

MEASUREMENT OF KINETIC PARAMETERS IN THE SOURCE-DRIVEN FAST SUBCRITICAL CORE MASURCA WITH NOISE METHODS*

P. BAETEN¹, G. IMEL², C. DESTOUCHES³, C. JAMMES³, F. MELLIER³,
G. PERRET³, E. GONZALEZ-ROMERO⁴, D. VILLAMARIN⁴,
J.L. KLOOSTERMAN⁵, Y.RUGAMA⁵

¹ *SCK-CEN, Boeretang 200, B-2400 Mol, Belgium (pbaeten@sckcen.be)*

² *ANL, P.O. Box 2528, Idaho Falls, ID 83403, USA*

³ *CEA, Centre de Cadarache, F-13108 Saint Paul lez Durance, France*

⁴ *CIEMAT, Avda. Complutense 22, Madrid, Spain*

⁵ *IRI, Delft University of Technology, Mekelweg 15, Delft, Netherlands*

In the framework of the European 5FP MUSE measurements are performed to investigate the neutronic behaviour of the fast subcritical core MASURCA coupled with the pulsed GENEPI neutron generator. Noise techniques, such as the Rossi-alpha method, Feynman-alpha and spectral methods were applied in several measurement conditions. Different driving sources were used: the intrinsic plutonium source and a pulsed neutron source. This paper summarizes the main first results from the application of noise methods in the MUSE-4 configuration. Also the first conclusions are presented with respect to the applicability of individual noise techniques for ADS.

1. Introduction

The 5FP MUSE is aimed at studying the physics of subcritical systems in view of the development of future Accelerator Driven Systems (ADS). The choice for the most suited reactivity monitoring technique, an accurate determination of kinetic parameters and a thorough understanding of the specific kinetic behavior of deep subcritical systems ($k_{eff} = 0.95-0.97$) are indeed key points to guarantee a safe operation of an ADS. To give a satisfactory answer to these questions, the MUSE project makes use of the fast subcritical core MASURCA coupled to the GENEPI deuteron accelerator.

Reactivity and other kinetic parameters have been measured successfully in the past in (near) critical systems with well-known noise methods such as the Rossi-alpha method, Feynman-alpha technique or the analysis of auto- or cross power spectral densities [1]. The application of these techniques in subcritical systems driven by an external source is subject to several specific features. At

* This work is supported by the European Commission via the 5FP MUSE

subcritical levels, the number of induced fissions and thereby neutron correlations is reduced. Since the above mentioned methods all rely on the detection of correlated neutrons, their application will be rendered more difficult. Due to the presence of an external source and the non-criticality of the system, the fundamental mode approximation is no longer strictly valid and therefore the interpretation of the measurements can be more complicated. Since moreover most ADS are based on fast core physics, the conventional measurement conditions applied in thermal reactors will have to be modified.

In this paper, we will investigate the feasibility of the Rossi-alpha method, the Feynman-alpha and power spectral density analysis with the accelerator ON and OFF for application in ADS.

2. Experimental set-up

The MASURCA facility is dedicated to neutronic studies of fast reactors lattices. The MUSE-4 Reference configuration is based on the ZONA2 fuel cell, representative of a fast Pu burner core (Pu enrichment of $\approx 25\%$ with $\approx 18\%$ content of ^{240}Pu) with sodium coolant. The fuel zone is radially and axially reflected by a stainless steel/sodium (75/25) shielding. Preliminary calculations yielded for the values of the kinetic parameters: the mean neutron generation time $\Lambda = 0.516 \mu\text{s}$ and the effective delayed neutron fraction $\beta_{\text{eff}} = 327 \text{ pcm}$.

The GENEPI (GÉnérateur de NEutrons Pulsé Intense) neutron generator has been especially developed for the MUSE experiments in the MASURCA facility for brief neutron injections with a very fast intensity decrease (about 500 ns). In this way, deuteron impulses are created, then focussed, accelerated and guided onto a deuterium or tritium titanium target (TiD or TiT respectively). The beam peak intensity is about 50 mA for a width of less than $1 \mu\text{s}$, and the repetition rate can vary from a few Hz up to 5 kHz, providing (with the TiD target) about $4 \cdot 10^4$ neutrons per pulse ($\sim 1.6 \cdot 10^8 \text{ n/s}$ at 4 kHz) and about $3 \cdot 10^6$ neutrons per pulse with the TiT target ($\sim 1.2 \cdot 10^{10} \text{ n/s}$ at 4 kHz).

