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Report on the development of fibre-based scintillator

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Summary

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Approval

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Abbreviations

COLIBRI	CROCUS Oscillator for Lateral Increase Between u-metal Rods and Inner zone
DAQ	Data acquisition system
EPFL	Ecole Polytechnique Fédérale de Lausanne
FPGA	Field-Programmable Gate Array
HDPE	High-Density Polyethylene
LVDS	Low-Voltage Differential Signalling
MCB	Multi-Channel Buffer
p.e.	photo-electron
PMMA	Poly(methyl methacrylate)
POM	Polyoxymethylene
PSD	Power Spectral Density
PSI	Paul Scherrer Institut
SiPM	Silicon Photomultiplier
TUD	Technische Universität Dresden
WP	Work package

Summary

In the framework of the CORTEX project, the work package 2 targets the generation of high quality neutron noise experimental data for the subsequent validation of computer methods and models developed in work package 1. The development of a novel type of detection array targeting highly localized and neutron current measurements for noise applications is presented. It is based on neutron scintillators, cutting-edge light collection technology, fast electronics, and FPGA acquisition. Early results are successful for high spatial resolution, as demonstrated during the second campaign at AKR-2, and encouraging for accessing the neutron current.

1 Overview

The CORTEX project aims at developing an innovative core monitoring technique for anomaly detection in nuclear reactors, such as excessive vibrations of core internals, flow blockage, and coolant inlet perturbations. The technique will be primarily based on using the inherent fluctuations in neutron flux recorded by in-core and ex-core instrumentation, from which the anomalies will be differentiated depending on their type, location and characteristics. The method is non-intrusive and does not require any external perturbation of the system. The project will result in a deepened understanding of the physical processes involved. This will allow utilities to detect operational problems at a very early stage and to take proper actions before such problems have any adverse effect on plant safety and reliability.

We present here the development of a novel type of detection array based on neutron scintillators, cutting-edge light collection technology, fast electronics, and FPGA electronics. A first prototype was developed in a Swiss collaboration between the Paul Scherrer Institut and EPFL. In the framework of the generation of high quality experimental data for code validation purposes, it targets highly localized and possibly neutron current measurements for perturbation noise, or modulation, applications. In the first Section of the report, we present the detector design and the development of front-end electronics. In the second Section, we present its test for noise and direction sensitive applications. In the last Section, we present the development of a 3D core mapping array in CROCUS.

2 Detector design

The development of a new type of in-core neutron detector was conducted jointly by the Laboratory for Reactor Physics and Systems behaviour at EPFL and the Laboratory of Particle Physics at the Paul Scherrer Institut [1], [2]. It relies on the use of ZnS:^{6}LiF scintillator, and cutting-edge signal processing with SiPM technology, fast electronics, and digital FPGA treatment. In this Section, we present the principle of detection, as well as the development of electronics allowing scalability of the system to simultaneous acquisition of numerous detection channels.

2.1 Principle of detection

In the developed system, the neutron detection is carried out in several steps:

- Interaction of the neutron in a miniature scintillator of ZnS/Ag with ^{6}Li doping: interaction with a ^{6}Li nucleus, then interaction of the secondary charged particles with ZnS, and emission of multiple photons (see Figure 1), i.e. a "train of photons",
- Collection of the emitted light using a PMMA plastic fiber (up to 15 m-long in our case),
- Detection of light using a silicon photomultiplier array (SiPM): conversion of photon detection events into pulses coded in current amplitude,
- Signal amplification in a fast preamplifier: conversion of current coded pulses into voltage coded pulses,
- Discrimination and shaping of pulses for the counting of photon detection events.

At this stage, the signal can be processed either in analogue, or in digital. The signal processing in analogue is presented in Figure 2.

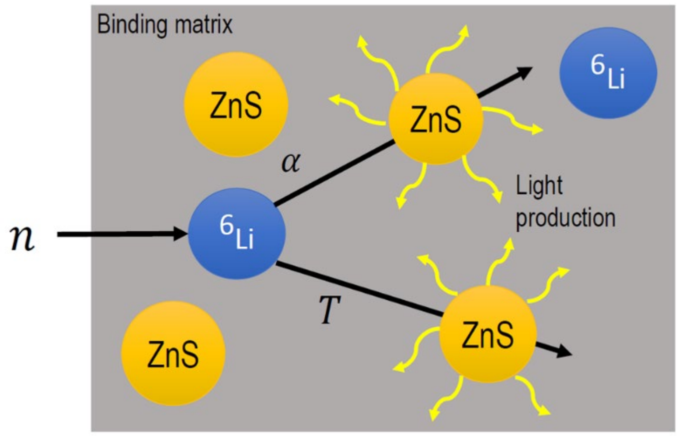

Figure 1: Neutron detection process, from neutron interaction to light production.

In analogue, the train of photon pulses corresponding to a neutron detection event is converted in a second (slow) spectrometry amplifier into a Gaussian pulse, which amplitude depends on the number of photons in a given time window (shaping time). Then these neutron event pulses can be treated using standard or more evolved data acquisition systems (DAQ).

In digital, the train of photon pulses is directly fed into a fast acquisition system, where custom signal treatment is applied for counting the number of neutron interactions using a Field-Programmable Gate Array (FPGA), in our case a CAEN V2495 FPGA. It allows the use of more advanced methods for detection counting, for the discrimination of events such as parasitic gamma rays interactions, but also reduced price and equipment requirements, as spectrometry Gaussian amplifiers are complex and expensive electronics.

