CORTEX

Core monitoring techniques and
experimental validation and demonstration

CROCUS experimental campaigns

TUD | 23-24.03.2021, online

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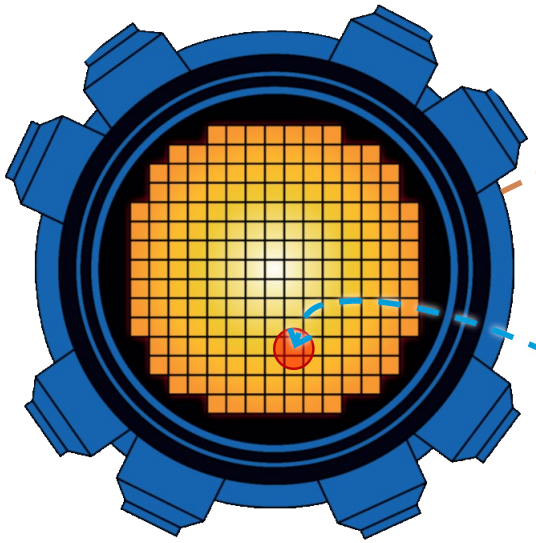
CROCUS experimental campaigns



In-core and ex-core detectors' signals

Signal processing

Machine learning trained with validated simulation tools

Anomaly characterisation and localisation

Contents

Introduction

- The CROCUS reactor
- The COLIBRI fuel rods oscillator
- Experimental campaigns

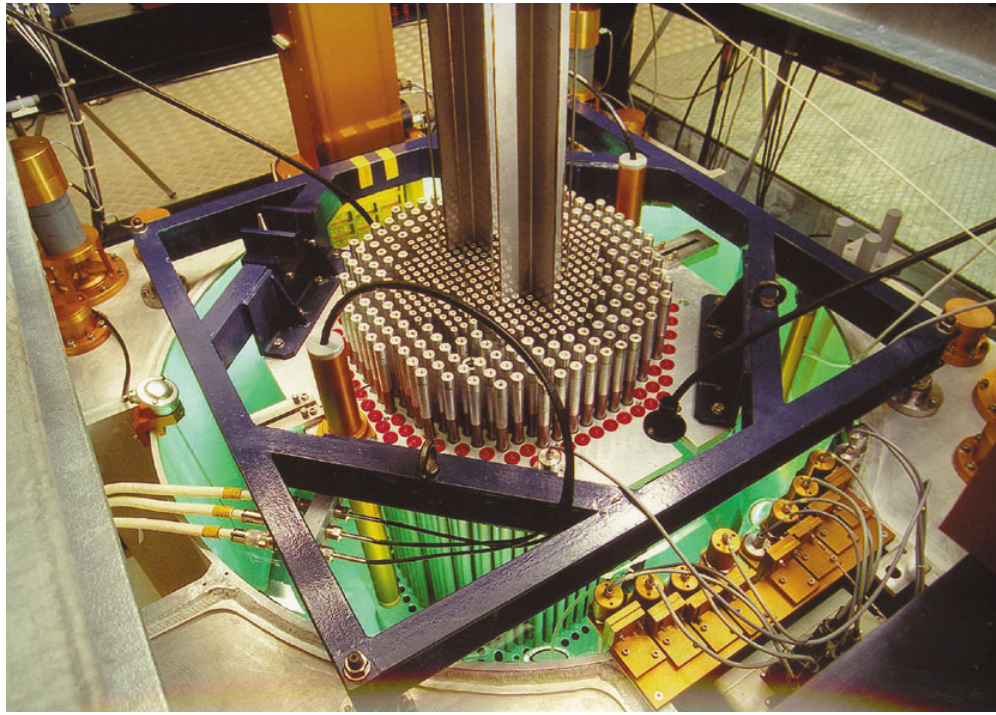
Conclusions & outlook

CROCUS and COLIBRI

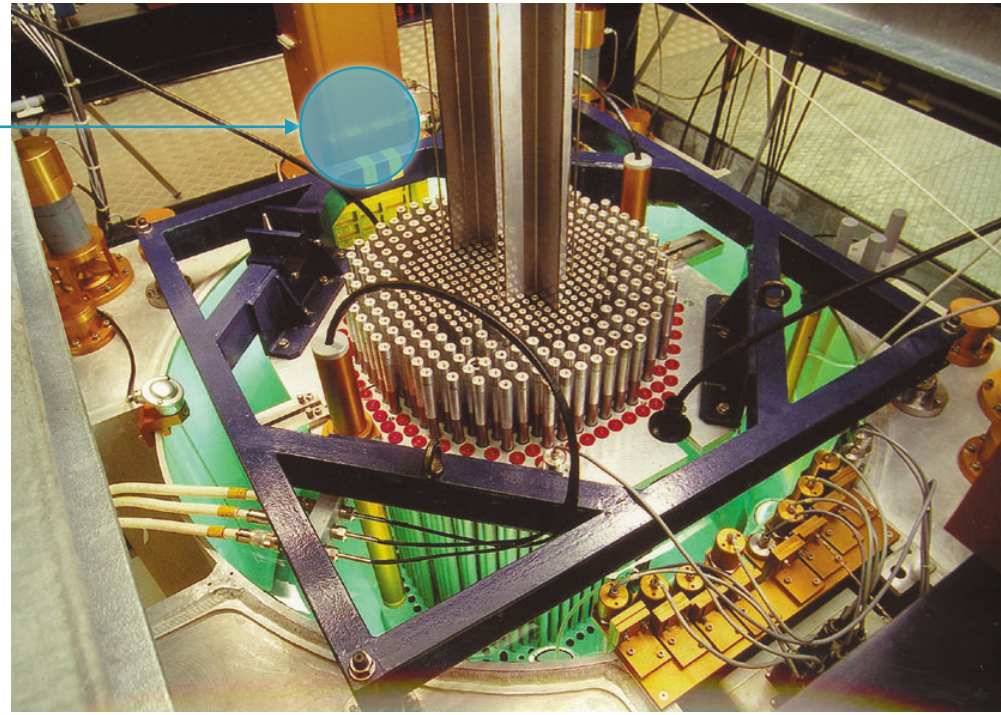
The CROCUS reactor

Reactor type

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



The CROCUS reactor

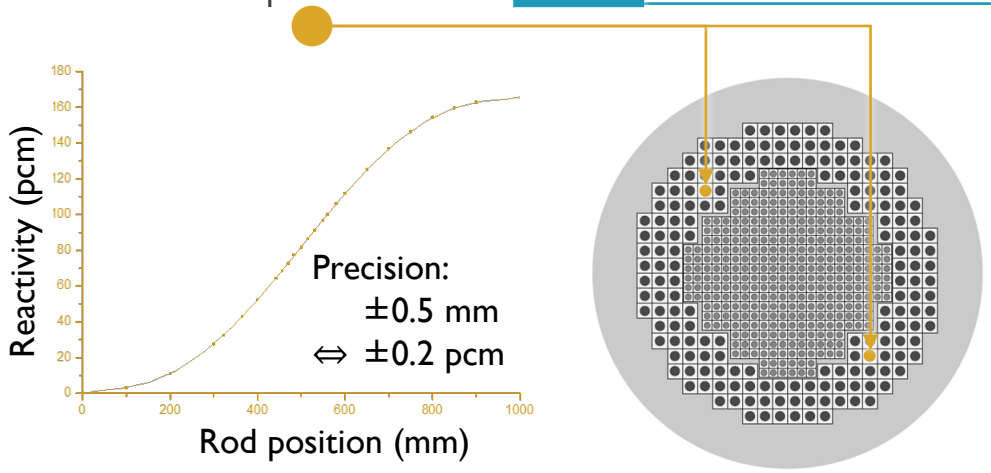


