Measuring neutron noise in a research reactor using a 3D core mapping system

M. Saliba and O. Pakari**
*Nuclear Energy and Safety Research Division
Paul Scherrer Institut
5232 Villigen PSI Switzerland

Abstract:
Neutron noise analysis in zero power reactors is a powerful instrument that can provide valuable insights into integral parameters, like the prompt decay constant α, which can be used for code validation, notably codes that predict time dependent behaviour (reactor transients). The zero-power research reactor CROCUS has been frequently used to conduct a variety of noise experiments. Recently, CROCUS has been expanded by a new detection system called SAFFRON. It consists of an array of 149 miniature neutron detectors, evenly dispersed through the core, enabling 3D core mapping capabilities. To test the new capabilities, we performed a neutron noise experiment using the new 3D detector array to determine the prompt decay constant α. Using the Rossi-α method, we found the prompt decay constant to agree with Serpent 2 Monte Carlo code predictions within 1σ of the respective estimated uncertainties. The results indicate a powerful measurement tool that can be expanded to active perturbation experiments, 3D flux maps, and other high fidelity reactor physics experiments.

1 INTRODUCTION

The concept of neutron noise [1] can be illustrated by considering the steady state operation of a nuclear reactor. The theoretical output power of a steady state reactor is a scalar, fission rate times energy released per fission. Real signals contain fluctuations around this scalar value, often referred to as noise. In a neutron multiplying medium, however, the so-called neutron noise is not purely random and can contain usable information within correlations found in time. Via neutron noise analysis we can extract information about the point kinetic integral parameters of the system, such as the prompt decay constant. Measuring the prompt decay constant during steady state reactor operation offers a non-invasive approach to measure point kinetic parameters that are utilized for code validation and predicting reactor transients and especially during accidents, such as Reactivity Induced Accident (RIA).

To observe uniquely neutron noise in a nuclear reactor, we must rely on zero power systems where the noise comes solely from the neutron fluctuations. In contrast to power reactors where neutron noise is mixed with thermal-hydraulic noise [2] which make the detection and analysis of neutron noise very intricate. Therefore, the CROCUS zero power research reactor at EPFL is an adequate facility for conducting experiments related to neutron noise [3] and for code validation [4].

EPFL's Laboratory for Reactor Physics and Systems Behaviour (LRS) has developed a high-resolution detection system named SAFFRON, consisting of 149 evenly distributed array detectors within the CROCUS reactor core. The primary objective of SAFFRON is to enable time resolved of three-dimensional space-dependent neutronics effects, thereby providing valuable data for the validation of high-fidelity deterministic and probabilistic neutronics codes in both steady-state and kinetics scenarios. Additionally, the system can spatially characterize perturbation noise induced by neutron modulation, making SAFFRON an appropriate tool for neutron noise analysis.

In this paper, we present the experiment and results of a neutron noise campaign suing SAFFRON. In Section 2, we present the CROCUS reactor and SAFFRON detector, the methodology to determine the prompt decay constant, and Monte Carlo. In Section 3, the results are presented and discussed. In Section 4, we provide a concise conclusion summarizing the key findings from the overall experiment and offering insights into future research directions.

2 MATERIALS AND METHODS

2.1 CROCUS zero power Research Reactor

The CROCUS reactor, located at the Swiss Federal Institute of Technology in Lausanne (EPFL), as shown in Figure 1, is a critical assembly that operates with uranium fuel and is moderated by light water. It is primarily utilized for educational and research purposes and operates at a maximum power of 100 W. One notable characteristic of the reactor is its utilization of two different fuel types arranged in concentric fuel zones, i.e., an inner zone consisting of UO2 and outer zone consisting of metallic U, both with aluminium cladding. The reactor's geometry has been evaluated and established as a benchmark in the International Handbook of Evaluated Reactor Physics Benchmark Experiments (IRPhE) for modelling purposes [5].