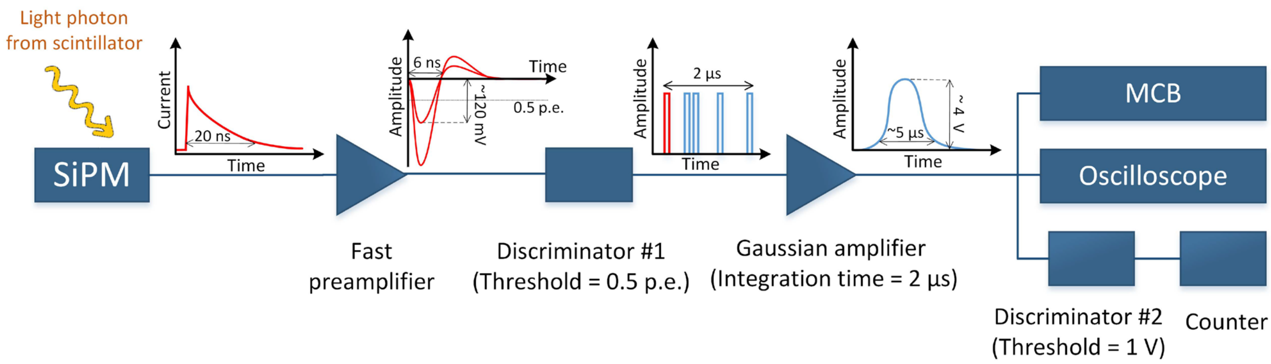

Figure 2: Signal processing from light production in the SiPM to neutron counting in analogue, with a Multi-Channel Buffer, an oscilloscope or a simple counter.

2.2 Development of electronics

The first prototype for in-core use was developed in collaboration between LRS at EPFL, and the Laboratory of Particle Physics at the Paul Scherrer Institut. The acquisition system of the miniature fiber neutron detectors was substantially upgraded with respect to the analogue read-out used for the tests performed [2]. We present here the development of single channel units' prototyping the electronic design. In a second part, a final prototype of rack with simultaneous detection capabilities of 32 channels is presented.

2.2.1 Single units front-end electronics

As a first step towards the multiplication of available channels, the initial front-end electronics were replicated, and upgraded mainly for photon collection efficiency, pulse shortening, as well as noise reduction for preventing the risk of light pollution and cross-talk in the prospect of scalability. After several prototypes, it resulted in the development of three functional individual SiPM modules, as well as four individual fast pre-amplifiers, which were tested in CROCUS, and successfully used in the second campaign at the AKR-2 reactor (see Section 3.2 p.7, and [3]), concluding their developments.

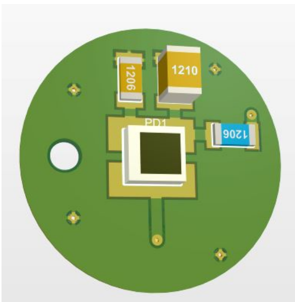
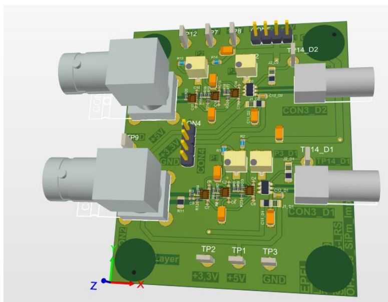

Figure 3: CAD models of individual SiPM (left) and fast preamplifier (right) modules.

2.2.2 Front-end electronics for digital acquisition

A novel stand-alone 32-channels electronics module was developed in-house at EPFL for the simultaneous acquisition and processing of the scintillation light inputted by 32 different fiber detectors (see Figure 4). The module front-end presents 32 openings where each optical fiber can be connected and coupled with the respective SiPM. SiPMs are isolated from each other and kept in the dark in order to minimize background noise and cross-talk events. The alimentation for the bias voltage applied to the 32 SiPMs is built-in in the module. Each SiPM output is sent and processed by one of the 32 separated electronics boards included in the module and dedicated to the conversion of the SiPM signal into a photon counting on the basis of a user-selected threshold level for electronic noise removal. The final output of the 32-channels module consists in the photon counting in each channel under the form of LVDS signals. The LVDS photon counting is then sent to a CAEN FPGA board equipped with a custom firmware that performs a software-based analysis of the input signal and its processing into neutron counting. Photon detections can occur from background events, but a neutron event induces a characteristic train of photons, i.e. a variation of detected photon density (see Figure 5). A moving counting technique in time is applied to identify these variations, thus discriminating and collecting neutron events based on their magnitude.