3. The Rossi-alpha method

3.1. Rossi-alpha measurements with the intrinsic source

In conventional (near)-critical systems, Rossi-alpha distributions for subcritical (near-critical) situations are almost always recorded with a stationary driving source. Since future ADS are not necessarily driven by a pulsed neutron

source, it is important to investigate the applicability of the Rossi-alpha method in these measurement conditions.

By switching off the accelerator, the subcritical assembly will be driven by the intrinsic source resulting from the spontaneous fissions from the MOX fuel. The Rossi-alpha distribution is then adequately represented by the the following expression (e.g. Spriggs, 1993):

$$S(t)dt = Adt + Re^{-\alpha t} \alpha dt \quad (1)$$

$$\text{With } \alpha: \text{ the fundamental-mode decay: } \alpha = \frac{\beta_{\text{eff}} - \rho}{\Lambda} = (1 + \rho_s) / \left(\frac{\Lambda}{\beta_{\text{eff}}} \right) \quad (2)$$

Measurements were performed at a reactivity level of $\rho = -0.367 \pm 0.002$ \$. To obtain sufficient statistics for the determination of the alpha decay constant in the Rossi-alpha method, the most efficient monitors had to be moved to the reflector region. The smaller core detectors with a lower detection efficiency do not allow to accurately estimate α -values because of low statistics. While for the larger detectors in the reflector, the standard errors are about 1%, the discrepancies between α -values are quite large. Their uncertainty can be expressed by the means of the type-B uncertainty and yielded about 10%.

An additional measurement was made at a deep subcritical level of -11.33 \$ to analyse the applicability of the method for more realistic ADS conditions. The recorded Rossi-alpha distribution for this experimental condition is depicted in Figure 1 together with the fitted curve.

From figure 1, it can be seen that the statistics for deep subcritical situations are deteriorated as expected and an accurate determination of the alpha decay constant is much more difficult.

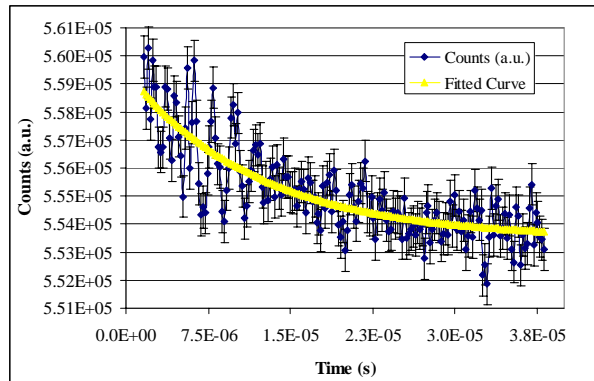


Figure 1. Rossi-alpha distribution for a subcriticality level of -11.33 \$

To increase the statistics on the recorded distribution longer measurement times and/or higher efficient detectors are needed. Since higher efficient detectors generally imply larger detector volumes and higher fissile deposits, the core will be more strongly perturbed and thus (spatial) accurate correction factors are needed for the analysis of the measured distributions. Therefore, the use of the Rossi-alpha method driven by the intrinsic source will be difficult at subcritical levels of -3000 pcm to -5000 pcm present in real ADS and requires high efficient detectors that in practice mostly need to be located in the reflector.

3.2. Rossi-alpha measurements with the GENEPI pulsed source

When the accelerator is switched on, the correlation between neutrons will be enhanced. Measurements were performed at different frequencies and reactivity levels with the TiT target.

The Rossi-alpha expression for a periodically pulsed source basically comes down to a convolution of the reactor response with a train of dirac pulses in the time domain as can be noticed in figure 2. Figure 2 depicts a measured Rossi-alpha distribution for a subcritical assembly driven by a pulsed neutron source.

