Local and high distance neutron and gamma measurements of fuel rods oscillation experiments

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Abstract— **We report in the present article on the successful observation using noise analysis of the lateral oscillation of one fuel rod by ±2.5 mm around nominal at 0.1 Hz frequency, using an mm^3 miniature neutron scintillator *at the rod level*, and a BGO gamma detector *seven meters away from the reactor core center*. The experiment was conducted as part of the COLIBRI program in the CROCUS reactor, which is dedicated to the investigation of reactor noise induced by fuel vibrations. It consists in experiments on rod lateral displacement (static) and oscillation (dynamic) with different rods' numbers at various relevant amplitudes and frequencies. Its main motivation is the increased amplitudes in the neutron noise distributions recorded in ex- and in-core detectors that have been observed in recent years in Siemens pre-Konvoi type of PWR reactors. The obtained experimental data are used for the purpose of code validation, especially within the framework of the European project CORTEX on reactor noise applications. During the first phase of COLIBRI, the observation of a spatial dependence of the perturbation noise, also called neutron modulation, was demonstrated. In the second phase of COLIBRI starting 2021, it is planned to use a core mapping array of neutron detectors to record its propagation. It consists in about 150 miniature scintillators coupled to optical fibers and SiPM readouts, to be distributed in the reactor core. As a feasibility test, experiments were performed using a miniature scintillator prototype placed on a fuel rod, and oscillating the instrumented rod or the one directly adjacent to the detector. In addition, it is theoretically possible to measure branching or perturbation reactor noise using gamma radiation. Following recent developments on gamma measurements in CROCUS, the fuel oscillation was simultaneously recorded with a gamma detection array, LEAF. Its large BGO detectors were used by placing them at the maximum distance to the core, i.e. seven meters away with a clear line of sight using an experimental channel through the shielding of the reactor cavity.**

Keywords — **Reactor instrumentation, miniature neutron detector, neutron scintillator, gamma scintillator, reactor noise, noise analysis, zero power transfer function.**

I. INTRODUCTION

An expertise on perturbation and branching neutron noise was progressively acquired at the Laboratory for Reactor Physics and System behaviour (LRS) at École polytechnique fédérale de Lausanne (EPFL), thanks to a variety of instrumentation developments and experiments since the restart of experimental activities a bit less than a decade ago [1]–[10]. In particular, the COLIBRI program is dedicated to the experimental investigation of reactor noise related to fuel vibrations in the CROCUS zero power reactor. It consists in experiments on fuel rod lateral displacement and oscillation with different rods' numbers at various relevant amplitudes and frequencies. Its original and main motivation is the increased amplitudes in the neutron noise distributions recorded in ex- and in-core detectors that have been observed in Siemens pre-Konvoi type of pressurized water reactors, as recently in the Swiss Gösgen nuclear power plant. Thanks to this experimental program, EPFL contributes to the Horizon 2020 European project CORTEX, which is dedicated to the understanding and simulation of reactor perturbations for the development of novel core monitoring techniques [11], [12].

During the first phase of COLIBRI, the observation of a spatial dependence of the perturbation noise, also called neutron modulation, was demonstrated [13]. In the second phase of COLIBRI starting 2021, it is planned to use a core mapping array of neutron detectors to record its propagation [14]. It consists in about 150 miniature scintillators coupled to optical fibers and silicon photomultiplier (SiPM) readouts, to be distributed in the reactor core. As a test of local neutron noise measurements, experiments were performed using a miniature neutron scintillator prototype developed at LRS in collaboration with the Paul Scherrer Institut (PSI). With the detector directly placed on a fuel rod, the instrumented rod or the one directly adjacent to the detector were successively oscillated within the lattice at an amplitude of ±2.5 mm around nominal and a frequency of 0.1 Hz.