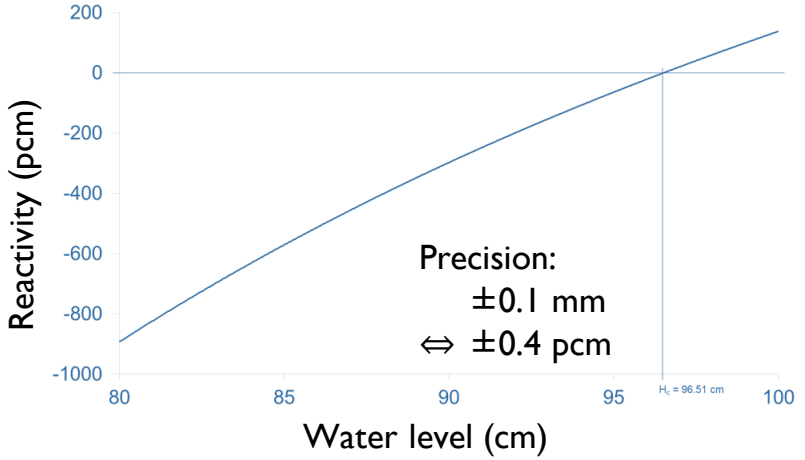
Reactor type

- 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





The CROCUS reactor

Reactor type

- LWR with partially submerged core
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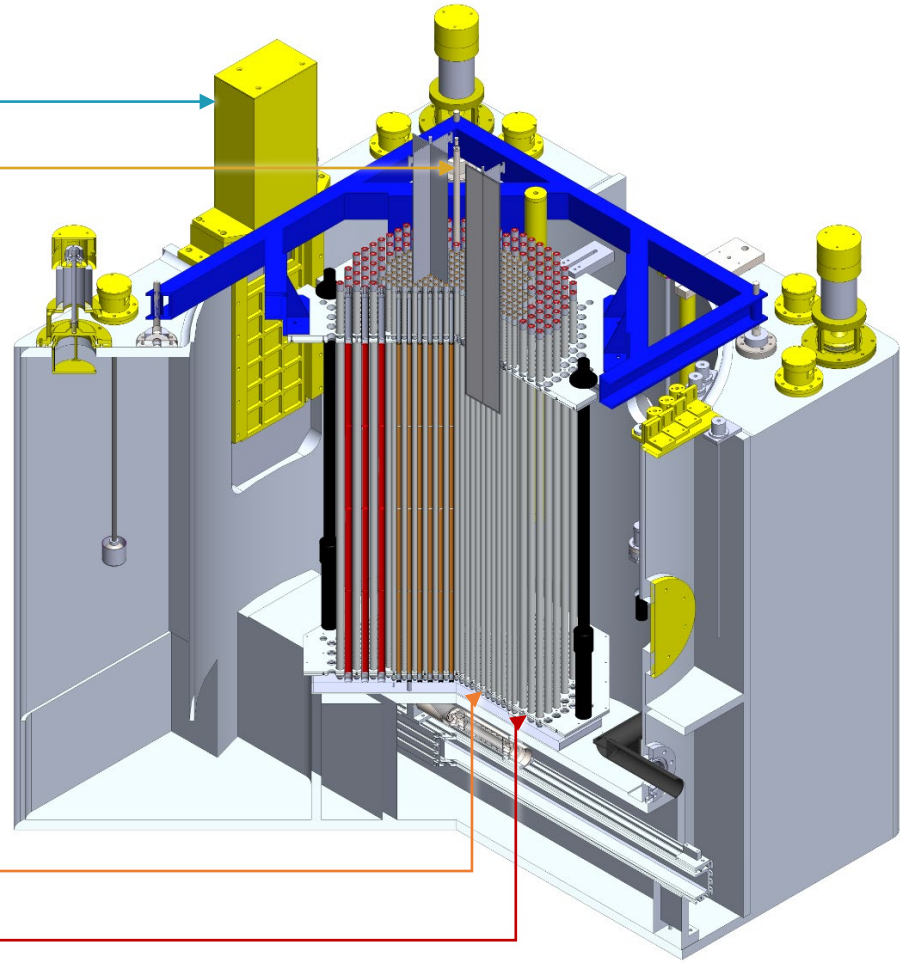
- Forced water flow (160 $l.min^{-1}$)

Operation

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

Core

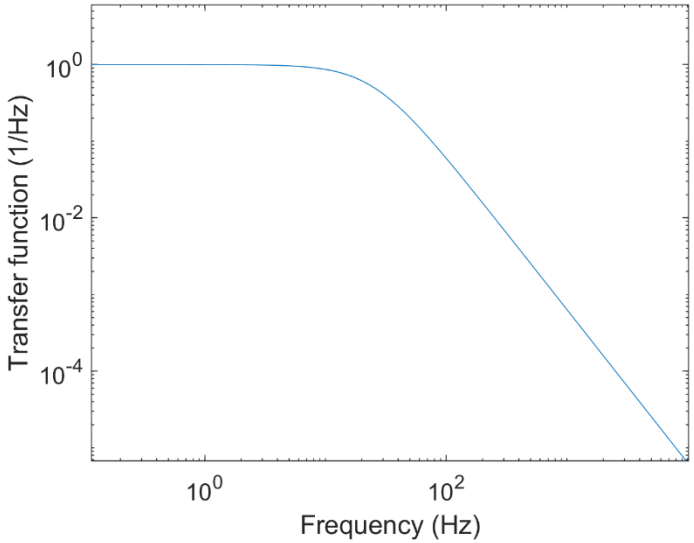
- ⌀60 cm/100 cm, 2-zone
- Inner: 336 UO_2 1.806 wt% 1.837 cm
- Outer: 176 U_{met} 0.947 wt% 2.917 cm



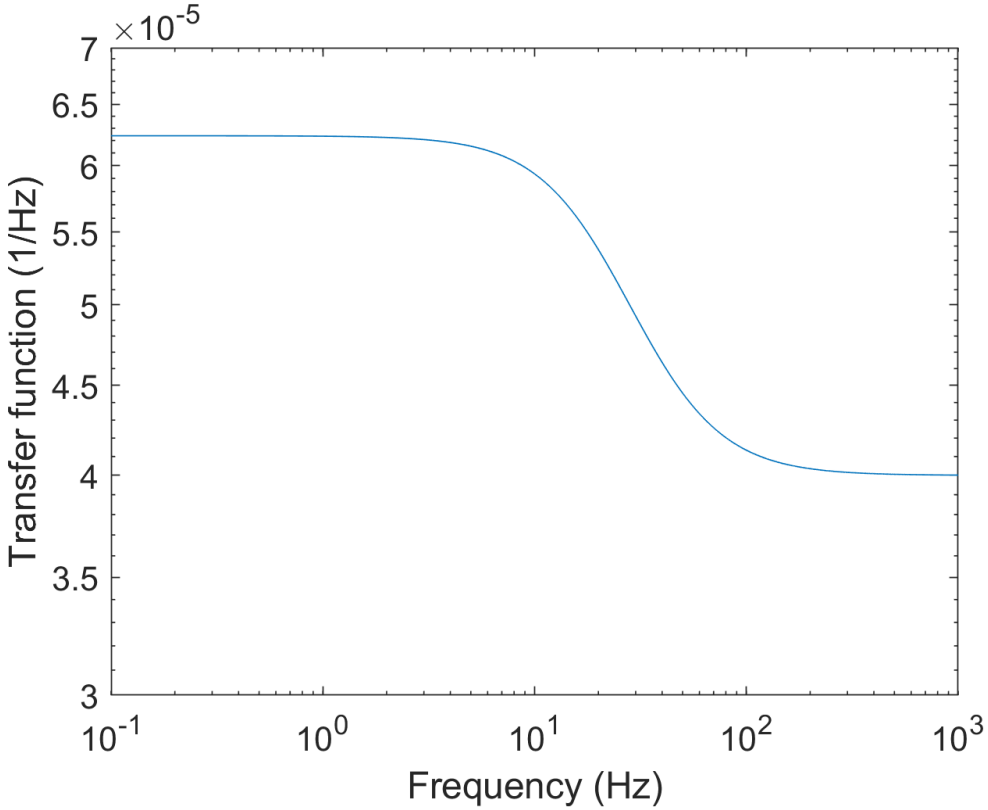
The CROCUS reactor

Kinetic parameters & ZPTF

MCNPv5-1.6 with JEFF 3.1.1		**Estimate**
Generation time	Λ	47.82 ± 0.05 µs
Beta effective	β_{eff}	759 ± 7 pcm



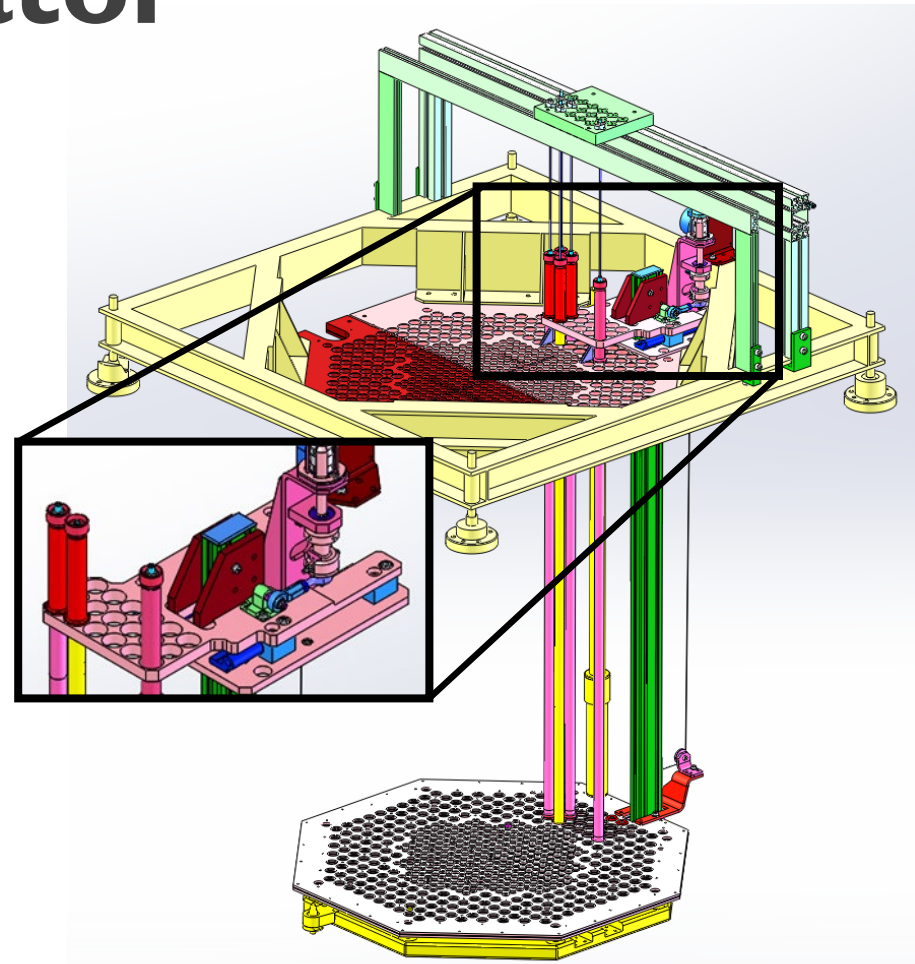
ZPTF



Estimated intrisic APSD from an efficient detector (10^{-5})

