FIRST MEASUREMENTS OF THE KINETIC RESPONSE OF THE MUSE-4 FAST ADS MOCK-UP TO FAST NEUTRON PULSE

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On behalf of the MUSE international collaboration

Abstract

The MUSE-4 experiment has started its first commissioning measurements at the beginning of the year 2001 at CEA/Cadarache (France). This international experiment co-ordinated by CEA, included in the 5FWP of the European Union and GEDEON, is intended to study the physics of fast sub-critical assemblies coupled with a pulsed external source.

To achieve this objective, the GENEPI accelerator, a (d,d) or (d,t) neutron source developed at CRNS/IN2P3/ISN (Grenoble), has been coupled with the MASURCA reactor, a uranium-plutonium MOX-based fast reactor, with solid sodium simulating a liquid metal coolant and a lead buffer to simulate a spallation target. The very short neutron pulse (1 μs) provided by GENEPI, together with the possibility to change the pulse repetition rate up to 5 kHz and the different levels of sub-criticality available will facilitate a study of the reactor kinetic parameters in situations close to most of the proposed accelerator-driven Systems (ADS).

The paper presents the first experimental results for dynamic measurements performed in MUSE-4 configurations. Several pulsed neutron source experiments have been carried out using the (d,d) GENEPI neutron source in configurations going from USD 1.33 to USD 12.6. In addition, noise techniques (Rossi and Feynman-alpha) have been applied to stationary states in the same range of sub-criticalities.

Reactivity levels obtained by these techniques have been compared with more classic rod drop/source multiplication measurements. The kinetic parameters, β (which ranges between 330 and 360 pcm) and β/Λ (with a value of approximatively 6 270 s^{-1}), have been determined by Monte Carlo and/or deterministic codes.

Introduction

One major objective of experimental data requests to support accelerator-driven sub-critical system (ADS) studies is to develop and qualify methods of reactivity measurements and monitoring. In any nuclear multiplicative system, critical or sub-critical, the reactivity is one of the most important safety-related parameters because it defines the mid and long-term response (after a few ms) of the system after any variation of its operational conditions. It seems likely that any regulatory body will demand that the physics of sub-critical reactivity monitoring in commercial ADS are well understood, and the methods are qualified before considering a license for such a system.

The MUSE (multiplication with an external source) series of experiments, currently being performed at the Cadarache centre of CEA in France by an international collaboration funded by an EU 5FWP project, are providing an environment for contributing to this objective. [1] The availability of a deuteron accelerator (GENEPI), built at ISN (Grenoble), and the possibility of using two types of reactions (d,d) and (d,t), will allow the validation range of the dynamic techniques that could be used in a future demonstrator or power plant to be extended. Furthermore, the experimental results obtained during the MUSE-4 experiments will also allow the validation of the calculation tools by means of an international Benchmark [2] under the auspices of the NSC-NEA/OCDE thanks to the physics subgroup of the WPPT.

In the following paragraphs, the first experimental results for the time evolution in different sub-criticality levels of the MUSE-4 core will be presented. Also, the experimental results obtained in "close-to-criticality" configurations with two noise techniques, Feynman-α and Rossi-α, will be shown. In all the cases, the reference reactivity levels have been determined using a revised rod drop technique and static source multiplication method.

Experimental set-up

MASURCA (Figure 1) is a fast spectrum experimental facility which, for the MUSE-4 experiments has been loaded with a MOX fuel of ~25% plutonium enrichment (^{240}Pu/Pu ~18%) and sodium, in order to be representative of a fast plutonium burner with sodium coolant. A lead central buffer surrounding the deuterium (or tritium) target at the end of the GENEPI accelerator tube plays the role of a spallation target. A stainless steel/sodium reflector surrounds the core, and the shielding is made axially with stainless steel and radially with iron.

For the experiments performed up to now, the neutron pulses generated by GENEPI via the (d,d) source had a FWHM duration of ~1μs, and the frequency of the pulse was varied from 1 kHz to 4 kHz depending on the experiment. To measure the time evolution after the neutron burst, detectors 2, 3, 7 (^{235}U fission chambers) and a ^{237}Np fission chamber have been used. For the noise experiments, detectors 3 and 4 were used. The data presented in this report have been collected by two different data acquisition systems specifically designed for the MUSE experiment by CIEMAT and CEA. Both systems allow the time of each individual fission detected by the fission counters to be recorded.