In addition, it is theoretically possible to measure branching or perturbation reactor noise using gamma radiation. In-core and at distance branching gamma noise measurements were recently conducted in CROCUS, thanks to recent developments on gamma measurements at LRS [3], [15]–[18]. As a test to measure perturbation noise at distance, the fuel oscillation was simultaneously recorded with a gamma detection array, LEAF [15]. Its two large and high efficiency BGO detectors were used by placing them at the maximum distance to the core, i.e. seven meters away with a clear line of sight using an experimental channel through the reactor cavity, in the same configuration than the most distant branching noise measurements.

The article is structured as follows: in Section II, we introduce neutron modulation and the used methodology; in Section III, we present the experimental campaign, including the CROCUS reactor, the COLIBRI fuel rod oscillation device, the neutron and gamma detection systems, as well as the conducted experiments. We then present and discuss the results in Section IV, for both detection systems separately, and in comparison. Finally, we conclude in Section V.

II. NEUTRON MODULATION AND METHODOLOGY

When a small and periodic reactivity perturbation $\rho(t) = \rho_0 + \delta\rho(t)$ is applied to a critical assembly, its kinetic behavior with respect to the neutron population $N(t) = N_0 + \delta N(t)$ can be modelled by a linear time invariant system represented in the frequency domain by the zero power transfer function, or ZPTF [19]:

$$\frac{N(j\omega_0)}{\rho(j\omega_0)N_0} = H(j\omega_0) = \left(j\Lambda\omega_0 + \sum_i^n \frac{j\omega_0\beta_i}{j\omega_0+\lambda_i} - \rho_0\right)^{-1} \quad (1)$$

Where j is the unit imaginary number, ω_0 is the angular frequency of the perturbation, $(\beta_i)_{i=1,2,\ldots,n}$ the effective fractions and $(\lambda_i)_{i=1,2,\ldots,n}$ the decay constants for the precursor group i. The function, as in the complex domain, is conventionally represented by its modulus (amplitude) and argument (phase).

The ZPTF is commonly determined experimentally by modulating periodically the reactivity at several frequencies and measuring its effect on the neutron population. Experimental data consist of time series obtained from radiation detectors sensitive to the core neutron flux, such as the miniature neutron scintillators used in this study and presented hereafter. In addition, it was already demonstrated that fission gamma rays can be used for reactor noise analysis, in the specific case of branching noise, as they are time stamping fission and decay events as neutrons do [3]. We hereby test the hypothesis using gamma scintillators on the specific case of modulation, or perturbation noise, which can be considered an extension of branching noise.

The time series are analyzed in the frequency domain by typically calculating Auto- and Cross Power Spectral Densities (APSD/CPSD) of respectively one or two detectors' signals. As a consequence, a fuel rod oscillation in COLIBRI at a given base frequency would induce a peak at this given frequency. The amplitude in the power spectral density would depend on the corresponding reactivity change, and frequency.

III. EXPERIMENTAL SETUP

A. The CROCUS reactor

CROCUS is an experimental zero-power reactor located at EPFL, uranium-fueled and water-moderated, dedicated to teaching radiation and reactor physics, and to research [20]. A complete description of the reference core can be found in the International Reactor Physics Experiments Handbook (IRPhE) [21], [22]. It has been licensed for operating at a maximum power of 100 W, i.e. a total neutron flux of ~$2.5\cdot10^9$ $cm^{-2}\cdot s^{-1}$ at the core center. Criticality is controlled either by water level using a spillway, or by two B_4C absorber control rods, with an accuracy of ±0.1 mm (equivalent to approximately ±0.4 pcm) and ±0.5 mm (up to ±0.2 pcm), respectively. CROCUS operates at room temperature using a controlled water loop with secondary and tertiary circuits, two heat exchangers and an electrical heater.

