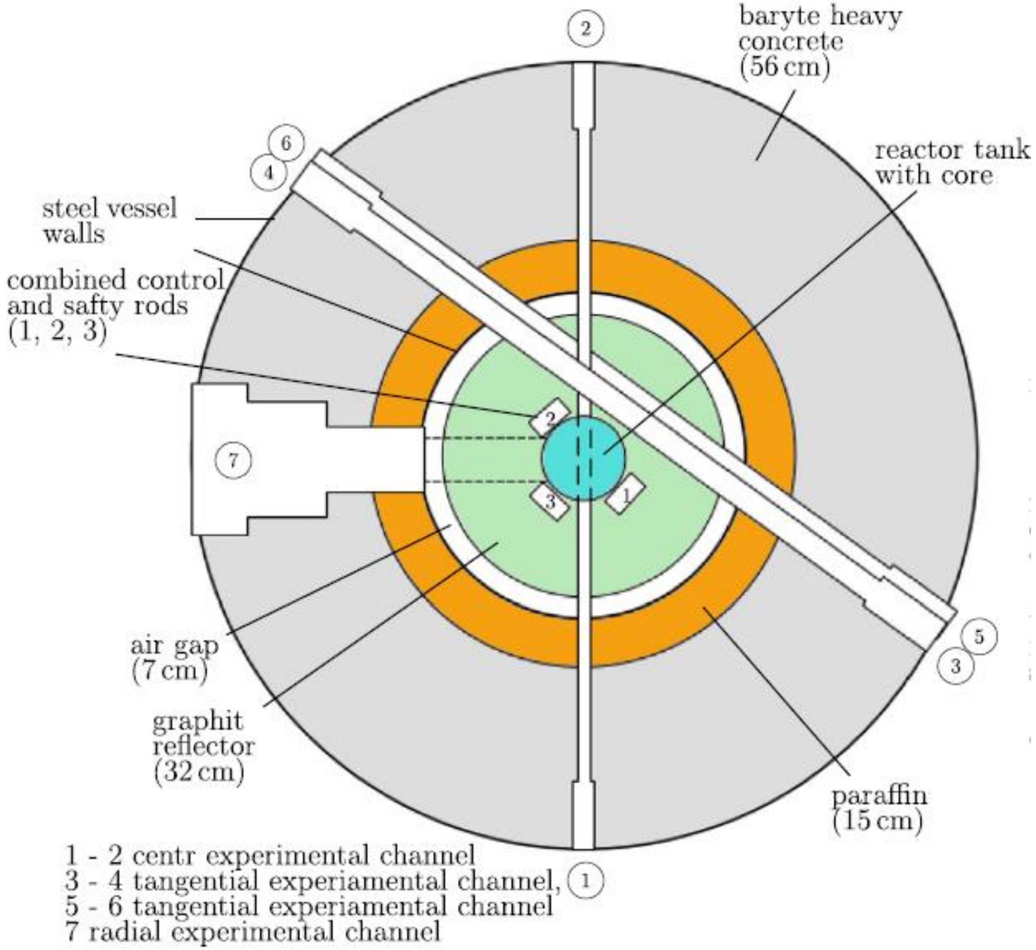
  - **Phase** $\phi_\mathrm{i} = \phi_{i,ref}(f) = arg\left(conj\left(F_i(f)\right) \cdot F_\mathrm{ref}(f)\right)$

- Focus on the frequency of perturbation (base, fundamental, ω_0, etc…)

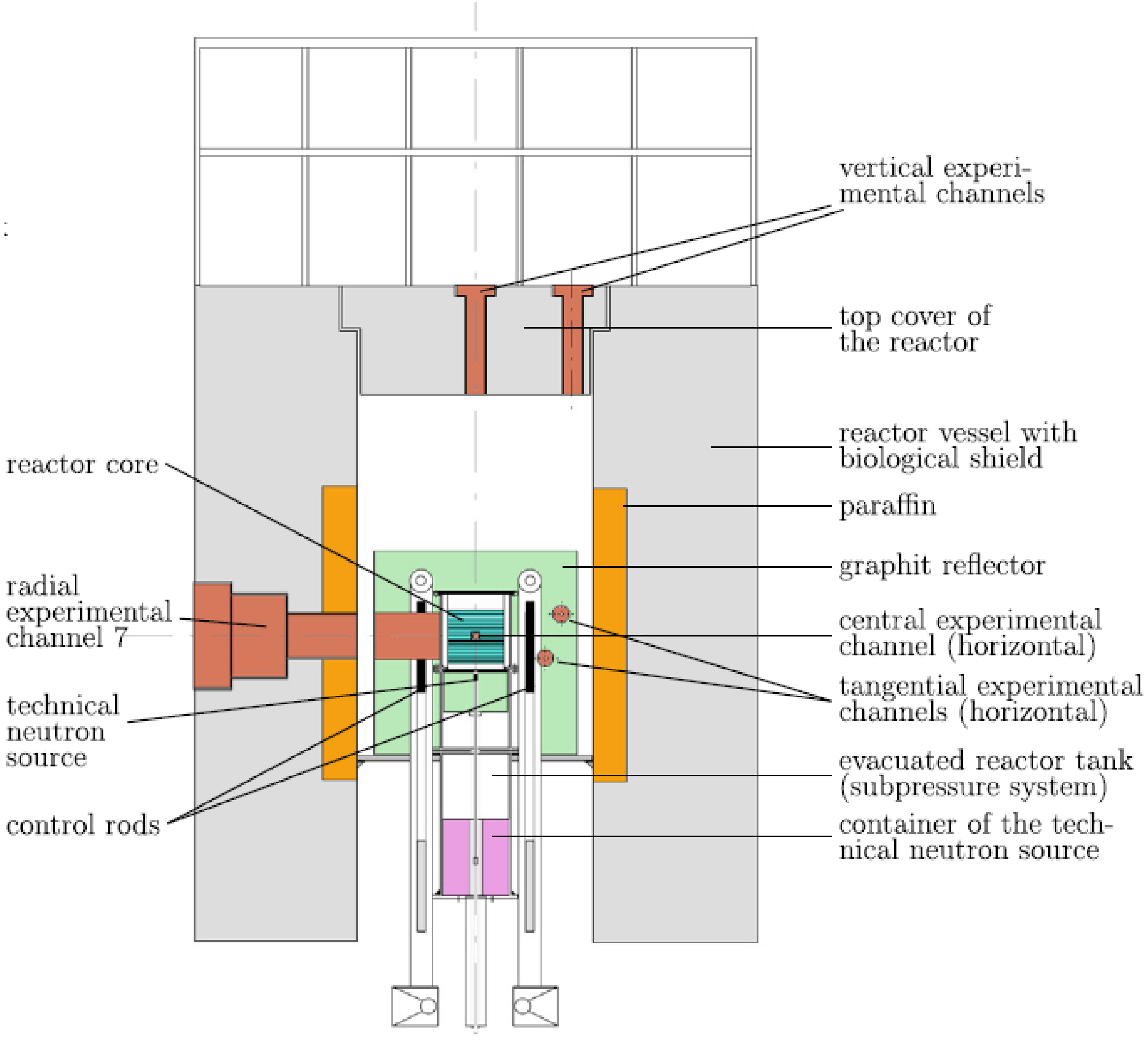
Generation of experimental data at AKR-2

The education and training reactor AKR-2

- is a thermal, homogeneous zero power reactor, moderated by polyethylene
- was completely upgraded in 2005
- is equipped with a state-of-the-art digital I&C control system Teleperm XS
- is designed for education in reactor physics, nuclear engineering and radiation protection/dosimetry



(a) Horizontal section at the core level. The horizontal section extends through the horizontal line of symmetry of channel 7, shown by the vertical section on the right (b).



(b) Vertical section at the core level.

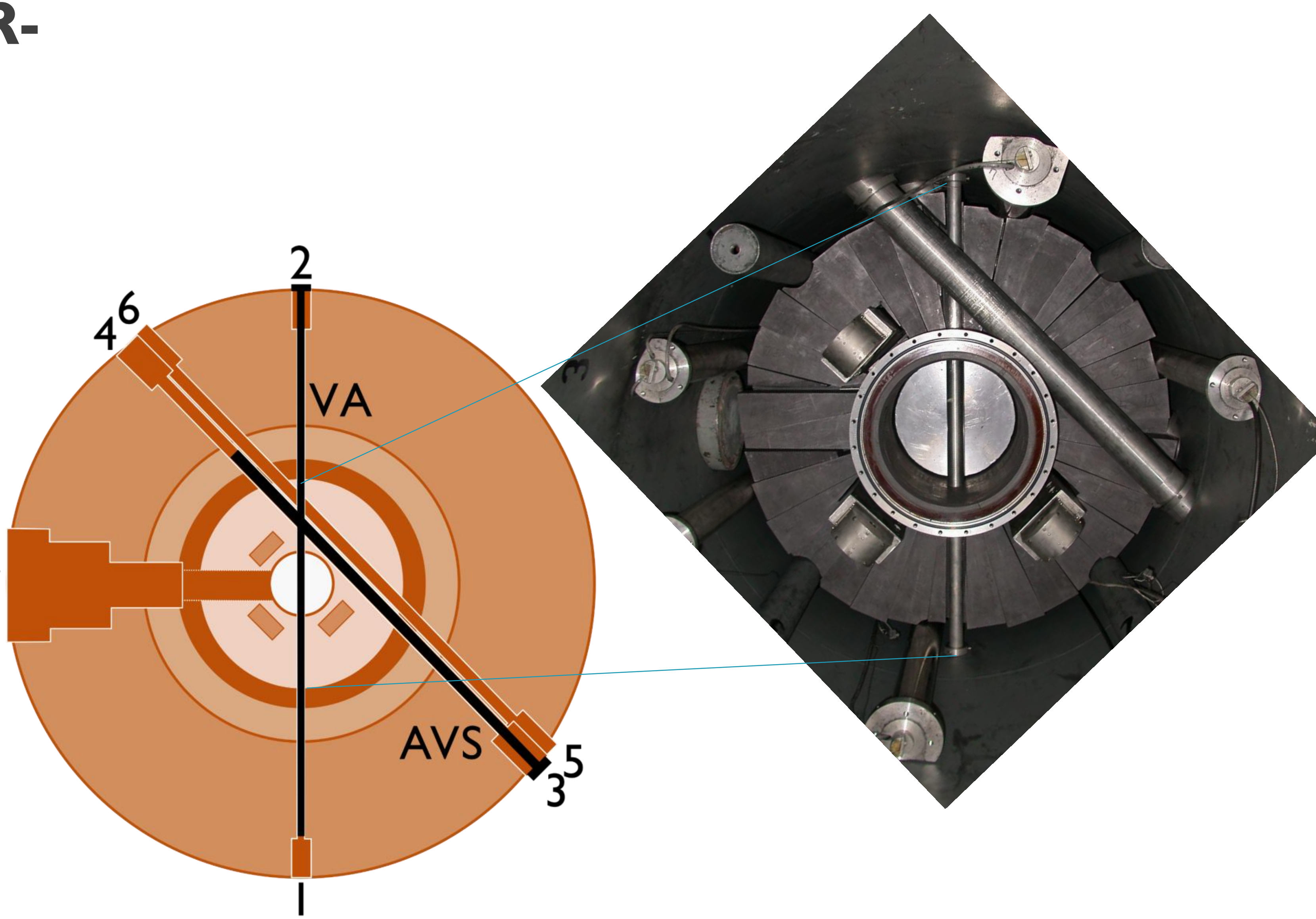
Location of the AKR-2 perturbation devices

Vibrating absorber (VA)

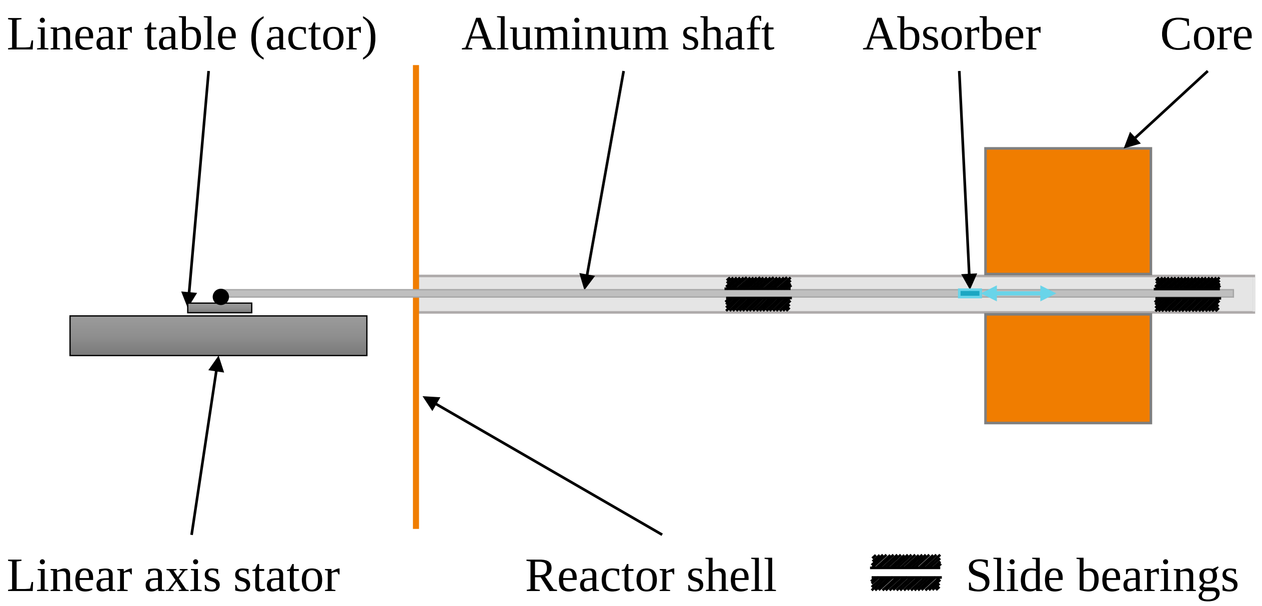
Inserted into the central channel 1-2

Absorber of variable strength (AVS)

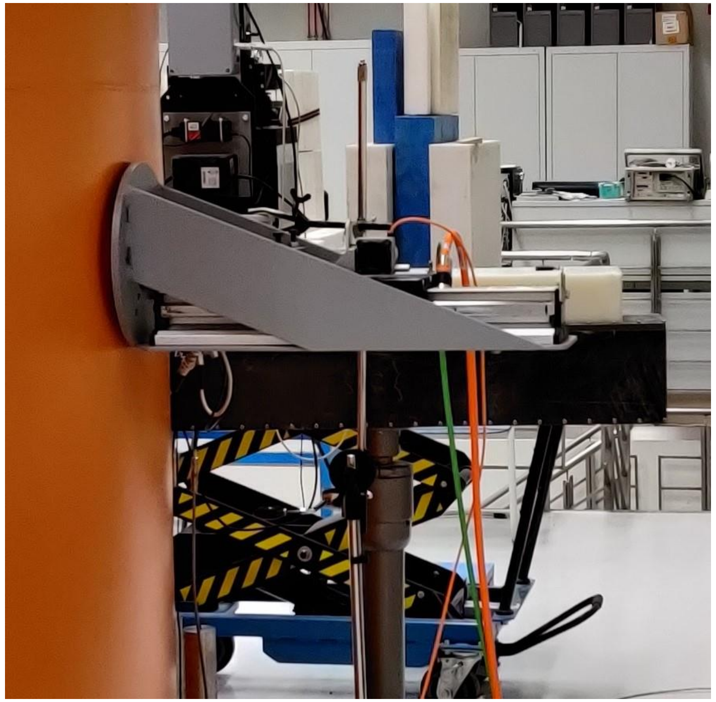
Inserted into one of the tangential channels 3-4 or 5-6



Vibrating absorber (current setup)



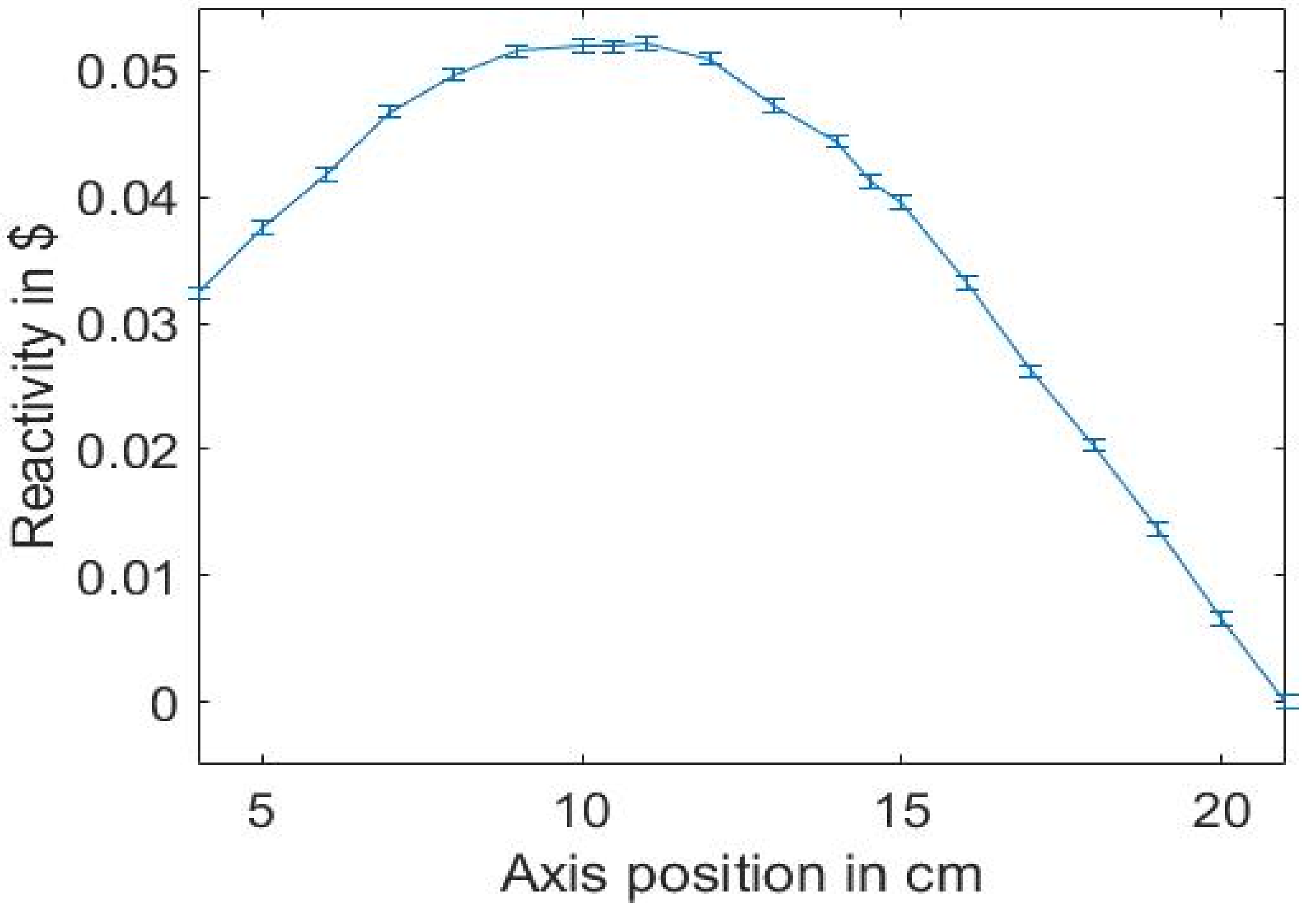
Schematic of the Vibrating absorber



Vibrating absorber mounted to opening 2

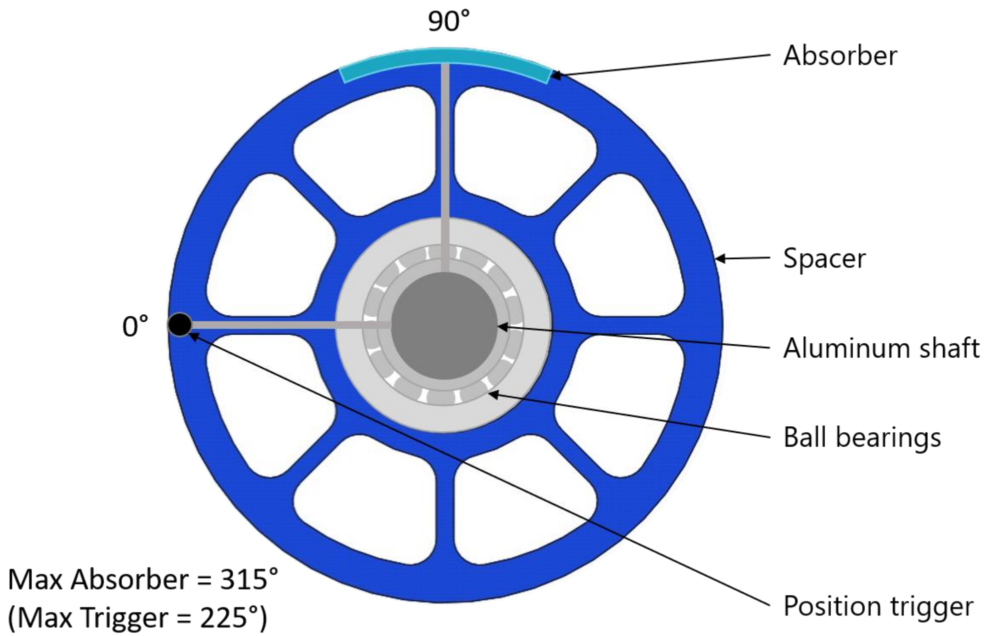
- Realized as a a set of indium foils moving in the experimental channel 1-2
- Driven by a linear motor axis with frequencies 0.01 Hz - 10 Hz