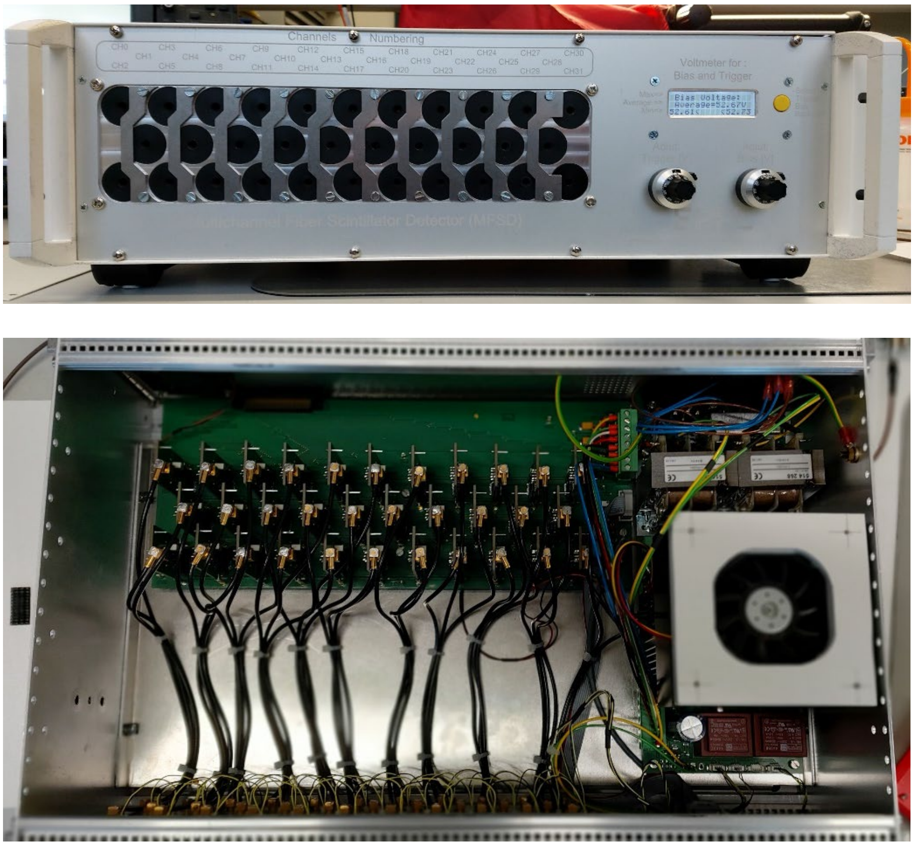

Figure 4: First prototype of front-end electronics for the simultaneous acquisition of 32 detector channels. On the top part, front of the rack with its 32 openings for fibers, and selection screen and buttons. On the bottom part, internals comprising the power unit (right), and the main board with individual amplification and discriminator boards plugged on it, and connected to the individual SiPM in front of the fiber openings.

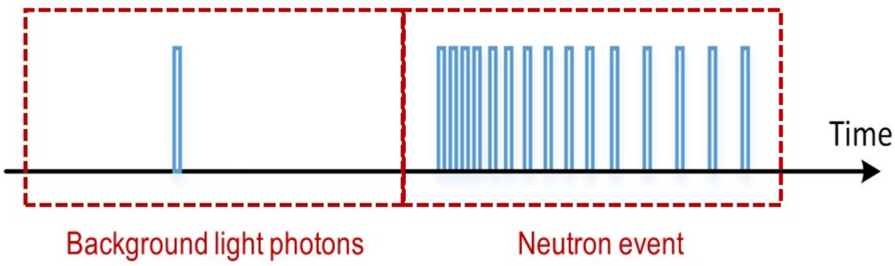

Figure 5: Representation of typical digital signals issued by the front-end electronics and used for neutron detection identification using the FPGA board.

3 Detector testing

3.1 Tests for noise applications in the CROCUS reactor

As the high spatial resolution of our first prototype was assessed [1], [2], a first test was carried out in December 2019 in order to observe the feasibility of the miniature scintillator prototype to observe a perturbation, as well as its sensitivity. It was set on one of the rods of the COLIBRI device. In two separated experiments, the instrumented rod was oscillated alone, as well as the adjacent rod alone. It resulted in a first successful observation of local neutron modulation with this detector design, as can be seen in Figure 6.

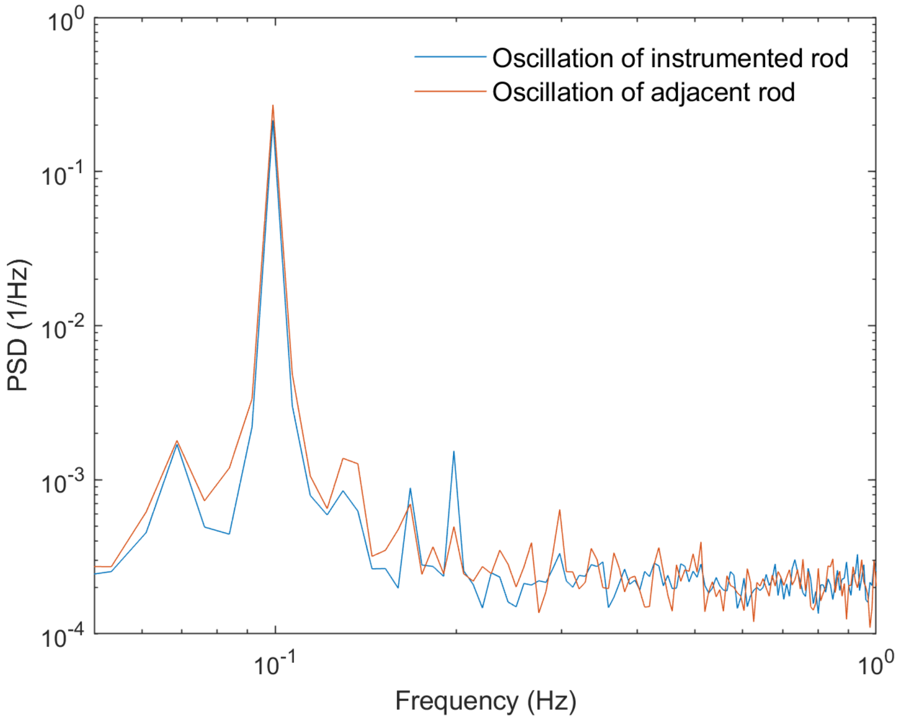

Figure 6: Power spectral densities obtained with the first detector prototype set on a rod, for two separated fuel oscillation experiments at a 0.1 Hz frequency and a ±2.5 mm amplitude: oscillation of the instrumented rod, and oscillation of the adjacent one.