COLIBRI fuel rods oscillator

Design for investigating power fluctuations induced by fuel oscillations

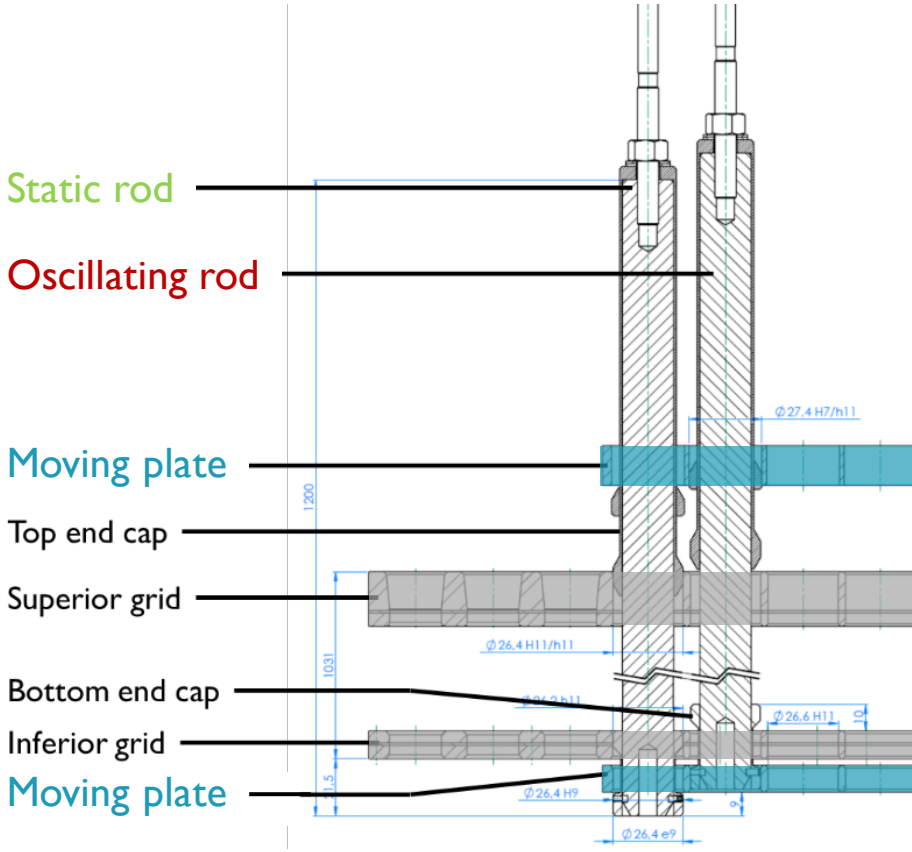


Oscillator with core structures,
and few pins inserted in the device

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

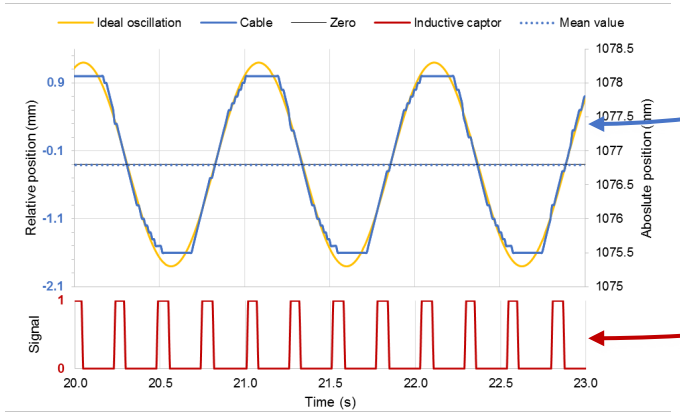


Working principle of the final design

COLIBRI fuel rods oscillator

Design[1] 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



Cable

Inductive captor

Mechanical captors and signals
(1 rod in air, ±1.5 mm and 1 Hz)

[1] V. Lamirand *et al.*, "The COLIBRI experimental programme in the CROCUS reactor: development and licensing of a fuel rods oscillator," *RRFM/IGORR 2019*, Swemieh (Jordan), 24-28 March 2019.

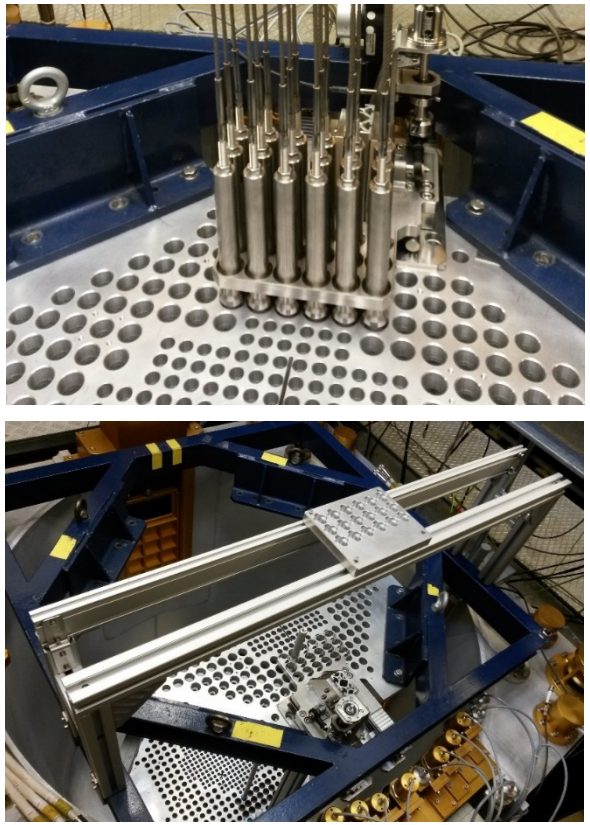
COLIBRI fuel rods oscillator

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.