Vibrating absorber (current setup)

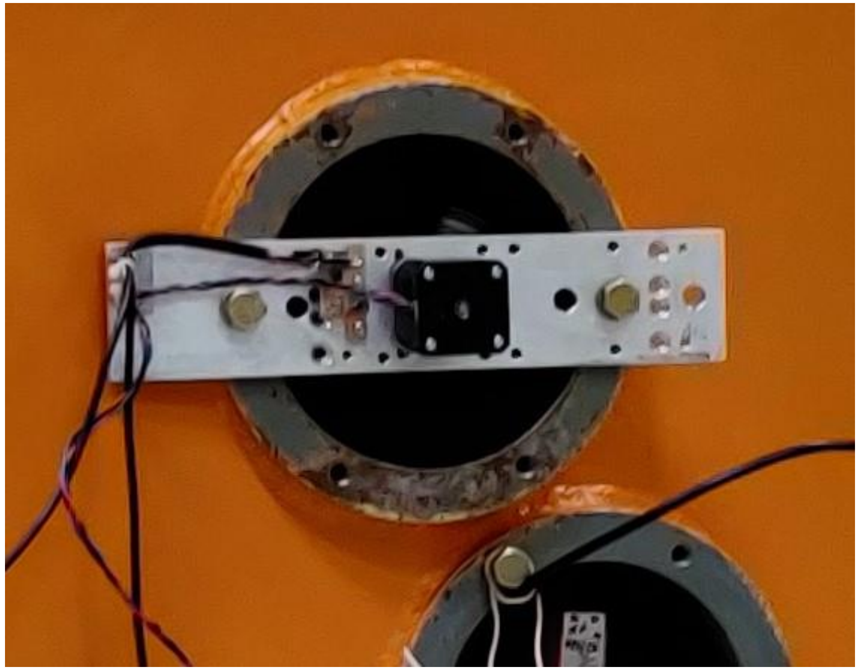


Measured reactivity of VA, center is at 10.5 cm

Absorber of variable strength (current setup)



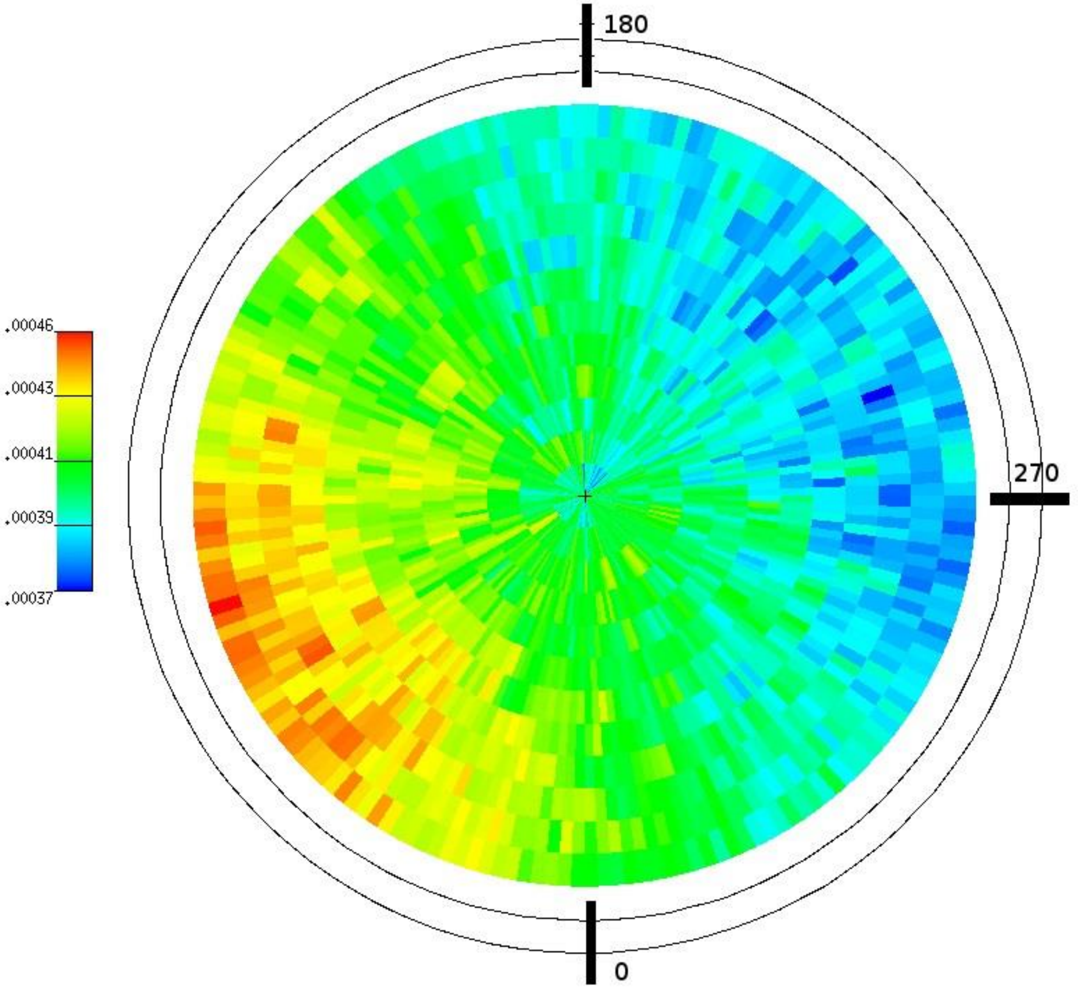
Schematic of absorber of variable strength



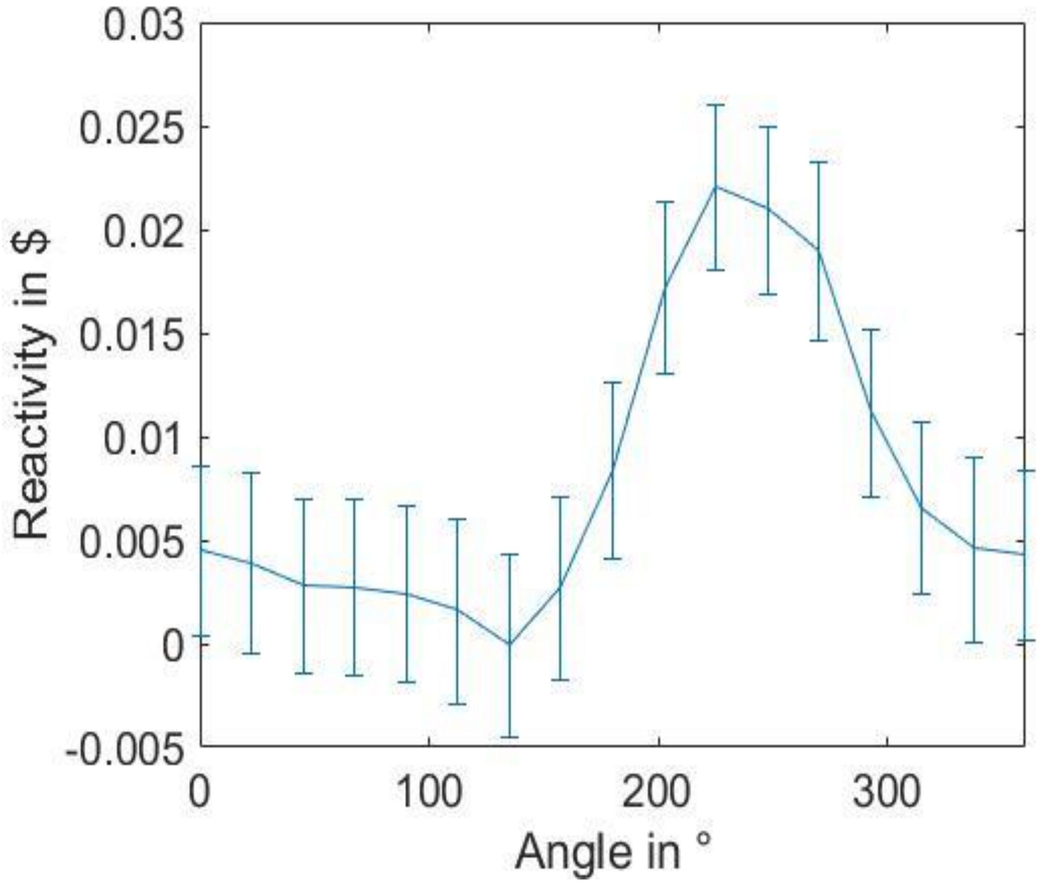
Absorber of variable strength mounted opening 3

- Realized as a cadmium sheet rotating in the experimental channel 3-4
- Driven by a stepper motor with frequencies 0.1 Hz - 15 Hz

Absorber of variable strength



MCNP simulations of the flux in the experimental channels



Measured reactivity of AVS in channel 3-4

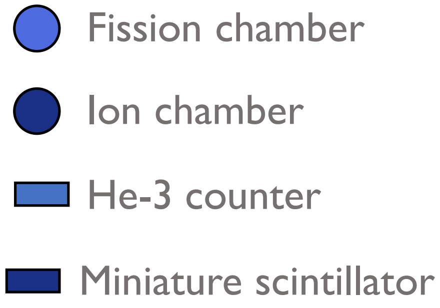
Timeline of measurements

Experiments were constantly improved and requests of modelers was taken into account.

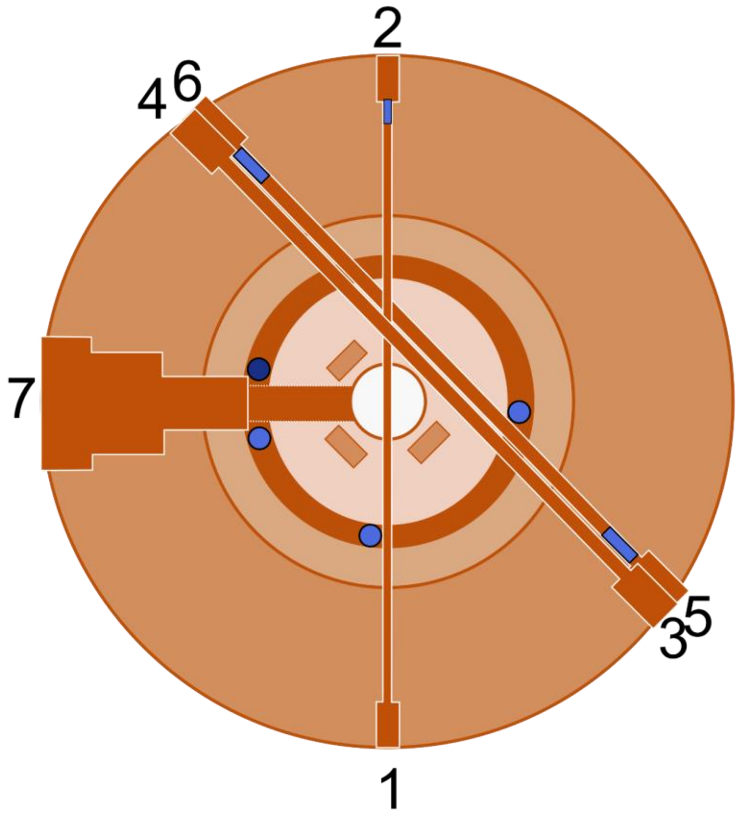
	1	2	3
Overall Setup:	7 detectors 27 measurements	9 detectors 27 measurements	7 detectors 46 measurements
Main Goals:	Qualification of the AKR-2 DAQ	Generation of data close to the core	Uncertainty estimation
Dates	06.03.-15.03.	06.07.-15.07.	22.02.-26.02. (+2 days)

2018 2019 2020 2021

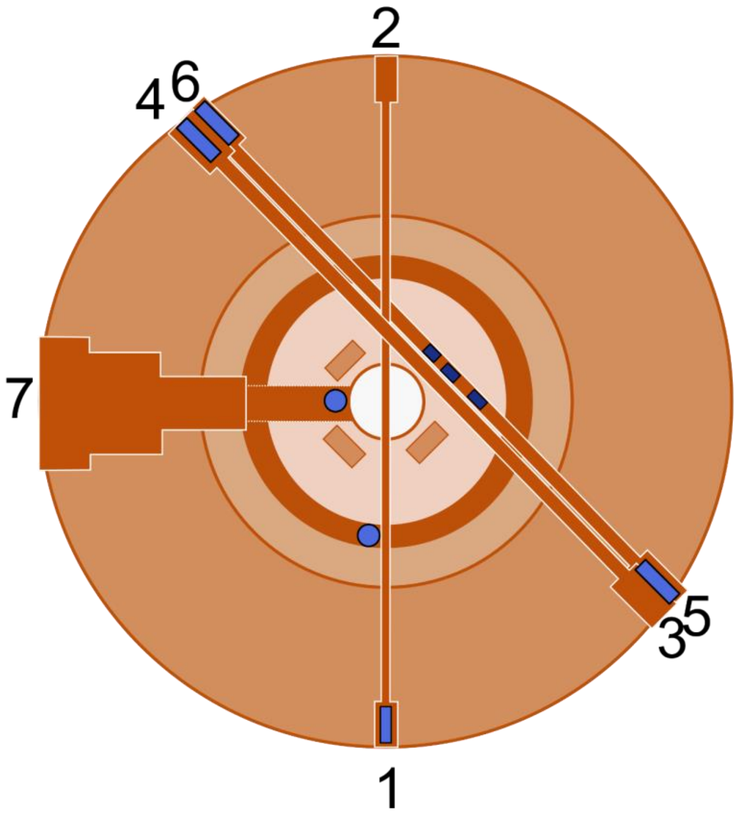
Detector setup



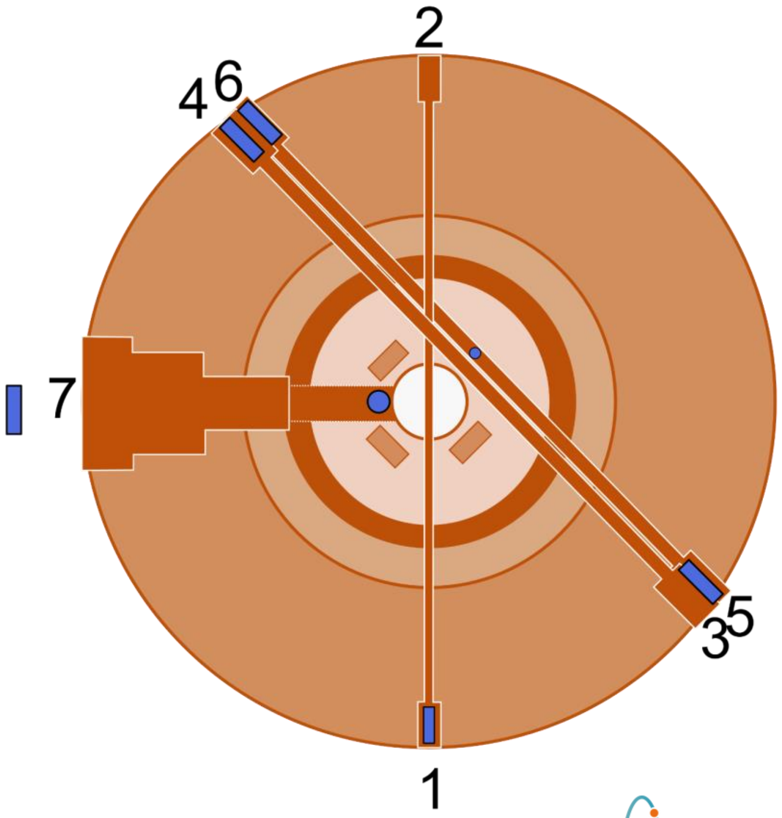
Detector setup of the first campaign



Detector setup of the second campaign



Detector setup of the third campaign



Generation of experimental data at CROCUS

The CROCUS reactor

Reactor type

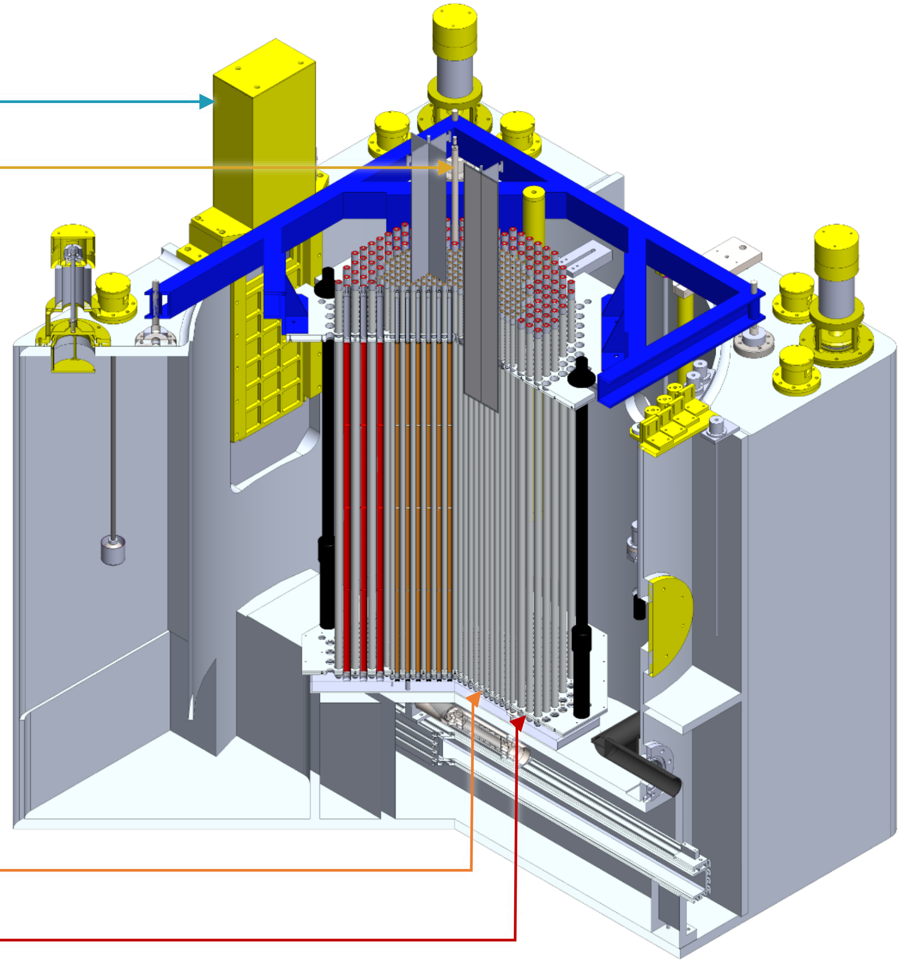
- LWR with partially submerged core
- Room T (controlled) and atmospheric P
- Forced water flow (160 $l.min^{-1}$)

