FIRST CIEMAT MEASUREMENTS OF THE MUSE-4 KINETIC RESPONSE

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ABSTRACT

The MUSE-4 international experiment, coordinated by CEA and included in the 5FWP of the European Union, is intended to study the physics of fast subcritical assemblies coupled with a pulsed neutron source. To achieve this objective, the GENEPI accelerator, a (d,d) or (d,t) neutron source developed at ISN (Grenoble), has been coupled with the MASURCA reactor, a plutonium MOX-based fast reactor, with sodium simulating this type of coolant and a lead buffer to simulate a spallation target.

The paper presents the first experimental results for the time evolution in different subcriticality levels of the MUSE-4 core to short neutron pulses, ~1 μs, and a repetition rate varying from 1 kHz to 4 kHz. The analysis of these measurements together with detailed Monte Carlo simulations shows that it is possible to use this technique to estimate and monitor the criticality constant of the system in the region of interest for the ADS projects.

Several experiments have been also performed in close to criticality configurations, in order to apply noise techniques to calculate the reactivity of the system. Both, Feynman-Alpha and Rossi-Alpha analysis have been applied, and the obtained results are presented and compared here.

1. INTRODUCTION

In the way to a future demonstrator for the ADS concept, it is necessary to validate experimentally the theoretical methods and calculation tools developed to characterize the physics of fast subcritical assemblies in presence of an external source. For that reason, the MASURCA experimental facility located in Cadarache (France) started in 1995 the MUSE programme.

The first two phases of the MUSE experiments [1, 2] were dedicated to the analysis of the same subcritical medium in presence of a well-known ^{252}Cf source. The third phase [3] was devoted to the study of a pulsed 14 MeV (d,t) neutron source produced by a “commercial” generator.

For the fourth phase [4], the availability of a new deuteron accelerator (GENEPI), built at ISN (Grenoble), plus the possibility to use two type of reactions (d,d) and (d,t), will allow extending the validation range of the dynamic techniques that could be used in a future demonstrator or power plant. Furthermore, the experimental results obtained during the MUSE-4 experiments will also allow the validation of the calculation tools by the meanings of an international Benchmark [5] under the umbrella of the NSC-NEA/OCDE inside the physics subgroup of the WPPT.

In the following paragraphs, the first experimental results for the time evolution in different subcriticality levels of the MUSE-4 core to short neutron pulses, ~1 μs, and a repetition rate varying from 1 kHz to 4 kHz will be presented. Also, the experimental results obtained in close to criticality configurations with two noise techniques, Feynman-Alpha and Rossi-Alpha, will be shown.

2. PULSED NEUTRON SOURCE, PNS, EXPERIMENTS

2.1 EXPERIMENTAL CONFIGURATIONS

MASURCA (figure 1) is a fast experimental facility that for the MUSE-4 experiments has been loaded with a MOX fuel of ~25% plutonium enrichment ($^{240}Pu/Pu$ ~18%) and sodium, what is 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.

The neutron pulse generated by GENEPI via the (d,d) source had a FWHM duration of ~1μs, and the frequency of the pulse varied from 1 kHz to 4 kHz depending on the experiment. To measure the time evolution after the neutron burst, several detectors have been used, but for simplicity, only the four marked in figure 1 will be shown here.

In order to achieve the different reactivity levels measured until the moment, the system was perturbed with the insertion of pilot and safety rods. Four subcriticality levels have been measured depending on the positions of these rods, k_{eff} = 0.86, 0.963, 0.9943 and 0.9957.

2.2 EXPERIMENTAL RESULTS

After the first measurements in a configuration with very low neutron multiplication, $k_{eff} \cong 0.86$ [6], important structures were observed in the time response of the reflector and shielding fission chambers, identified with Monte Carlo simulations as mainly produced by low energy neutrons. These deformations of the signals outside the core made more difficult to obtain the intrinsic reactor kinetic parameters. The same Monte Carlo simulation 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.