In order to achieve the six different measured reactivity levels, the system was perturbed either the insertion of pilot and control rods or by using a different number of fuel cells.

Figure 1. **The MUSE-4 core – detectors and rods**

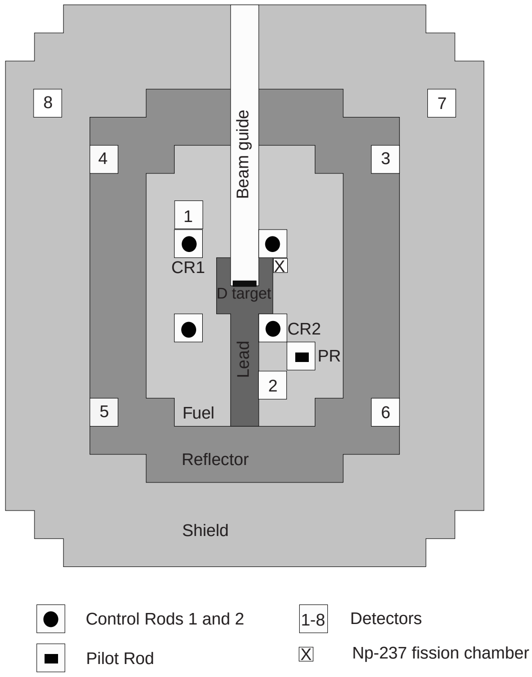


Table 1. **Sub-critical reactivity levels in dollars using rod drop / source multiplication methods**

Configuration	**Core** (USD)	**Reflector** (USD)	**Final** (USD)
I	0.077 ± 0.004	0.077 ± 0.004	0.077 ± 0.004
II	0.373 ± 0.024	0.372 ± 0.022	0.372 ± 0.024
III	1.35 ± 0.09	1.33 ± 0.08	1.34 ± 0.08
IV	1.77 ± 0.12	1.73 ± 0.10	1.75 ± 0.10
V	12.5 ± 1.2	12.8 ± 1.1	12.6 ± 0.8
VI	13.0 ± 1.0	13.0 ± 0.8	13.0 ± 0.8

Rod drop and source multiplication experiments

Sub-critical levels I and II are determined using the pilot rod drop from critical state to down. Reactivities are assessed using inverse kinetic procedures with source adjustment [3] to take into account the intrinsic source due to the MOX fuel. Effective kinetic constants such as neutron delayed yields α_j and radioactive decay constants λ_j are derived from the Tuttle evaluation [4] and ERANOS calculations via a 33 groups R-Z geometry. [5]

Reactivity levels III to VI are obtained using the detector-averaged reactivity level II (ρ_{ref} = 37.2 ± 0.1 ¢) as a reference for source multiplication techniques. Configurations V and VI are determined using spatial/energetic correction factors (MSM factors). [6] These factors are also obtained using the ERANOS code suite.

Table 1 presents the detector-averaged reactivities obtained for each configuration in the core and reflector region. Sources of uncertainties [3] are (a) counting rates (negligible), (b) source adjustment (~1%), (c) kinetic constants (~5%) and in case V and VI (d) MSM factors (~3%). Because the dispersion between fuel and reflector levels of sub-criticality is low, a region- and detector-independent final value is given for each configuration.