3.2 Tests for noise applications in the AKR-2 reactor

The detection system was tested and utilized during the second experimental campaign at the TUD AKR-2 reactor in July 2020. Three new miniature scintillators were built for the campaign, and used in conjunction with the prototypes of individual front-end electronics (see Section 2.2.1) with analogue counting electronics: single SiPM and preamplifier-discriminator modules along with Canberra 2022 amplifiers and Canberra 2030 single channel analysers. The counting was performed using a CAEN V2495 FPGA logical unit in conjunction with the CAEN V1718 PC communication bridge for collecting the data with a workstation. The new detectors and electronics were tested up-front in CROCUS, at selected reactor powers and power changes, so as to verify signals, count rates, and linearity.

At AKR-2, the detectors were located outside of the core in experimental channel 6, extending right out of the core at three different positions [3]. The linearity response was checked again, yielding between 700-3700 cps/W as seen on Figure 7. During the experiments themselves and for the post-processing, dwell-times of 30-40 ms were used, which gives counts in the range of 100-150 counts/dwell time at a reactor power of 1.5 W.

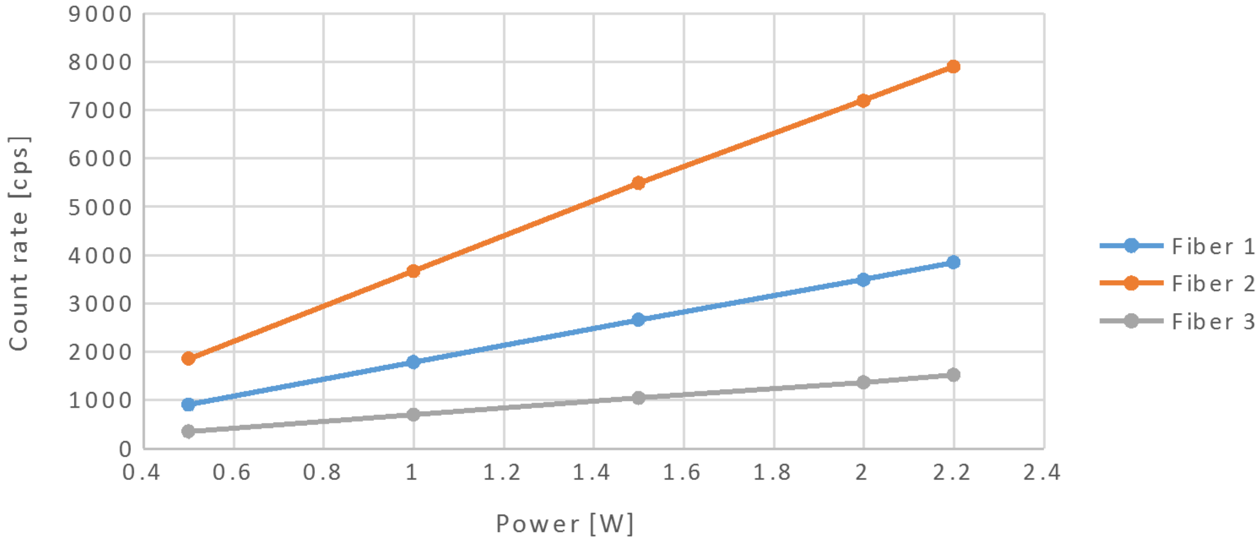

Figure 7: Fiber linearity test at AKR-2 in experimental channel 6.

Compared to other detectors, the fiber based detectors are extremely small and are insensitive to electronic noise. The prototype interface between the fiber and the SiPM proved successful as very little of ambient light contributed to signal noise by a tight fit between the fiber and SiPM module, as well as the appropriate setting of the detection system discriminator. The evaluated APSD from experiment 8 (2 Hz @ 1.5 W) of the fiber detector closest to the core centre is displayed in Figure 8.

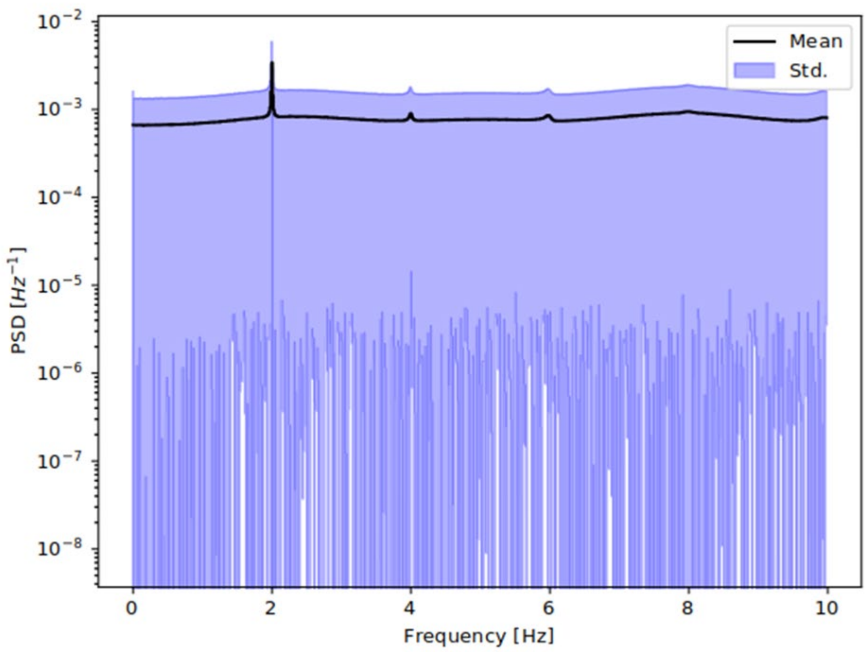

Figure 8: APSD of the fiber closest to the core centre for experiment no. 8 during the second campaign at AKR-2. Mean represents the computed central value of the PSD, and the standard deviation of each computed points is represented in violet.