The core is located in an Al-6060 grade vessel of 130 cm in diameter, 160 cm in height, and 1.2 cm in thickness. The vessel is filled with demineralized light water used as both moderator and reflector. The core active part has the approximate shape of a cylinder of 100 cm in height and about 60 cm in diameter. It consists of two interlocked fuel zones with square lattices of different pitches:

- an inner zone of 336 UO_2 rods with an enrichment of 1.806 wt.% and a pitch of 1.837 cm;
- an outer zone of 176 U_{metal} rods for these experiments, 0.947 wt.% and 2.917 cm;
- a varying water gap between the two zones because of the two different pitches.

A picture of the facility and core configuration is shown on Figure 1. Both uranium fuels consist of a 1-m pile of cylindrical pellets cladded in aluminum. The rods are maintained vertically by two octagonal aluminum grid plates spaced 1 m apart. In the COLIBRI program, the grids have a 1 mm cadmium layer to limit axial neutron leakage to the environment, i.e. structures activation, with the active zone of the fuel starting in the middle of the lower cadmium layer.

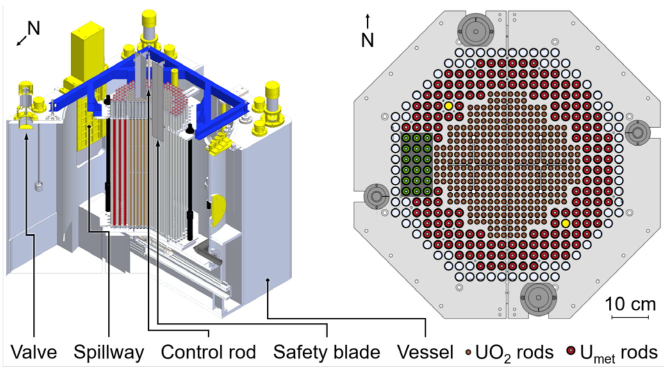

Fig. 1. View of the CROCUS reactor (left), and the core superior grid and configuration with the oscillation location (highlighted with green U_{met} rods).

B. The COLIBRI fuel rods oscillator

The COLIBRI fuel rods oscillator is designed to simultaneously oscillate laterally any of 18 metallic uranium fuel rods in the west region of the core periphery zone. It consists of two moving plates set above and below the core grids, and rigidly connected by an aluminum beam (see Fig. 2). Each plate carries an extremity of the fuel rods, top and bottom respectively. The top moving plate is fixed on the superior grid *via* gliders. Its oscillation is produced by a motor: the motor rotation is converted to a linear translation using an eccentric sheave and a connecting rod. The oscillation is transferred to the bottom moving plate *via* the aluminum beam. The bottom moving plate is not constrained by gliders, and is displaced only due to its connection to the transmission beam.

The selection of the moving fuel rods is performed by letting the rods lay on the reactor base plate (non-moving), or suspend them up 10 mm above the base plate to insert them in the moving plates. Top and bottom end caps are fixed to each rod to allow the insertion in the enlarged holes of either the static grids or the moving plates. The weight of the oscillating rods is supported by a platform. The amplitude of the oscillation is precisely tuned by changing the eccentricity of the sheave with calibration plates, 0.5 mm by 0.5 mm from 0 to ±2.5 mm. Its frequency depends on the speed of the motor.

The oscillation is controlled and monitored *via* a LabVIEW-developed software with 10 ms time-steps. An inductive captor is set at the rotation axis (i.e. at the top), which detects the actual movement of the motor by detecting the passage of four metallic pins per rotation. A cable coder is used to measure the displacement of the moving plate, i.e. at the bottom, with a 0.1 mm precision. The software produces a csv file output with the recordings of the motor position and speed, the signal of the inductive captor, and the position measurement of the cable. The inductive captor signal is also extracted for live and synchronized recording with the detection instrumentation.