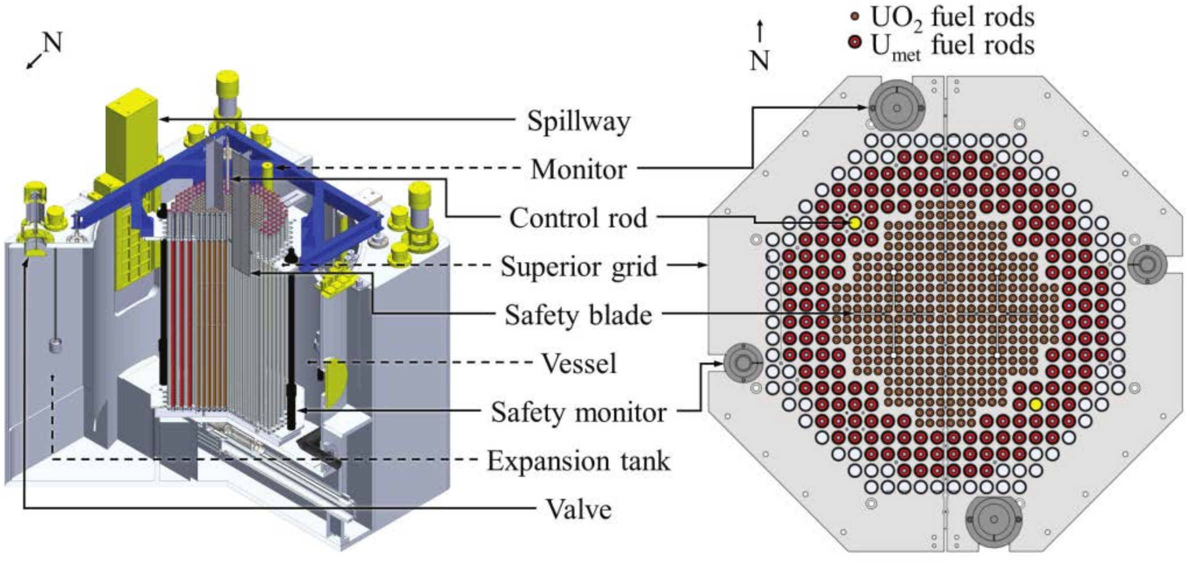

Figure 1 - CROCUS research Reactor scheme

2.2 SAFFRON: a 3D core-mapping system in CROCUS

The SAFFRON [6] detector array is a new specialized system comprising 149 *minimalist and miniature* (also called *MiMi*) neutron detectors [7] dispersed in-core as shown is Figure 2 (Right), specifically designed for the CROCUS zero-power research reactor.
Each MiMi detector consists of a thin sheet of Zinc Sulphide (ZnS) mixed with Lithium-6 Fluoride (^{6}LiF, making it a thermal neutron detection system. The operational mechanism of these detectors is shown in Figure 2 (Left). The emitted light is collected via optical fibres out of the reactor core into silicon photomultiplyer (SiPM) devices, and then the signal is processed by a computer.

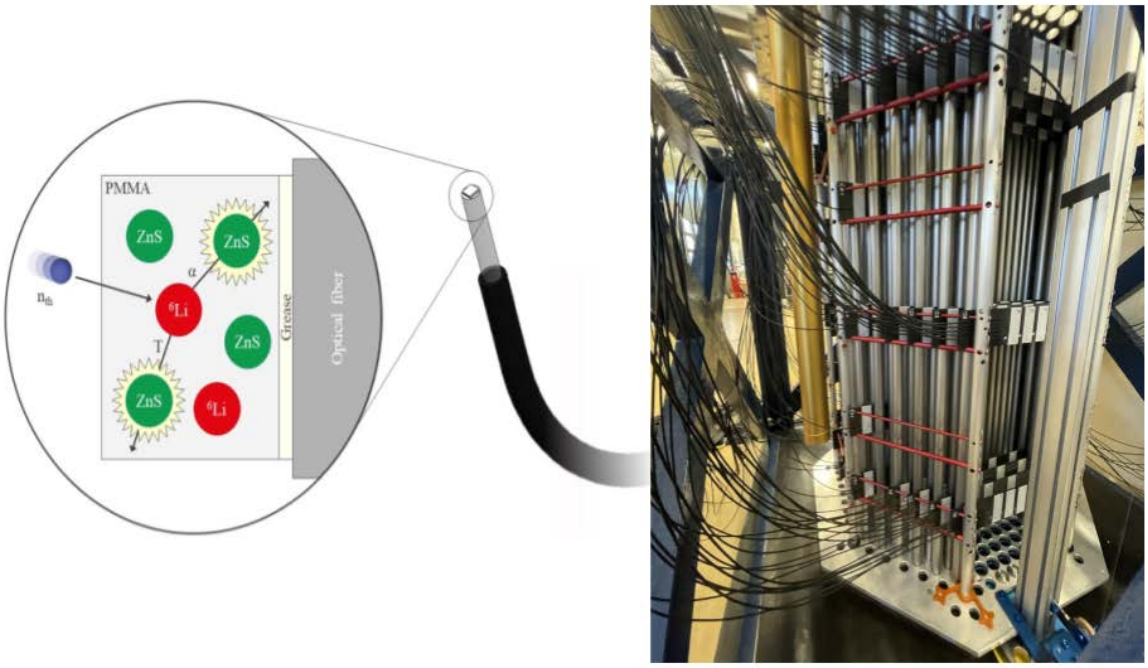

Figure 2 - (Left) Scheme of MiMi neutron detection mechanism which involves the absorption of a thermal neutron by the lithium-6, which has a significantly large cross-section. This absorption leads to the generation of tritium and alpha particles as products of the nuclear reaction. The alpha and tritium particles interact with the scintillator, ZnS, resulting in the emission of photons. (Right) The SAFFRON system inside the core. The optical fibres that carry the detection signal can be seen exiting from between the fuel rods.