Pulsed neutron source experiments (PNS)

The one-group point kinetic model (with one delayed family) of a reactor predicts that the time dependence of the neutron flux after a pulse of neutrons is injected is:

$$f(t) = \frac{1}{\beta - \rho}\left(\beta e^{-\lambda' t} - \rho e^{-\alpha t}\right) \quad (1)$$

In this expression, $\lambda' = \rho\lambda/(\rho - \beta)$ and ρ is the reactivity, β is the effective delayed neutron fraction, λ is the delayed decay constant and α is the prompt decay constant, $\alpha = (1 - \rho_{\$})\Lambda^*$. In most cases of interest GENEPI is operated at some frequency, and multiple pulses are added to form a time response as if one very large pulse were produced. As the lowest frequency of GENEPI is 50 Hz, this provides a simplification of the above relation, since for all cases of interest then, we can make the assumption that $\lambda' t \ll 1$. This yields an approximation:

$$f(t) = \frac{1}{\beta - \rho}\left(\beta - \rho e^{-\alpha t}\right) \quad (2)$$

Thus, the delayed neutrons only provide a constant (with time) source of background. This background must be identified, and correctly subtracted before the slope of the prompt decay α can be determined from experimental data.

Figures 2 and 3 illustrate the observed counting rate of different ^{235}U fission chambers in MUSE-4 after a (d,d) pulse from GENEPI for different reactivities. These data are accumulated for many neutron pulses and after subtraction of the constant level of counting produced by the delayed neutrons and the intrinsic source of MASURCA.

After the first measurements in a configuration with very low neutron multiplication, k_{eff}=0.86, [7] important structures were observed in the time response of the reflector and shielding fission chambers. These structures have been identified using Monte Carlo simulations as being mainly produced by low energy neutrons. These deformations of the signals outside the core made the determination of the intrinsic reactor kinetic parameters unfavourable. The same Monte Carlo simulations showed that fission chambers with isotopes like ^{237}Np, presenting a high-energy threshold for fission, reproduce the same time evolution in the detection rate outside and inside the core, after the first microseconds of propagation of the neutron flux. This common evolution of the detection rate in the different parts of the reactor simplifies the interpretation of the experimental data. Consequently a ^{237}Np fast fission chamber, from CEA, was used in the later measurements together with the standard ^{235}U monitors.

The general behaviour observed for all the configurations except the most sub-critical is that, after a few tens of microseconds, there is an exponential decay of the counting rate, which remains as long as there is enough signal compared with the noise level (background plus delayed neutrons). In the case where k_{eff}=0.86, there is still an initial exponential behaviour for the detector placed in the core, but the time evolution is too fast to be conclusive.

The second important aspect that must be stressed is that in all cases and regardless of the position, each different time evolution can be clearly distinguished from the others, even for levels of criticality as close as USD 0.5. This feature could be used for the reactivity monitoring of a full scale ADS.

Figure 2. **Prompt response of MASURCA after a 1µs neutron burst, observed by a detector placed in the core region for different reactivity levels**