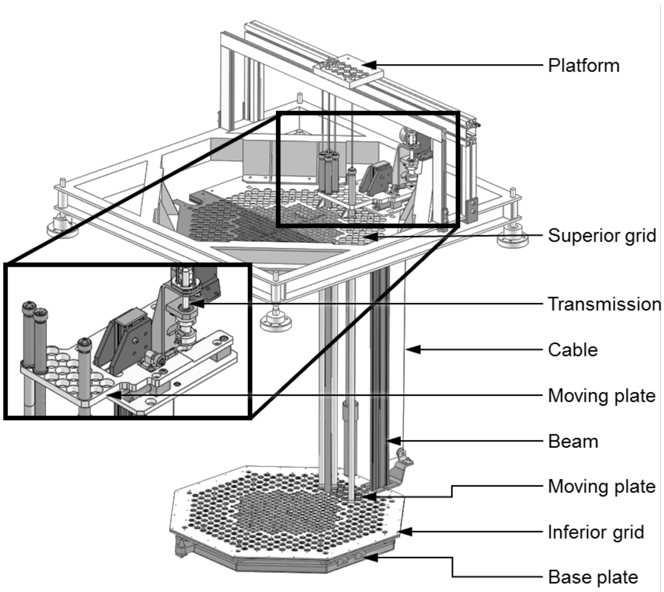

Fig. 2. Overview of the fuel rods oscillator with core structures and a few rods inserted in the device, and details of the top part with moving plate and motor.

C. Miniature neutron scintillator

The miniature fiber-coupled neutron scintillator used in this study has been developed at LRS in collaboration with the Paul Scherrer Institut [7]. Recent experiments demonstrated its applicability for the study of highly localized measurements, thanks to its miniature dimensions, as in this study [23]. In the used prototype version, the neutron sensitive area of the detector is a ~1 mm^2 Scintacor scintillator screen of zinc sulphide (ZnS) doped with ^{6}Li. The conversion of the incoming neutrons in charged particles is performed by the (n,α) reaction of ^{6}Li. The alpha and triton particles arising from the reaction induce the scintillation of the ZnS(Ag) molecules of the crystal at a peak wavelength of 450 nm. It has a typical light yield of 1.6×10^5 photons per neutron, and a decay time to 10% of about 80 µs. Through this two-step process, the incoming neutron radiation is converted to a light signal. An ESKA plastic optical fiber is coupled to the scintillator screen, guiding the scintillation photons to the read-out electronics. These consists of a silicon photomultiplier (SiPM) for photon detection, and in the present study of a standard analog detection chain setup, depicted in Fig. 3. Individual pulses from the SiPM signal are first pre-amplified, then converted into logic pulses (TTL). A second amplifier and a single channel analyzer (SCA) allow the conversion and discrimination of photon trains into individual neutron events, for neutron counting purposes.

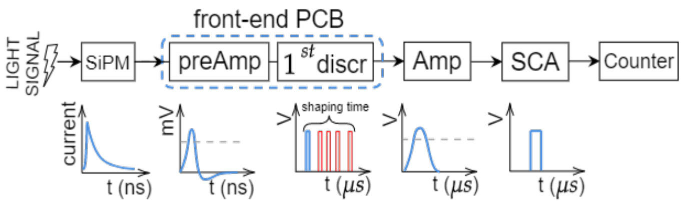

Fig. 3. Electronics and signal treatment of the miniature neutron scintillator, from light collection to neutron counting.

The detector consists of the scintillator, its fiber, and an aluminum cap. As represented in Fig. 4, it was set in a PTFE holder on one of the outmost rods on the second line (namely, A2) of COLIBRI, at an axial position of (525 ± 1) mm.

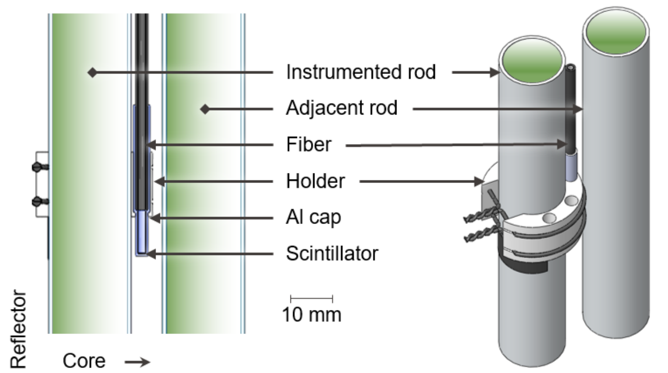

Fig. 4. East-West cross section and 3D view of the positioning of the miniature scintillator on one of the outmost fuel rods of COLIBRI (A2), with respect to its adjacent one (B2).