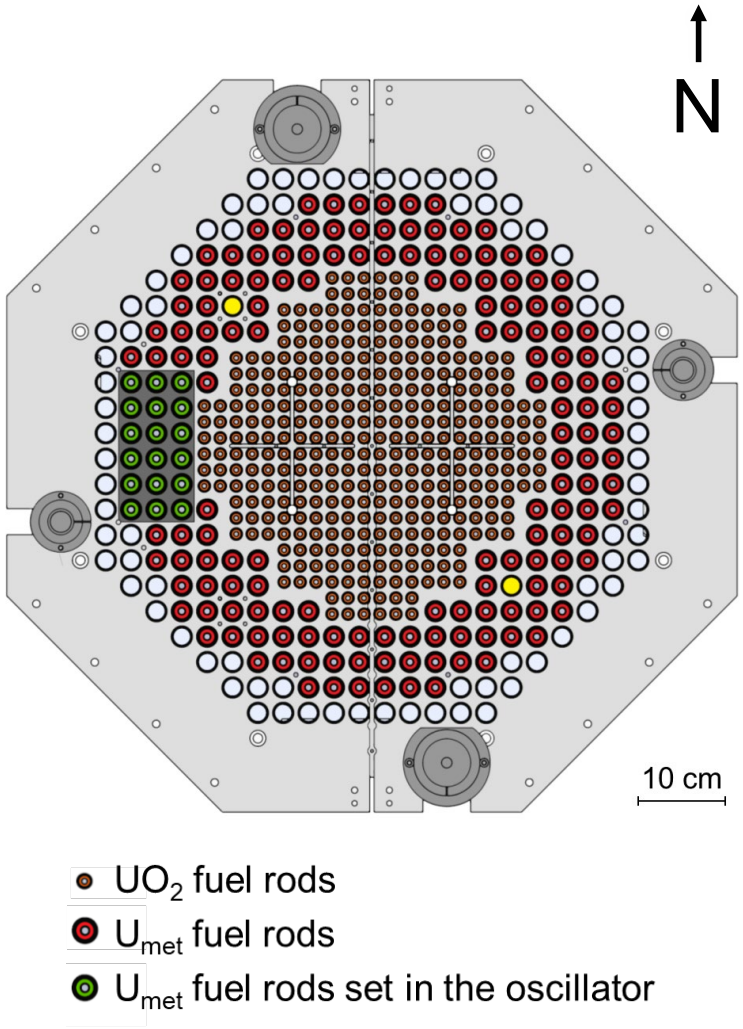
I st Experimental campaign

17-21 September 2018

Detection setup

Goals

- Catch non-point kinetics spatial dependence

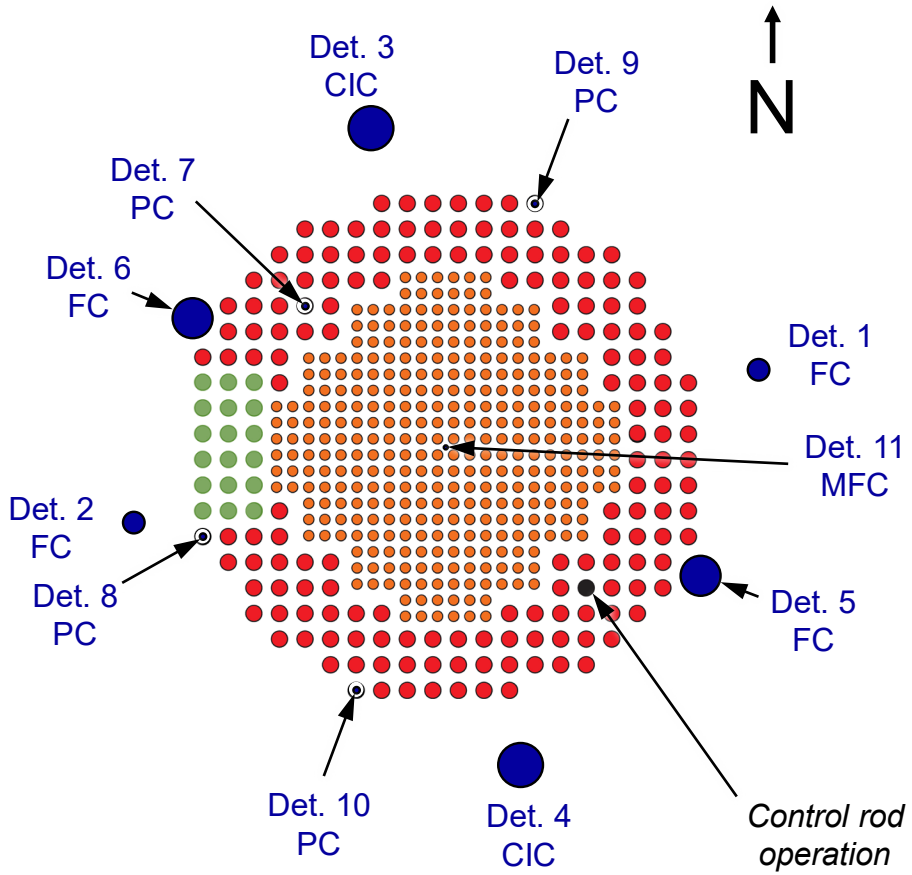


Detection setup

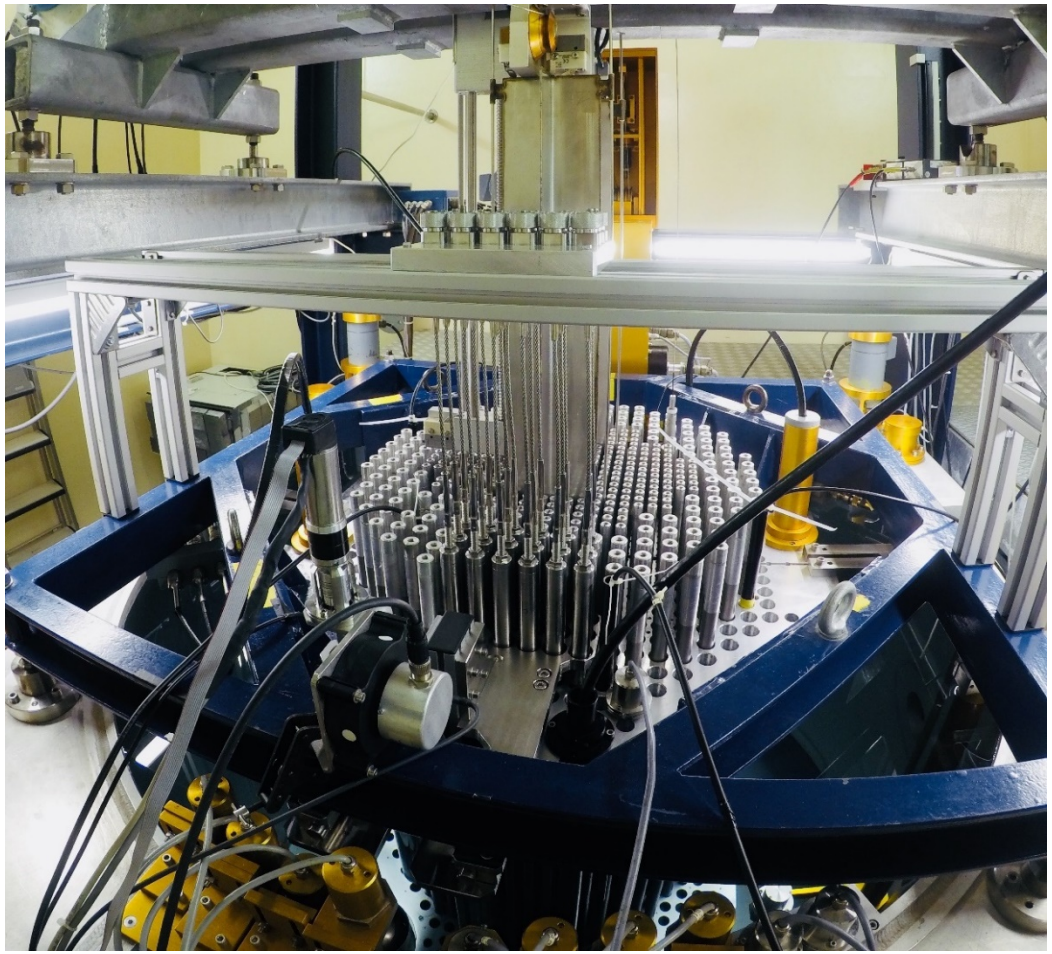
Goals

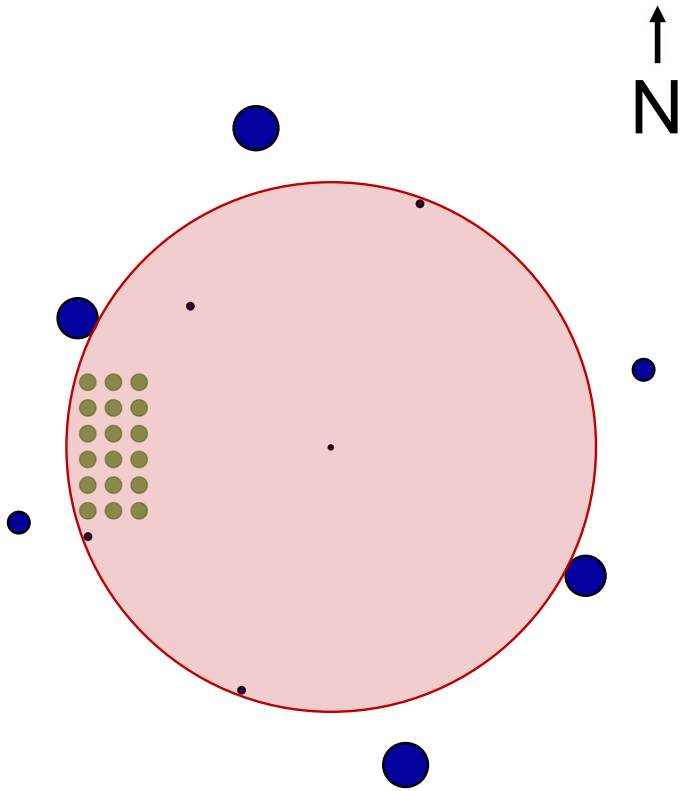
- Catch non-point kinetics spatial dependence

As many distributed detectors as possible



Detection setup



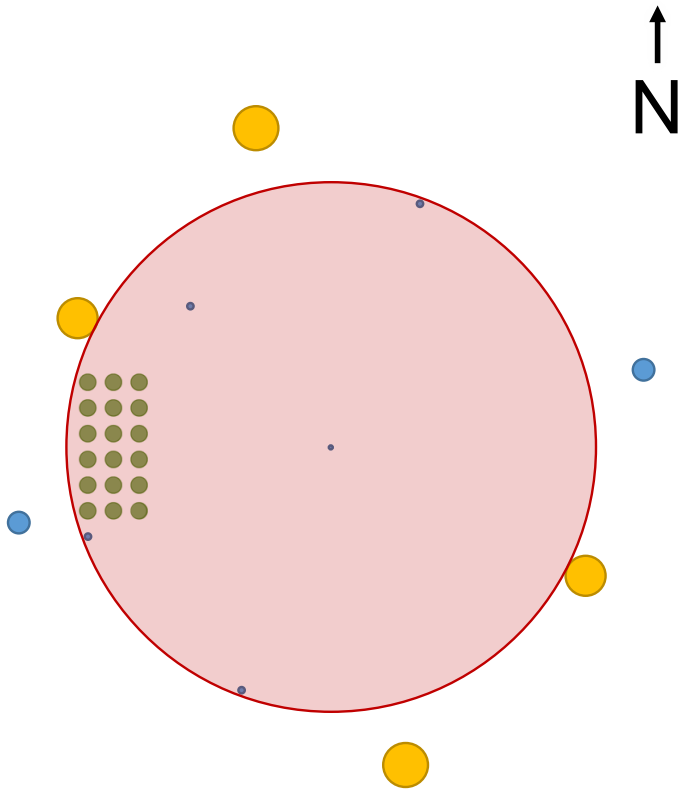


Electronics

Goals

- Catch non-point kinetics spatial dependence

As many distributed detectors as possible



Mode	Pulse	Current
Electronics	Spectro.	In-house

Data acquisition systems

Goals

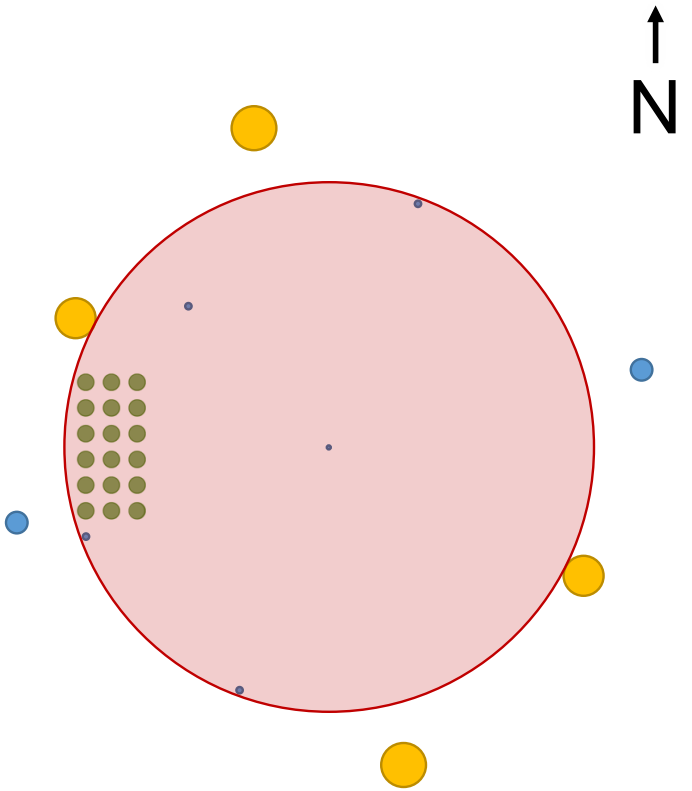
- Catch non-point kinetics spatial dependence

As many distributed detectors as possible

- Qualify the acquisition systems ✓

3 DAQ, including ISTec SIGMA qualified DAQ

Mode		Pulse		Current
Electronics		Spectro.		In-house
DAQs	**TUD**	Ortec	MCS	
	EPFL	Ortec	LabV	Lecroy WS10
	ISTec		SIGMA	



Conducted experiments[3,4]

Goals

- Catch non-point kinetics spatial dependence

As many distributed detectors as possible

- Qualify the acquisition systems

3 DAQ, including ISTec SIGMA qualified DAQ

- Cover the range of interest in freq. & amp.