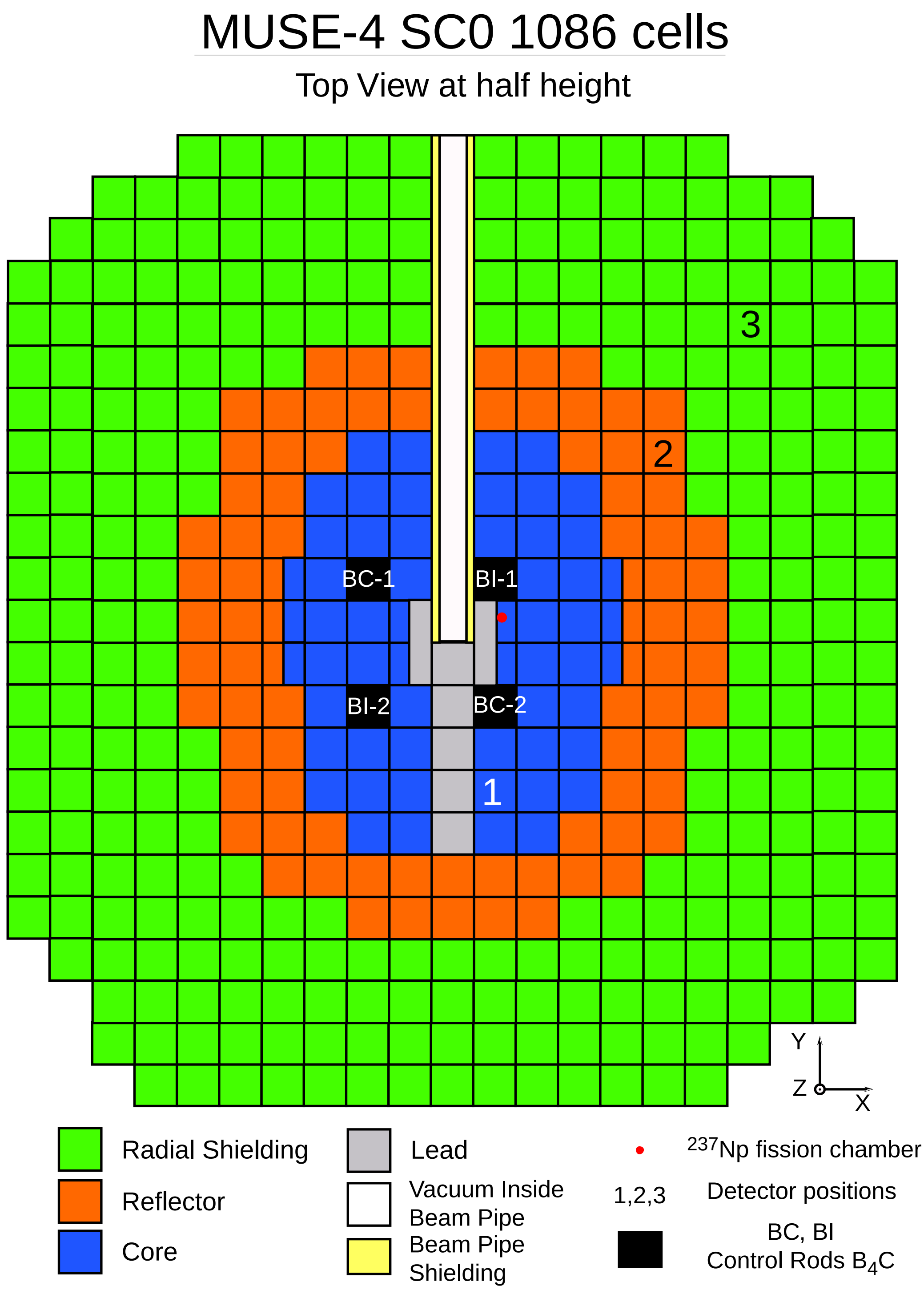

Figure 1. MASURCA loading for the first subcritical configuration of the MUSE-4 experiments.

In the next pages, figures 2, 3 and 4 illustrate the observed counting rate of different ^{235}U fission chambers, measured with the CIEMAT data acquisition system, in MUSE-4 after a (d,d) pulse from GENEPI for different reactivities, 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.

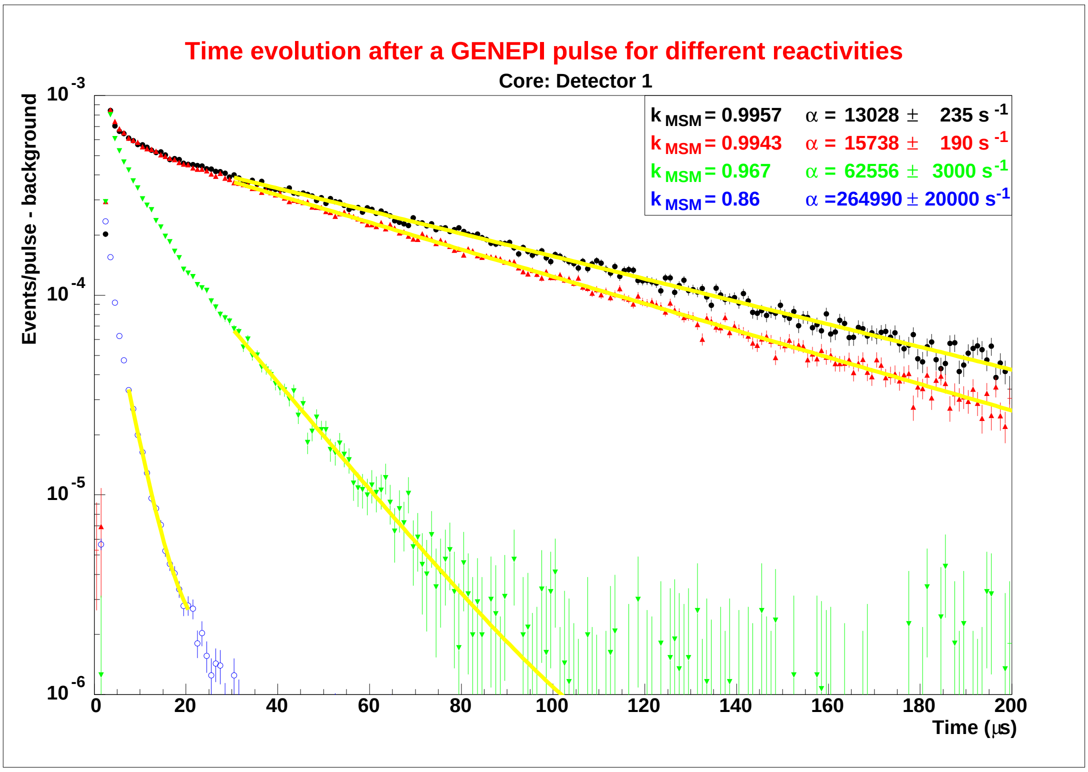

Figure 2. Prompt response of MASURCA after a 1µs neutron burst in a detector placed in the core region for different reactivity levels.

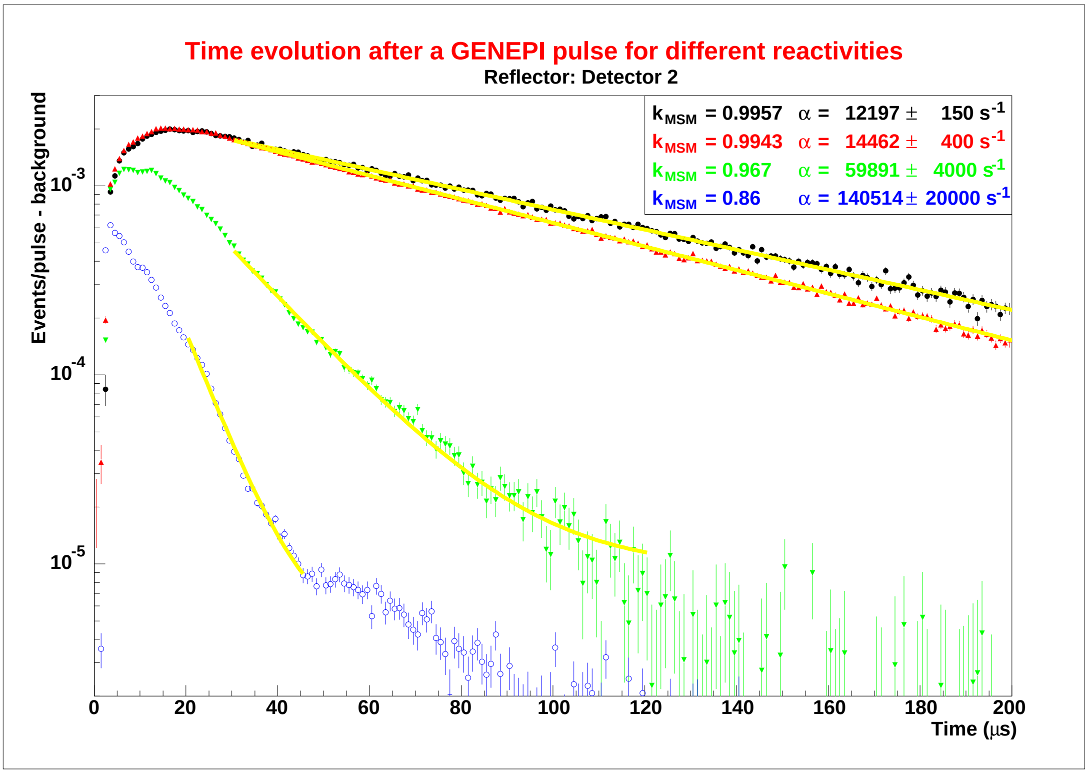

Figure 3. Prompt response of MASURCA after a 1µs neutron burst in a detector placed in the reflector region for different reactivity levels.