D. The LEAF gamma detection array

The LEAF gamma detection array consists of two pairs of gamma scintillators, namely two small cerium bromide ($CeBr_3$) and two large bismuth germanate (BGO) detectors [15]. Each detector is directly coupled to a photomultiplier tube (PMT) of matching dimensions. The two small $CeBr_3$ detectors are designed for in-core use in CROCUS, whereas the BGO detectors are those of interest in the present study. The crystal type and their important size of 127 mm diameter and 250 mm height are selected for efficiency purposes. These detectors house a Photonis 5" Type XP4578 PMT. The powering, signal treatment and acquisition are performed using the integrated system Canberra DSA-LX. For both detectors, the high voltage is -1260 V, the coarse gain is 6.4, and the lower level threshold is 0.5 % of the maximum channel (2^{14}). The rise time and flat top are set at 0.2 µs and 0.0 µs, respectively. For the noise application at hand, the analog output of the amplifier is used for synchronized acquisition with other signals.

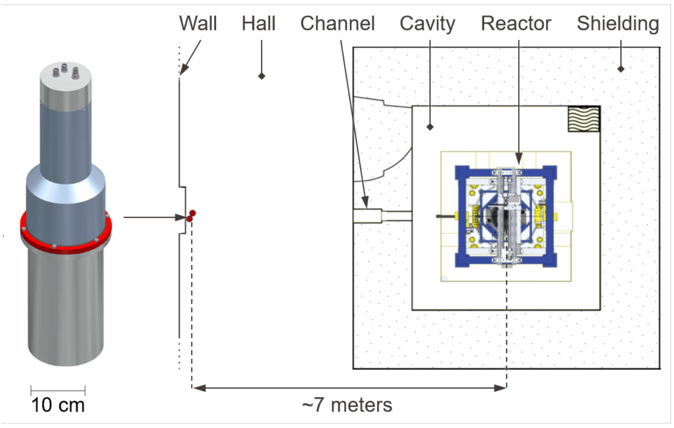

Fig. 5. CAD model of a BGO gamma scintillator (left), and positioning at about seven meters with respect to the reactor core center with a direct line of sight.

E. Conducted experiments

The experimental campaign was carried out on 19th and 20th December 2019. It consists of static fuel rod displacement and dynamic fuel rod oscillation experiments. Whereas COLIBRI is designed for displacing up to 18 rods, only individual rods are moved in these experiments, in order to single out the local effect of one rod only with the miniature neutron scintillator, and to test the smallest perturbation case with the large gamma scintillators set at distance. Thus only the rods on line 2 (North is line 1), and outmost (column A) and central (column B) positions are displaced individually: the instrumented rod is A2, the one adjacent to the detector is B2 (see Fig. 6). We hereby present the results for the fuel rod oscillation, whereas a corresponding static displacement study will be presented in a further article currently under preparation. The experiments consist of two 30-minutes oscillations at ± 2.5 mm amplitude and 0.1 Hz frequency carried out on 20th December: one oscillation of the B2 adjacent rod from 11:56, and one of the A2 instrumented rod from 15:17. The detectors signals and the inductive captor signal from COLIBRI are acquired together with the EPFL/PSI pulse acquisition system with a 0.5 ms dwell time [25].

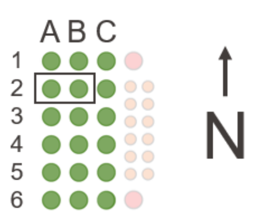

Fig. 6. Identification of fuel rods in COLIBRI. Fuel rods oscillated during this campaign are circled in black, with A2 the instrumented one.