When the pulsation period is not too small in comparison with the alpha decay constant, there is no overlap between the consecutive responses to a source dirac pulse. Since in practice this decay constant is rather small in fast reactor cores, it is easy to find a pulsation frequency which satisfies this condition and is still high enough to obtain sufficient statistics in a reasonable measurement time. When such a pulsation frequency is chosen, the response to the first pulse can be isolated.

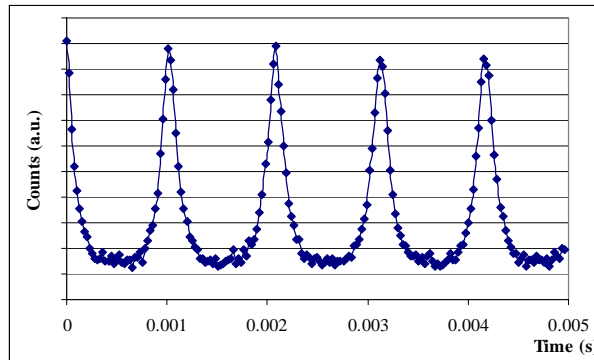


Figure 2. Rossi-alpha distribution of a pulsed neutron source ($f= 1$ kHz).

Since the obtained isolated Rossi-alpha distribution is characterized in the beginning of the distribution with a fast decaying contribution, the fitting of the

obtained distribution with a mono-exponential was complicated. Therefore the distribution was fitted to the sum of two exponentials to take into account the first fast decaying part which is due to the presence of higher harmonics [8]. The decay time of the second exponential is the fundamental mode decay constant we are looking for [8].

These presented results are from measurements on detectors that are located in the core region. The results from detectors located in the shielding are less accurate due to the larger distortion of the Rossi-alpha spectrum caused by the thermalisation of the neutrons and are hence not included .

The spread of the results for different detectors and frequencies is very small. The obtained value is therefore independent of GENEPI frequency and the detector position in the core. In table 1 we compare the experimental value of the decay time and its estimated uncertainty with the "theoretical" value obtained from the calculated values of the mean neutron generation time and the effective delayed neutron fraction and the reactivity (in dollars) determined with the Source Multiplication method.

Table 1. Comparison of measured and "theoretical" decay times

Reactivity level (\$)	$1/\alpha$ (μ s)	Uncertainty on $1/\alpha$	(E-C)/C % for $1/\alpha$
-11.2	16,87	2,0 %	32 %
-1.95	59,24	1,1 %	12 %
-1.57	69.40	0.9 %	14 %

From table 1, it can be concluded that a systematic bias between measured and theoretically predicted values exist, even for small subcriticality levels. For a larger subcriticality level, the deviation increases. The small spread in the results for the decay time at every subcriticality level suggest that the decay times from the Rossi-alpha measurements are correct and equal to the fundamental mode decay constant. Further investigations will have to point out whether the reactivity level in dollar determined with the ASM method experiences a systematic bias or whether the calculation of the mean neutron generation time and the effective delayed neutron fraction has to be reinvestigated.

4. The Feynman-alpha method

4.1. Feynman-alpha measurements with the intrinsic source

Since the Feynman-alpha method is closely related to the Rossi-alpha method, similar results were obtained in the case of a stationary drivig source. Again for a reactivity of $\rho = -0.367 \pm 0.002$ \$, the α -estimates obtained with the core detectors had to be rejected because of their poor statistical indicators. For the larger detectors in the reflector, the discrepancies between α -values are quite large even if the standard errors are less than 2%. Their uncertainty is measured in the same manner as the Rossi- α case and was found to be almost 10%, which is compatible with the results obtained with Rossi- α method.

For large subcritical levels of e.g. $\rho = -12.7$ \$, the signal-to-noise ratio is strongly reduced as can be seen in Figure 3.