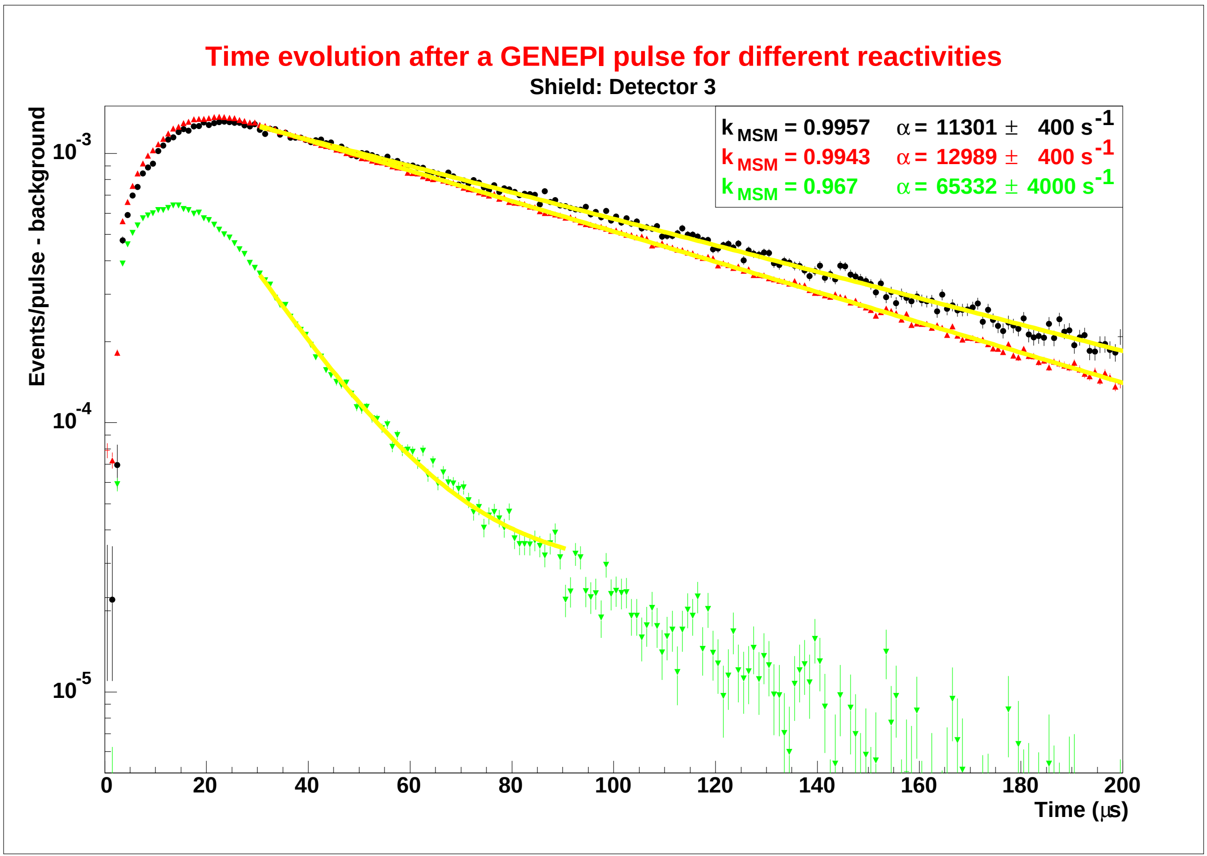

Figure 4. Prompt response of MASURCA after a 1μs neutron burst in a detector placed in the shielding region for different reactivity levels.

The general behaviour observed for all the configurations except the most subcritical 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 the position, the different time evolution can be clearly distinguished one from the other, even for criticality levels as close as 140 pcm. This feature could be used for the reactivity monitoring of a full scale ADS.

In figures 4 to 6, the time evolution for the different detectors at a same criticality constant is presented. Looking the results of the prompt decay constants obtained by an exponential plus a constant fit, a good agreement between the different positions is found, and a simple point kinetic model can be fairly (although not enough good or final) used to model the time response.

So, using the point kinetic relation between the logarithmic derivative of the neutron population and the kinetic parameters of the reactor (the values of β and Λ must be assumed to be known from previous experiments or simulations), $\alpha=(\rho-\beta)/\Lambda$, a value for the reactivity can be extracted.