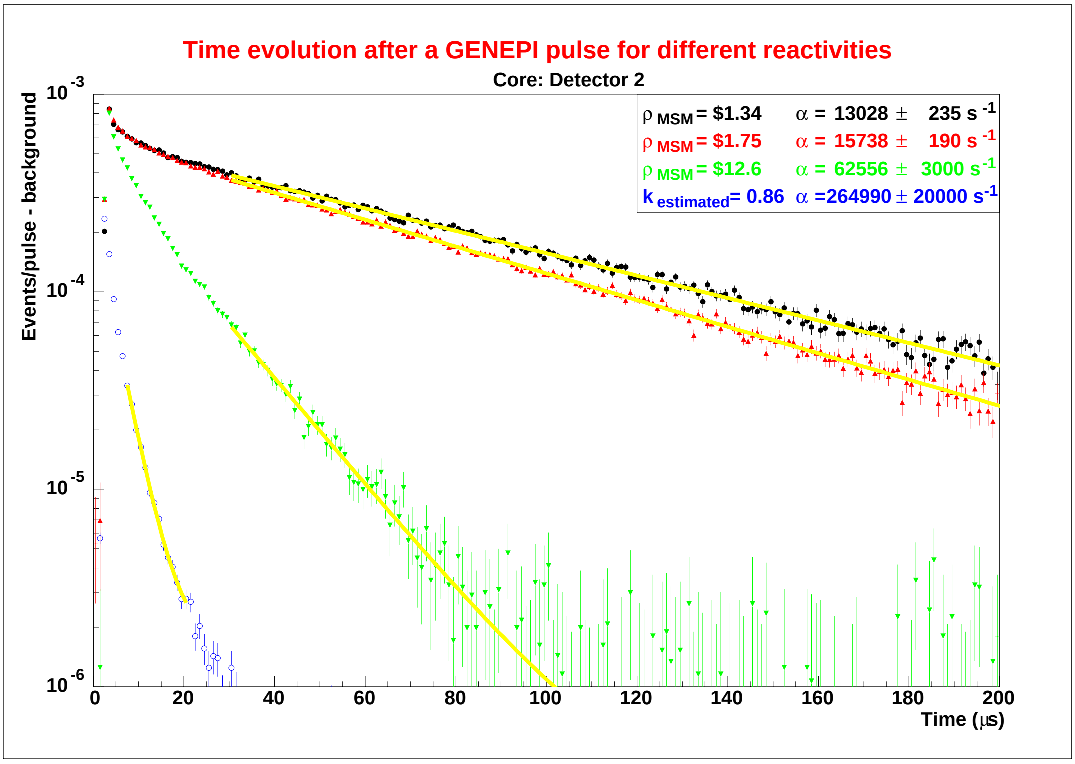


Table 2. **α-values (s^{-1}) obtained in the PNS experiments**

Configuration	III	IV	V
Detector2(core)	13028±235s-1	15738±190s-1	62556±3000s-1
Detector3(reflector)	12197±150s-1	14462±400s-1	59891±4000s-1
Detector7(shield)	11301±400s-1	12989±400s-1	65332±4000s-1
Detector9(^{237}Np-reflector)	12614±1000s-1	15584±1000s-1	

In Figure 4, the time evolution for the different detectors at the same level of sub-criticality is presented. Looking at the results of the prompt decay constants obtained by an "exponential plus a constant" fit (see Table 2), it is clear that the fundamental mode has been reached in the sub-critical system, and a simple point kinetic model can be justifiably used to describe its time response.

Noise experiments

Noise experiments on stable states (GENEPI off) have been performed to derive α-values and infer reactivities of tested configurations. The Rossi and Feynman-α techniques have been applied in configurations I, II and VI with reflector-detectors 3 and 4 (see Figure 1).

Figure 3. **Prompt response of MASURCA after a 1µs neutron burst, observed by a detector placed in the reflector region for different reactivity levels**