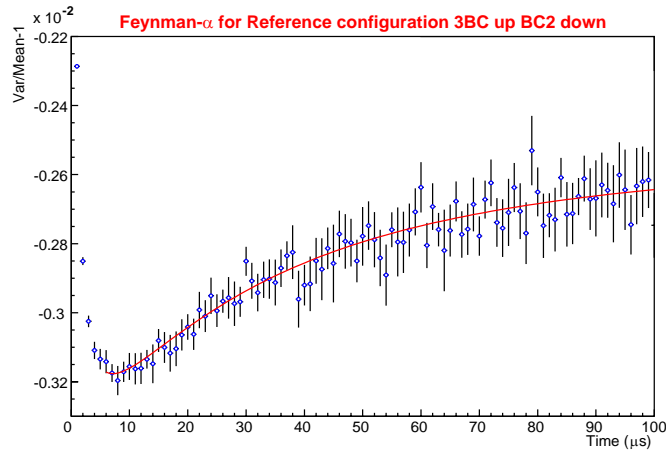


Figure 3. Feynman-alpha measurement at a subcritical level of $\rho = -12.7$ \$

The discrepancy between the measured and calculated value of $1/\alpha$ is about 36%, which is comparable with the deviation obtained with the Rossi-alpha technique in similar measurement conditions.

4.2. Feynman-alpha measurements with the GENEPI pulsed source

For a pulsed reactor system, the well-known Feynman- α formulation [1,2] has to be adapted to include the time-dependence of the source. Depending on the way the opening of the measurement gate is triggered, stochastically or deterministically with regard to the source pulses, different Feynman- α expressions are obtained.

For a randomly or stochastically pulsed system, which in practice means that in the analysis of the experimental data, the start of each time interval is chosen randomly with respect to the source pulses, we have used the Feynman- α expression developed by Pazsit and Ceder [3].

Measurements were performed at a small reactivity level of 1.57 \$ and with an accelerator repetition rate of 4.4 kHz. In figure 4a, the curve of the variance-to-mean minus one is plotted as a function of the width of the time interval.

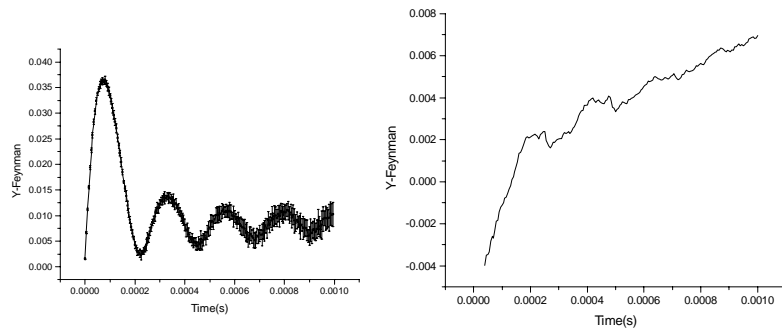


Figure 4. The variance-to-mean ratio minus one as a function of the gate width for a stochastically (a) and deterministically (b) pulsed system. [5]

In principle, the alpha value could be extracted from this curve in figure 4a using the equations by Pazsit and Ceder [3]. The interpretation of this equation reveals that in figure 4a only two minima contain information on the alpha value, which is not sufficient to extract from these data an accurate value for alpha. These measurements are difficult to analyse with the experimental conditions of the MUSE-4 experiments and, in particular, because of the too low repetition rate of GENEPI. More measurements are planned, but our preliminary thought is that the Feynman- α technique for stochastically pulsed sources cannot be used for ADS, since no high repetition rates are to be expected in ADS.

A second type of analysis proposed by Pazsit and Ceder [3] and Yamane [4] is a Feynman- α technique using deterministic pulsing. In this case, the gates used in the analysis are synchronised with the accelerator pulses. As shown in Figure 4b, this second type of analysis has the advantage that the oscillating deviations from the smooth Feynman- α curve are much smaller. The trends predicted by Pazsit and Ceder [3] and Yamane [4] are confirmed quite well by these experimental data, but the extraction of the correct alpha value is still quite difficult.

5. Cross Power Spectral Density (CPSD) method

5.1. CPSD measurements with the intrinsic source

The measurement of the Auto or Cross Power Spectral Density with a stationary driving source is a well-known technique [2]. From the break frequency in the response of both spectral densities, the α -value of the system can be obtained.

Measurements were performed at a reactor power level of 20 W, which means that the reactor is at delayed critical, and with high efficient detectors in the reflector for a measurement time of 50 minutes [6]. The combination of a very small subcritical level and a high efficient detector allowed us to work in the desired current mode. From the APSD of either detector, it was not possible to get an accurate value for α because of the strong inherent spontaneous fission source, which leads to a very low signal to noise ratio. The α obtained from the CPSD, however, corresponds reasonably well with the values obtained with the pulse-mode experiments.