Operation

- 100 W: zero-power reactor
- i.e. maximum 2.5×10^{9} $cm^{-2}.s^{-1}$
- Control: B_4C rods and spillway

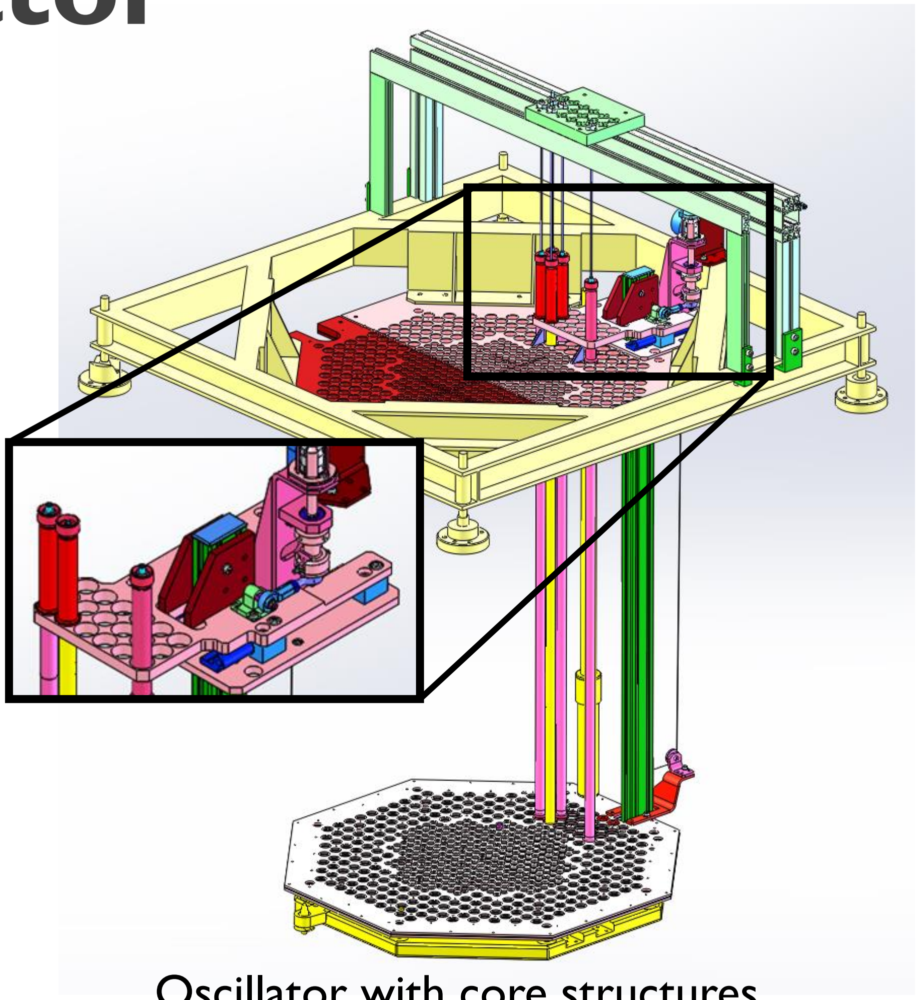
Core

- ⌀60 cm/100 cm, 2-zone
- Inner: 336 UO_2 1.806 wt% 1.837 cm
- Outer: 176 U_{met} 0.947 wt% 2.917 cm



COLIBRI fuel rods oscillator

Design for investigating power fluctuations induced by fuel oscillations

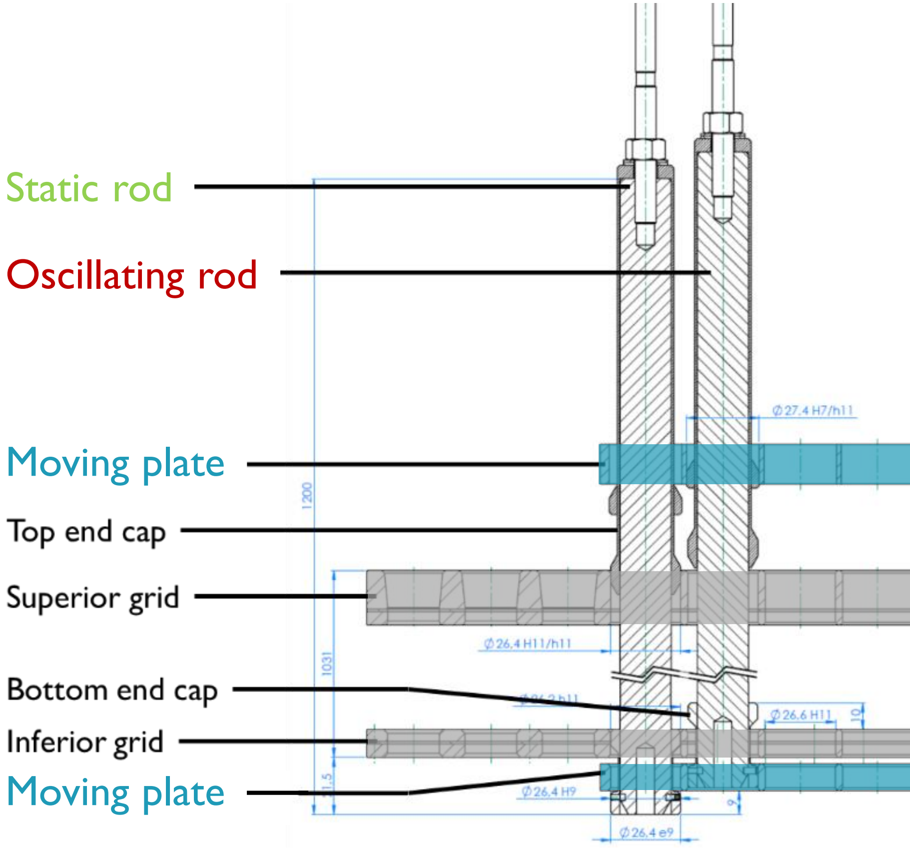


Oscillator with core structures, and few pins inserted in the device

COLIBRI fuel rods oscillator

Design for investigating power fluctuations induced by fuel oscillations

- Top and bottom moving plates
- Rigid transmission via an Al beam
- Up/down position for rod selection



Working principle of the final design

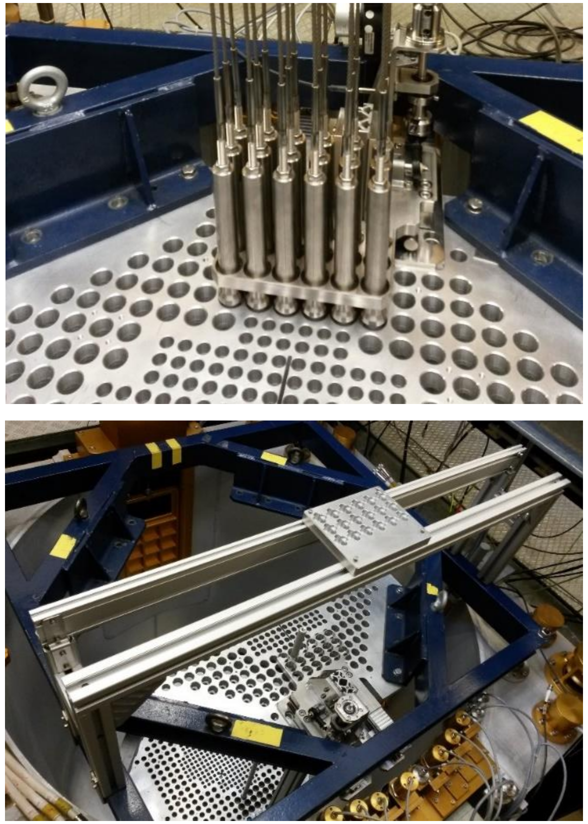
COLIBRI fuel rods oscillator

Design for investigating power fluctuations induced by fuel oscillations

- Top and bottom moving plates
- Rigid transmission via an Al beam
- Up/down position for rod selection
- Inductive and cable captors for position

Following the qualification campaign[2]

Up to 18 U_m rods, ±2.5 mm (i.e. 8 pcm), 2 Hz



View of the oscillation device for testing in the vessel

[2] V. Lamirand et al., “The COLIBRI experimental program in the CROCUS reactor: characterization of the fuel rods oscillator,” *EPJ Web Conf.*, vol. 225, p. 04020, Jan. 2020.

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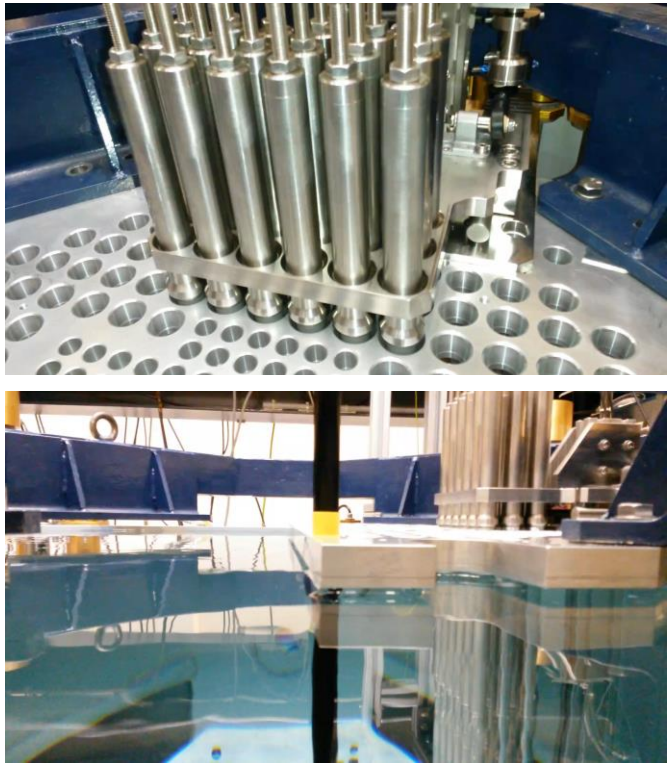

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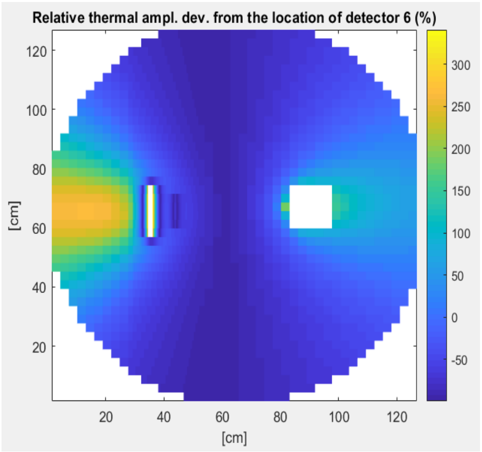
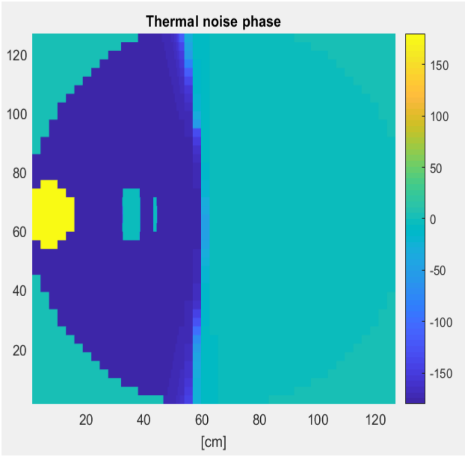
POLLEN vibrating absorber

Goal: improvement of space dependence

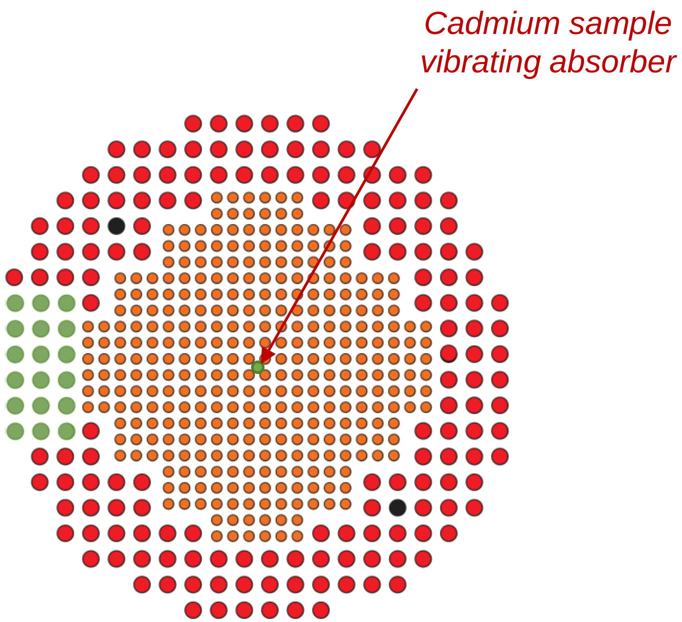


Power

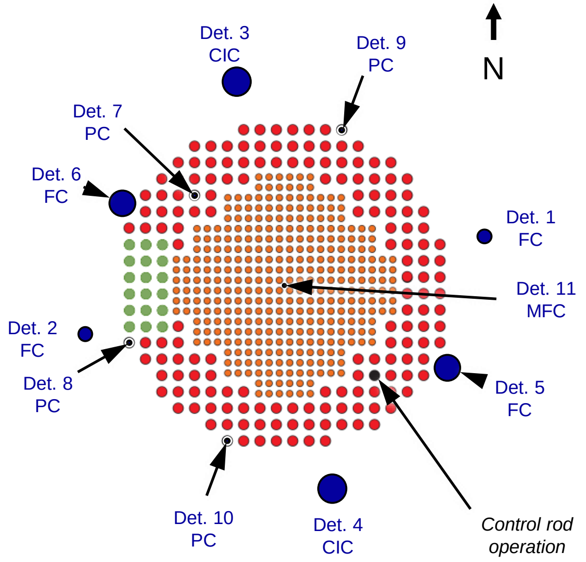


Phase

CORE SIM+ calculation with COLIBRI and the addition of an absorber of variable strength (courtesy DREAM)



Detection setup

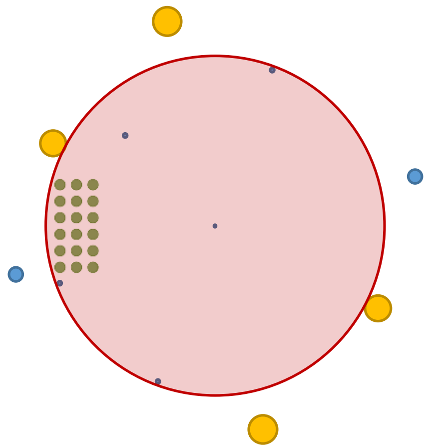


Goal: non-point kinetics spatial dependence

➡ As many distributed detectors as possible

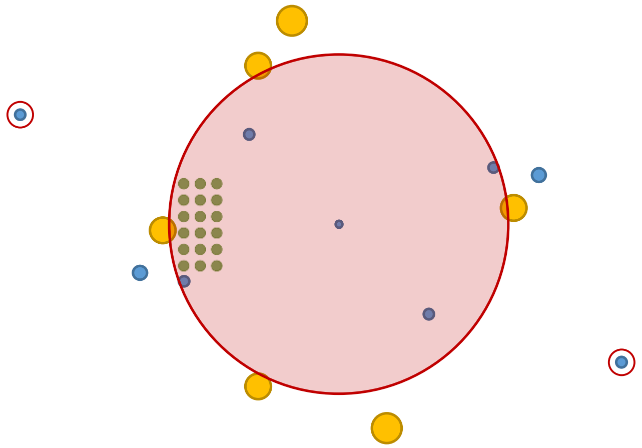
Detection setup

Campaign 1
(2018)



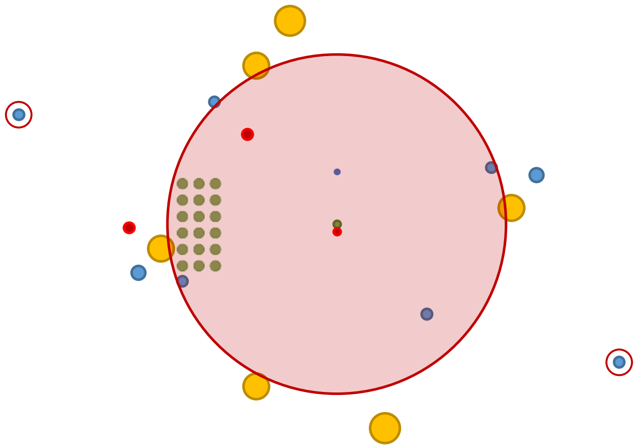
11 detectors
- Pulse mode
- Current mode

Campaign 2
(2019)



15 detectors
- More robust detectors

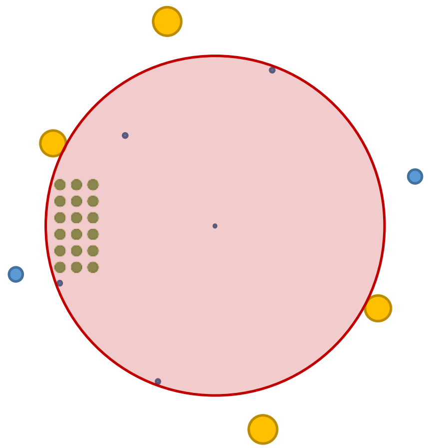
Campaign 3
(2021)



18 detectors
- Miniature scintillators

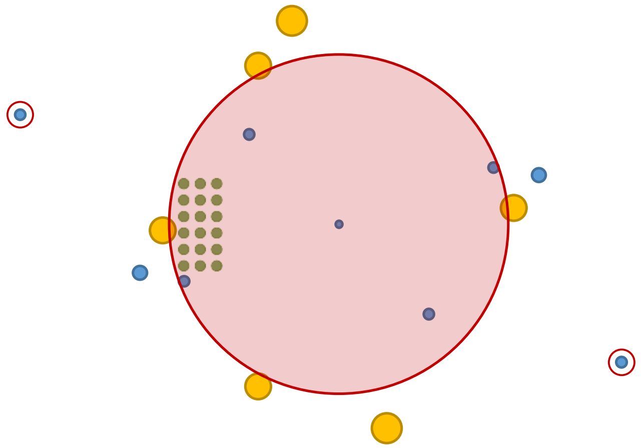
Conducted experiments

Campaign 1
(2018)



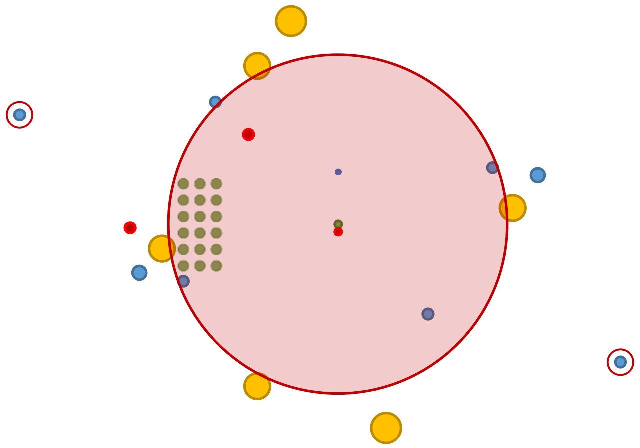
Cover the range of interest
- Frequency: 0.1 to 2 Hz
- Amplitude: ±0.5 to ±2.0 mm

Campaign 2
(2019)



Uncertainty reduction
- Repetitions of a reduced set
- More high efficiency detectors
- Higher power/detection rate
- Longer measurements

Campaign 3
(2021)



Enhanced spatial dependence
- POLLEN vibrating absorber at core center, in phase/out of phase with COLIBRI