The tests carried out in AKR-2 provided additional high quality data points for the experiments, critical for validation purposes as they were closest to the core. They also allowed successfully test the detection system for reactor noise applications. The quick response time, low noise and small size proved ideal for reactor noise measurements in zero-power reactors, and for core mapping experiments such as the future array in CROCUS.

3.3 Tests for direction sensitive applications in CROCUS

In nuclear reactors the monitoring of the distribution of neutrons is usually performed by measuring the reaction rate in detection materials, which can be related to the scalar neutron flux given by an angular integral over the angular flux. As a consequence, the reaction rates in detectors do not contain any information about the direction of neutrons. In a preliminary study [4], it was possible to experimentally highlight the scalar flux gradient in two perpendicular directions inside an instrumentation channel close to the core reflector of CROCUS.

The same periphery position possesses a higher share of thermal neutron streaming from the reflector zone. Knowing already the local flux gradient, it is reasonable to presume that a measurement of possible partial neutron currents can be performed in this position. As a test for direction sensitive applications, the experimental setup was modified to aim at the measurement of angular dependency of the neutron flux. The detector was positioned in the centre of the same channel, with a cadmium layer set all around it but for an opening of about 30˚. Without moving the detector, the cadmium opening was oriented for successive measurement at different angular positions, the direction towards the reflector (i.e. NW) being identified as reference (0°). The neutron counts should be depending on the cadmium angle, and allow first validation of computed angular distribution of the local flux.

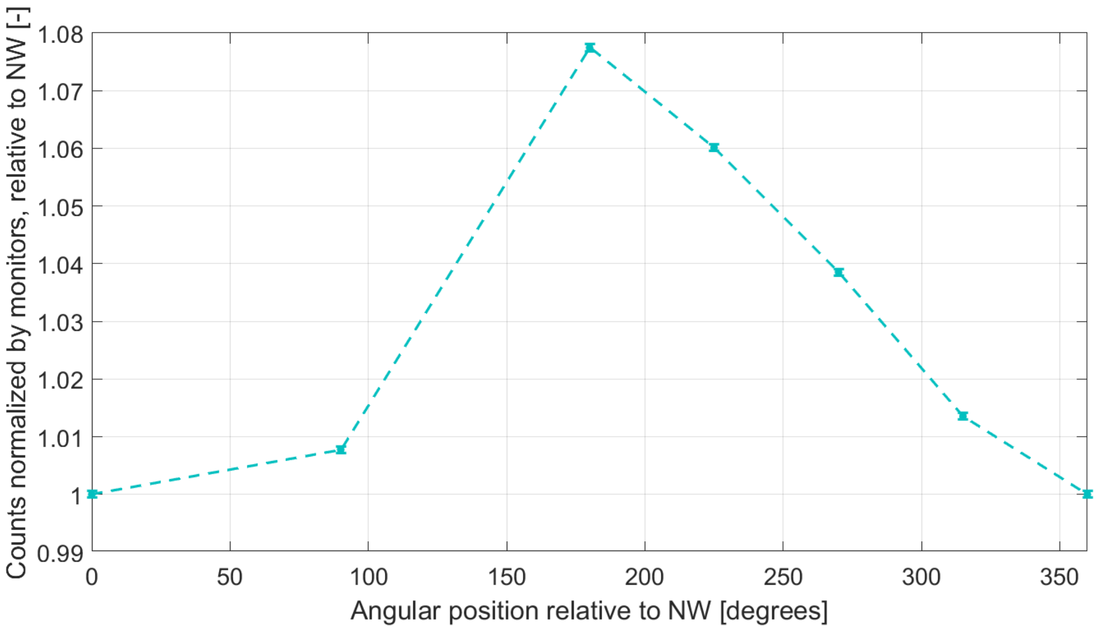

Figure 9: Normalized neutron counts as a function of angle for the angular experiments.

The preliminary experimental results in neutron counts are presented in Figure 9. We indeed observe a clear variation as a function of angle, far larger than the limited experimental uncertainties. As the detector is always set at the same position, with only the cadmium layer and its opening turning, the difference can only be explained by an angular dependence of the local neutron flux. However, the measurements' results are expressed in neutron counts, i.e. proportional to the local reaction rate, and require appropriate modelling for analysis purposes. Two MCNP simulations of the experiments were carried out to provide a first insight on the possible effects given by the neutron direction of flight on the ^{6}Li reaction rate in the periphery, and consequently on the number of neutron events detected by the scintillator [5]. The MCNP geometry is presented in Figure 10 according to the experimental setup and depending on its orientation. Indeed, the cadmium layer must be included in the MCNP geometry with its real material composition. Thus, different simulations corresponding to the cadmium orientations must be performed to reproduce the measurements.