Many experiments with different conditions

Reactor: 100 mW
Oscillation: 18 rods, up to 2 h

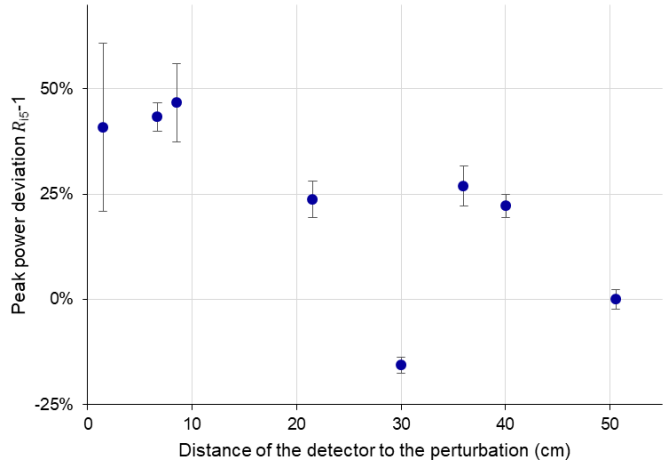
Amplitude (mm)	Frequency (Hz)				
	0.1	0.5	1.0	1.5	2.0
±0.5					
±1.0					
±1.5					
±2.0					

[3] V. Lamirand et al., "Neutron noise experiments in the AKR-2 and CROCUS reactors for the European project CORTEX," EPJ Web Conf., vol. 225, p. 04023, Jan. 2020. [4] V. Lamirand et al., "Experimental report of the 1st campaign at AKR-2 and CROCUS," CORTEX Deliverable 2.1, 2018.

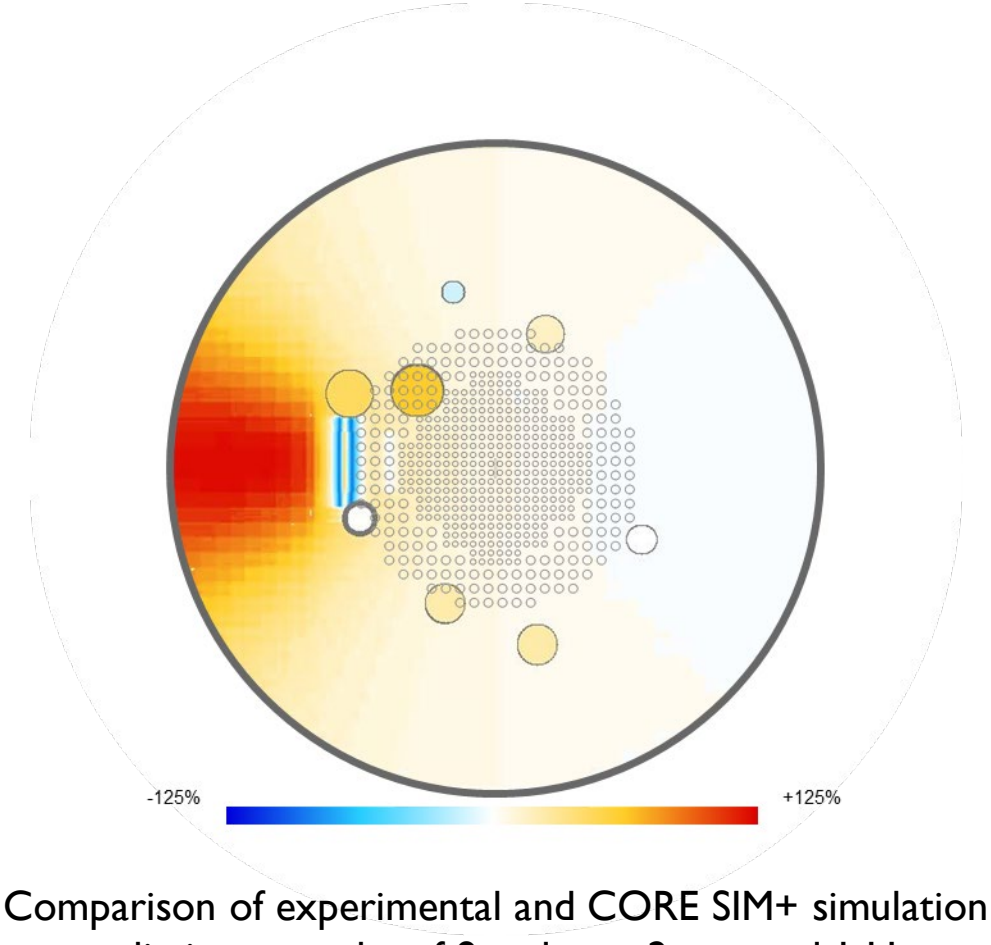
A peek at the results

A spatial dependence was observed![5]

- Noise level not following the flux map
- Accessible within the uncertainties



Results in relative noise powers, as a function of distance to the perturbation (18 rods at ±1.5 mm and 0.1 Hz)



Comparison of experimental and CORE SIM+ simulation preliminary results of 8 rods at ±2 mm and 1 Hz (courtesy DREAM)

[5] V. Lamirand et al., "Analysis of the first COLIBRI fuel rods oscillation campaign in the CROCUS reactor for the European project CORTEX," EPJ Web Conf., vol. 247, p. 21010, Feb. 2021.

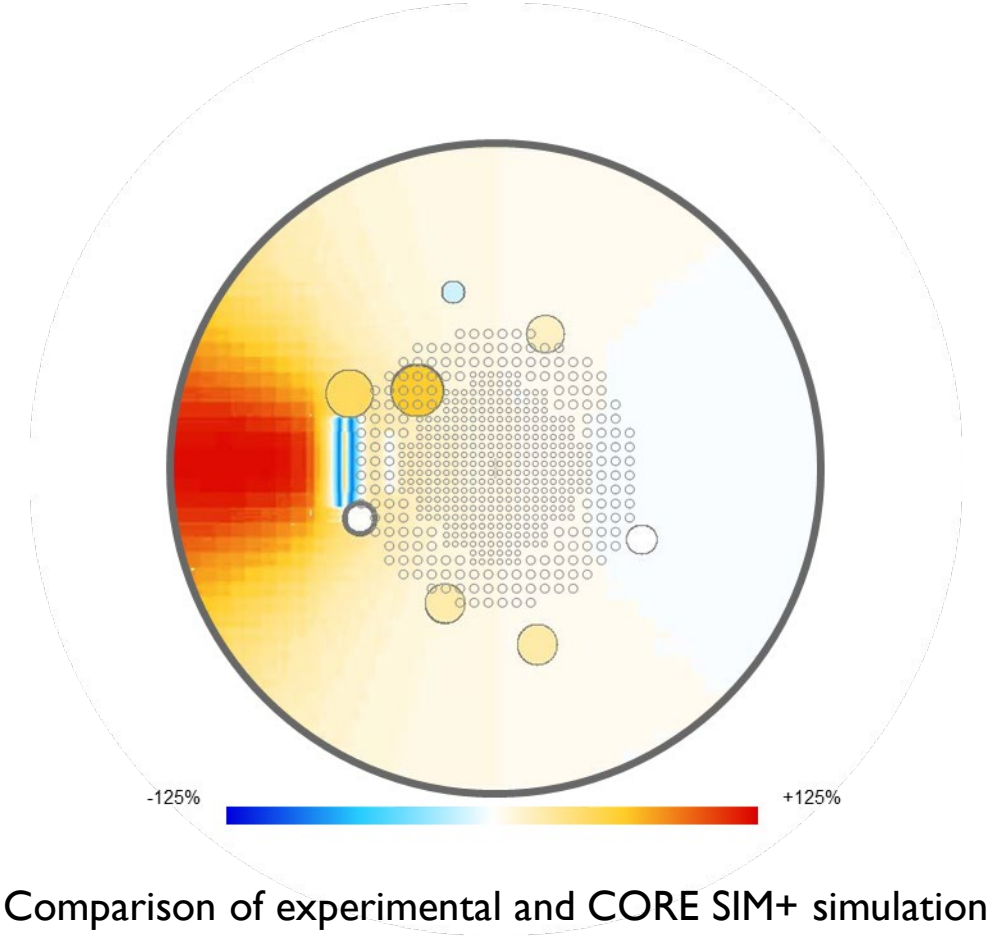
A peek at the results

A spatial dependence was observed!

- Noise level not following the flux map
- Accessible within the uncertainties

… with limitations & inconsistencies:

- Statistics to be improved
- Outliers & repeatability issues
- Syncing issues
- Space dependence to be improved



Comparison of experimental and CORE SIM+ simulation preliminary results of 8 rods at ±2 mm and 1 Hz (courtesy DREAM)