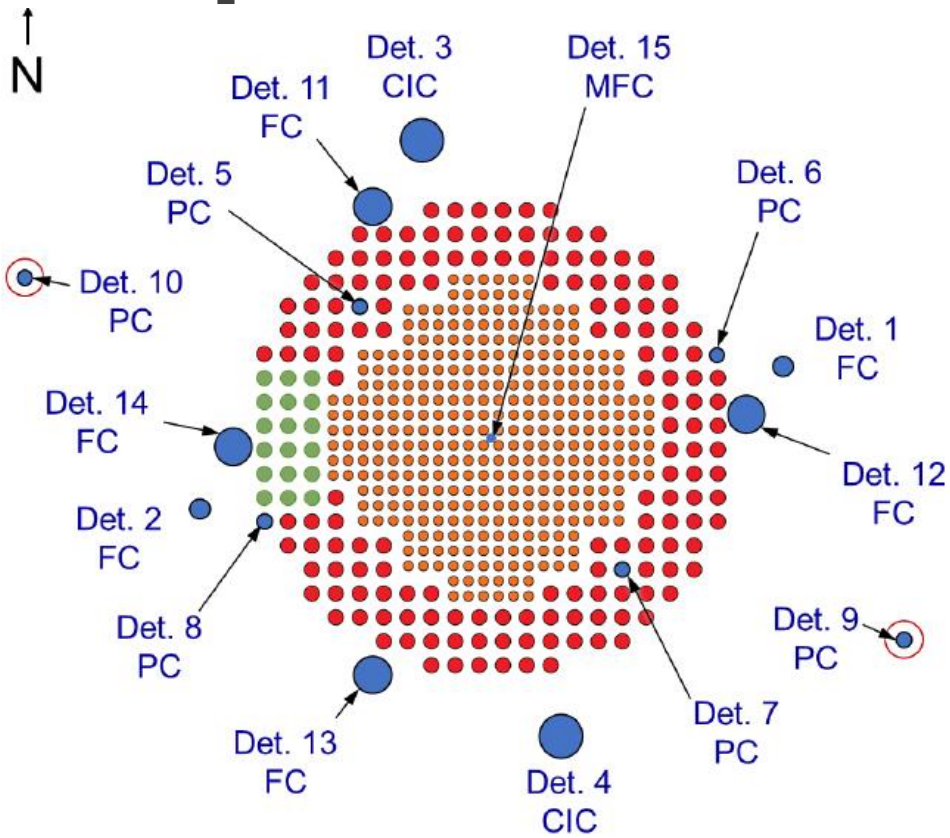
Modelling the beasts

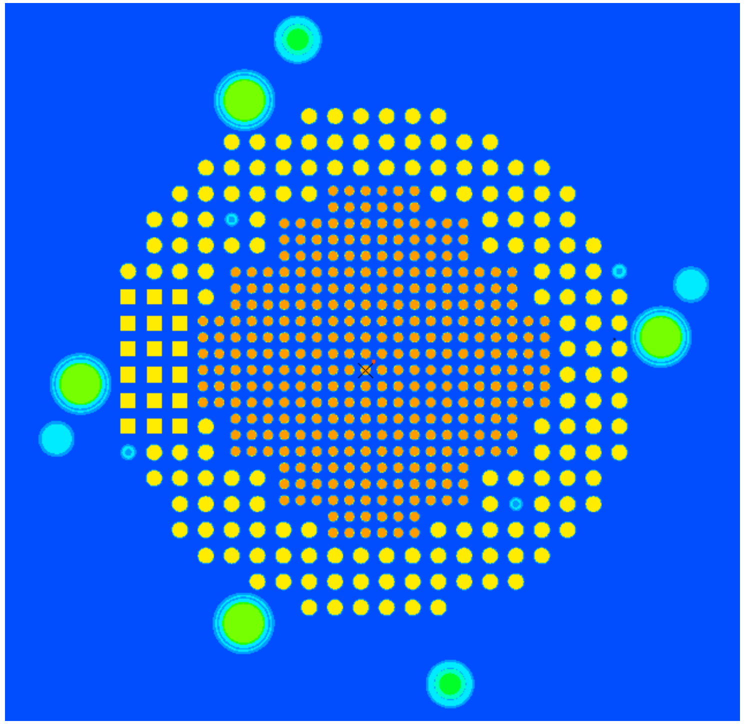
Neutron Noise Simulators

Code				
	Boltz. Eq.	Noise Eq.	Response	Det. Model
TRIPOLI-4	Monte Carlo	Freq.	Th. Φ	yes
MCNP	Monte Carlo	Freq.	Reac. Rate	Yes
CORESIM+	Diffusion	Freq.	Th. Φ	No
APOLLO3	Deterministic Transport	Time Dep.	Reac. Rate	No
PARCS	Diffusion	Time Dep.	Th. Φ	No
FEMFFUSION	Diffusion	Time Dep.	Th. ϕ	No
NOISE-SN	Deterministic Transport	Freq.	Th. Φ	No

+ Uncertainty Quantification using CORESIM+

Tripoli-4: the Colibri model





Continuous-energy treatment, with JEFF3.1.1 nuclear data

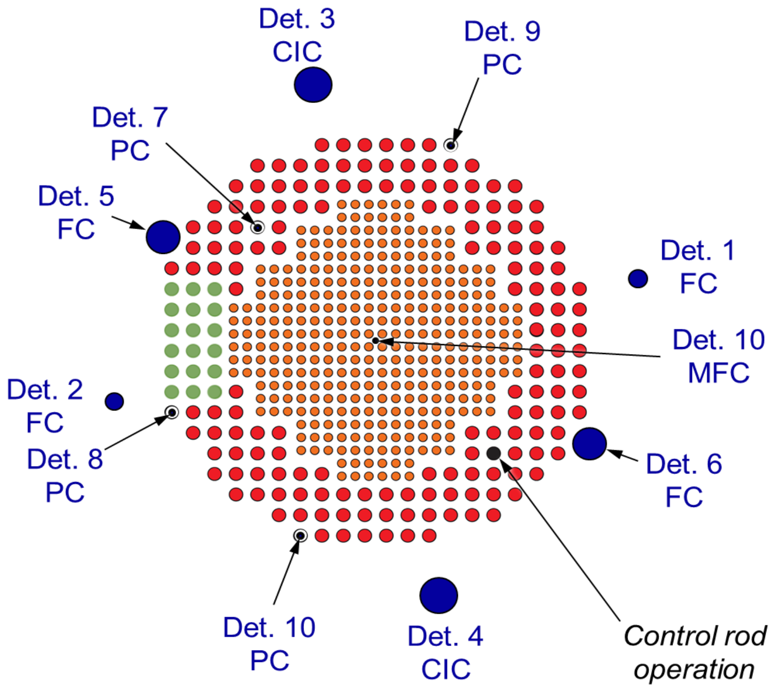
Fully detailed 3D model for the first and second experimental campaign

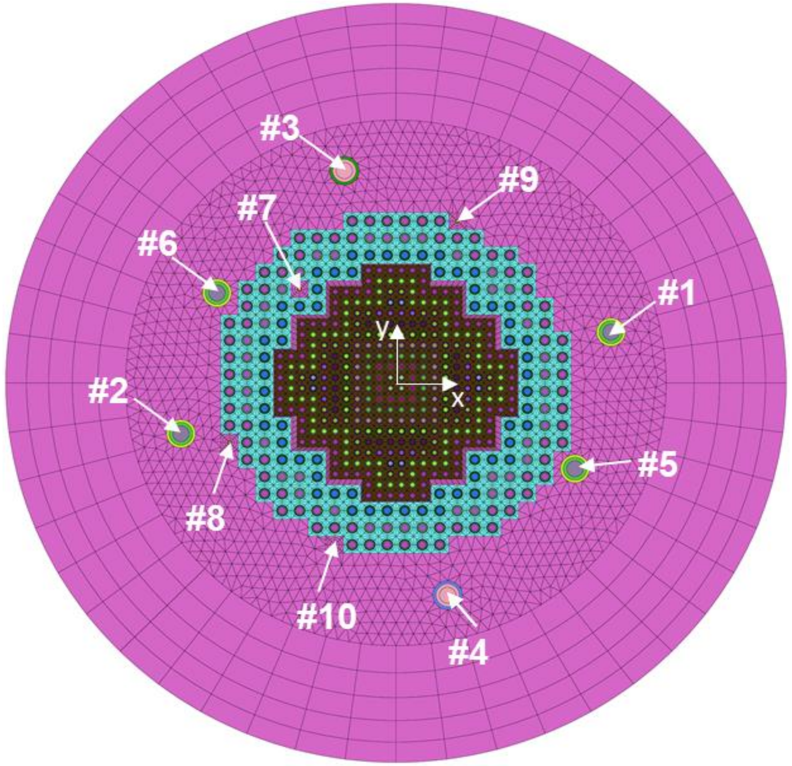
Detectors explicitly described

Noise field (real and imaginary parts) computed over a spatial mesh and in the detectors

- ❑ Noise model: frequency domain & orthodox linearization of the noise equations
- ❑ Noise source: no approximations (all harmonics included)
- ❖ Statistical convergence “issues” for noise induced by mechanical vibrations

APOLLO3: the Colibri model





Multi-group treatment, with JEFF3.1.1 nuclear data

2D model for the first experimental campaign

Detectors explicitly described

Noise field computed over a spatial mesh and in the detector regions

- ❑ Noise model: time domain, via the Improved Point-Kinetics (IPK) approach
- ❑ Transport description (2D + axial buckling)
- ❖ Hypothesis: spatial and energy distributions follow the fundamental mode

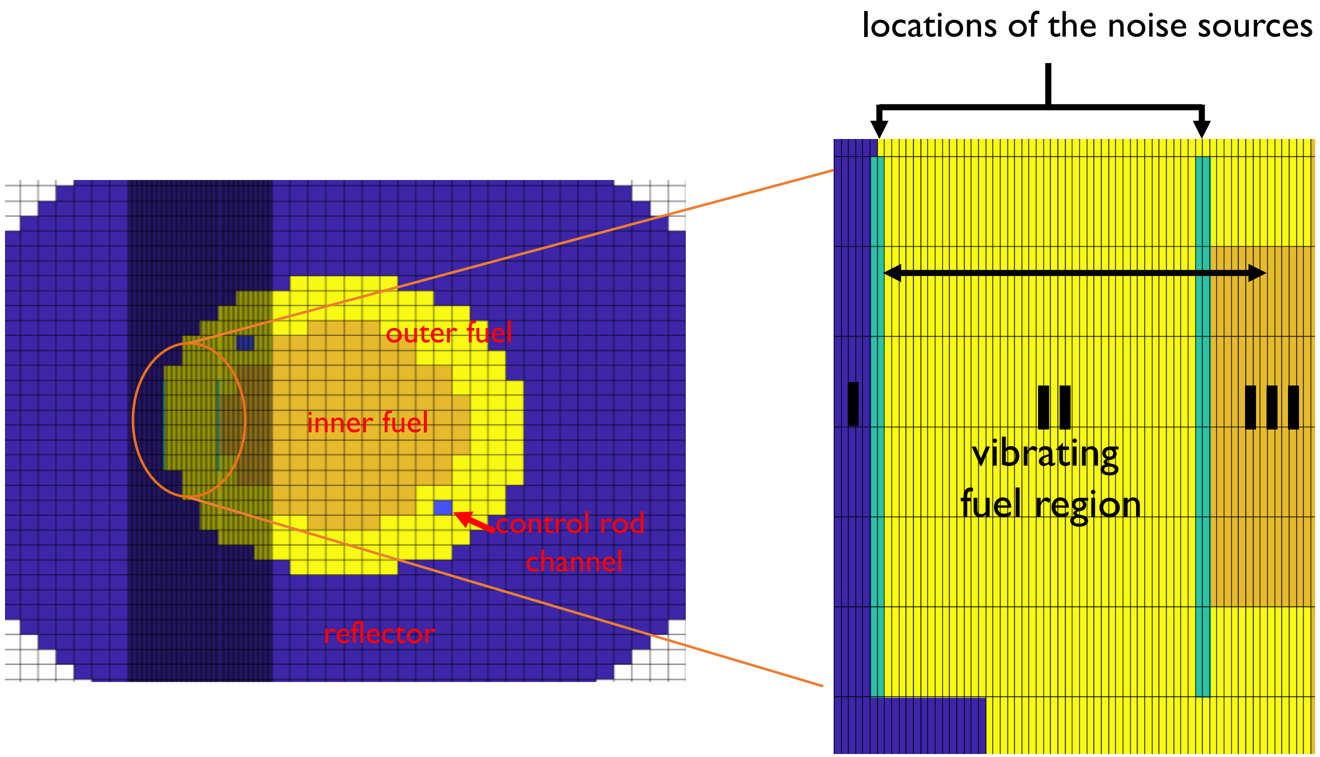
CORE SIM+ and NOISE-SN: the Colibri model

CORE SIM+

Diffusion theory
Fine mesh

NOISE-SN

Discrete ordinates
(S16 approximation)



- Frequency-domain simulations
- 2-energy groups
- Group constants generated with Serpent
- Exact noise source & ε/d approximation, only 1st harmonic simulation

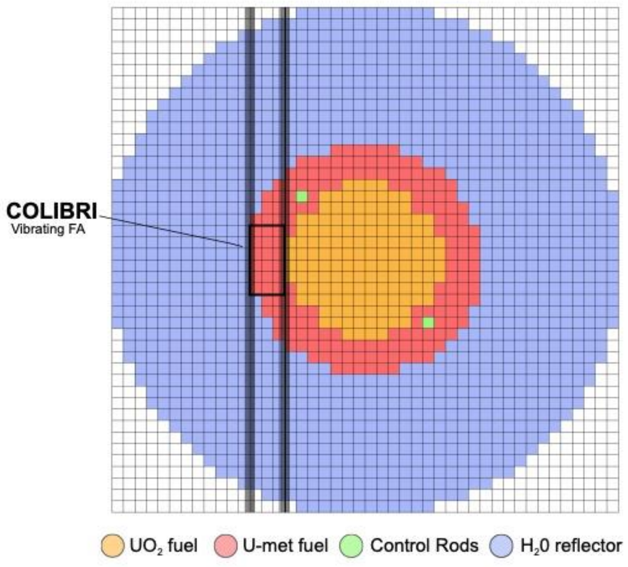
FEMFFUSION: the Colibri model

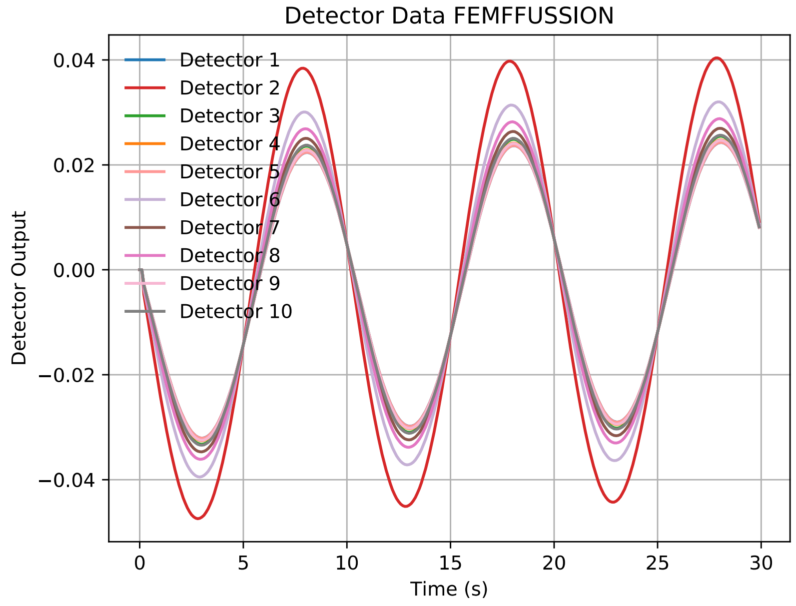
- Open-source time-domain finite element code developed in Universitat Politècnica de València.
  - Openly available at www.femffusion.imm.upv.es .

- 2D grids refined near the vibrating assembly .

- Diffusion and SP3 time-domain calculations.
  - Each experiment was simulated during 3 full oscillations.
  - Monochromatic results.

- As the differences between each time step are subtle (noise), it is required:
  - High spatial resolution.
  - Low numerical tolerances.

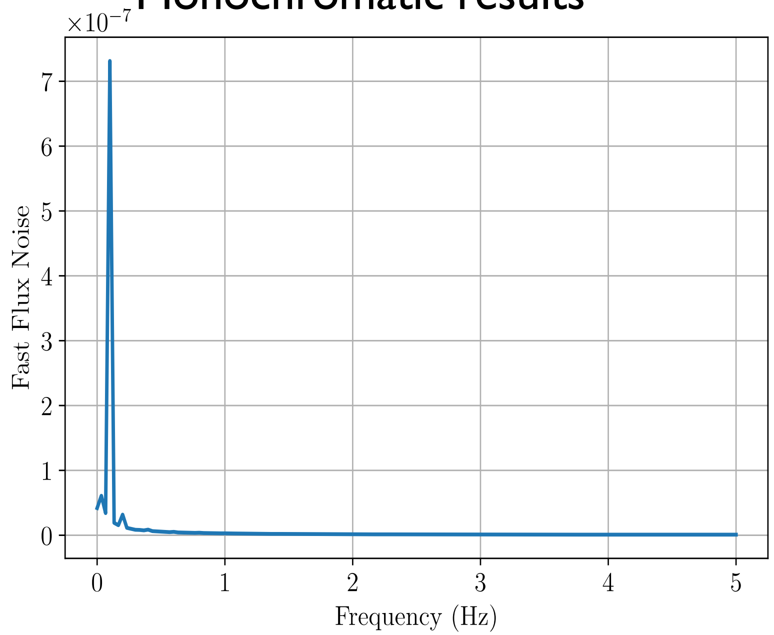


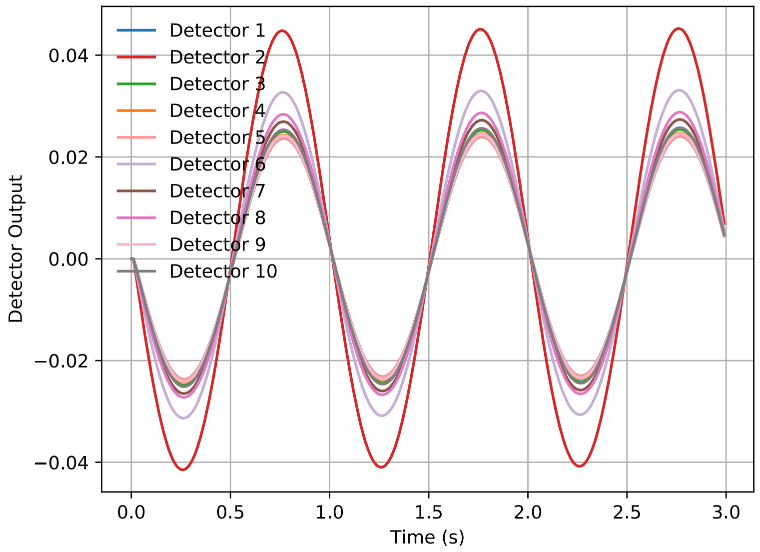


PARCS: the Colibri model

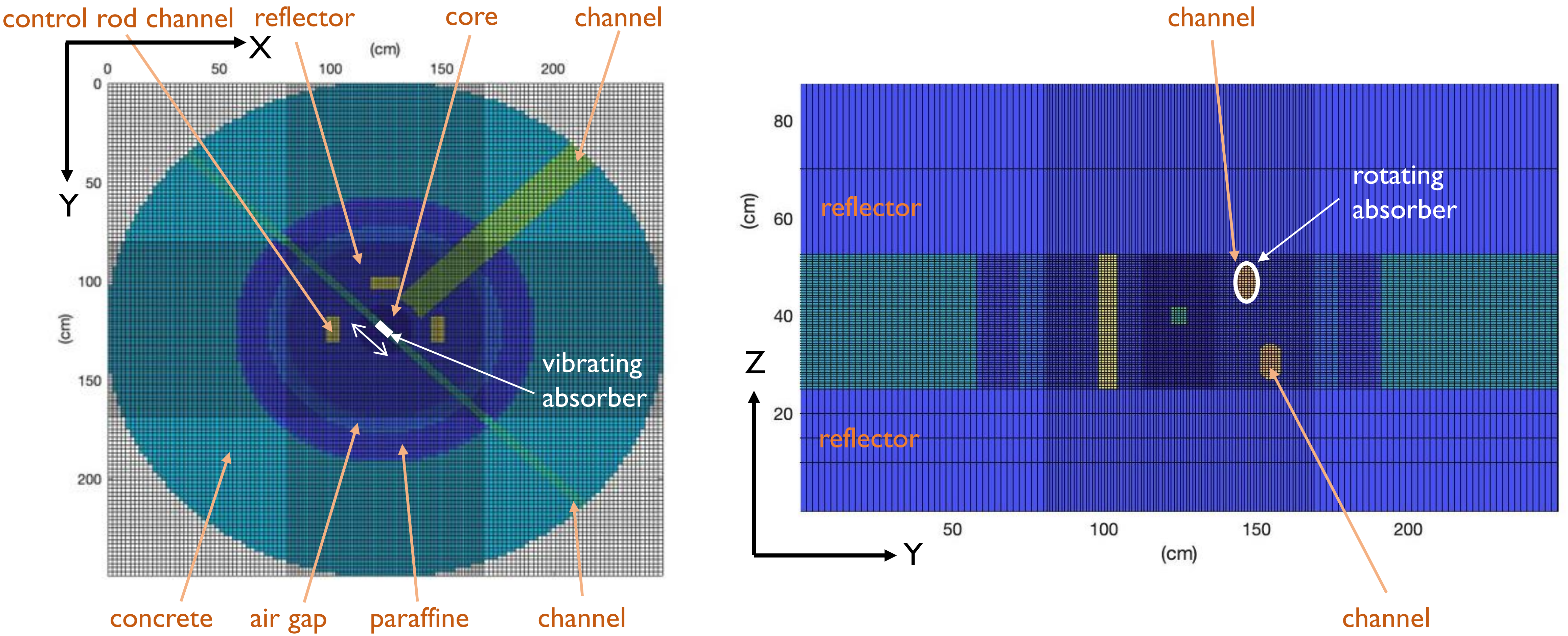
- Purdue Advanced Reactor Core Simulator (PARCS).
- Time-domain 2-group diffusion code.
  - Due to the numerical accuracy required the central finite difference module was used.
- Mechanical vibrations inserted as a custom set of time domain XS.
  - A module to read these XS was developed.
  - The movement was considered a purely sinusoidal.
- Same grids, XS and parameters as FEMFFUSION.
  - Similar result obtained.