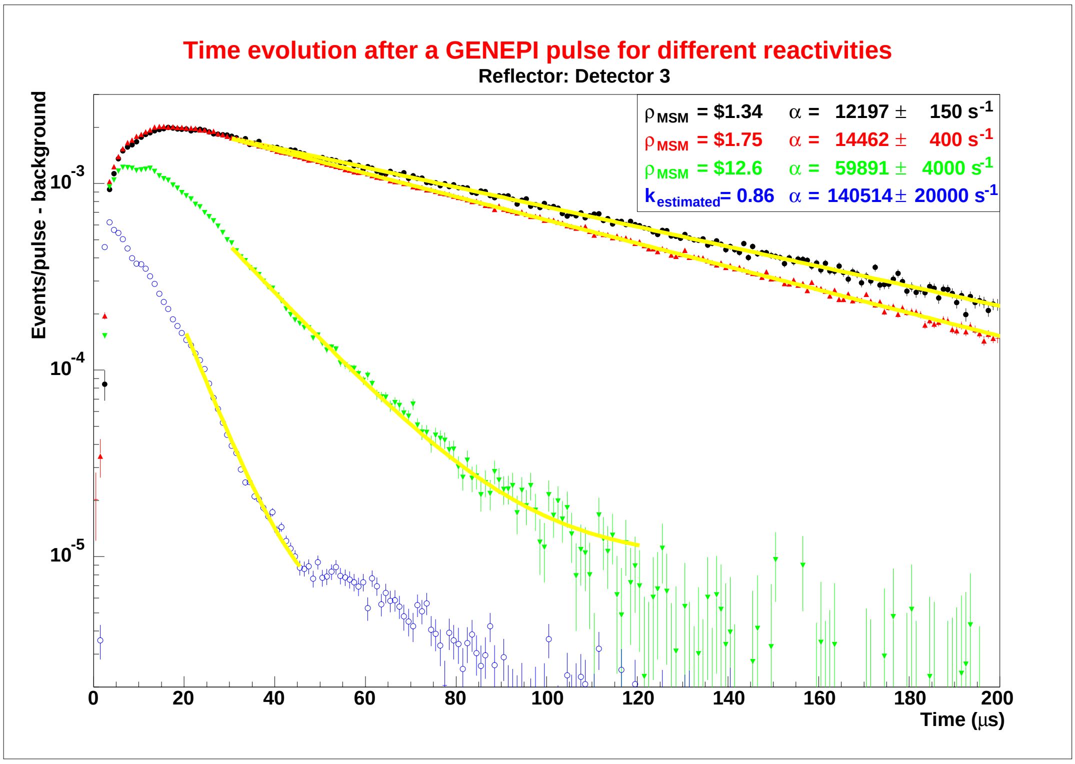
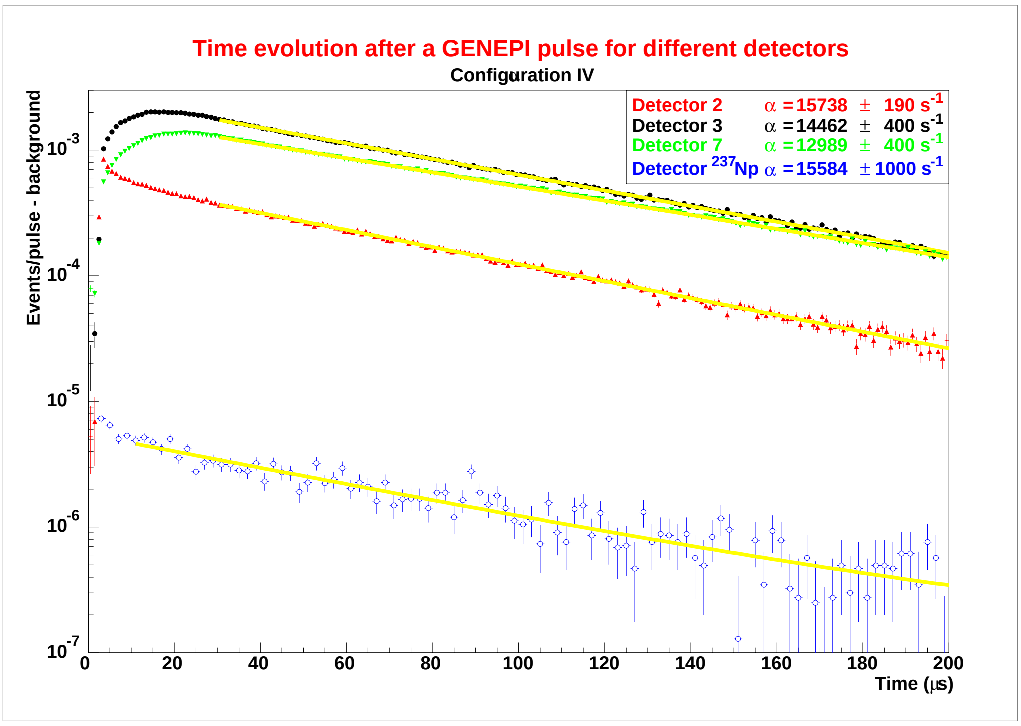


Figure 4. **Prompt response of MASURCA after a 1µs neutron burst, observed by different detectors for a same reactivity level**



Rossi-α

The Rossi-α technique is based on the probability distribution of secondary detection after a given primary detection. A standard Rossi-α model of type I based on point kinetics and without delayed neutrons has been used for configurations I and II. It yields: [8]