2nd Experimental campaign

9-22 October 2019

Updated detection setup

Goals & means

- Improvement of space dependence

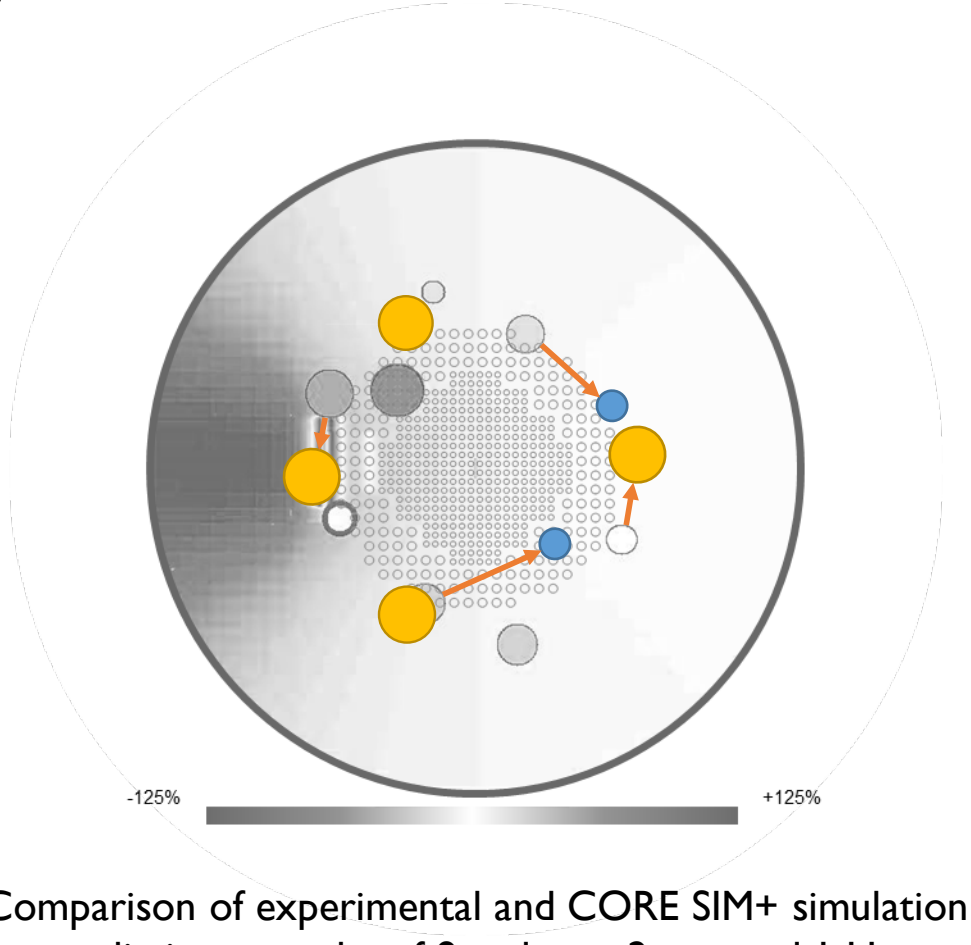
More detectors, better placement

- Outliers and repeatability

More "robust" detectors

- Statistics to be improved

More high efficiency detectors



Comparison of experimental and CORE SIM+ simulation preliminary results of 8 rods at ±2 mm and 1 Hz (courtesy DREAM)

Updated detection setup

Goals & means

- Improvement of space dependence

More detectors, better placement

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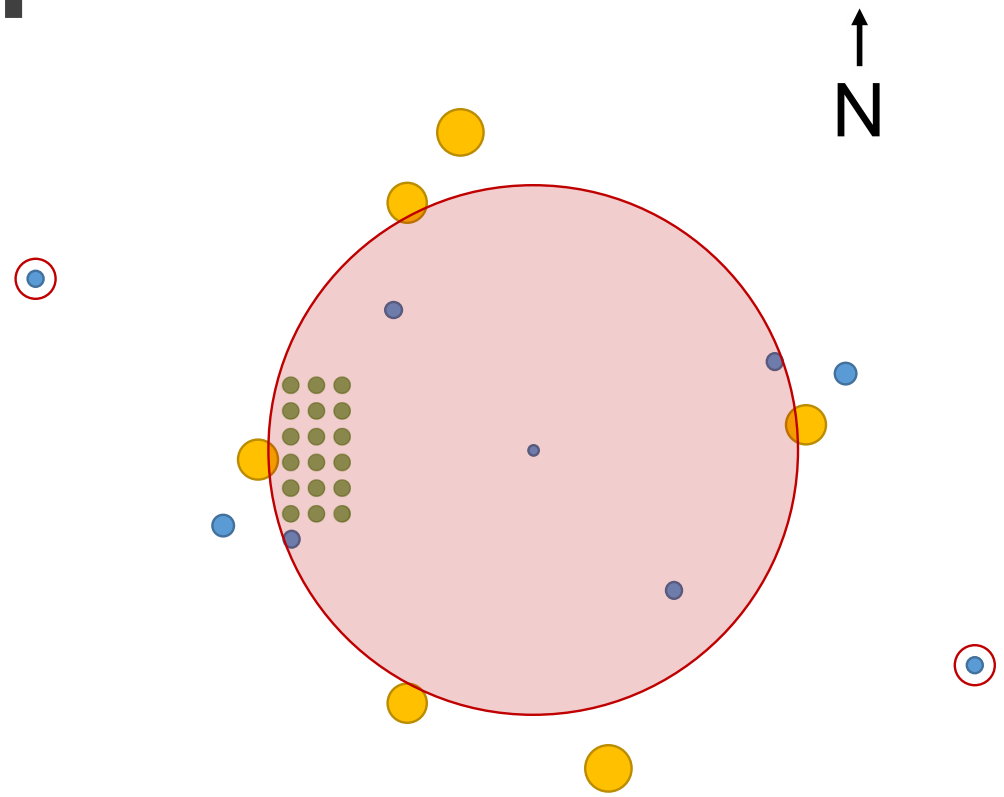
More high efficiency detectors



Updated electronics & DAQ

Goals & means

- Improvement of space dependence

More detectors, better placement

New FPGA based DAQ: CAEN V2495

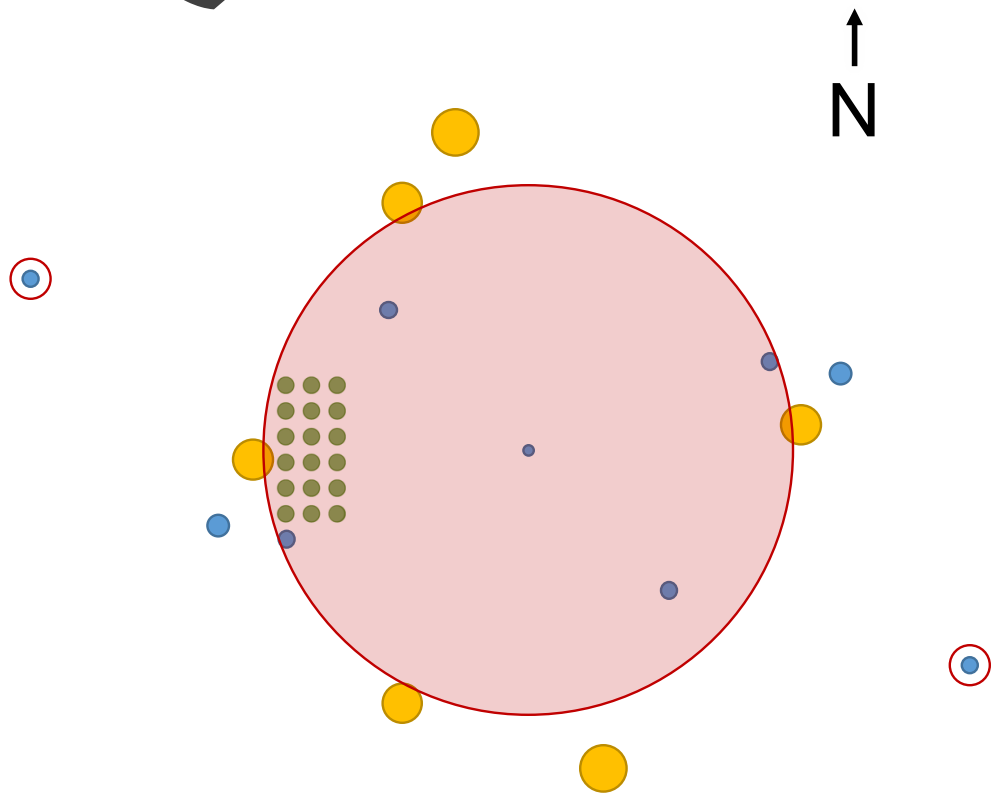
- Outliers and repeatability

More "robust" detectors with add. oscilloscope

- Statistics to be improved

More high efficiency detectors

Fast electronics for higher power/rate



Conducted experiments

Goals & means

- Improvement of space dependence

More detectors, better placement

New FPGA based DAQ: CAEN V2495

- Outliers and repeatability

More "robust" detectors

Repetitions of a reduced set of parameters

- Statistics to be improved

More high efficiency detectors

Fast electronics for higher power/rate

Longer measurements at higher power

	C 1	×10	C 2
Reactor:	100 mW		1 W
Oscillation:	18 rods, 2 h	×3.5	18 rods, **7 h**

Amplitude (mm)	Frequency (Hz)				
	0.1	0.5	1.0	1.5	2.0
±0.5	I	I	I		
±1.0	I	I	I	I	I
±1.5	I **2**	I	I **2**	I	I
±2.0	I	I	I		

- Syncing: trigger + analysis

Conducted experiments[6]

Goals & means

- Improvement of space dependence

More detectors, better placement

New FPGA based DAQ: CAEN V2495

Split exp.: same perturbation, different location

- Outliers and repeatability

More "robust" detectors

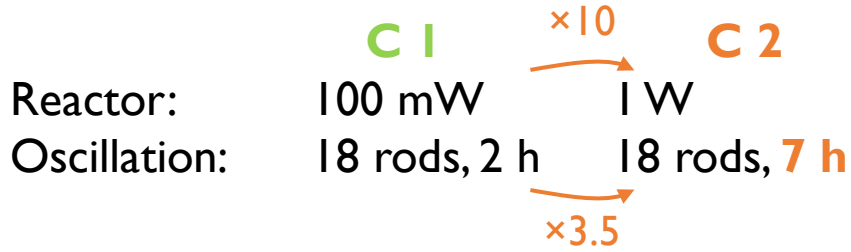
Repetitions of a reduced set of parameters

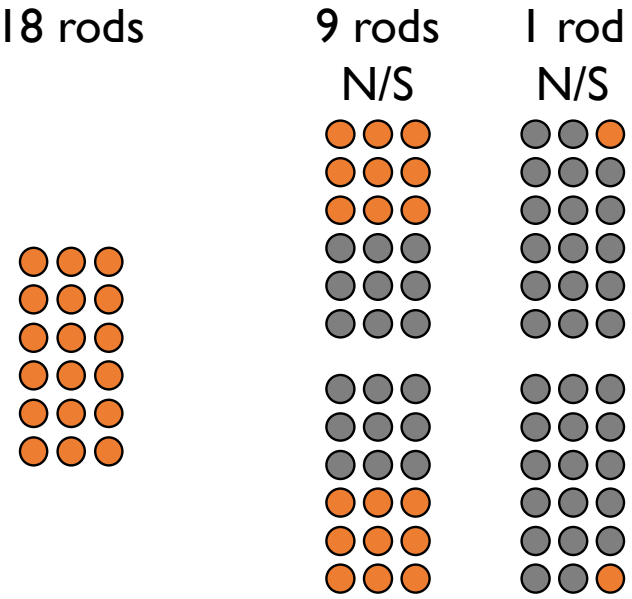
- Statistics to be improved

More high efficiency detectors

Fast electronics for higher power/rate

Longer measurements at higher power





[6] V. Lamirand et al., "Experimental report of the 2nd campaign at AKR-2 and CROCUS," CORTEX Deliverable 2.2, 2020.