Monochromatic results



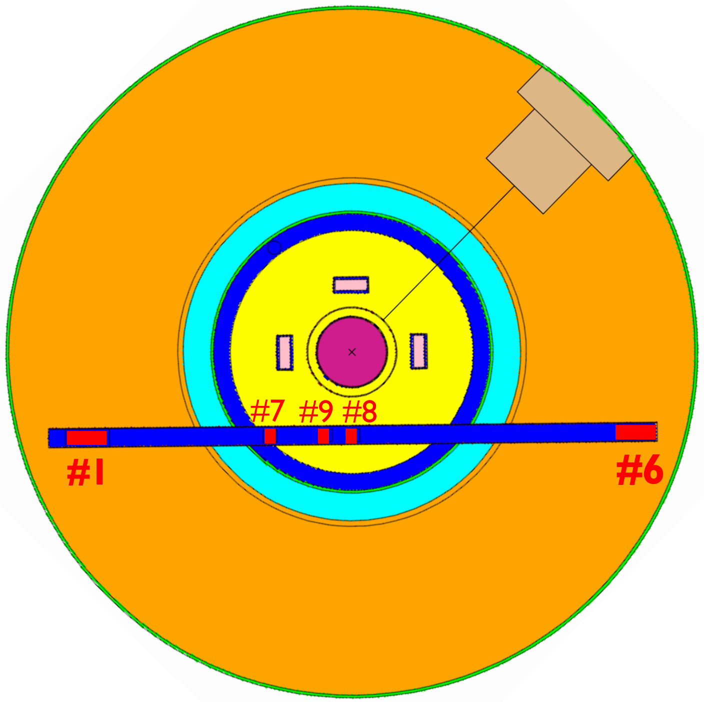


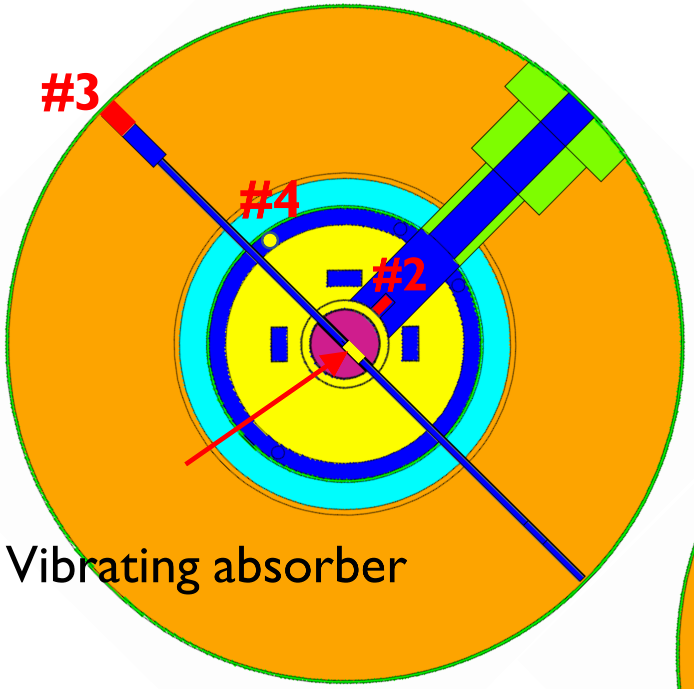
CORE SIM+: the AKR-2 model

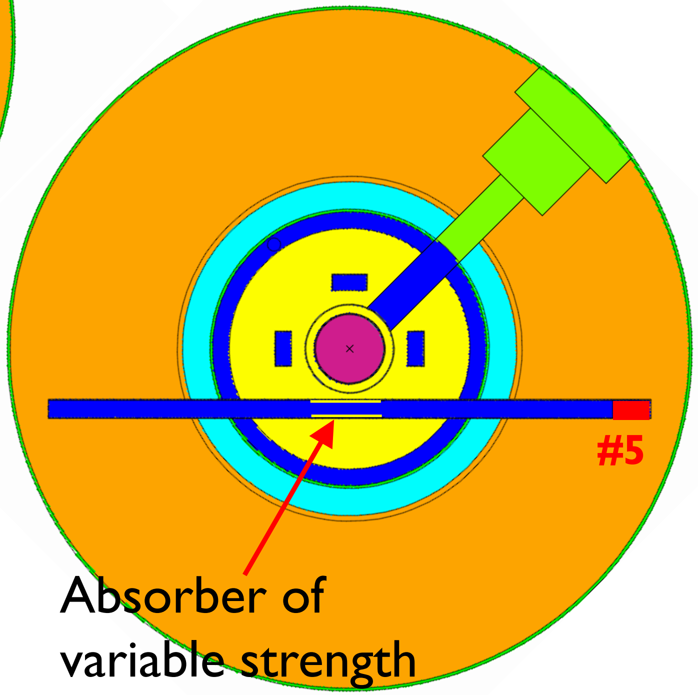


- frequency domain simulation
- 2 energy groups
- group constants generated with Serpent
- exact noise sources, only 1st harmonic simulation
- numerical issues, a special convergence acceleration method was developed in CORE SIM+

MCNP: the AKR-2 model







- Frequency domain calculation with MCNP modified for this purpose
- Detector sizes and locations were adjusted from the actual ones in order to detect more particles in Monte Carlo calculations.
- Continuous energy cross section with JENDL-4.0 nuclear data
- Noise source particles with complex-valued weights were emitted from the absorber. The particles were transported in the calculation domain.
- Reaction rates of complex-valued weights with the detector materials were calculated.

Uncertainty Quantification

***N* sets of input parameters**

-Design/operating parameters (only for CROCUS)
-Nuclear data
-Noise source data

CORE SIM+ simulation

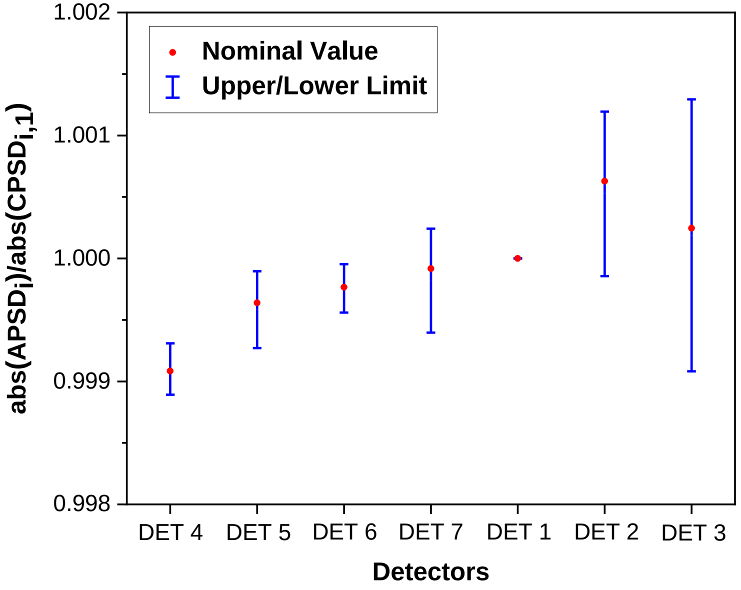
***N* model results**

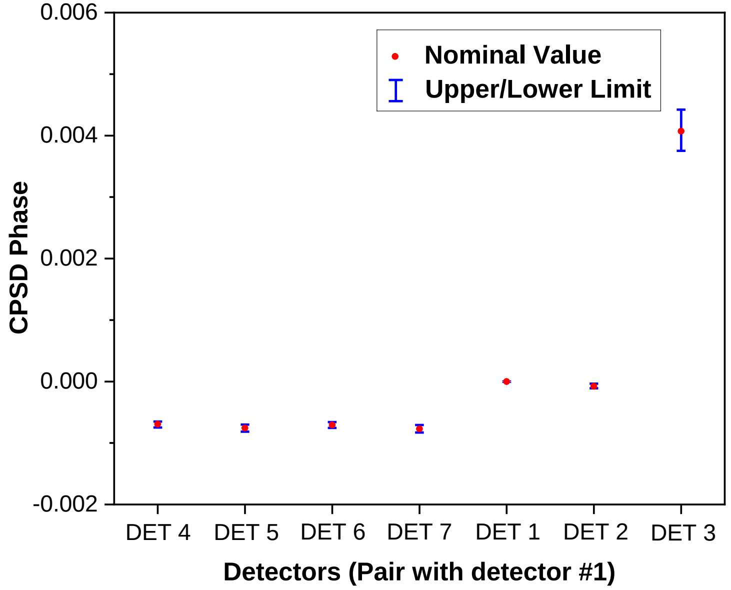
Neutron Noise
(Amplitude, Phase)

UP

SA

I[st] campaign, <u>AKR-2 reactor</u> (Vibrating absorber, Exp 22) ***Uncertainty propagation***



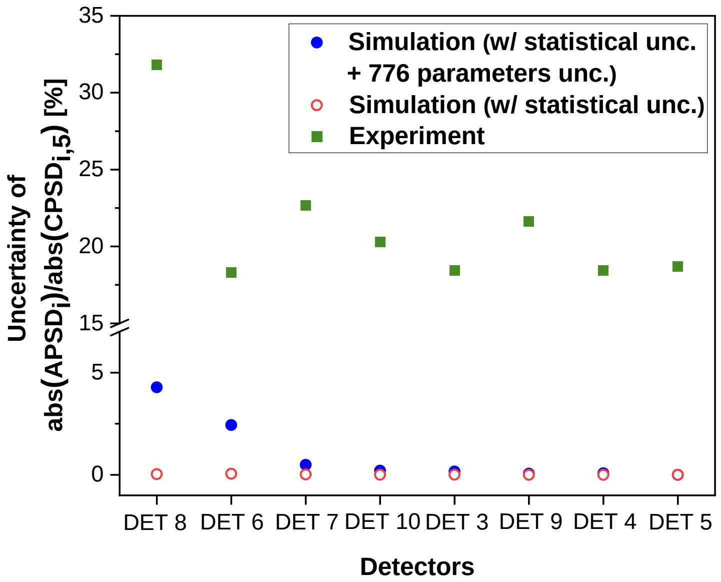


I[st] order Wilks' formula for two-sided limits (based on 93 data sets)

Uncertainty Quantification

1st campaign, CROCUS reactor (Exp13)

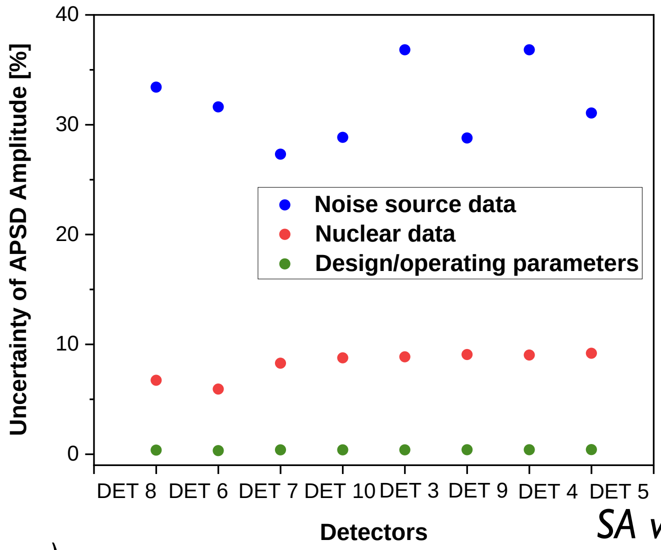
Uncertainty comparison



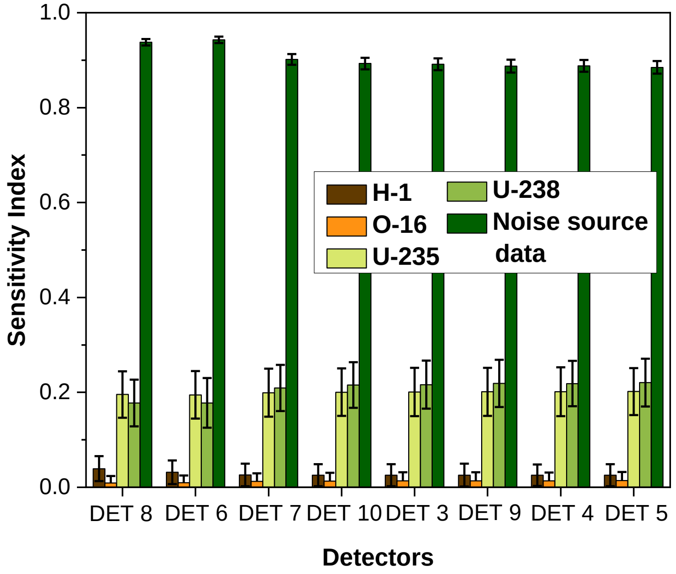
4th order Wilks' formula for two-sided limits (based on 260 data sets)

Sensitivity analysis

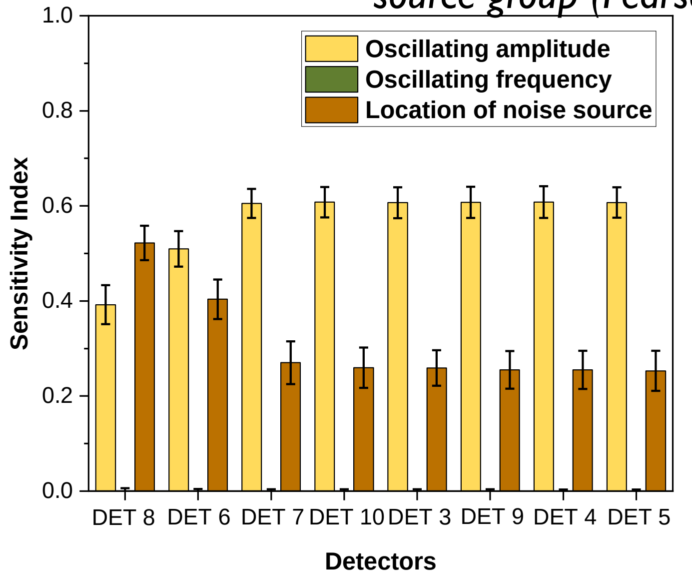
Simplified approach (Grouping parameters into 3 groups)



Groupwise SA (Pearson)

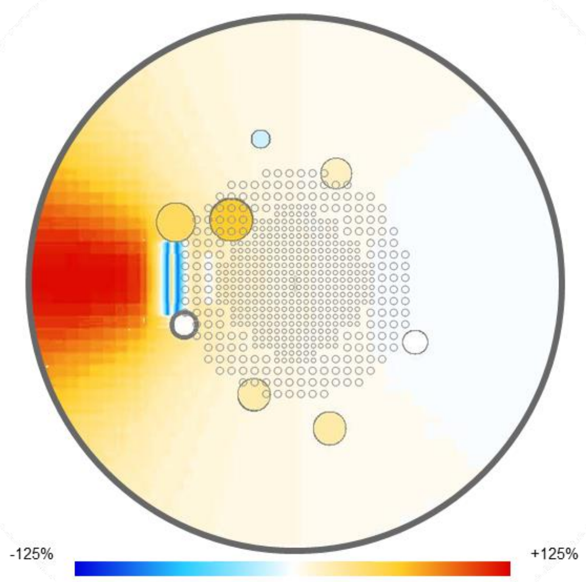


SA with parameters in noise source group (Pearson)