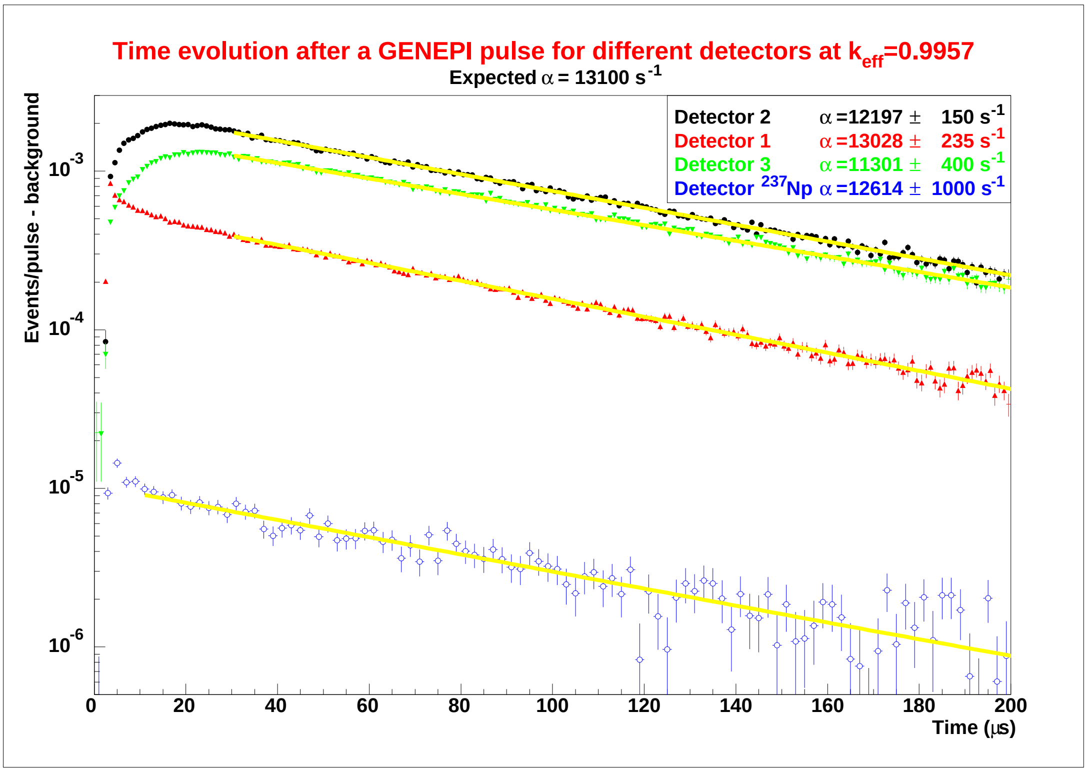

Figure 5. Prompt response of MASURCA after a 1µs neutron burst for a same criticality level in different positions of the MASURCA reactor.

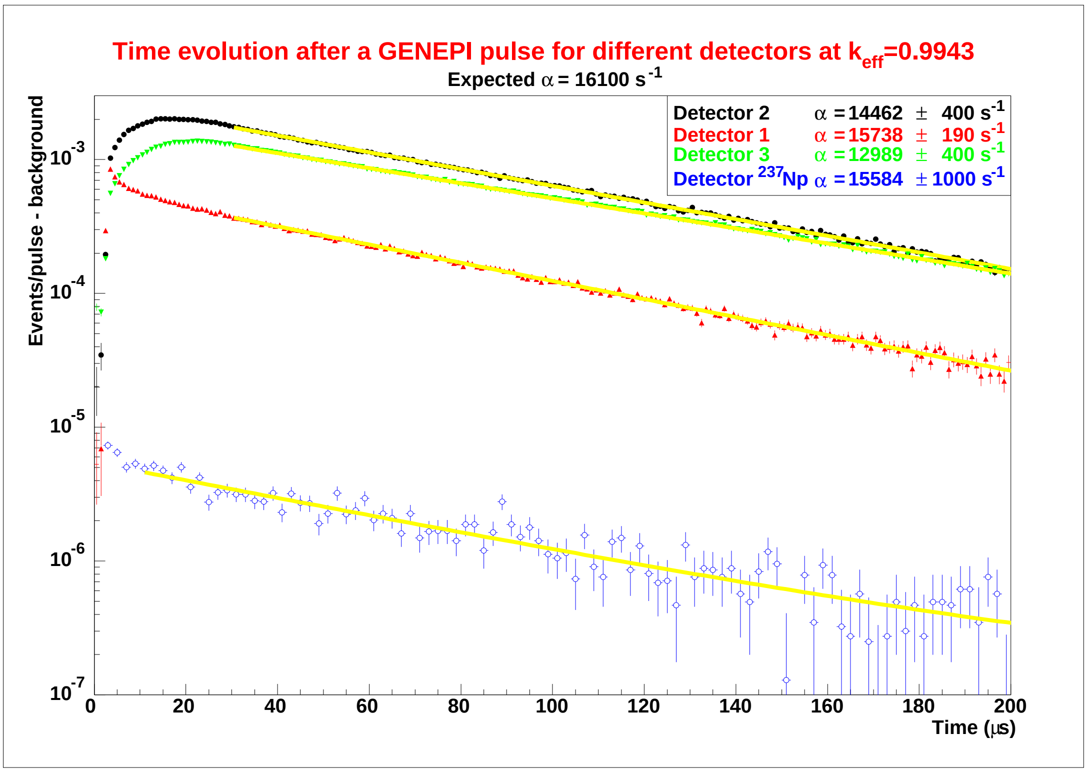

Figure 6. Prompt response of MASURCA after a 1µs neutron burst for a same criticality level in different positions of the MASURCA reactor.

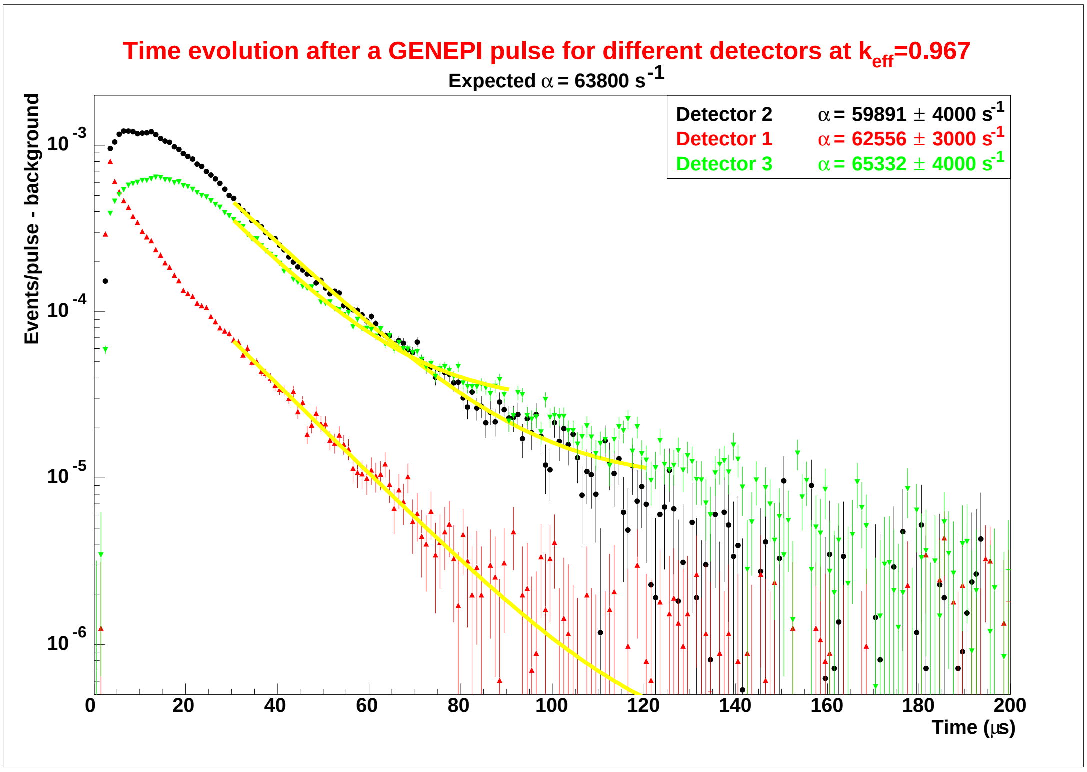

Figure 7. Prompt response of MASURCA after a 1μs neutron burst for a same criticality level in different positions of the MASURCA reactor.