Since CPSD measurements rely on neutron detectors working in current mode, its application in ADS at large subcritical levels and without the presence of a pulsed source as a driving source will be very difficult, although future developments in electronics might solve the problem.

5.2. CPSD measurements with the GENEPI pulsed source

The Cross Power Spectral Density (CPSD) is the Fourier transform of the covariance with more than one pulse per time window present in the analysis. [9]. To simplify the mathematical derivation of this expression, we assume that the time dependency of the source can be described by a train of Dirac delta pulses and obtain after some manipulation the expression for the CPSD:

$$CPSD_{D_1, D_2}(w) = \frac{\epsilon_1 \epsilon_2}{2\alpha(\bar{v}\Lambda)^2} \left[\frac{F_I \bar{v}_I + F_S \sum_{n=0}^N \exp(-iwnT_p)}{\alpha\Lambda} \frac{1}{v(v-1) + F_I \bar{v}_I (v_I - 1)} \right] \frac{1}{(\alpha^2 + w^2)} \quad (3)$$

From this expression we can conclude that the $CPSD_{23}$ depends on the source frequency ($\Theta = 2\pi/T_p$) and the reactor break frequency α .

It is seen from figure 5 that the CPSD shows peaks corresponding to the source frequency and its harmonics. To avoid the peaks in the fitting, we have used a weight function proportional to the inverse of the variance function at each point, except in the peaks, where the weight function was taken zero (infinite variance). The second method we propose consists of removing the

peaks before fitting. Both fits are in good agreement and correspond to the reactivity values obtained with the pulsed neutron techniques.

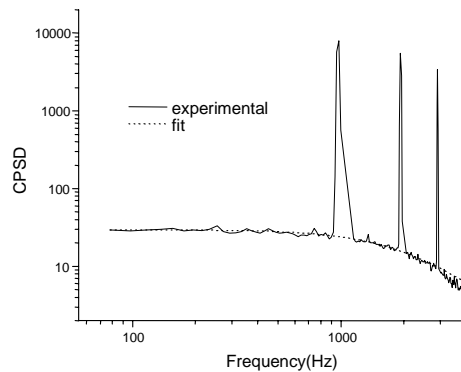


Figure 5. The CPSD of the measurements with fission chambers in the reflector with GENEPI operating in (D-T) mode at a repetition rate of 1 kHz. [5]

The main problem with this continuous current technique in the MUSE-4 experiments remains the very small magnitude of the signals coming from the detectors when the multiplying assembly is very subcritical. In an ADS, the external source could be higher. The analysis of the CPSD for a pulsed source is also more complicated than in the case of a stationary driving source due to the presence of pulse frequency peaks which have to be filtered out.

6. The determination of kinetic parameters

6.1. *Kinetic parameters derived from the Rossi-alpha method with the intrinsic source*

When the Rossi- α method is combined with the measurement of a reactivity by another method, the mean neutron lifetime in the effective delayed neutron fraction can be determined, given the knowledge of the detector efficiency or the integral fission-rate in the core.

In this case, the reactivity worth was estimated through the inverse kinetic method and yielded -0.365 ± 0.018 \$. For the Rossi- α method with the intrinsic source, two high efficient fission chambers located within the reflector region were used. Three different combinations of detectors were analysed. The total measurement time was about 5.5 hours.

A weighted mean of the α -value, where weights are the reciprocal of variances gives $\alpha_p = 7800 \pm 180 \text{ s}^{-1}$ (2%). Since we also measured the reactivity worth corresponding to the considered core configuration, we can infer the reduced generation time $\Lambda^* = \Lambda/\beta = 175 \pm 4 \text{ } \mu\text{s}$ (2%). Since the integral fission rate was derived from calculation and flux traverses measurements, the neutron generation time can be estimated $\Lambda = 0.555 \pm 0.020 \text{ } \mu\text{s}$ (4%) together with the delayed neutron fraction $\beta = 317 \pm 13 \text{ pcm}$ (4.2%) [7].