IV. RESULTS AND DISCUSSION

The estimation of the Auto Power Spectral Densities (APSD) was performed with a MATLAB script using the Welch method. A rectangular window with 50% overlap was chosen. The 0.5 ms dwell time, i.e. a sampling frequency of 2 kHz, is sufficient for capturing the frequency of interest, 0.1 Hz. With a window length of 2^{18} samples, the spectral resolution is consequently 8 mHz.

In Fig. 7 are represented the two APSD obtained with the miniature neutron scintillator. Both oscillations of the instrumented rod and its adjacent one present a sharp peak at the expected frequency of 0.1 Hz, or 0.97 Hz more precisely. A slight but significant difference can be observed in amplitude between instrumented and adjacent rods' oscillation, 0.21 vs. 0.27 Hz^{-1}, respectively, with a maximum for the adjacent rod oscillation. The existence of a difference is consistent with the observation of local variations thanks to the miniature size of the detector. Harmonics seem to be present as well, at 0.2 Hz for instance, but are relatively lost in the baseline noise.

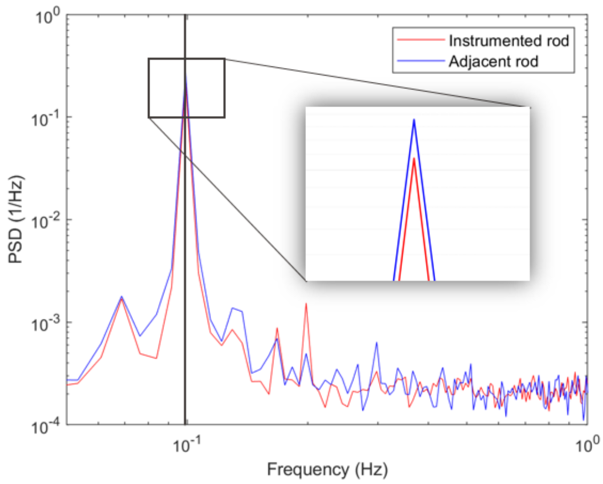

Fig. 7. Auto power spectral densities obtained with the miniature neutron scintillator for the oscillation of the instrumented fuel rod (red), and its adjacent one (blue).

In Fig. 8 are represented the APSD obtained with one of the BGO gamma scintillators. A sharp peak at 0.1 Hz is successfully observed, as well as significantly high harmonics, i.e. at 2 Hz and 4 Hz, and additional frequencies, e.g. 0.17 Hz. It is to be noted that only minimal differences are observed between the two oscillations cases (5.4×10^{-2} Hz^{-1}), which is expected due to the global nature of the measurement. Especially, numerous peaks are consistently observed for both oscillation cases at higher frequencies.

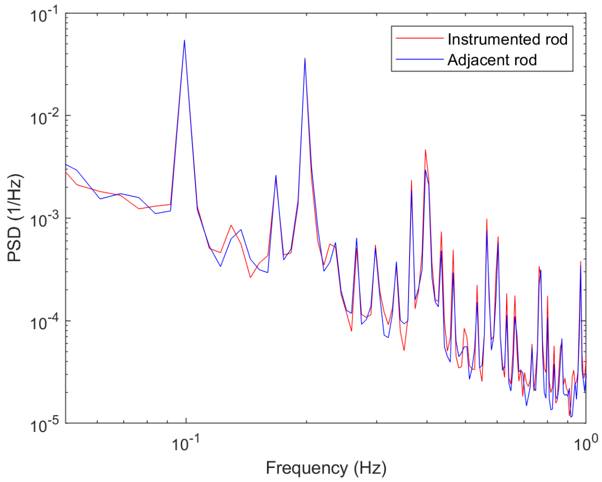

Fig. 8. Auto power spectral densities obtained with the large BGO gamma scintillator for the oscillation of the instrumented fuel rod (red), and its adjacent one (blue).