Figure 5. **Rossi-α distributions for monitor in the reflector**

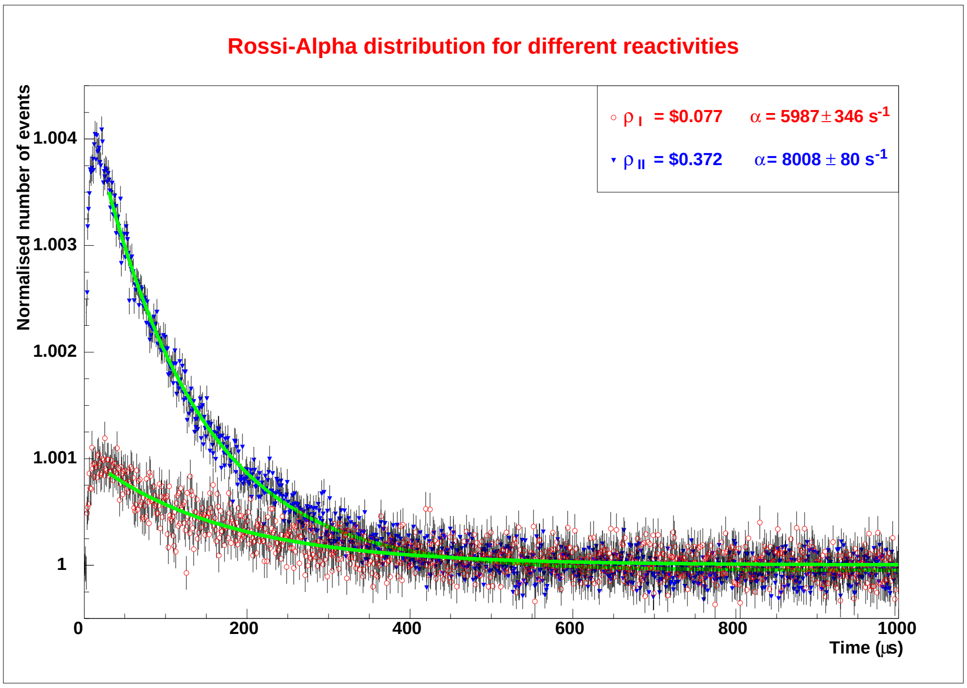


Table 3. **α-values (s^{-1}) from Rossi-α experiments in configuration II**

Auto-correlations			Cross-correlations		
(3,3)	(4,4)	(3-4)	(3,4)	(4,3)	$\bar{\alpha} \pm \delta$
8 901±98	7 853±110	8 008±80	7 555±91	7 757±93	8 015±673

$$p(T) = 1 + \frac{QD}{2\alpha\Lambda^2} e^{-\alpha T} \tag{3}$$

where the lag T is the time between primary and secondary detection in one (auto-correlation) or two different detectors (cross-correlation) and the other notations are standards.

A detailed study of configuration II has been made using either auto-correlations for detectors 3 and 4 or cross-correlation between them. In order to increase the number of events, the counts of detectors 3 and 4 have been merged as if they belonged to one single detector (3-4). This was possible due to the similarity of detectors and the symmetry of locations. [9] Results are illustrated in Table 3 where uncertainties for auto- and cross-correlation data are purely statistical. On the other hand, the dispersion $\delta = (\alpha_{max} - \alpha_{min})/2$ on the averaged value $\bar{\alpha}$ is about ±12% and cannot be explained merely by the statistical uncertainties of Table 3. However, the auto-correlation (3,3) might be an outlier and the dispersion then becomes 3%. Nevertheless, the uncertainties linked to the fitting method and limitations of the model are also to be considered in the future.

Using the merged detector (3-4), the α value for the configuration I is α_I = 5 987 ± 346 s^{-1}. The Rossi-α distributions for configurations I and II with the detector (3-4) are shown on Figure 5.

Exponential decay starts for correlations with time lag longer than 30 to 40 μs. This is a spatial effect due to location of detectors 3 and 4 in the reflector. The time shift is related to the time needed by the secondary neutrons to arrive in the reflector.

Exponential decays relative to configurations I and II are clearly different. This method can be used for monitoring reactivity, but it can only be used very close to criticality.