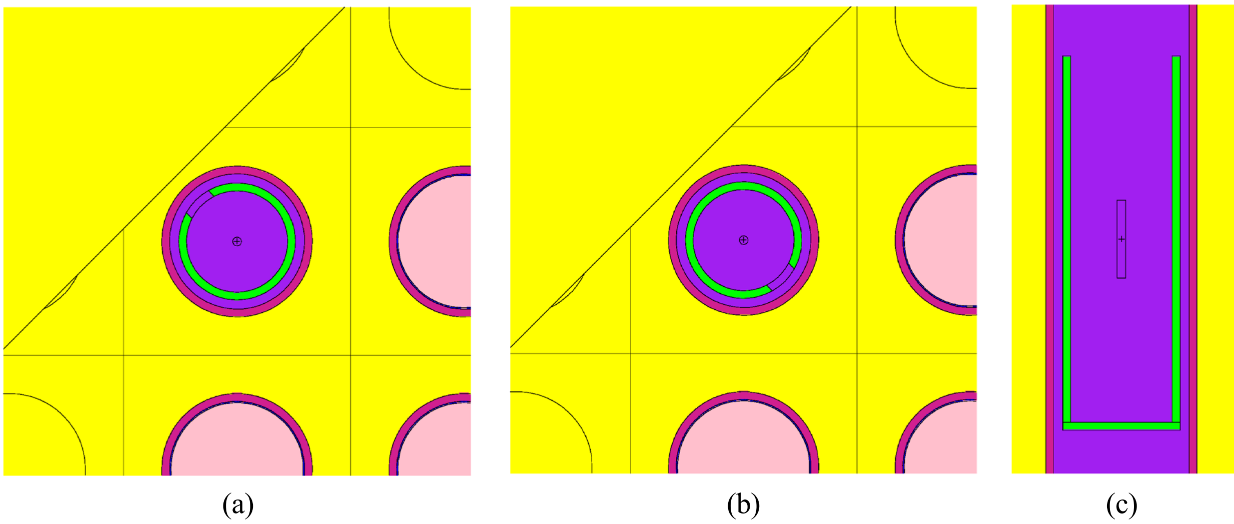

Figure 10: MCNP geometry of the experiments, the detector set at the channel centre, and surrounded by the cadmium layer (in green): top views of the NW direction (a) and SE direction (b) measurements; (c) transversal mid-height axial cut in the centre of the channel.

The neutron flux and ^{6}Li reaction rate inside the scintillator tally have been scored running 2 billion neutron histories during each simulation run in criticality mode. From the first simulation results presented in Table 1, no differences in the reaction rate are visible within the uncertainty range. The introduction of a cadmium layer drastically reduces the neutron flux and therefore for the same number of simulated neutron histories the uncertainty on the reaction rate is significantly increased. In order to overcome these limitations different solutions are currently investigated. Possible options are: a higher number of neutron histories in combination with variance reduction techniques; the repetition of these experiments in a control rod guide tube, which is set in the CROCUS inner zone and where the average neutron flux is higher.

Table 1: Computed neutron fluxes and reaction rates in the detector for two experimental setups corresponding to the cadmium opening set at opposite angles (NW and SE).

Cadmium orientation	Flux ($cm^{-2}.s^{-1}.W^{-1}$)	Reaction rate ($cm^{-3}.s^{-1}$)
NW	$(2.63 \pm 0.04) \times 10^{6}$	$(5.2 \pm 0.2) \times 10^{4}$ (4%)
SE	$(2.66 \pm 0.04) \times 10^{6}$	$(5.4 \pm 0.3) \times 10^{4}$ (5%)

Despite the analysis being still ongoing, the observed experimental trends are encouraging with respect to the goals of the Subtask: an angular dependence was observed and should allow a reconstruction of the neutron current. The same setup will be tested in noise conditions during the third campaign in CROCUS in March 2021. An upgrade of the detection system was carried out to increase its neutron sensitivity. In addition, more appropriate core locations are considered to observe directional effects both in static state and with induced reactor noise, i.e. in-core in the control rod guide tube (close to the water gap), or in the reflector at a further distance from the core.

4 Development of a core mapping array in CROCUS

The detectors array is designed to perform a detailed 3D in-core measurements of the neutron flux, possibly with angular sensitive positions. It is based on the same detection technology than described above, but in a larger scale, as it should include about 150 detectors distributed in-core, in both inner and outer zones of CROCUS. It would make use of up to six electronics racks such as presented in Section 2.2.2 (p.5).

4.1 Mechanical design

For its mechanical part, the design of the detectors array consists of:
- vertical hollow aluminum support tubes, set in the available grids holes around the active core of CROCUS, holding horizontal support rods,
- horizontal support rods set in between the vertical tubes for holding plastic rulers,
- plastic rulers, crossing the core in-between the fuel rods, holding the fibers and miniature scintillators,
- miniature scintillators set at chosen positions along the rulers, connected to the fibers,
- fibers set in tracks machined in the rulers.

Two arrangements of support tubes are considered, with maximized and reduced numbers. The actual number should be decided following the current prototyping. The plastic rulers are to be set on three axial planes of detection, at bottom, mid-, and top heights. At each plane, a number of about 50 detectors is placed in-core, relatively evenly, with a focus around the fuel rods oscillation of COLIBRI [6]. In Figure 11, a CAD model illustrates the principle of the design (with reduced rods number) for two rulers set at mid-height.