The comparison of local neutron and distance gamma APSD (see Fig. 9) for the instrumented rod case allows to complement the observation. First, as observed in previous noise experiments, the branching noise baseline is visible in the BGO results, but not in the miniature neutron scintillator ones: its sensitivity – per fission event – is too low to capture the reactor noise itself [26]. In addition, it would seem that the relatively small peak (9×10^{-4} Hz^{-1}) at 0.17 Hz in the neutron APSD remains significant, as both detectors detect it consistently.

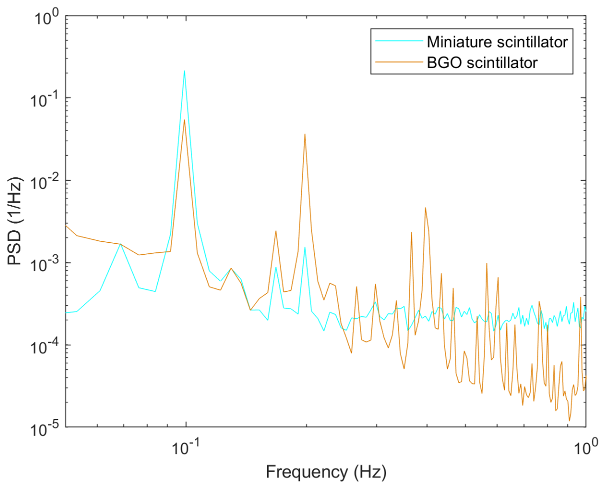

Fig. 9. Auto power spectral densities obtained with the miniature neutron scintillator (cyan) and the large BGO gamma scintillator (orange) for the oscillation of the instrumented fuel rod.

V. Conclusions

The COLIBRI program in CROCUS consists in experiments on the lateral displacement (static) and oscillation (dynamic) of fuel rods in their lattice. As a feasibility study for further experiments, we report here on the successful observation of individual fuel rods' oscillations, using neutron and gamma noise, locally and at meters-distance, respectively.

One of the outmost fuel rods of CROCUS and its adjacent one were oscillated successively, ±2.5 mm from core center to reflector around their nominal position, and at about 0.1 Hz frequency. Two different detection systems were employed: a miniature neutron scintillator set directly on the outmost fuel rod, and a BGO gamma scintillator set at about seven meters from core center, in front of an opening in the cavity shielding.

Both systems were able to detect the fuel rod oscillations. The miniature detector seemed to observe a difference between the two oscillations, with amplitudes of 0.21 vs. 0.27 Hz^{-1} for instrumented and adjacent rod oscillations, respectively. As a difference on the local neutron flux is indeed expected, this confirms its capability to differentiate highly localized effects. Limited harmonics and branching noise contents were observed, aside from a harmonic at 0.17 Hz which was confirmed thanks to the gamma noise results. On these latter, we successfully observed gamma oscillations that correspond to an in-core single rod perturbation at seven meters to the reactor core center. It confirms the possibility to monitor local perturbations and the corresponding very small changes in reactivity, at an unprecedented and unforeseen high distance. No visible differences were observed between both oscillations, as can be expected for the observation of a global effect of the perturbation. Numerous higher harmonics are visible too, as well as branching noise as observed previously in dedicated experiments.

These positive results on both local neutron noise and distance gamma noise open up for a variety of prospects. First, the campaign will be further analyzed to complement the neutron noise results with the static measurements of a single fuel rod's displacement, as well as providing quantitative results with propagated uncertainties [27]. The next planned outlook consists in the implementation of 149 detectors to map CROCUS in 3D. In addition to noise studies, the array will be used for static and dynamic experiments as well, e.g. control rod withdrawal, representing a unique experimental data set for validation purposes. On the gamma noise side, further publications are on-going on branching noise, and data analysis of a larger data set is ongoing for detailed and quantitative results of perturbation noise.

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