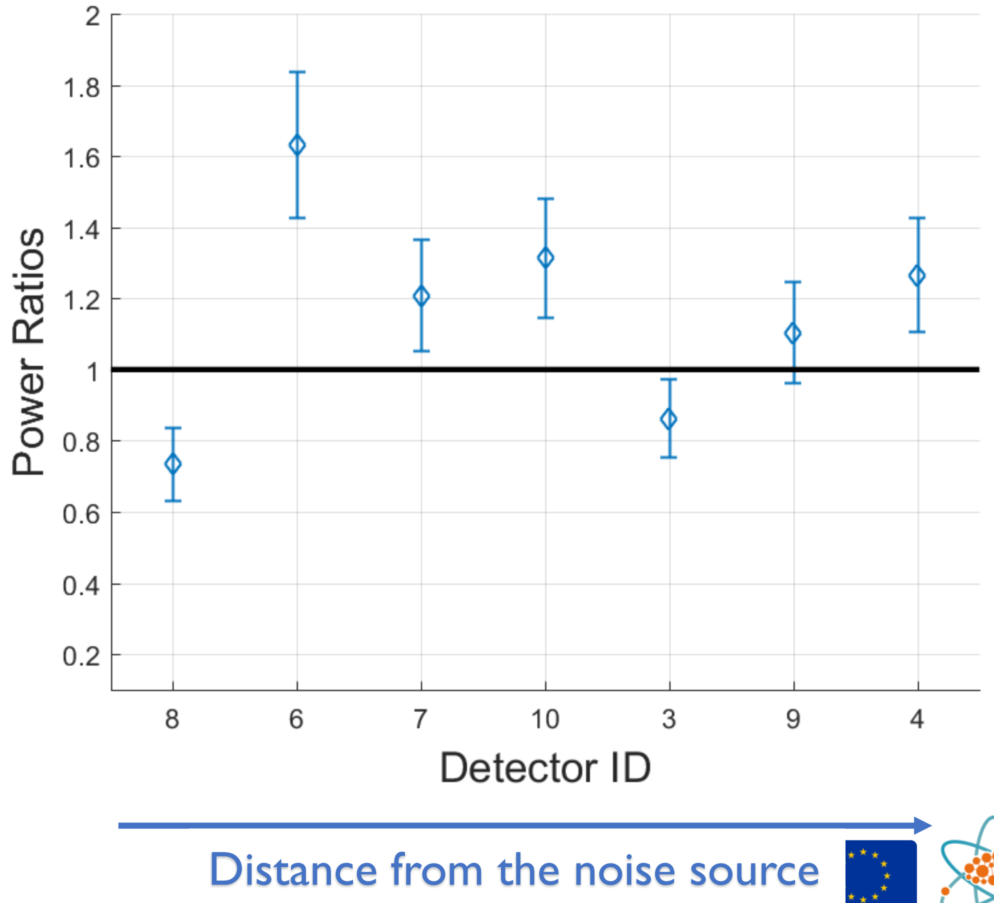


Validation exercises

Comparing measurements and simulations



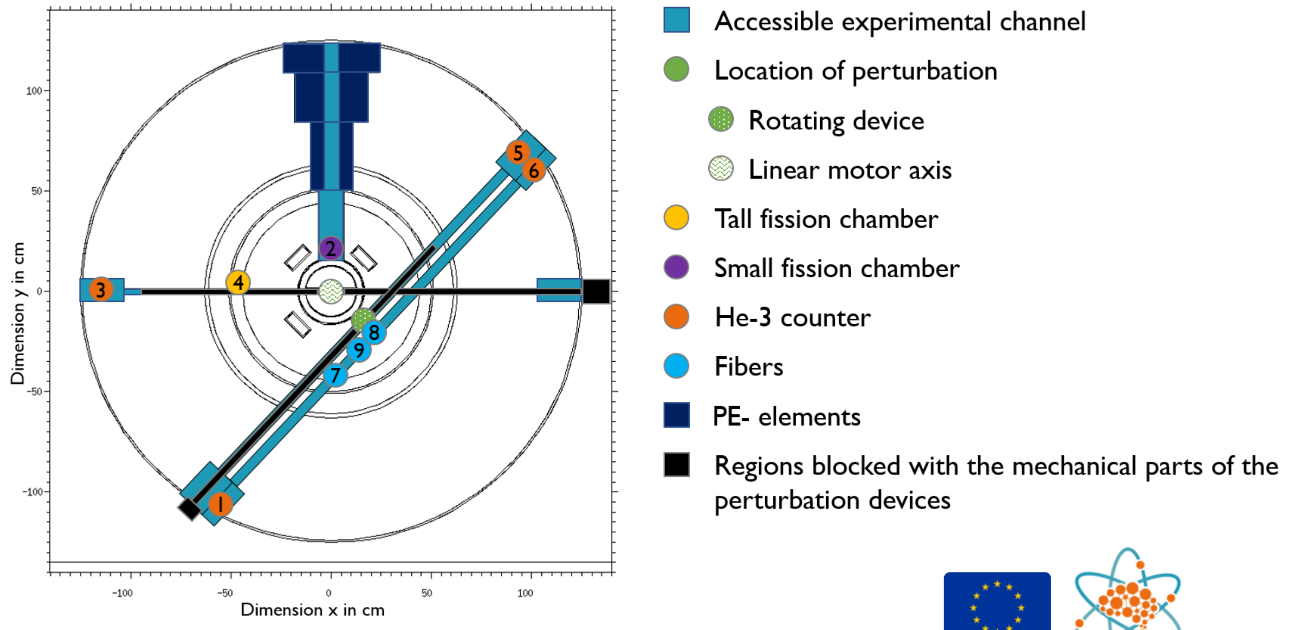
Relative noise amplitude with respect to reference detector (CORESIM+)



AKR-2 benchmarks based on the 2^{nd} campaign

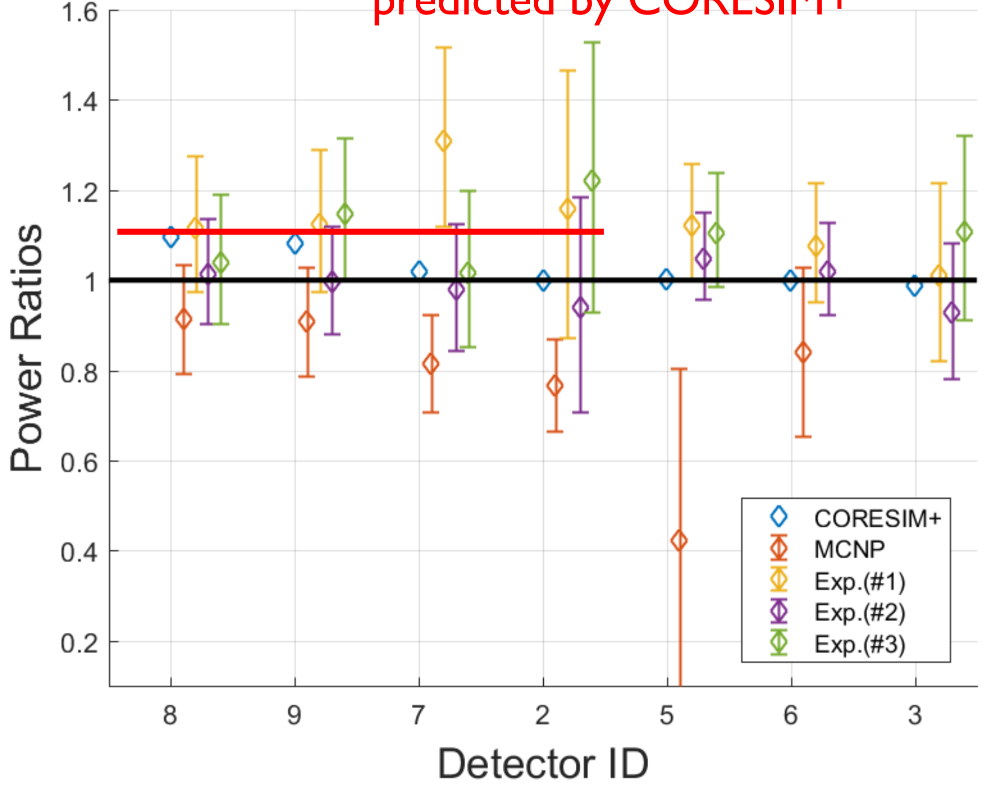
- Measurements
  - # 1 AVS - Freq. 2 Hz
  - #20 VA - Freq. 2 Hz - Amp. ±3 mm – Core center

- Simulations
  - Chalmers – CORE SIM+
  - Kyoto University - MCNP

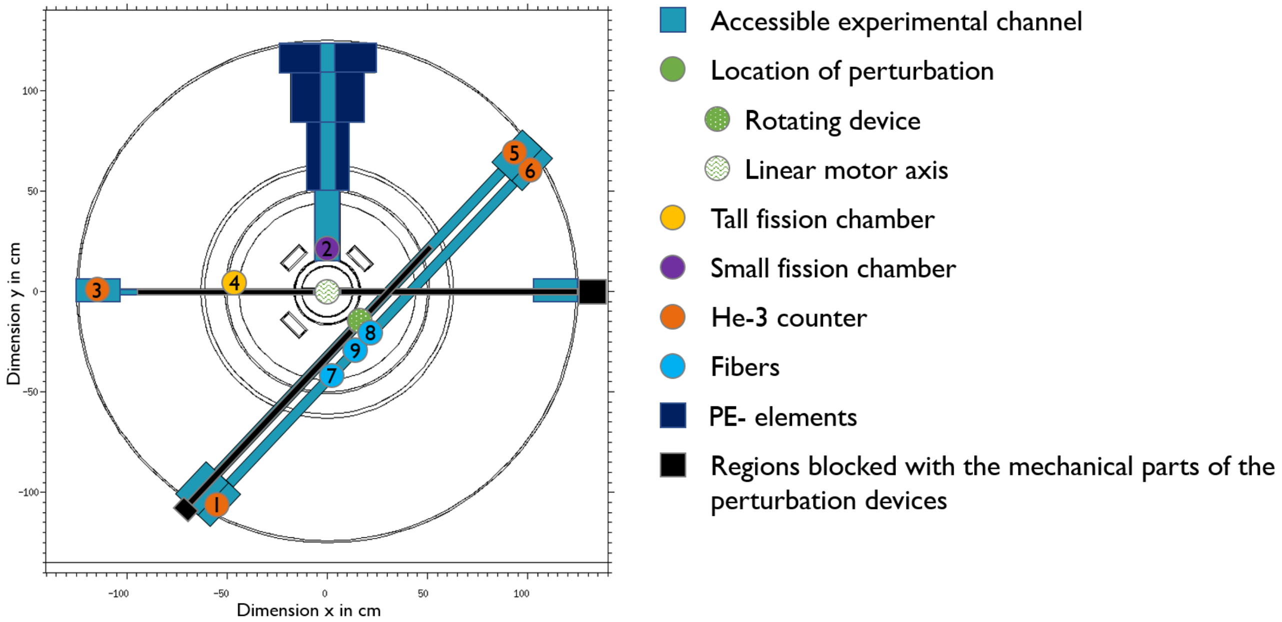


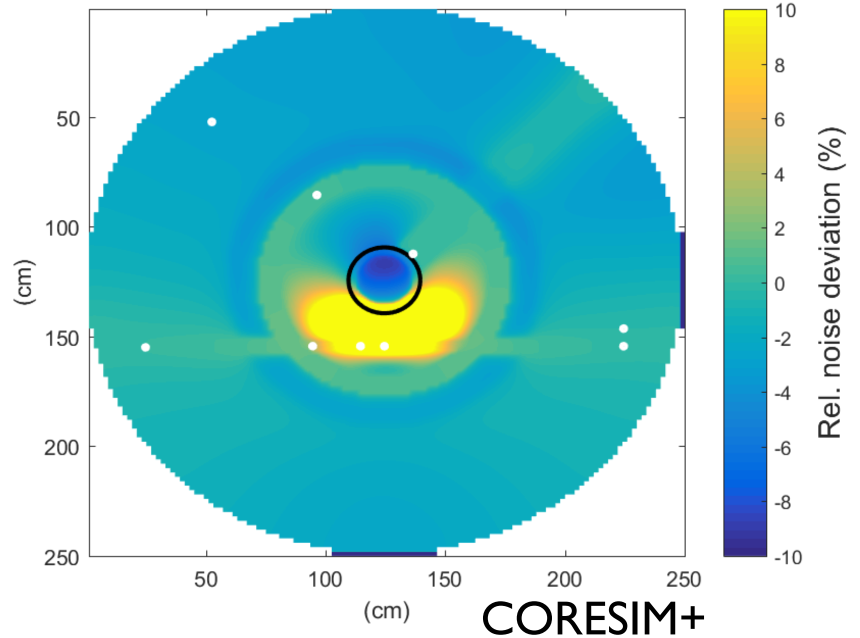
Absorber of Variable strength

Spatial variation (deviation from 1) predicted by CORESIM+



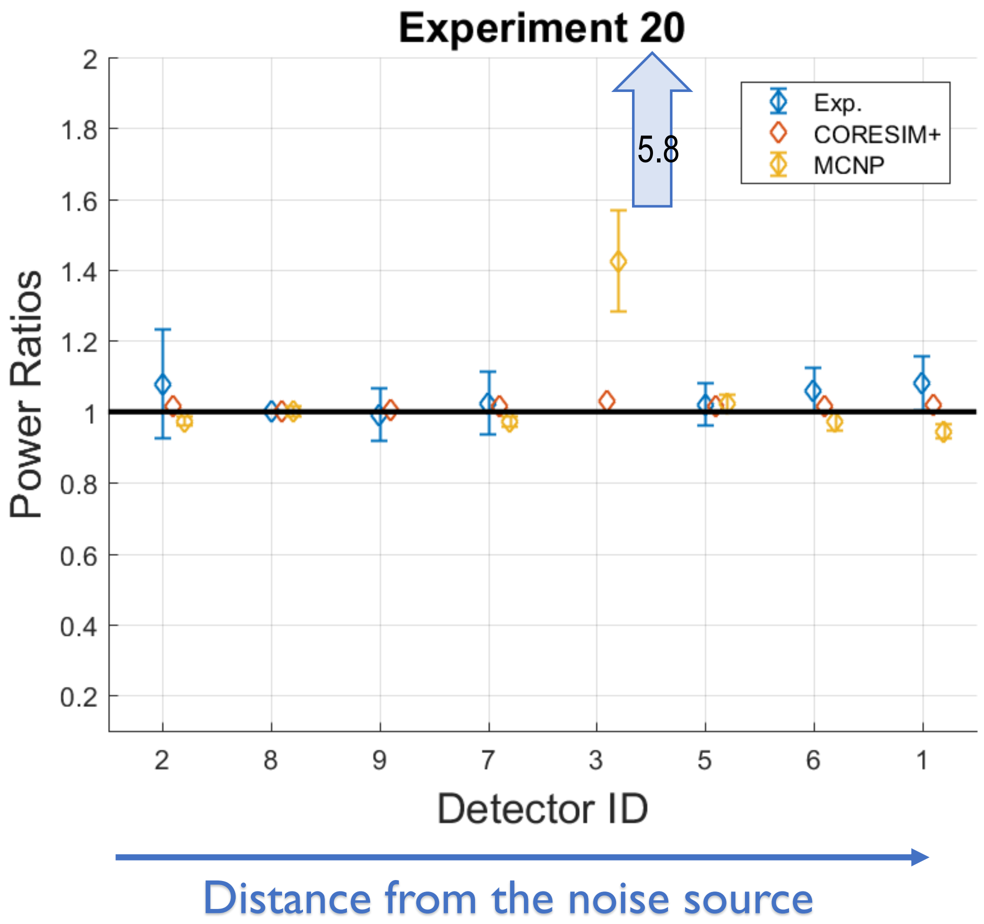
Distance from the noise source

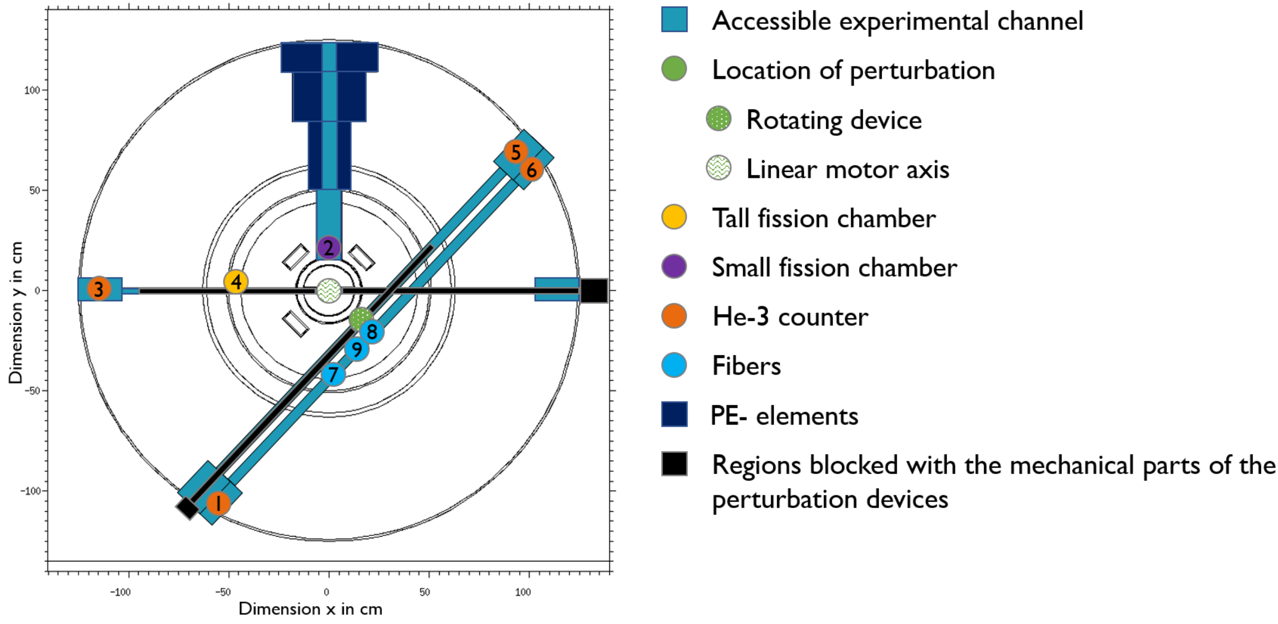




CORESIM+

Vibrating Absorber





Summary of the AKR-2 validation exercises

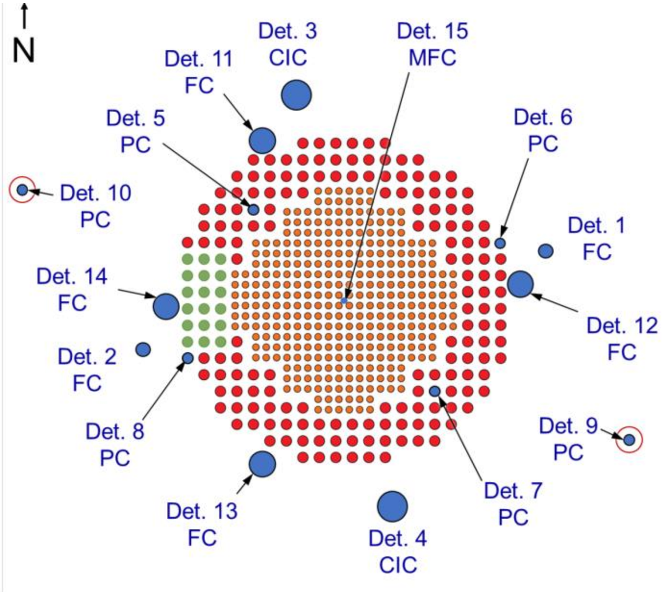
- Overall, codes managed to capture the noise behavior of AKR-2
  - Converging Monte Carlo solution was difficult for certain noise sources
  - Challenging problem for deterministic codes (channels, size of model)

- Repetition of experiments suggests the "computed" experimental uncertainties are reliable

- Observation of spatial effects in AKR-2
  - Experimental uncertainties are too large to resolve the spatial variations predicted in AvS case
  - Some spatial effects are visible experimentally with Det #3 during campaigns 2 & 3
    - ✓ not captured by CORESIM+
    - ✓ partly captured by MCNP

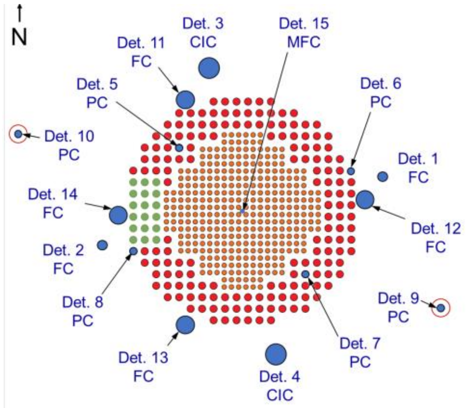
COLIBRI benchmarks based on the 2^{nd} campaign

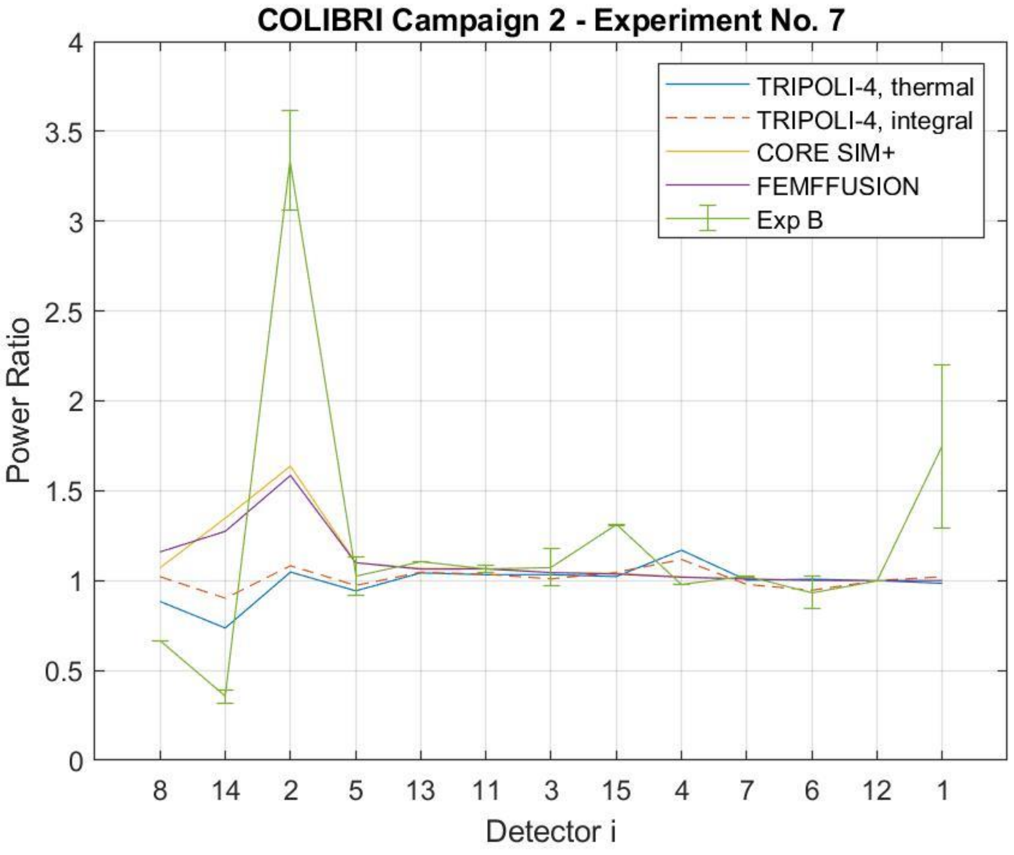
- Measurements
  - # 7. Power: 1 W - Amp.: ±1.5 mm - Freq.: 0.1 Hz
  - # 8. Power: 1 W - Amp.: ±1.5 mm - Freq.: 1 Hz
  - Detector #12 is the reference