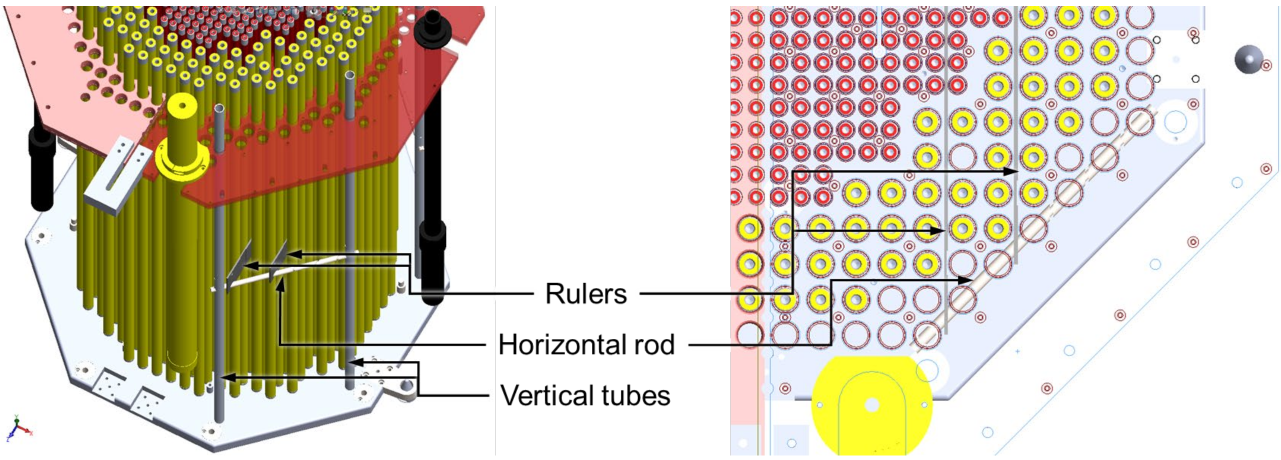

Figure 11: CAD model of the core of CROCUS with fuel and grids, and two vertical tubes holding a horizontal rod at mid-height, and two rulers crossing the core.

In addition to the experimental setup presented in Section 3.3 (p.9), it is intended to add a cadmium layer between the ruler and some scintillators in order to cut the contribution of thermal neutrons from one side. These “half-blind” scintillators would be used in comparison to non-blinded scintillators to gain some insights on the neutron current.

4.2 Neutronics design

The effect of the whole detectors array on the reactivity of the reactor is studied computationally in order to ensure that the CROCUS reactor could be operated with it, i.e. being critical in a feasible fuel configuration with the safety limits respected. In the current case, a negative reactivity insertion is expected. A detailed MCNPX model of a typical configuration of CROCUS was used as a baseline and reference. As much as possible, the design still under development was followed.

The scintillator material composition, especially the ^{6}Li enrichment modeling, was based on the data provided by the supplier (95% enrichment) and previously published work [2]. The supplier provided enrichment was roughly 19.7% higher compared to previous work. Since we are aiming for a conservative assessment, the latter was used for modeling. In addition, for validation purposes, measurements were performed to assess the reactivity effect of a single scintillator-fiber combination in February 2019 and November 2020 with different scintillator amounts, and were modeled as well. They yielded computational results in agreement with experimental data within the computational uncertainty, as presented in Table 2. JEFF 3.1 nuclear data libraries were used in these simulations, and the core loading pattern and the water level as well as control rod positions were modeled in details.

Table 2: Measured and modelled reactivity worth of two prototypes with different scintillator amounts.

Experiment date	Measured reactivity worth (pcm)	Simulated k_{eff}, no scintillator	Simulated k_{eff} with scintillator	Simulated reactivity worth (pcm)
25.02.2019	1.2 ± 0.2	1.00134 ± 2 pcm	1.00133 ± 2 pcm	1 ± 2
06.11.2020	0.7 ± 0.2	1.00182 ± 1 pcm	1.00181 ± 1 pcm	1 ± 1

The rulers were modeled as straight plastic strips with width of 6 cm and thickness of 3 mm. The plastic fibers themselves were not modeled, due to their complicated routing along the rulers, small volume and mass compared to the ruler and similarities of material compositions of fiber with the ruler. Rectangular scintillator pieces were modeled inside the rulers at predetermined positions. 10 rulers per single axial level were modeled in total, containing between 3 to 6 detectors, depending on the position inside the core. The envisioned setup crosses the safety cadmium blades, and additional support was considered. Both the material composition of the rulers was varied between HDPE and POM, as well as for both scintillator thicknesses.

The aluminum rods used for holding the rulers with detectors were modeled with the dimensions similar to the U_{metal} fuel rod cladding in two ways:

- On either side of the ruler, two such rods clamp the ruler via a holder consisting of a 3 mm times 3 mm shaped aluminum square rod.
- These rods are located at strategic positions (6 in total), with aluminum holders providing all the necessary stability with special clamps.

Additional rods with diameter of 6 mm are to be placed in proximity to the rulers crossing the cadmium safety rods in order to be able to extend the detectors uniformly throughout the core and enable the safe shutdown of the reactor.

The detectors array with different support structure arrangements in the CROCUS reactor is modeled according to schematic displayed in Figure 1 (showing a single axial level). In order to cover the range of possible changes in the design, several options were considered:

- Two different nuclear data libraries were used: JEFF 3.1 and ENDF/B VII.1
- The middle ruler always at 50 cm (core mid-height), and the top and bottom rulers set 40 cm and 35 cm above and below for JEFF 3.1 and ENDF/B VII.1 respectively.
- Two possible types of the plastic used for the rulers: high-density polyethylene (HDPE) and Polyoxymethylene (POM)
- Two different scintillator thicknesses: 0.225 mm and 0.45 mm
- Axial aluminum tube holders:
    - One tube at the extremity of each axial ruler assembly
    - A reduced number of holders, only where necessary.

Computational results were obtained using eigenvalue calculations, i.e. simulating the operational reactor. Due to the small size of individual scintillator crystals, the relative transport importance of the scintillator crystals themselves, as well as their immediate surroundings in the plastic ruler was set to 10 instead of 1, which forces the particle to split and roulette and provides a better statistics. The results are reported in Table 3.