3rd Experimental campaign

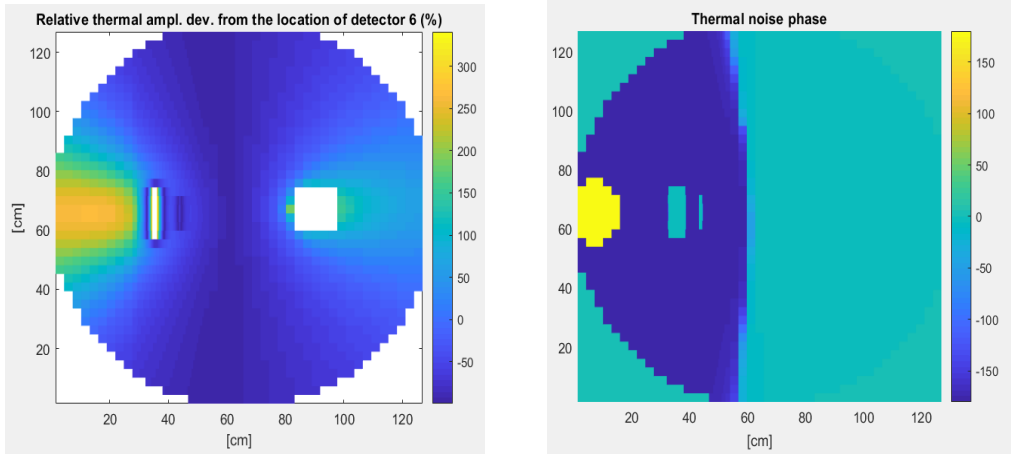
1-19 March 2021

Updated perturbations

Goals & means

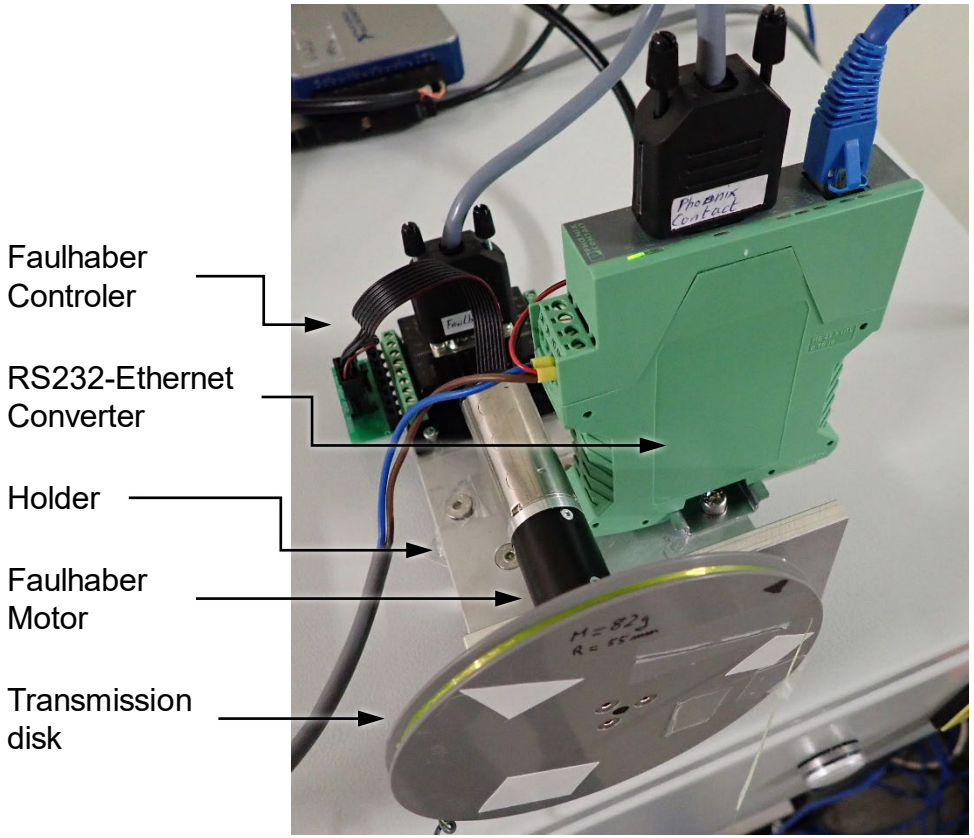
- Improvement of space dependence

Addition of a synced 2nd oscillator: POLLEN



Power Phase

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

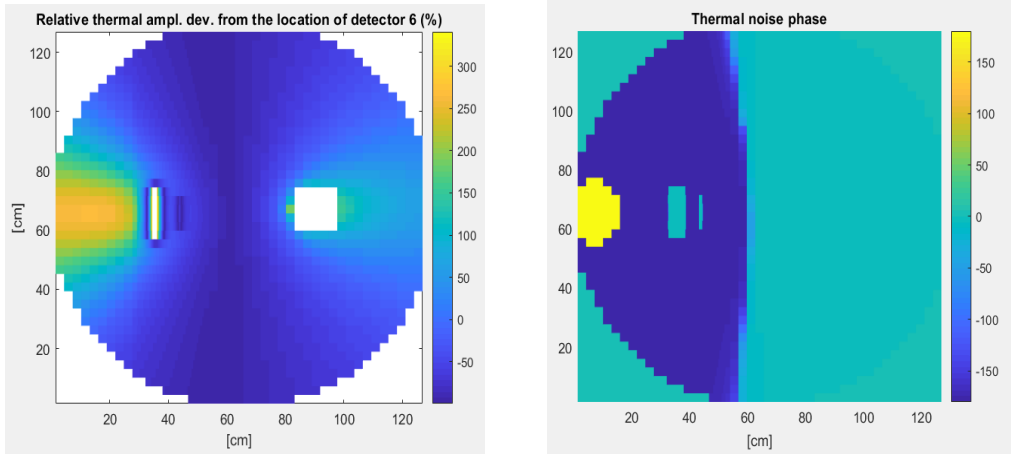


Updated perturbations

Goals & means

- Improvement of space dependence

Addition of a synced 2nd oscillator: POLLEN



Power Phase

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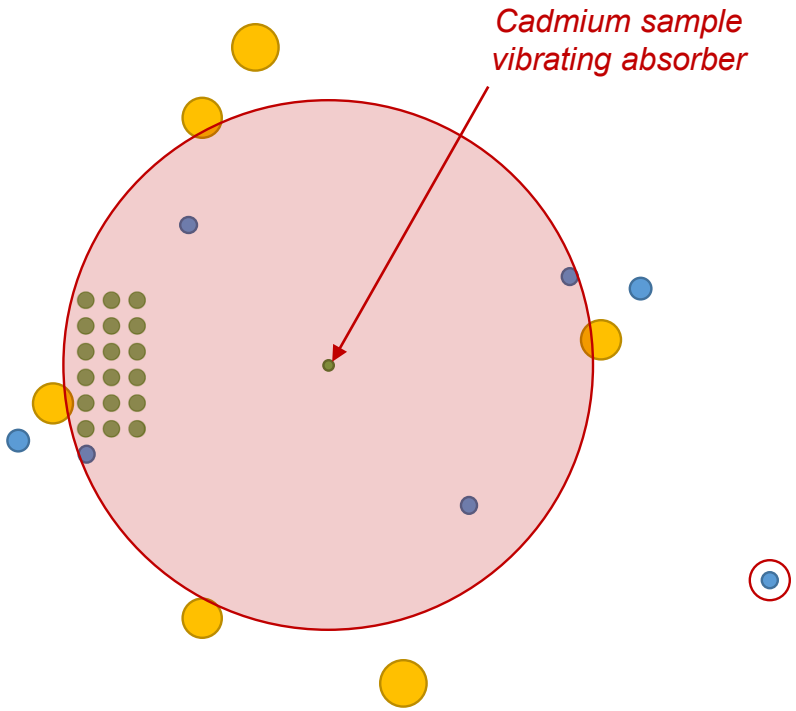