2.3 Temporal Correlation Analysis: The Rossi-α Method

Initially developed for fast reactor systems characterized by short neutron lifetimes and minimal overlap of nuclear chains over time, the Rossi-α method [8] has been adapted for thermal systems with suitable instrumentation. The idea behind this method is to directly measure the fission chains as they propagate through the reactor. Practically, the time differences calculated from the detector signal are binned in a time interval between 0s and 0.1s, to obtain a clear fit for the following function:

$$f(x) = Ae^{-\alpha x} + B \quad (1)$$

Equation (1) describes an exponential decay probability distribution. Physically it is the probability of detecting another neutron emerging from the same prompt chain. When fitted using the non-linear least squared method, α is determined, hence, obtaining the prompt decay constant.

2.4 Monte Carlo Simulation: Serpent 2

In this work we use Serpent 2 [9], a Monte Carlo neutron transport code widely used for reactor physics and radiation shielding studies. Serpent 2 has predominantly been utilized for evaluating group cross section libraries in diffusion codes and has been updated to also predict kinetic parameters [10]. In light of this, the forthcoming section aims to contribute to a direct comparison of Serpent 2 Monte Carlo code against experimental data, specifically targeting the assessment of its capability to accurately determine kinetic parameters such as the prompt decay constant α.

3 RESULTS AND DISCUSSION

3.1 The Prompt Decay Constant α in the CROCUS research Reactor

After acquiring data from SAFFRON during reactor steady state operation at 2 mW power for duration of 2.5 hours, the timestamps collected were processed with the Rossi-α method as shown in Figure 3.

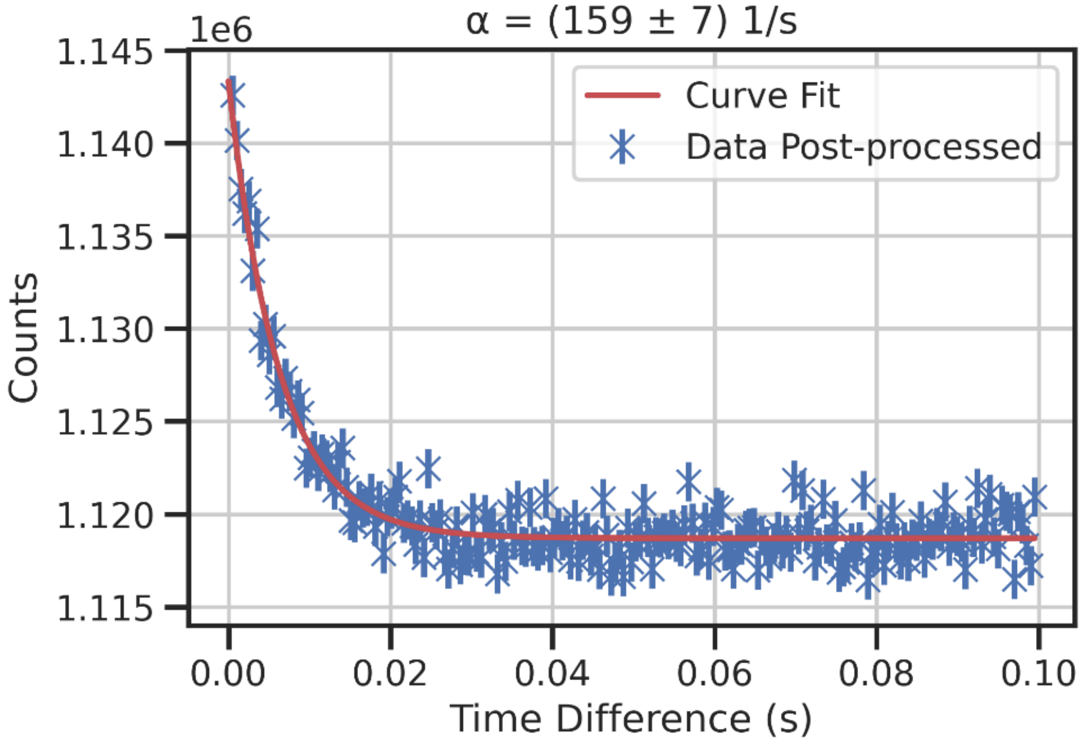

Figure 3 - The time differences are represented by the blue crosses with their associated error bars, the red line corresponds the fit of equation (1) conducted by the non-linear least-squared method.