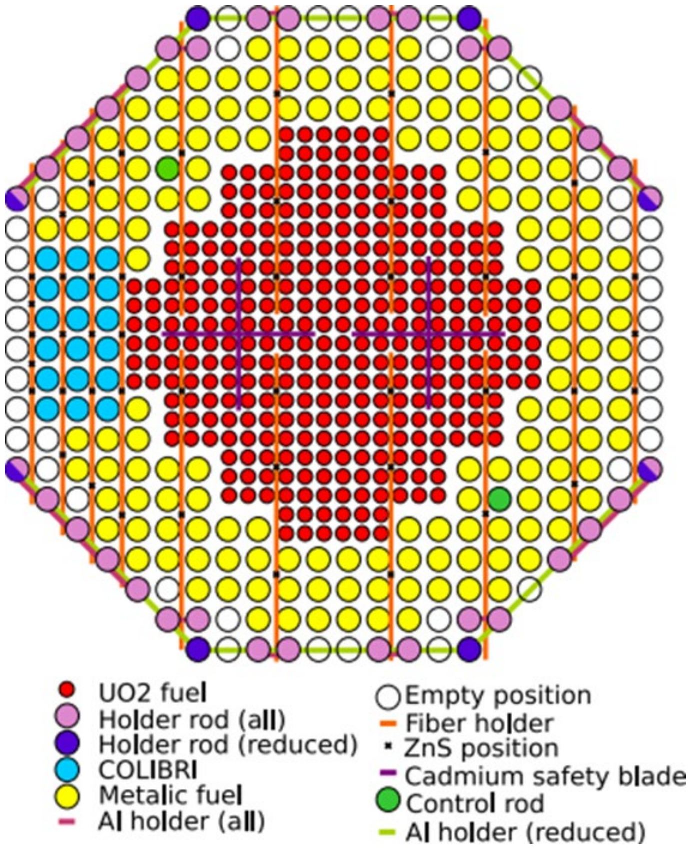

Figure 12: Schematic view of CROCUS reactor and detectors array with different holder arrangements.

Table 3: Computational results obtained for all studied cases: thin and thick scintillators, HDPE and POM rulers materials, complete and reduced number of tube holders, and finally JEFF 3.1 and ENDF/B-VII.1 nuclear data libraries. Please note that axial scintillator positions are 10 cm, 50 cm, and 90 cm, and 15 cm, 50 cm and 85 cm for each library, respectively.

Configuration	JEFF 3.1		ENDF/B VII.1	
	k_{eff}	Reactivity worth (pcm)	k_{eff}	Reactivity worth (pcm)
Without array	1.00240 ± 1 pcm	0	1.00289 ± 2 pcm	0
Thin / HDPE / all tubes	1.00204 ± 2 pcm	36 ± 3	1.00254 ± 2 pcm	35 ± 4
Thin / HDPE / reduced	1.00205 ± 2 pcm	35 ± 3	1.00258 ± 2 pcm	31 ± 4
Thin / POM / all tubes	1.00187 ± 2 pcm	53 ± 3	1.00244 ± 2 pcm	45 ± 4
Thin / POM / reduced	1.00189 ± 2 pcm	51 ± 3	1.00245 ± 2 pcm	44 ± 4
Thick / HDPE / all tubes	1.00202 ± 2 pcm	38 ± 3	1.00253 ± 2 pcm	36 ± 4
Thick / HDPE / reduced	1.00203 ± 2 pcm	37 ± 3	1.00257 ± 2 pcm	32 ± 4
Thick / POM / all tubes	1.00190 ± 2 pcm	50 ± 3	1.00238 ± 2 pcm	51 ± 4
Thick / POM / reduced	1.00197 ± 2 pcm	43 ± 3	1.00243 ± 2 pcm	46 ± 4

Simulating a variety of different options and using different nuclear data libraries, we conclude that the reactivity worth of the detectors array is below CROCUS operational limit of +200 pcm, and ranges from 32 pcm to 55 pcm, depending on the configuration and the nuclear data library used. The main elements of the simulated experiment will remain in the final execution. However some details, such as the shape of the aluminum holders at the end of the rulers, are subject to change. From the simulation results presented in the above two tables, a maximum of 2 pcm change is envisioned with most drastic modifications, e.g. all and reduced number of vertical Al tube supports.

4.3 Summary and prospects

The core mapping array was designed following the developments in detection technology presented aforesaid, and the feedback from the two first experimental campaigns in CROCUS and AKR-2. It is designed for allowing unprecedented spatial resolution of in-core neutron flux, possibly with directional dependence. As a consequence, the array would enable mapping of in-core neutron noise, specifically spectral power and phase of the modulation induced by a given perturbation, and targeting the discrimination of point kinetics-based vs. spatial effects in noise for code validation purposes. It is expected to provide a map of the neutron flux in CROCUS by the end of the CORTEX project, as a proof of principle for its use in future experiments.

5 Conclusion

In the framework of the CORTEX project, the work package 2 targets the generation of high quality neutron noise experimental data for code validation purposes. In this framework, a novel type of detection array was developed, targeting highly localized and neutron current measurements for noise applications. It is based on neutron scintillators, cutting-edge light collection technology, fast electronics, and FPGA electronics. Results demonstrates its successful application for noise in providing highly localized measurements. During the second experimental campaign in AKR-2, they provided high quality measurements as close as possible to the reactor core, and they will be used for the same purpose during the third campaign in CROCUS, planned for March 2021. With respect to neutron current measurements, first experiments are still under analysis for static experiments, but allowed the successful observation of a local angular dependence in a channel set in the reflector. Tests in noise conditions will be carried out during the third campaign in CROCUS as well. The design of an in-core detectors array was introduced. It aims at mapping in 3D the neutron flux in CROCUS, and will be installed and tested before the end of the CORTEX project.

6 References

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