The values obtained for the reactivity, ρ, for the four detectors in the configurations with k_{eff}=0.9957, 0.9943 and 0.963 are summarised in table 1. The parameters Λ (0.61, 0.58 and 0.59 μs) and β (363 pcm) have been obtained with MCNP simulations.

Table 1. ρ-values obtained with the pulsed neutron source technique.

	ρ_{MSM} = 435 pcm	ρ_{MSM} = 570 pcm	ρ_{MSM} = 3400 pcm
Detector 1 (Core)	-432 ± 14 pcm	-550 ± 11 pcm	-3328 ± 177 pcm
Detector 2 (Reflector)	-381 ± 9 pcm	-476 ± 23 pcm	-3171 ± 236 pcm
Detector 3 (Shield)	-326 ± 24 pcm	-390 ± 23 pcm	-3492 ± 236 pcm
^{237}Np Detector (Reflector)	-406 ± 61 pcm	-541 ± 58 pcm	

3. NOISE EXPERIMENTS

Additional information on the kinetic parameters has been obtained by several noise-technique experiments where the Rossi-Alpha and the Feynman-Alpha analysis have been applied.

3.1 EXPERIMENTAL CONFIGURATIONS

In figure 8, the experimental configuration used for these noise-technique experiments can be observed. The detectors used for these measurements were high efficiency ^{235}U fission chambers in order to increase as much as possible the statistics.

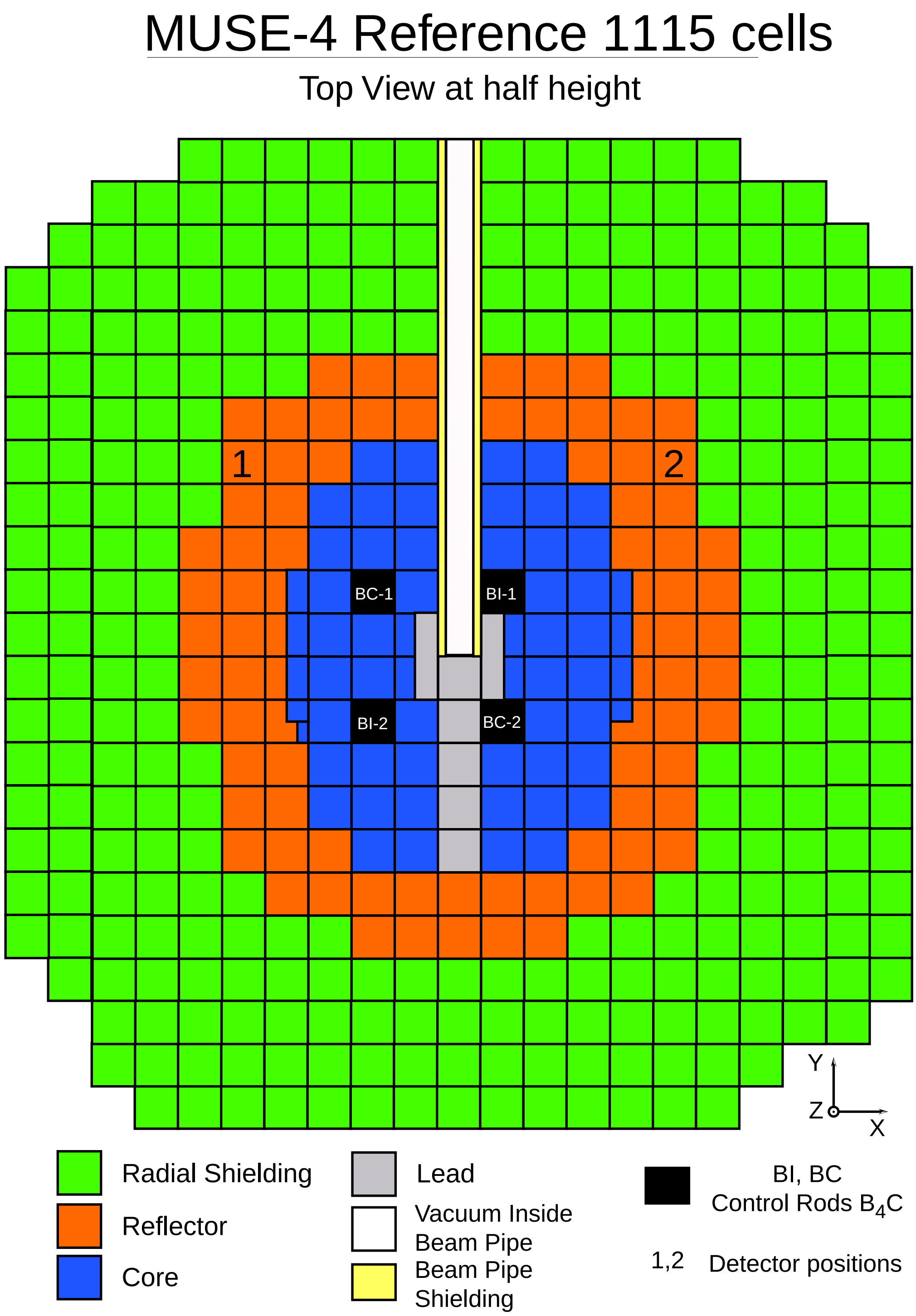

Figure 8. MASURCA loading for the close to criticality noise experiments of the MUSE-4 experiments.

The experiments were performed in MASURCA configurations very close to criticality (ρ_1= -20 pcm, ρ_2= -115 pcm, and ρ_3= -4200) and without the use of the GENEPI neutron source. The data recording was made with the CIEMAT data acquisition system.