Feynman-α

The Feynman-α technique is based on the difference between the variance to mean ratio issued from the fluctuation process induced by fission chains and a Poisson distribution. Generalisation of the point kinetic model without delayed neutrons to allow the use of many detectors and to take into account the effect of dead-time has been used. It yields: [10]

$$Y_1(T) = \frac{\overline{n^2} - \overline{n}^2}{\overline{n}} - 1 = \frac{\varepsilon_1 D}{\alpha^2 \Lambda^2}\left(1 - \frac{1 - e^{-\alpha T}}{\alpha T}\right) - 2\varepsilon_1 Q d_1 \quad (4)$$

$$Y_{12}(T) = \frac{\overline{n_1 n_2} - \overline{n_1}\,\overline{n_2}}{\sqrt{\overline{n_1}\,\overline{n_2}}} = \frac{\sqrt{\varepsilon_1 \varepsilon_2} D}{\alpha^2 \Lambda^2}\left(1 - \frac{1 - e^{-\alpha T}}{\alpha T}\right) \quad (5)$$

where n are neutron counts, T is the length of the gate on which averages are done d_1 is the dead time of the detector 1 and the other notations are standards. In the first equation, the term $2\varepsilon_1 Q\, d_1$ stands for the dead time correction and is fitted to a constant. It vanishes when using two different detectors. In addition, we used also the so-called bunching technique to increase statistics using our data timer.

Detailed study of configuration II is reported in table 4 for auto and cross correlations of detectors 3, 4 and (3-4) (see sect. Rossi-α). Again, dispersion δ is beyond statistical uncertainties for each measurement.

The merging of detectors 3 and 4 has also been used for configuration I and VI. Results with statistical uncertainties are: α_I = 4 735 ± 78 s^{-1} and α_{VI} = 58 356 ± 6 750 s^{-1}. Figure 6 presents the reduced variance to mean ratio in configuration II. The negative value of Y and the shape of the curve for times lower than 50 μs illustrate the dead time effect. Moreover, deviations from the point kinetic model for small times (≤ 30-40 μs) due to spatial effects in the Rossi-α technique are still valid for the Feynman-α technique since the Feynman-α expression is an integration of the Rossi-α.

Still, the Feynman-α technique can be used to monitor reactivity because α-values are sufficiently different from one configuration to another.

Table 4. **α values (s^{-1}) from Feynman-α experiments in configuration II**

Auto-correlations			**Cross-correlation**	
(3,3)	(4,4)	(3-4)	(3,4)	$\overline{\alpha}$ ±δ
8 046±41	7 691±39	7 627±100	7 850±16	7 804±210

Discussion of the results

In the previous sections we have presented the results of different dynamic techniques (PNS and noise techniques) that could be used for reactivity monitoring in a future ADS. Using the experimental values of α and the ratio β/Λ calculated with the simulation codes MCNP and ERANOS β/Λ= 6 270 ± 940 s^{-1}, where we have considered a 15% uncertainty), we can infer the reactivity of the system to be compared with the rod drop/MSM methods (see Table 5). It must be pointed out that the values of the prompt decay constant for the PNS have been chosen to be those in the core region.

Figure 6. **Feynman-α distribution for detector in the reflector and configuration II**