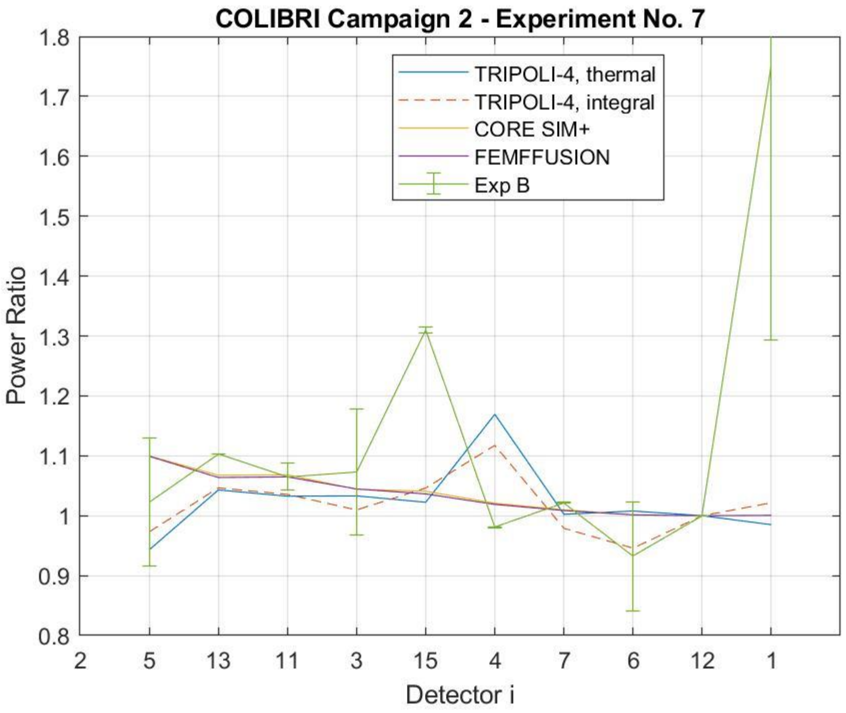
- Simulations
  - CEA – TRIPOLI-4® (w/ and w/o detector model)
  - UPV – FEMFFUSION
  - Chalmers – CORE SIM+

Experiment 7: abs(APSD(i))/abs(CPSD(i,12))



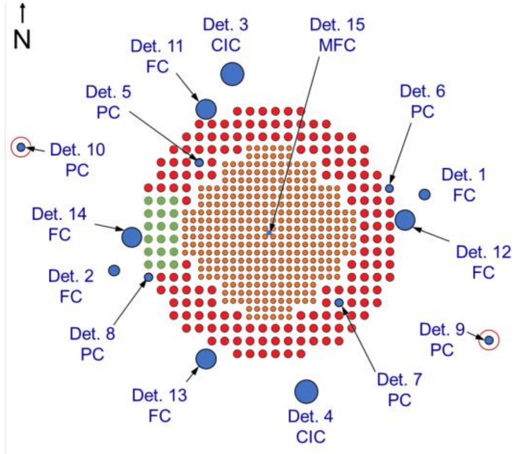


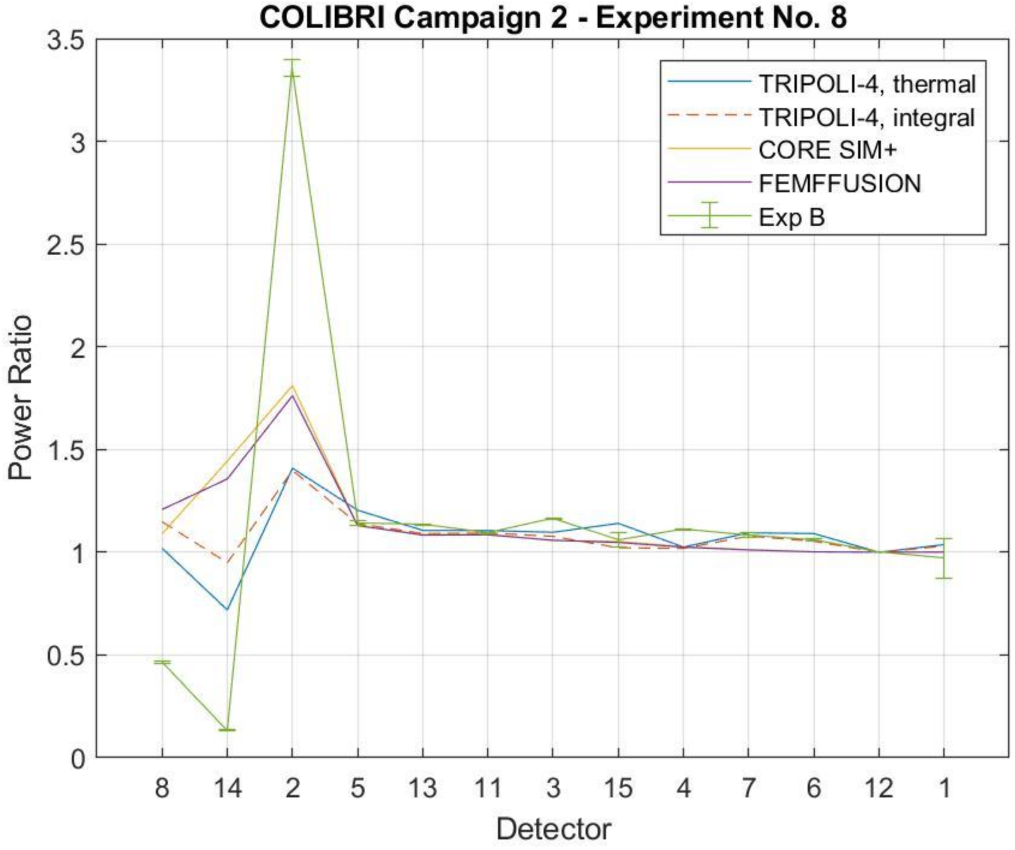
Distance from the noise source



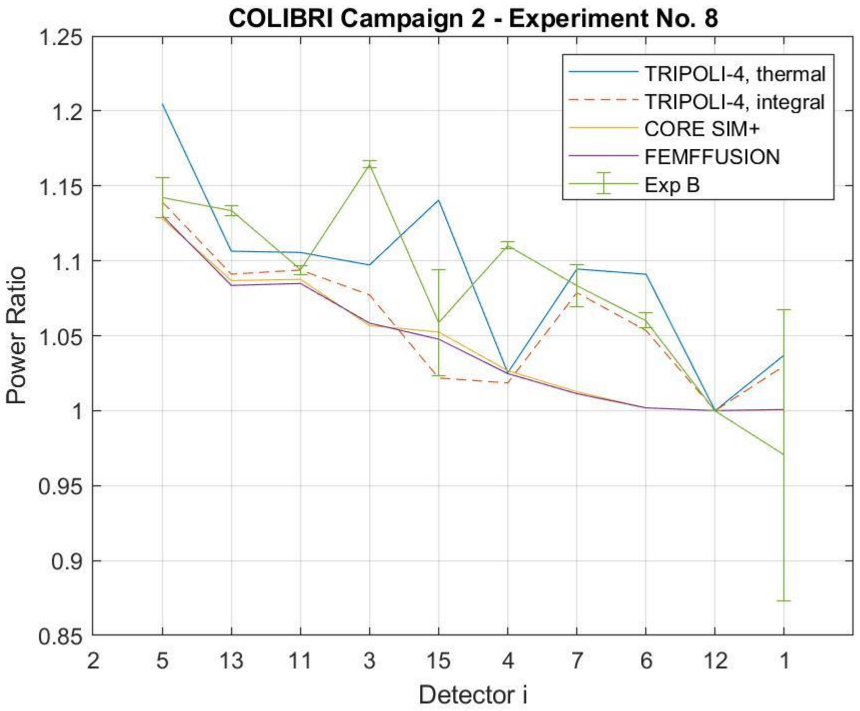
Distance from the noise source

Experiment 8: abs(APSD(i))/abs(CPSD(i,12))





Distance from the noise source



Distance from the noise source

Summary of the COLIBRI validation exercises

- Overall, the codes managed to capture the noise behavior in CROCUS, except close to the noise source.
- Statistically significant deviations from a power ratio equal to 1 are observed even relatively far from the source. The magnitude of the deviations increase with increasing frequencies.
- There is a clear phase difference for Det #14 (behind COLIBRI w.r.t to the core).
    - phase difference only capture partly by the MC solution (TRIPOLI)

Conclusions

Global Summary for WP2

- Modeling the research reactors has proven extremely difficult, both for determinist and stochastic approaches

- Overall, noise simulators performed very well, except close to the noise source and in certain locations

- Intense dialog between modelers and experimentalists was key to achieve those goals

- Our facilities do not allow large deviations from PKE behavior far from the source.
  - There may be experimental evidence of deviations.
  - Spatial effects have been observed in AKR-2

Thank you

Processing the time series

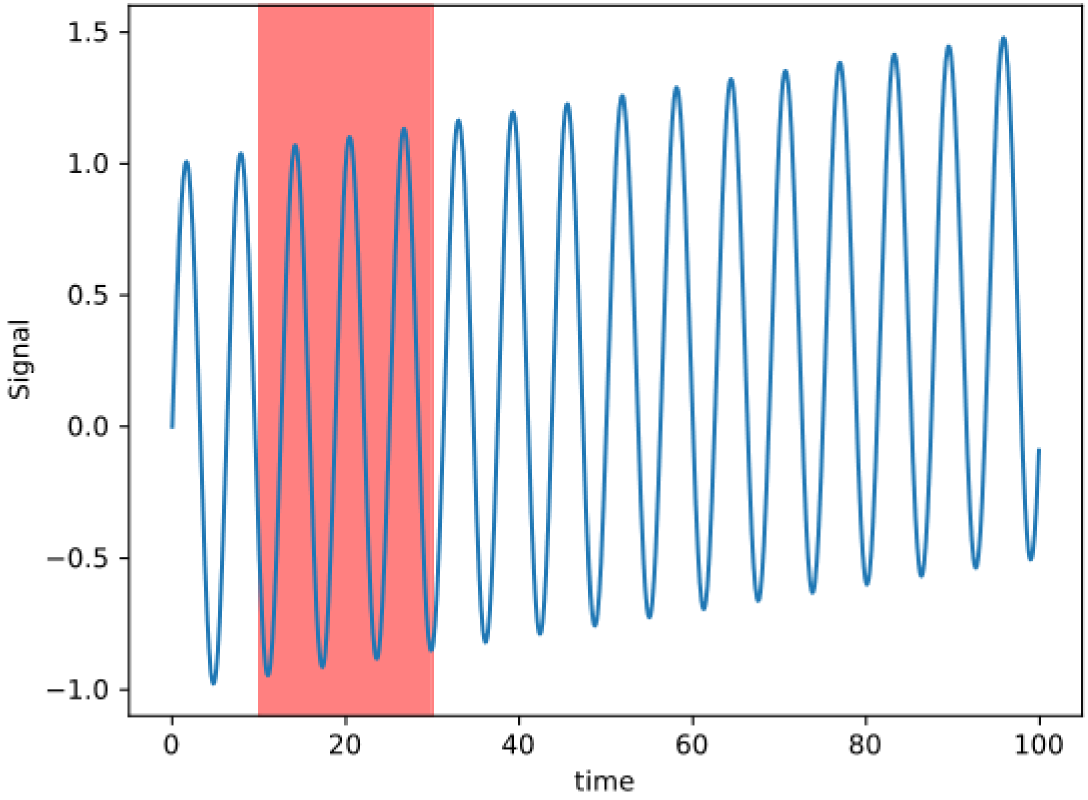
Detrending & normalization

- Subtraction and division of data by rolling mean

$$x_{norm}(t) = \frac{x(t) - \mu_{roll}(t)}{\mu_{roll}(t)}$$

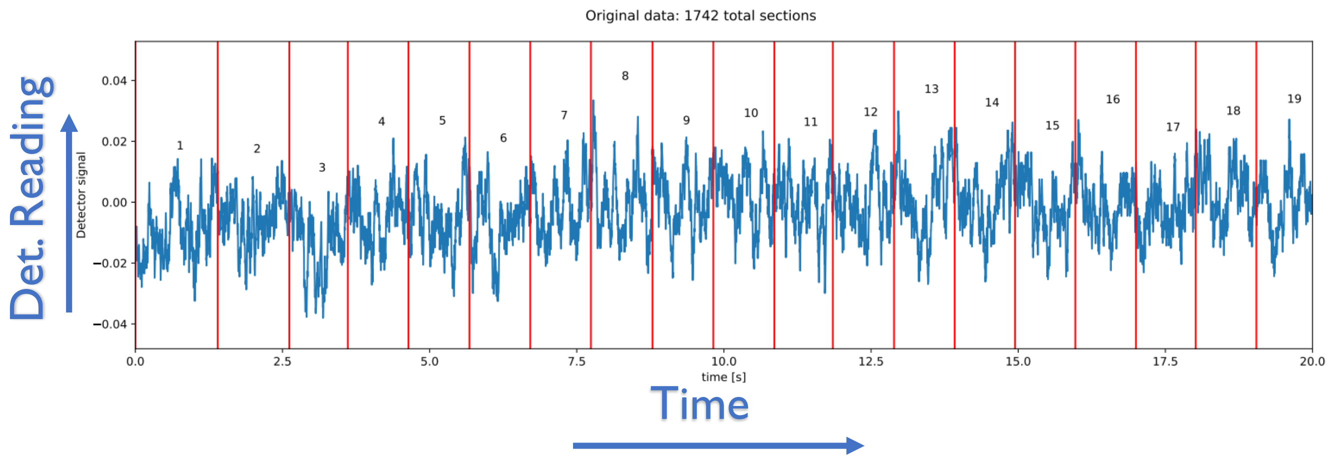
- Rolling mean usually calculated as moving average 10 base frequency periods (M samples).

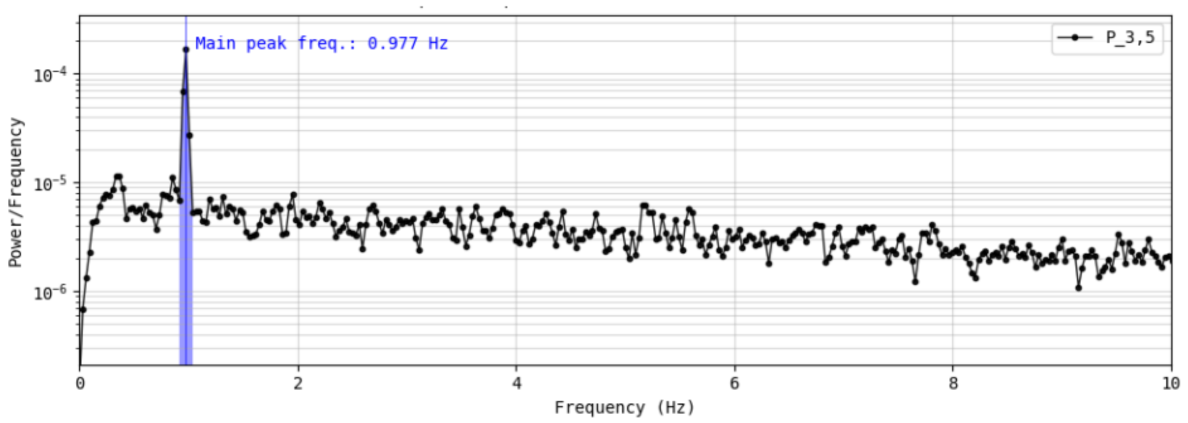
$$\mu_{roll}(t) = conv\big(x(t), Box(M)\big)$$



Extracting QoI from experimental data [1]

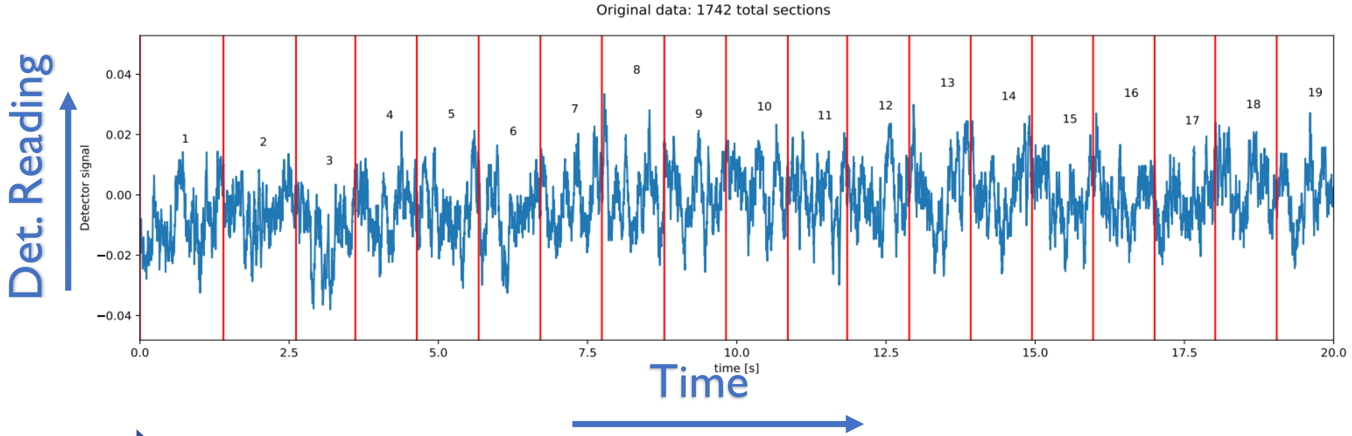
- Direct estimate from PSD calculation (Welch method) is not ideal:
  - Requires (very) long acquisition for statistical significance
  - Forcing sensitivity to local variations and biases (within sections), i.e. hidden temporal correlations





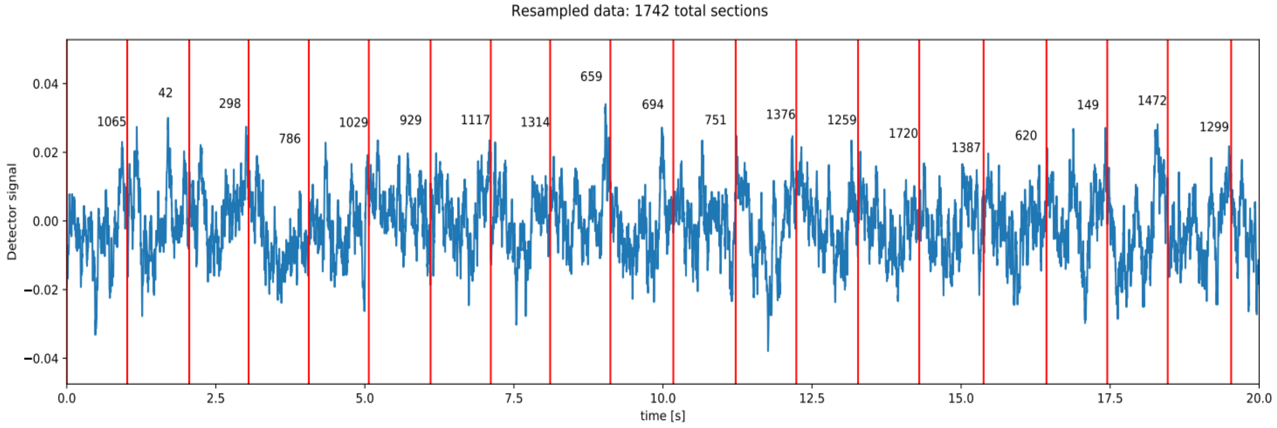
Extracting QoI from experimental data [2]