3.2 ROSSI-ALPHA ANALYSIS

The Rossi-Alpha technique [7] is based on the properties of the counting distribution obtained after a given detection. The theoretical expression for the Rossi-α distribution is:

$$P(t) = N\lambda_f \varepsilon_f + \frac{\lambda_f^2 \varepsilon_f \overline{\nu(\nu - 1)}}{2\alpha} e^{-\alpha t} \quad (1)$$

Where the symbols of the formula follow the definitions of the quoted reference.

In figure 9, the Rossi-Alpha distribution for configurations with a reactivity level of ρ= -20 pcm and ρ= -115 pcm are shown. Due to the high level of the intrinsic source, the ratio signal to noise is extremely small, around a 0.1%, what has made necessary to share the counts of the two detectors used in the experiments as if they were actually one. This is a good assumption if it is considered that both detectors have approximately the same mass and they are located in symmetrical positions.

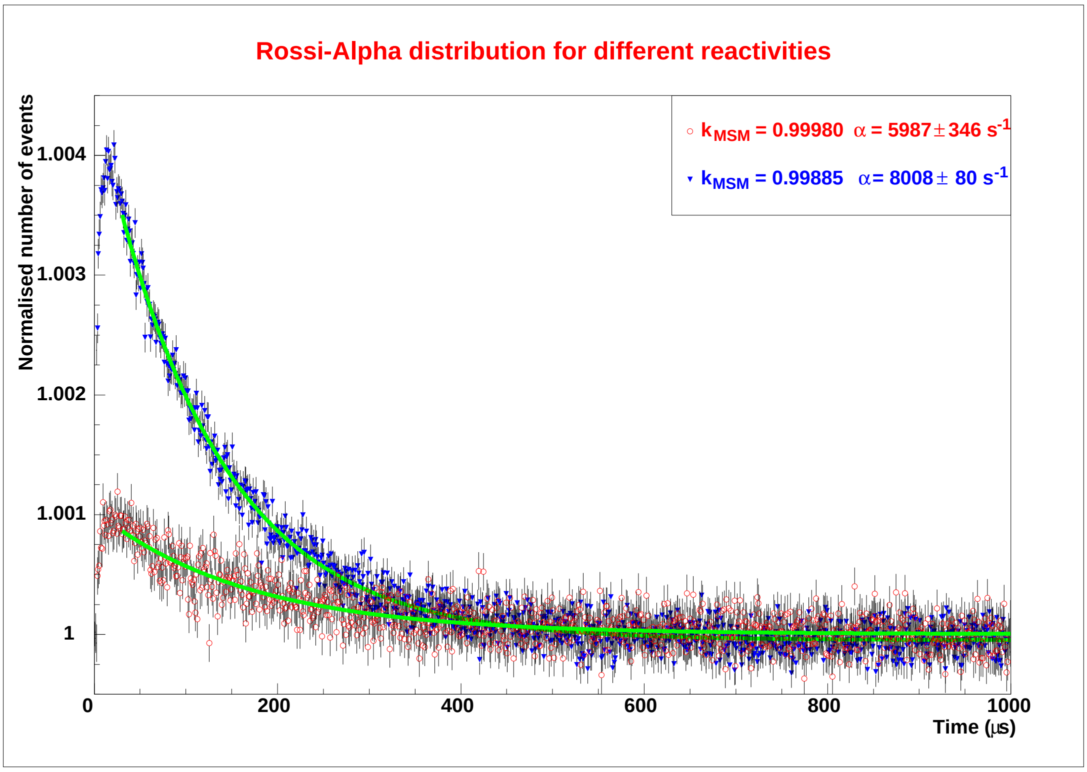

Figure 9. Rossi-Alpha distribution for a detector placed in the reflector region of the MASURCA reactor for two close to criticality configurations.

The first thing that can be observed, and which happens for both configurations, is that it is necessary a short time of around 30 or 40 μs to start the exponential decreasing. Although this is a non-punctual effect, it must be taken into account that the detectors are not placed in the fuel region but in the reflector, so this is the time the neutrons need to arrive into the detector (as it already happened in the case of the pulsed neutron source experiments).

Also, when comparing the different exponential decays, and as it already happened in the case of the PNS experiments, the different reactivity levels for the two different configurations can be clearly observed in the values of the prompt decay constant, α. This feature can be used for reactivity monitoring, however, very long acquisitions would be required for a more subcritical situation.

3.3 FEYNMAN-ALPHA ANALYSIS

The Feynman-Alpha analysis is a well-known technique [7, 8] based in the statistical properties of the distribution obtained when measuring repeatedly the counting rate in a detector. The expression of the variance to mean ratio of this distribution is:

$$\frac{V(t)}{N(t)} = 1 + \frac{\lambda_f^2 \varepsilon_f \overline{\nu(\nu-1)}}{\alpha^2}\left[1 - \frac{1-e^{-\alpha t}}{\alpha t}\right] e^{-\alpha t} \qquad (2)$$

Where *t* is the size of the time window used for the measurement (i.e. 100 μs) and the rest of the symbols are the same than in the Rossi-Alpha expression.

In order to perform an efficient analysis of the experimental data, it has been necessary to use a variation of the Feynman technique, the bunching method, and in addition some corrections due to the count loss from the electronic dead time, are necessary to describe properly the resulting distribution. Similarly to the Rossi-Alpha case, to increase the detection efficiency the two detectors used in the measurements have been joined as if they were just one.