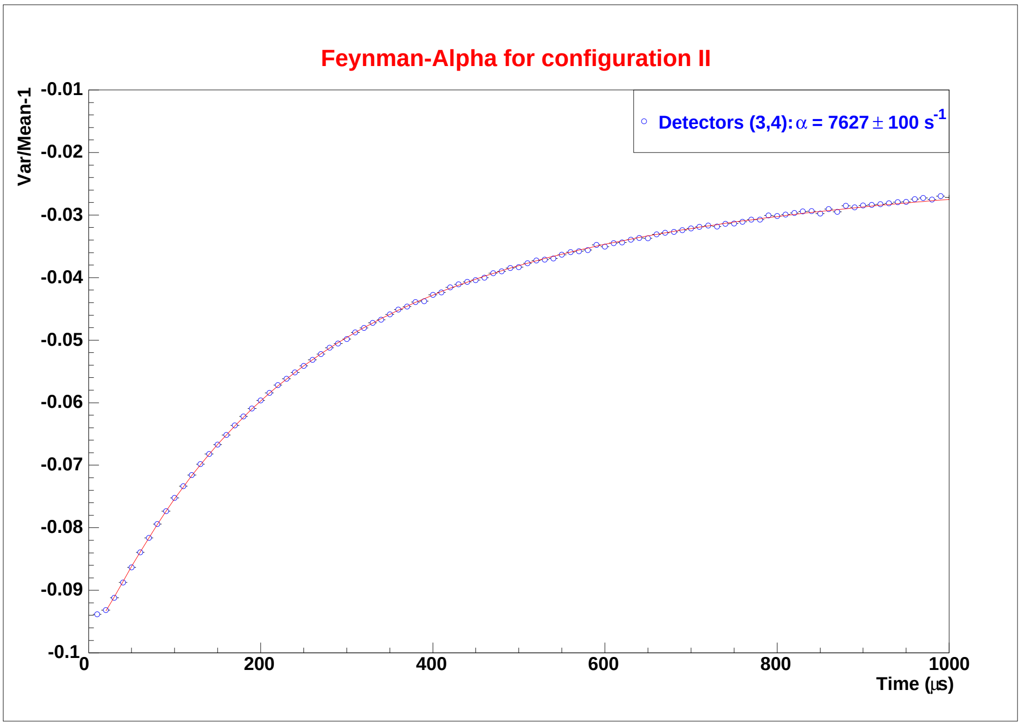


Table 5. **Inferred $\rho_\$$ and β/Λ values**

Configuration	Type of experiment	$\rho_\$$ (Rod drop/MSM)	$\rho_\$$ (inferred)	β/Λ(s-1)
I	Rossi-α	0.077 ± 0.004	-0.05 ± 0.15	5 559 ± 322 s^{-1}
I	Feynman-α	0.077 ± 0.004	-0.24 ± 0.11	4 396 ± 74s^{-1}
II	Rossi-α	0.373 ± 0.024	0.28 ± 0.22	5 842 ± 501s^{-1}
II	Feynman-α	0.373 ± 0.024	0.24 ± 0.19	5 688 ± 183s^{-1}
III	PNS	1.35 ± 0.09	1.08 ± 0.31	5 568 ± 215s^{-1}
IV	PNS	1.77 ± 0.12	1.51 ± 0.38	5 723 ± 219s^{-1}
V	PNS	12.6 ± 0.8	9.0 ± 1.6	4 600 ± 349s^{-1}
VI	Feynman-α	13.0 ± 0.8	8.3 ± 1.8	4 168 ± 538s^{-1}

A different approach, see also Table 5, is to use the values of the reactivity given by the rod drop/MSM method and the values of α to extract the ratio β/Λ (which is the rate above which the reactor can no longer significantly respond to perturbations).

Good agreement can be observed between the different techniques for "close-to-criticality" situations. In the configurations where the reactivity is much lower (more than USD 10), the results are still compatible although the uncertainties are large enough to render them inconclusive.

In the case of the ratio β/Λ it seems that there are two clusters around 4 500 s^{-1} and 5 600 s^{-1}. This fact could indicate that the model of a simple exponential decay after the pulse is deficient, and the time structure is more complex. Two potential explanations could be that (a) there is moderation occurring after the pulse, so detector efficiencies increases with time, which would decrease the α measured, (b) the insertion of the control or pilot rod could modify the β/Λ ratio. We are still in the process of investigating these phenomena.

Conclusions

In this paper, we have presented measurements based on the time series data collected in the MUSE-4 experiments. Both PNS and noise techniques (Rossi-α and Feynman-α) present a clear dependence on the measurable parameters, ie. logarithmic slope or the point kinetic equivalent α, of the sub-criticality level. This point by itself shows the capability of these techniques for reactivity monitoring.

In addition, the reasonably good agreement found within the reactivities estimated with the PNS method and the MSM/control rod drop standard methods shows that it is possible to use this technique to estimate the reactivity of the system and to design reactivity monitoring techniques for a full scale ADS.

However, several additional measurements in different configurations are needed before the possibility of inferring the level of sub-criticality with low uncertainty can be demonstrated. Indeed three additional clean sub-critical configurations are planned during the MUSE-4 programme (until end of 2003), which should allow the necessary measurements to be completed.

Acknowledgements

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