Updated detection setup

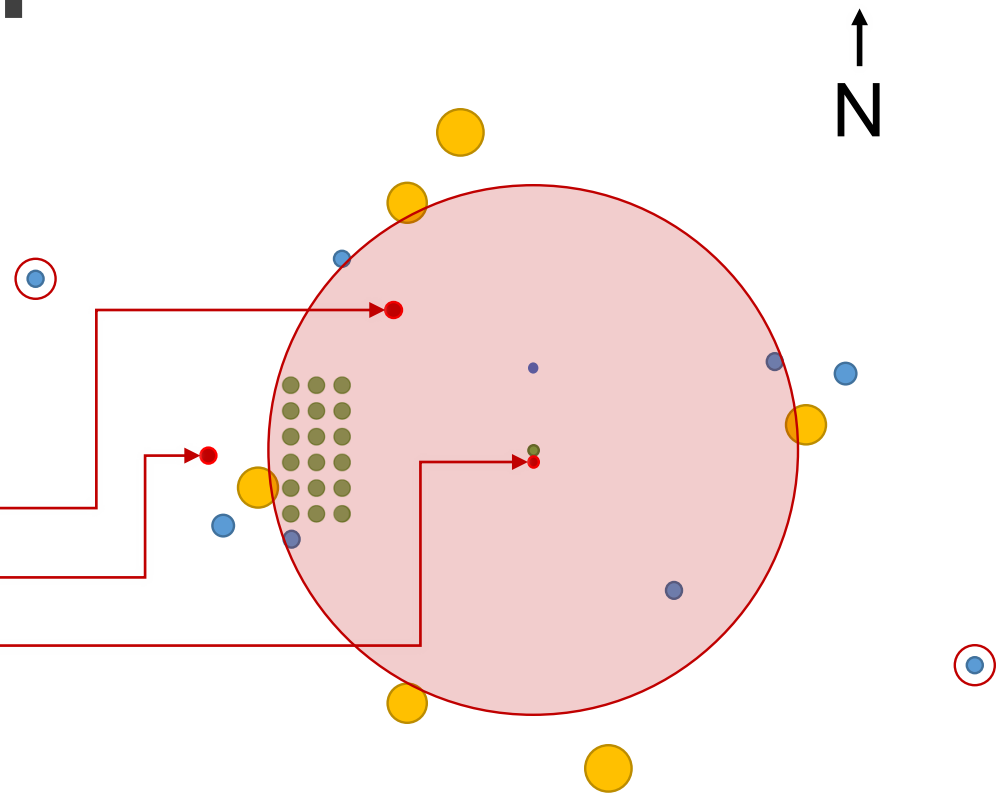
Goals & means

- Improvement of space dependence

Addition of a synced 2nd oscillator: POLLEN

Addition of miniature scintillators[7]

Local
- In an experimental channel
- On the beam of COLIBRI
- On the tube of POLLEN



[7] F. Vitullo et al., "A mm 3 Fiber-Coupled Scintillator for In-Core Thermal Neutron Detection in CROCUS," IEEE Trans. Nucl. Sci., vol. 67, no. 4, pp. 625–635, Apr. 2020.

Updated detection setup

Goals & means

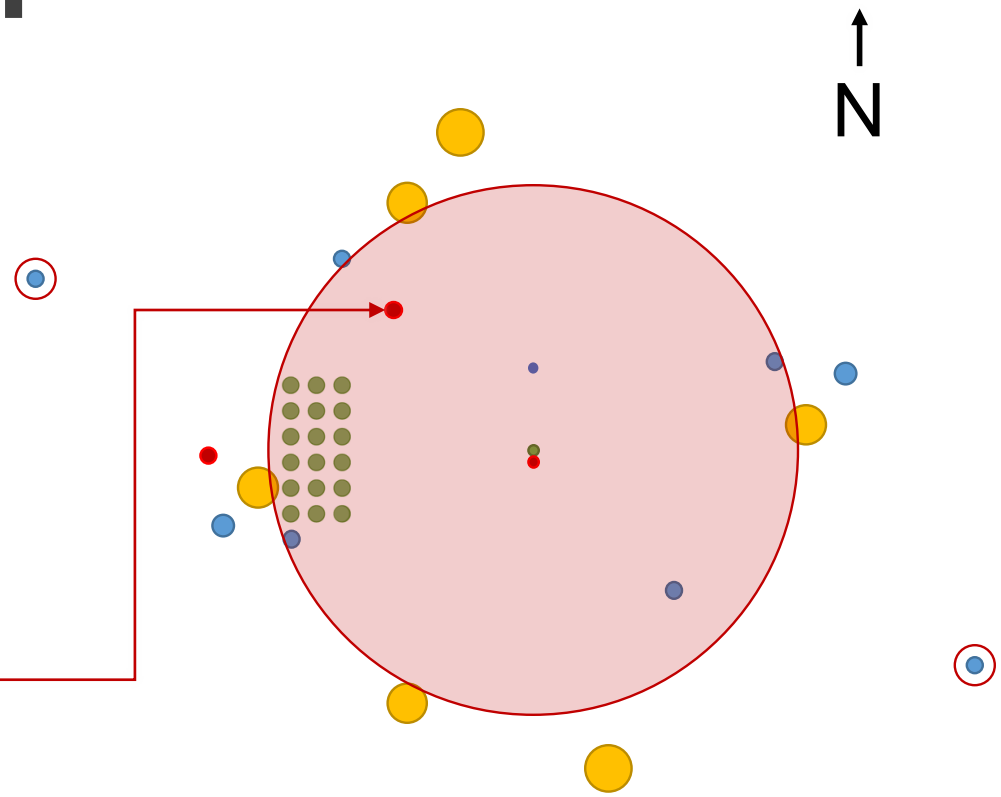
- Improvement of space dependence

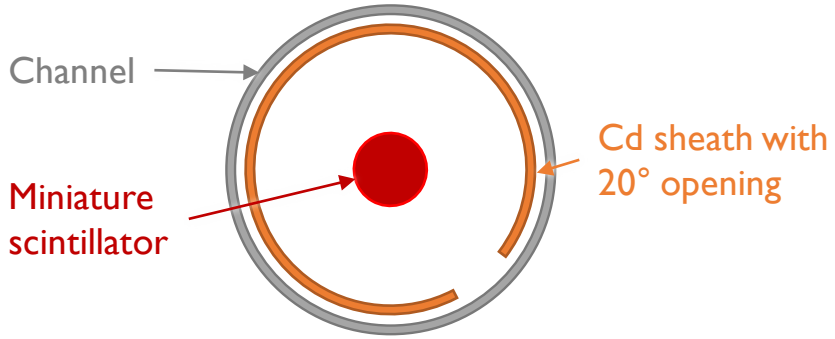
Addition of a synced 2nd oscillator: POLLEN

Addition of miniature scintillators

- Measuring neutron current

Test of an angular sensitive detector[8,9]





[8] F. Vitullo et al., "Highly localized azimuthal measurements in the CROCUS reactor towards the validation of high-fidelity neutronics codes," EPJ Web Conf., vol. 247, p. 08014, Feb. 2021. [9] V. Lamirand et al., "Development of fibre-based neutron scintillators," D2.3, 2021.

Conducted experiments

Goals & means

- Improvement of space dependence

Addition of a synced 2nd oscillator: POLLEN

Addition of miniature scintillators

- Measuring neutron current

Test of an angular sensitive detector

	C 2	C 3
Reactor:	1 W	1 W
Oscillation:	18, 9, 1 rods	18 rods **+VA**

Amplitude (mm)	Frequency (Hz)				
	0.1	**0.5**	**1.0**	**1.5**	**2.0**
±0.5	1	1	1		
±1.0	1	1	1	1	1
±1.5	12	1	123	1	1
±2.0	1	1	1		

Conducted experiments

Goals & means

- Improvement of space dependence

Addition of a synced 2nd oscillator: POLLEN

Addition of miniature scintillators

- Measuring neutron current

Test of an angular sensitive detector

	C 2	C 3
Reactor:	1 W	1 W
Oscillation:	18, 9, 1 rods	18 rods**+VA**
	COLIBRI alone	COLIBRI POLLEN	POLLEN alone

Conducted experiments

Goals & means

- Improvement of space dependence

Addition of a synced 2nd oscillator: POLLEN

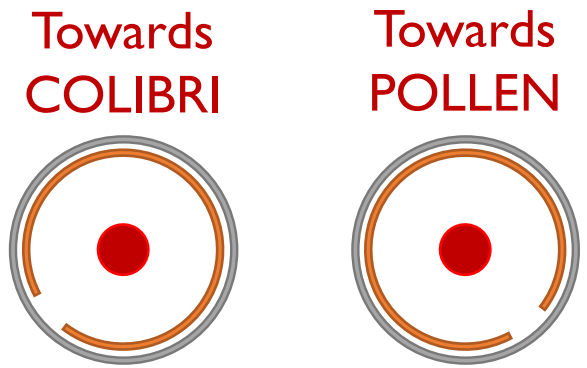
Addition of miniature scintillators

- Measuring neutron current

Test of an angular sensitive detector

Experiments with different orientations

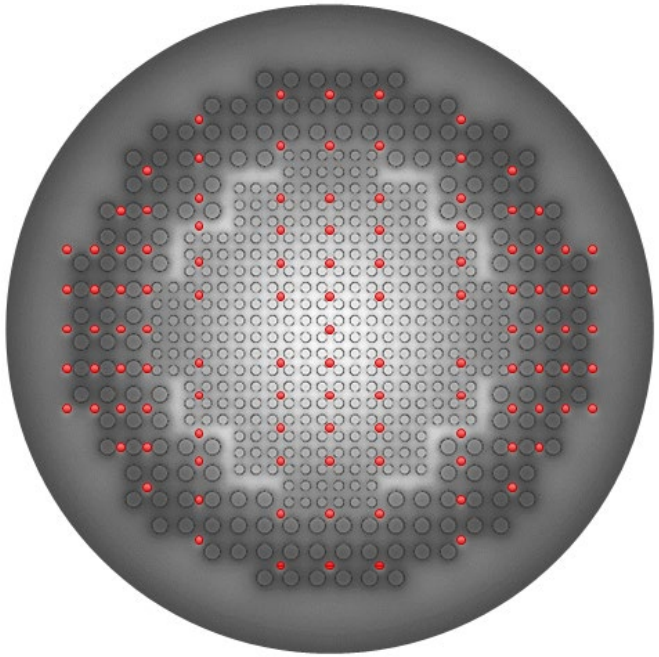
	C 2	C 3
Reactor:	1 W	1 W
Oscillation:	18, 9, 1 rods	18 rods+VA
	COLIBRI alone	COLIBRI POLLEN
	POLLEN alone	



Take-away and outlook

Three campaigns in CROCUS in 2018, 2019 and 2021 with:

- One-of-a-kind experiments
- Continuous improvement and upgrade following experimental analysis
- Constant iteration with modellers for analysis and design



Next step ☺

Thank you!