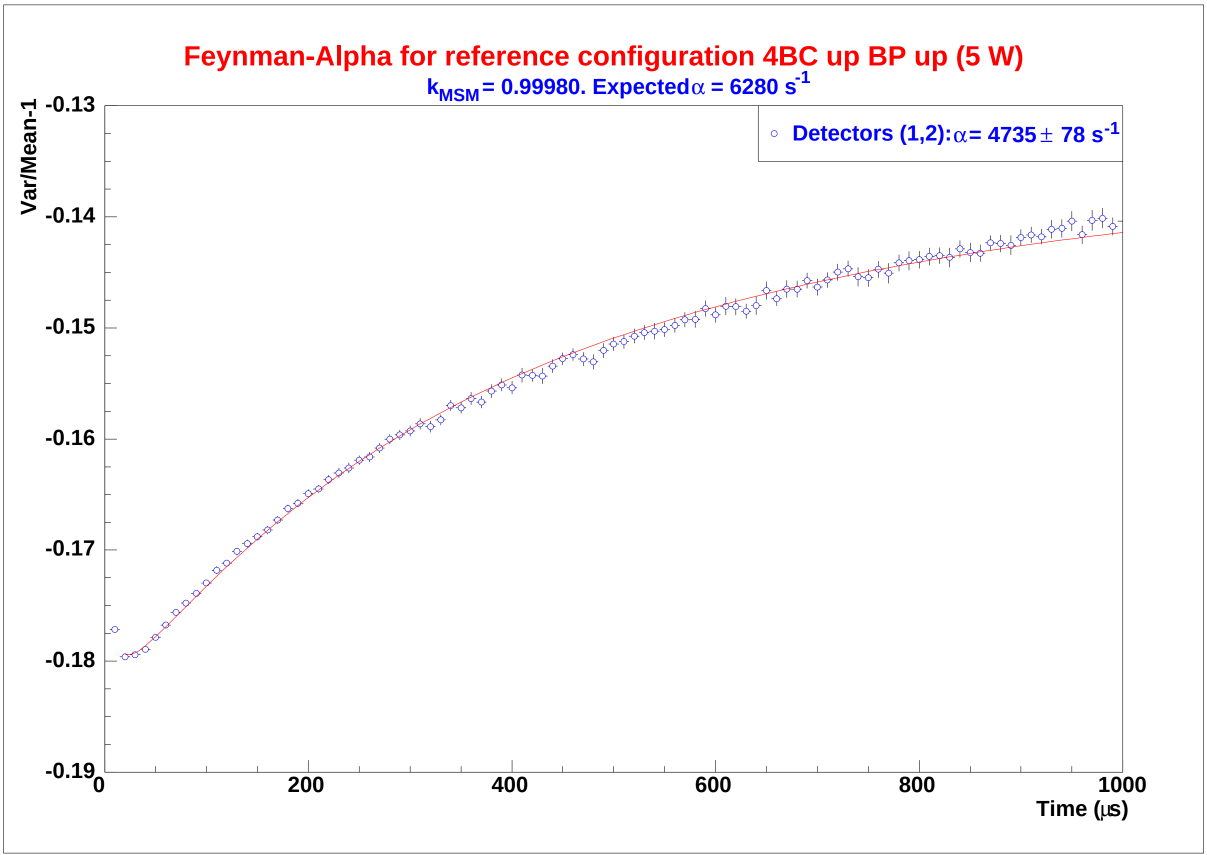

Figure 10. Feynman-Alpha distribution for a configuration close to criticality situation. The detector used is the same than in the Rossi-Alpha case.

In figures 10 and 11, the Feynman-Alpha distributions for configurations with a reactivity of ρ = -20 pcm and ρ = -115 are shown. It is interesting to see that in both cases, the values of the variance to mean ratio are lower than 1. However, after applying the corrections due to the dead time [8], the experimental results can be perfectly described by the classical model. Looking at the values of α, it can be noticed that they are slightly smaller than in the case of the Rossi-Alpha analysis. These differences might be explained taking in to account that the Feynman-Alpha expression can be obtained integrating the Rossi-Alpha formula, and that it has been shown that the Rossi-Alpha distributions present at short times some deviation from the point like core. Nevertheless, the two values of α from the Feynman-Alpha experiments are different enough to allow the use of this method for reactivity monitoring.

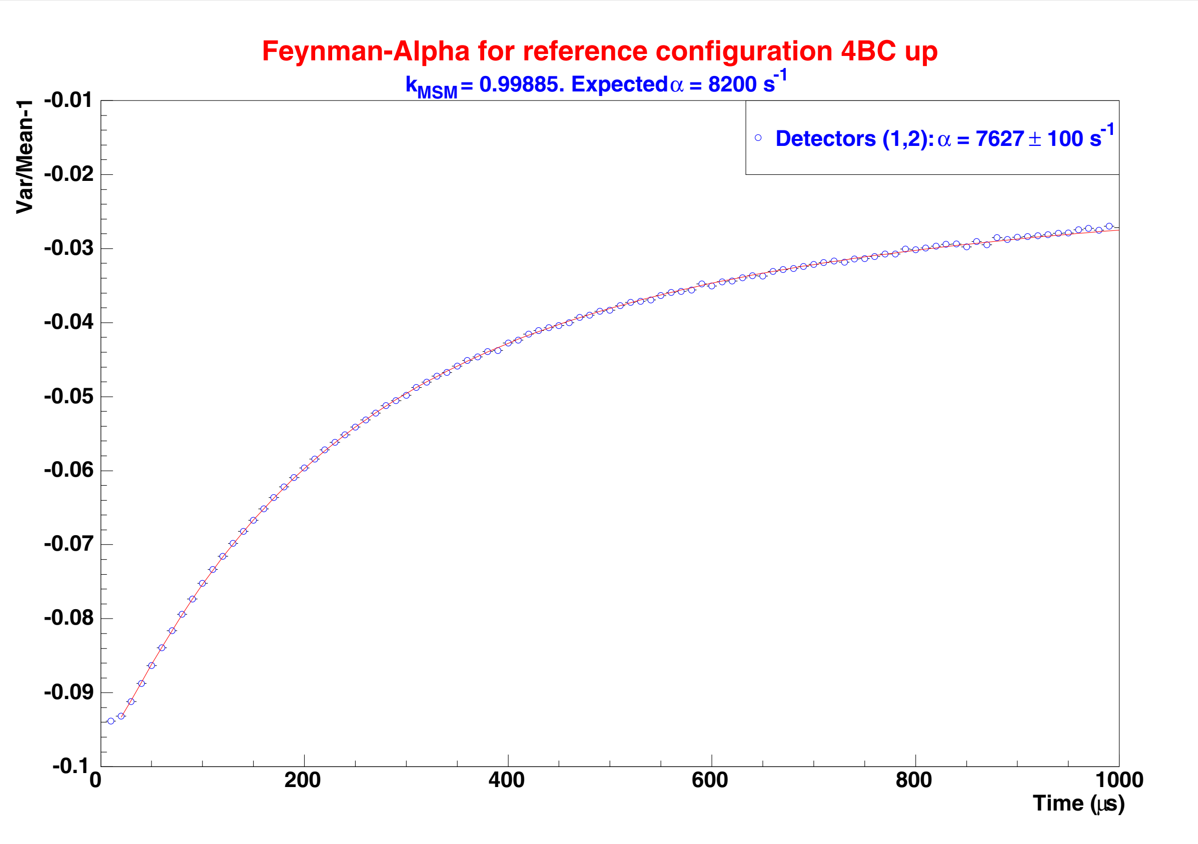

Figure 11. Feynman-Alpha distribution for a configuration close to criticality situation. The detector used is the same than in the Rossi-Alpha case.