The data takes the expected shape of an exponential decay. The prompt decay constant α is estimated to be (159 ± 7) 1/s. The uncertainty around the mean value is obtained by the covariance matrix generated by the non-linear least squared method. Hence, the interval of $\alpha_{experiment} \in [152,166]$.

3.2 Validation of Serpent Monte Carlo code

In Serpent version 2.1, the reactor with all its respective components were modelled, furthermore the SAFFRON detector was modelled as well. The simulation ran in source mode for 600 core-hours. During the simulation, every time a neutron was captured in SAFFRON, the time of the event is recorded (timestamp) via a custom script, because keeping track of every interaction is memory intensive. This allows a direct comparison of the experimental observable and the simulated system. The results of the comparison are shown in Figure 4.

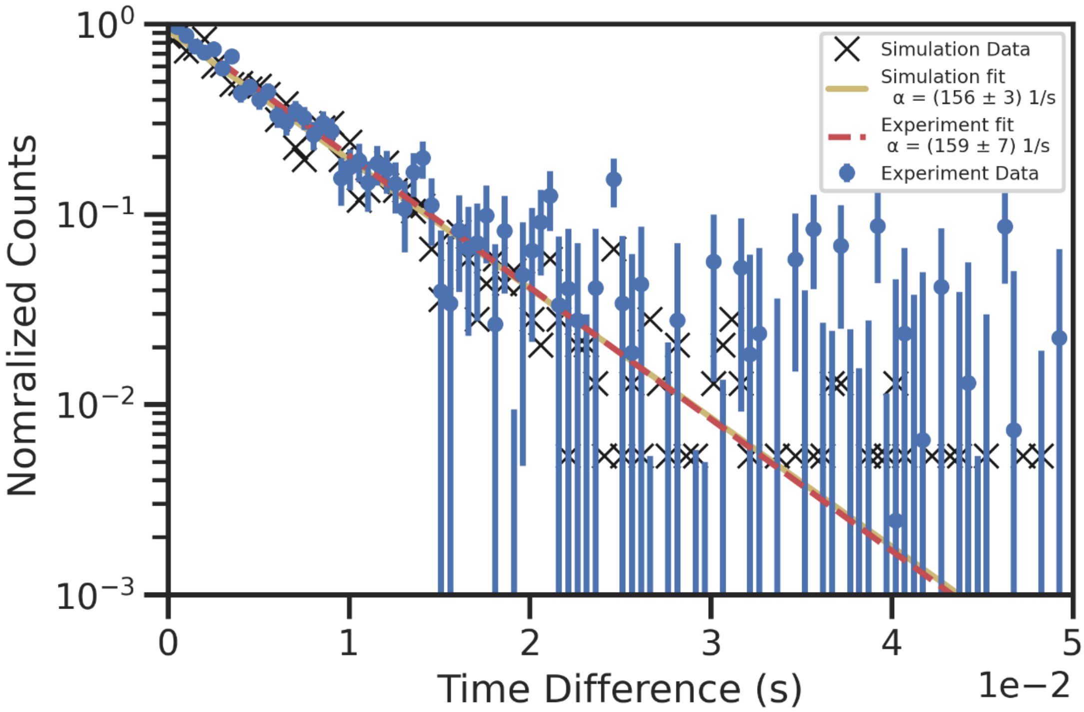

Figure 4 - The blue dots are the experimental points with their respective error bars, the red dashed line is the fitted function of the Rossi-α method to the experimental data points. The black crosses are the points obtained by simulation and the line in yellow is the fitted function of the Rossi-α method. The curves were normalized to represent only the exponential part of equation (1) for better contrast.

The obtained prompt decay constant from the simulation, 156 ± 3, falls within the experimentally determined interval of [152;166]. This demonstrates that the simulation results are consistent with the experimental findings. The relative mean difference of 1.89% indicates a relatively small deviation between the simulation and experiment, suggesting a good agreement between the two. These promising results shows the reliability of SAFFRON detector. Future experiments might be conducted in the study of the effect of neutron clustering, spatial correlation, or even spatial-dependent kinetics.

4 CONCLUSION

This paper presents an investigation into the neutron noise analysis technique applied in the scope of zero power research reactors via a new 3D core mapping detector system. By utilizing neutron noise analysis such as the Rossi-α method, kinetic parameters such as the prompt decay constant α was determined, providing insights into reactor dynamics and stability. Moreover, the Serpent simulation showed great agreement with the experimental determined value, having a discrepancy of 1.89% within 1σ. Zero power reactors play a important role in advancing reactor physics, validating codes, and education, as they enable the nuclear industry to use neutron noise analysis and its applications. Alongside with SAFFRON detector, potential experiments are now available thanks to the high resolution of the detector such as live flux maps and spatial correlation studies. By using these tools, the nuclear industry can improve reactor safety, efficiency, and overall performance, leading to ongoing development and progress in the field.

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