- Bootstrapping with replacement:
  - Signal is chopped into sections and reordered randomly
  - Sectioning based on oscillations
  - One periodogram obtained per sample of timeseries
  - Statistics on the population of periodogram results

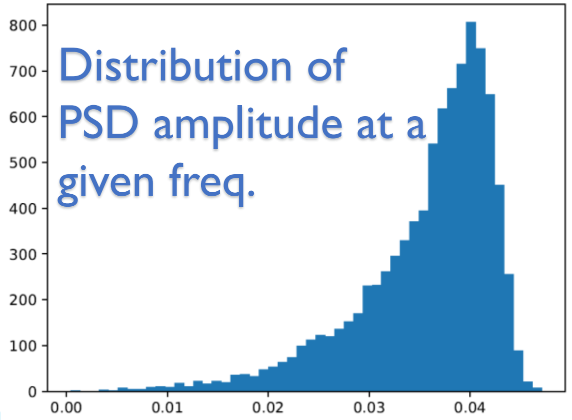


Cut and randomly reorder

Repeat n times

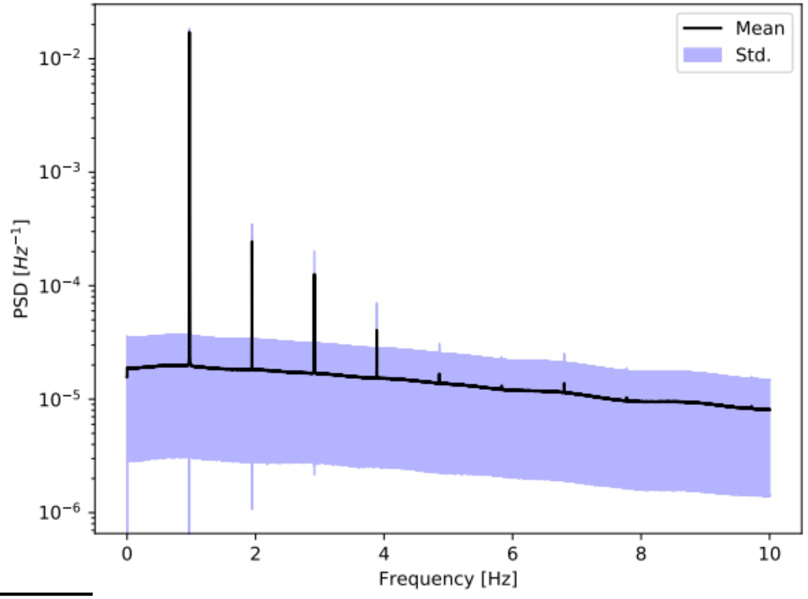


FFTs (n times)



Determine mean and standard deviation for a $PSD_{i,j}$

Extracting QoI from experimental data [3]



- Use of CPSD to filter intrinsic noise

- Combination of mean and standard deviations of CPSDs to produce Power Ratio for detector *i* at frequency *f*:

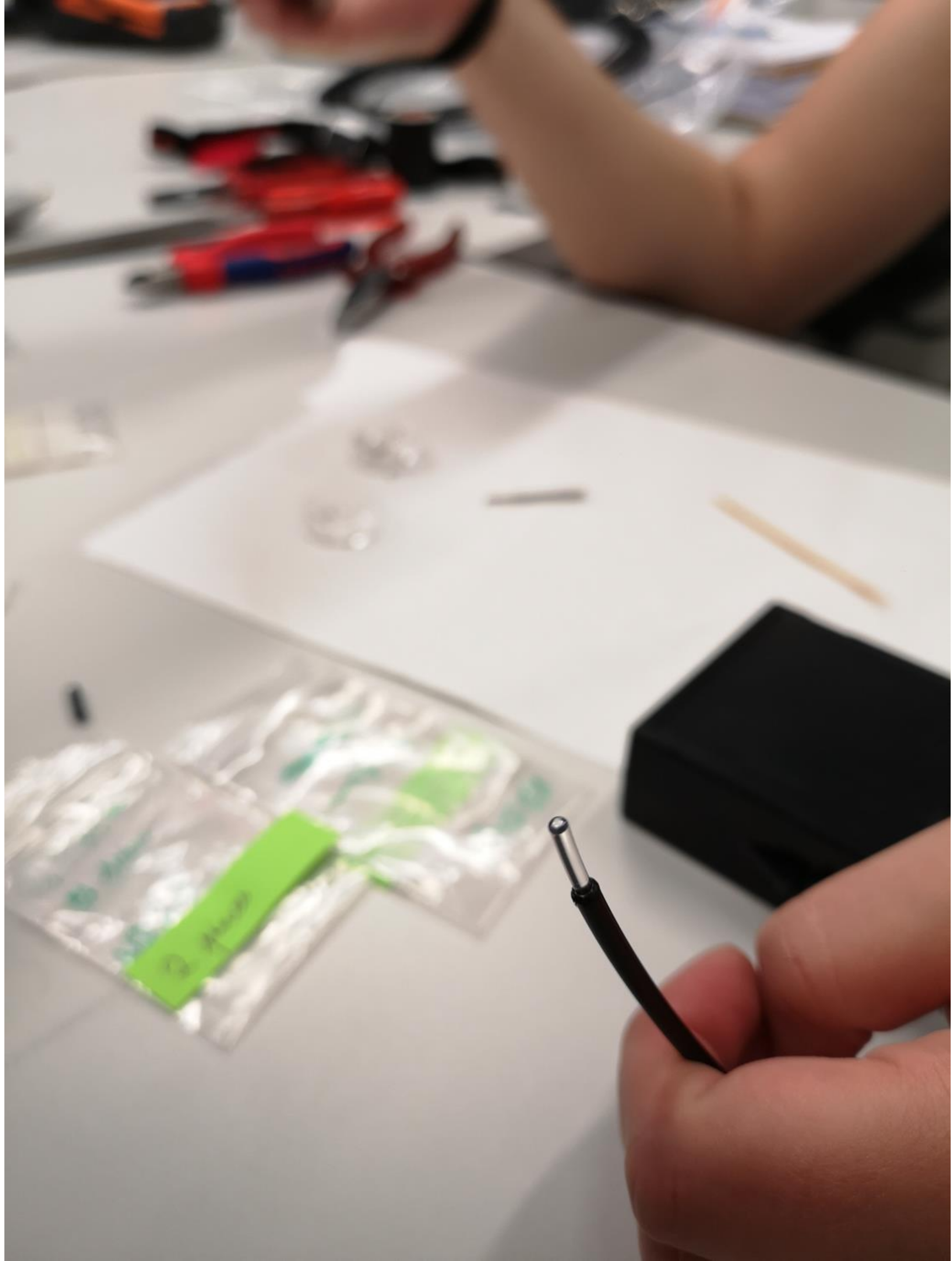
$$P_i(f) = \sum_j w_j \frac{CPSD_{j,i}(f)}{CPSD_{j,ref}(f)} \qquad \sigma_{P_i}(f) = \sqrt{\frac{1}{N-1}\sum_j \left(\frac{CPSD_{j,i}(f)}{CPSD_{j,ref}(f)} - P_i(f)\right)^2}$$

- w_j is based on :
  - the standard deviation of PSD distributions
  - the 90% percentile of the PSD distributions

Development of fiber-based detectors

Optical fibers

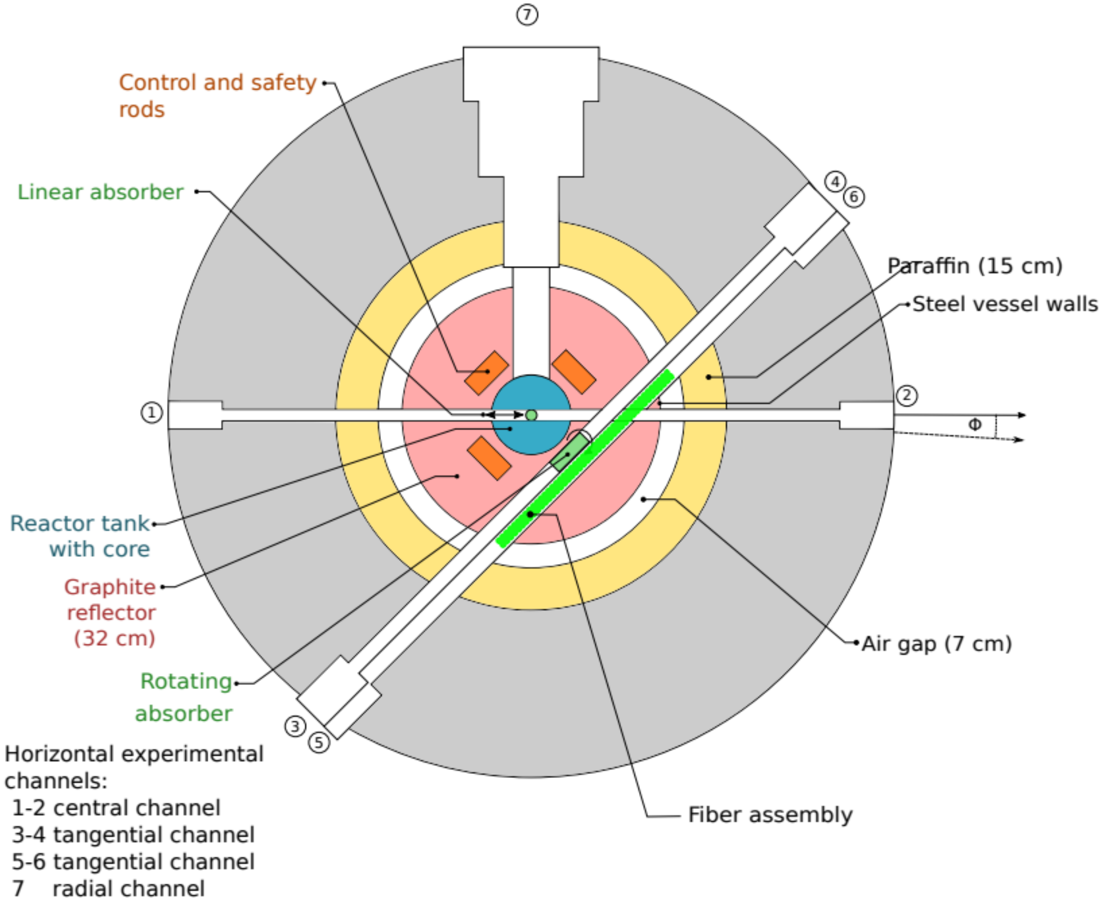
- **~0.5 mm x 0.5 mm Li6 ZnS scintillator**
- **Plastic optical fiber**
- Photo-multiplier
- Shaping preamp + discriminator
- Counter



Optical fibers

- ~1mm x 1mm Li6 ZnS scintillator
- Plastic optical fiber
- Photo-multiplier
- Shaping preamp + discriminator
- **Counter**

Utilization at AKR-2 second campaign



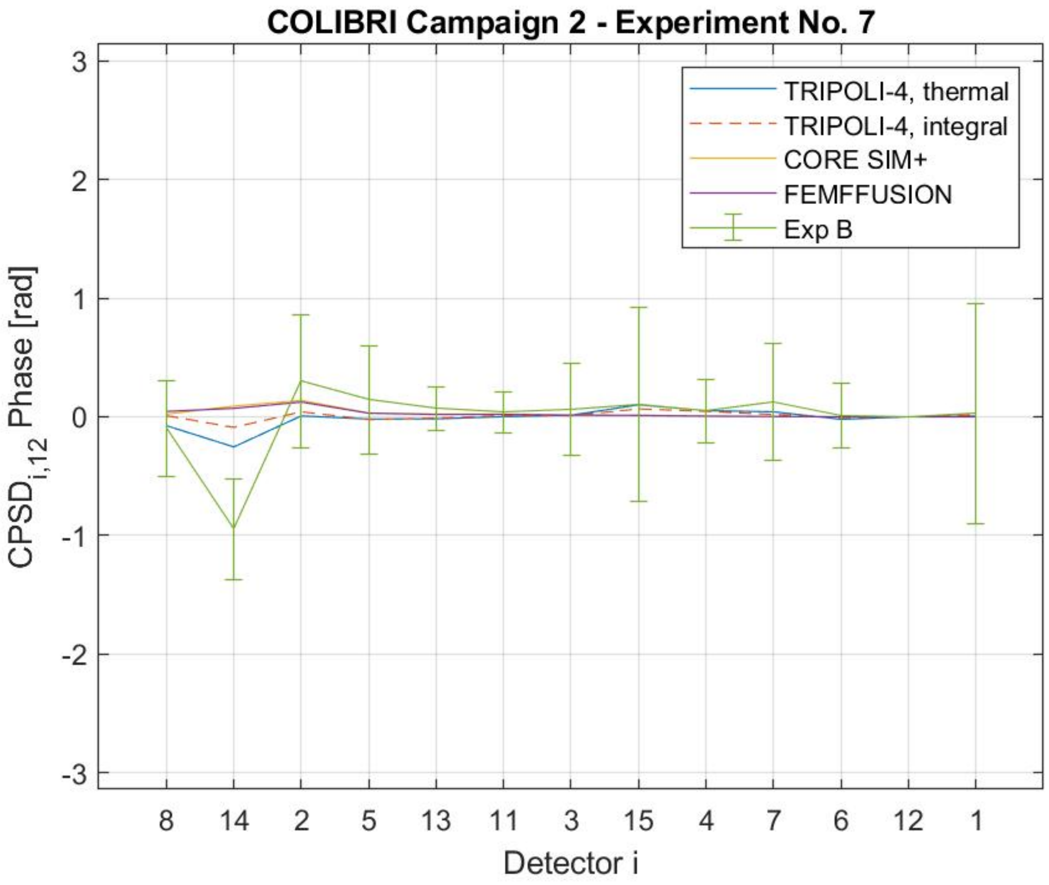
Prototype testing:

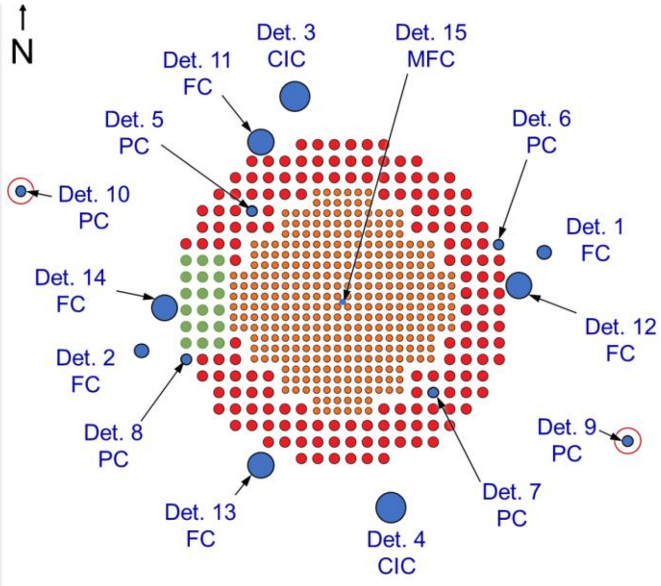
- Low dead time up to 15 W (CROCUS)
- Original fibers with jacket (thicker)
- Covered with aluminum cap
- Used with separate shaping amplifier + SCA

- Too large for core mapping

Validation exercises

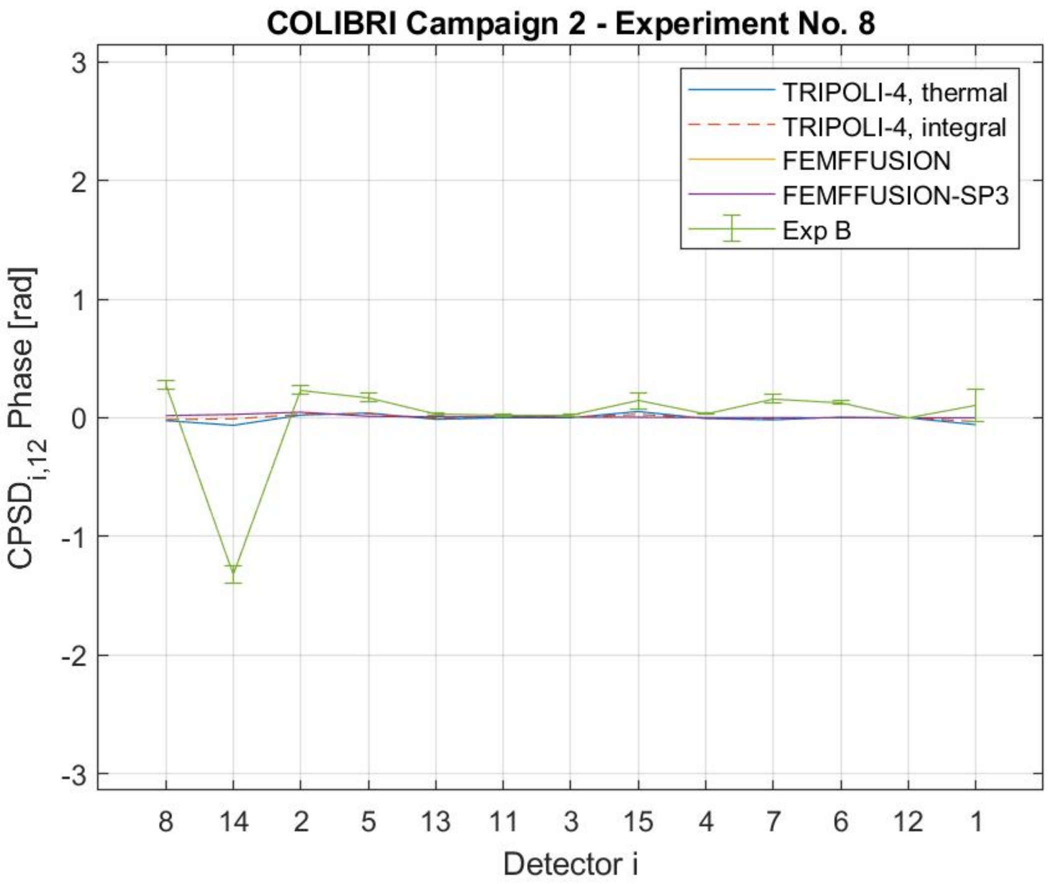
Experiment 7: angle(CPSD(i,12))

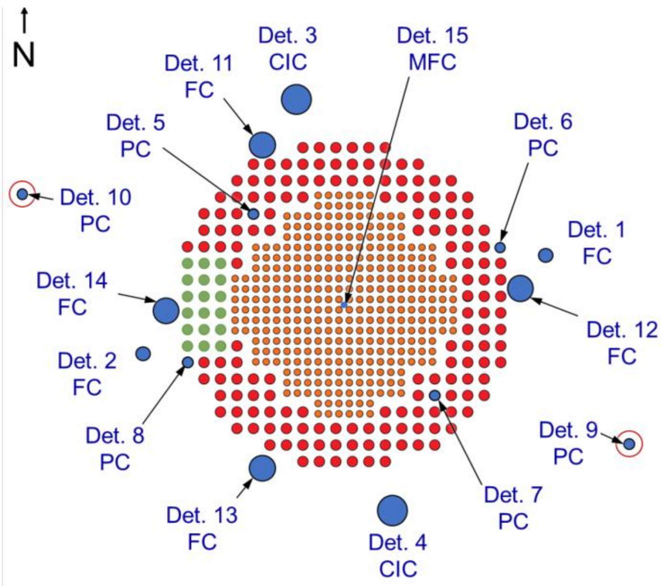




Distance from the noise source

Experiment 8: angle(CPSD(i,12))





Distance from the noise source