In figure 12, the Feynman-Alpha distribution for a configuration with ρ = -4100 pcm is shown. As in the previous cases, the effect of the dead time is clearly noticed at the beginning of the distribution and in the values less than unity.

Again, the value of α is enough different to be used for reactivity monitoring. However, and as it happened in the pulsed neutron source experiments, trying to extract a direct value of the reactivity from α can be considered as a first approximation but several corrections should be applied in order to give a precise value.

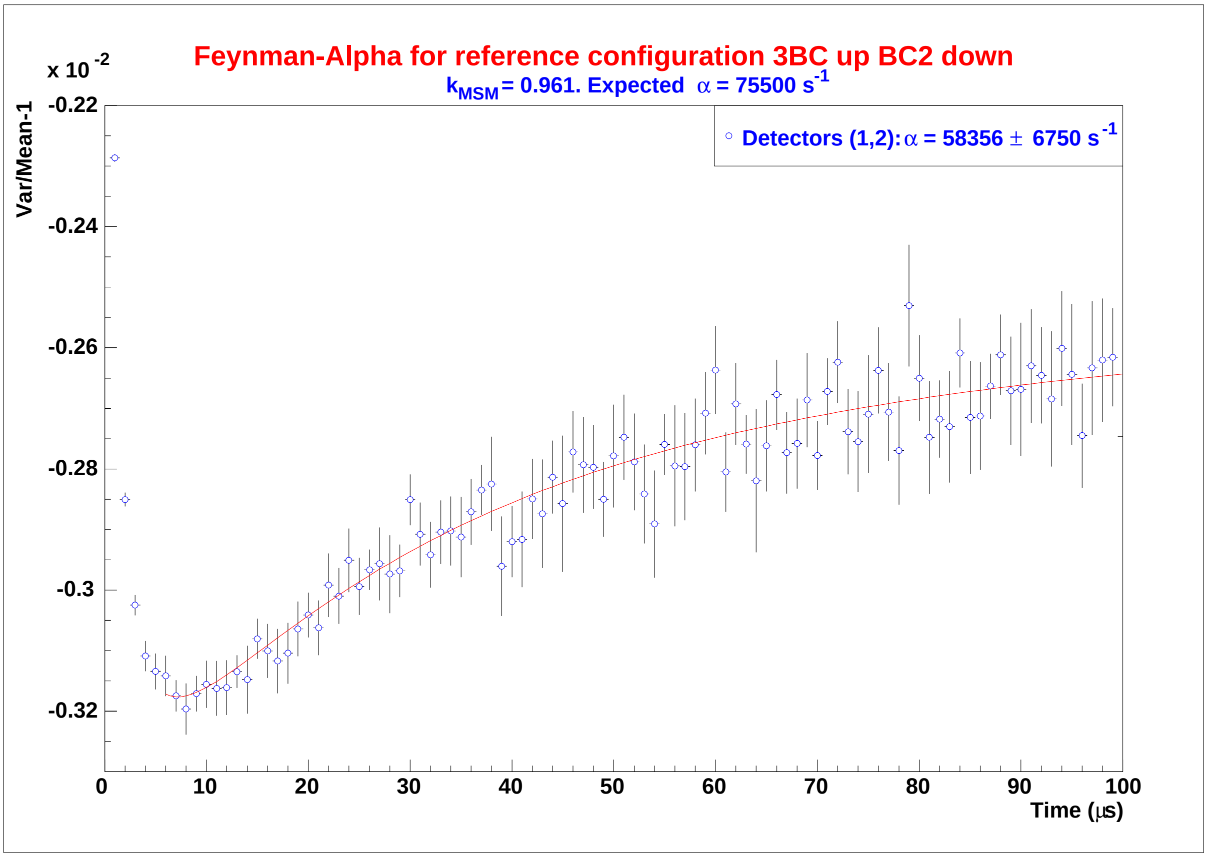

Figure 12. Feynman-Alpha distribution for a subcritical configuration. The detector used is the same than in the Rossi-Alpha case.

4. DISCUSSION OF THE RESULTS

In table 2 it is shown a comparison of the reactivities obtained with the MSM (Modified Source Multiplication) method and the different techniques presented in this paper for the different configurations measured. In the case of the pulsed neutron source experiments, the values of α obtained with the detector placed in the core have been used.

From the results can be observed that a very good agreement, less than 100 pcm, is obtained for configurations as subcritical as k_{eff}=0.967 when PNS or Rossi-Alpha methods are used.

In the case of the Feynman-Alpha analysis, the values obtained for the reactivity seem to be slightly lower than expected, however, an investigation is being carried on to include the pertinent corrections in the model.

Table 2. Values of ρ obtained from the prompt decay constant, α, using the values of β and Λ given by MCNP simulations.

Reactivity (Calculated with MSM method [9][†])	PNS	Rossi-Alpha	Feynman-Alpha
-20 pcm		-2 ± 5 pcm	74 ± 5 pcm
-115 pcm		-105 ± 20 pcm	-82 ± 6 pcm
-435 pcm	-432 ± 14 pcm		
-570 pcm	-550 ± 11 pcm		
-3400 pcm	-3328 ± 177 pcm		
-4100 pcm			-3036 ± 413 pcm

CONCLUSIONS

Different pulsed neutron source experiments and noise techniques have been successfully used in the MASURCA core (in the framework of the MUSE-4 program) to estimate the reactivity of a subcritical system.

Both PNS and noise techniques present clear dependence on the measurable parameters, logarithmic slopes or the point kinetic equivalent α, from the subcriticality level. This point by itself shows the capability of these techniques for subcriticality monitoring. The good agreement found within the reactivities estimated with the standard MSM method and those calculated with the pulsed neutron source technique and the Rossi-Alpha technique show that, in addition, it is possible to use these techniques to estimate the subcriticality of the system and that these techniques may be used to design subcriticality monitoring techniques for the full scale ADS.

The most promising technology looks, at present, to be based on the PNS experiments techniques. In the case of ADS with pulsed proton accelerator is the natural method, but also in the case of continuous proton beam accelerator it would be possible to introduce short (<1ms) and sharp beam interruptions with repetition frequencies as high as 1Hz, that would be simultaneously used for subcriticality measurements of the ADS core using the PNS concept and for accelerator maintenance and testing.

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[†] The 3400 pcm value has not been obtained with MSM corrections but with a tuned Monte Carlo simulation.

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