From these measurements, it is clear that for small subcritical levels and high efficient detectors and already long measurement times, the different kinetic parameters can be determined. For larger subcritical levels, statistics on the measured distribution will be deteriorated and much larger uncertainties on the derived values of the kinetic parameters will exist assuming a determination is still feasible.

6.2. Kinetic parameters derived from the CPSD method with the intrinsic source

Since the CPSD technique is closely related to the Rossi-alpha technique, we can also use the CPSD to determine the reactivity when the reactivity is provided by an independent technique and the detection efficiency or integral fission-rate is known.

Two series of measurements were performed with the GENEPI pulsed source OFF using two very high efficiency chamber (235U deposit is about 5g) [10]. In the first series, the chamber was surrounded with CH₂ to increase efficiency of the chamber and the correlation level (amplitude of the detector response increase ~100 times with CH₂). In the second one, the CH₂ was replaced by Al.

With Al, measurements provide incoherent β_{eff} values because of the low correlation level. With CH₂, one notes that the CPSD can no more be modelled by a 1st order low pass filter but requires a 2nd order low pass filter. This is due to the additional slowing-down of the neutrons in CH₂, which introduces a second time constant. Thus, the standard point kinetic model is not suited and it is necessary to develop a two points model to isolate the second zone "CH₂+detector" from the first "core+reflector" zone. With this 2 point model, one obtains two break frequencies ($\omega_1 = \alpha = (\beta - \rho)/\Lambda$, $\omega_2 = 1/\tau_{\text{CH}_2}$) and the same value for the plateau as in the 1 point noise theory and the same formula for the effective delayed neutron determination and mean neutron generation time.

Table 2. Estimated values of the kinetics parameter

Measurement	Reactivity (\$)	β_{eff} (en pcm)	Λ (in μs)
1	- 0.038	331	0.583
2	-0.246	335	0.575
3	-0.246	339	0.599
4	-0.63	355	0.621
5	-1.17	376	0.645

Table 2 summarizes the measurements performed at different small reactivity levels. From table 2, it can be seen that there exists a drift in the obtained results as a function of the reactivity. Especially measurements 4 and 5 with the largest subcritical level yield values for the kinetic parameters which are not consistent with the calculated values. The interpretation of these measurements need more supplementary calculations to take into account the spatial effects due to the real core configuration and to determine the MSM reactivity level instead of the SM reactivity level by including the MSM factors. Since the same need to introduce spatial correction factors exist in the analysis of Rossi-alpha measurements, both techniques are equivalent at that point. Based on measurement 1 to 3, one obtains for $\beta_{\text{eff}} = 335$ pcm, for $\Lambda = 0.586$ μs and for $\Lambda/\beta_{\text{eff}} = 175$ μs .

The results show that the use of a CH_2 embedded detector allows to work in current mode and hence makes the application of the CPSD technique feasible, but renders the interpretation more difficult. For larger subcritical levels, the current signal from the preamplifier will be become even smaller and the uncertainty on the determination of kinetic parameters will be strongly increased.

7. Conclusions

Measurements were performed at the fast MASURCA core coupled to the GENEPI accelerator. Different noise methods, such as Rossi-alpha, Feynman-alpha and Auto and Cross Power Spectral Density techniques were applied to a subcritical system driven by the intrinsic source or the pulsed source.

The measurements with the Rossi-alpha method with the intrinsic source pointed out that for small subcritical levels ($<1\%$) the alpha decay constant can be derived with an uncertainty of about 10%. When deeper subcritical levels are investigated, the statistics are strongly deteriorated and the extraction of valuable information becomes difficult. To improve the statistics at deep subcritical levels, higher efficient detectors have to used (leading to strong flux

perturbations) or/and longer measurement time are required, which are both not recommended actions.

When a pulsed source is used as a driving source in the Rossi-alpha method, the uncertainty on the determination of the alpha decay constant at even large subcritical levels of 11β is in the order of 1%. However, large discrepancies up to 30% exist for the decay constant between measured values and values derived on basis of calculated Λ and β_{eff} and a reactivity measured with the MS method.

Since the Feynman-alpha method for an intrinsic source is strongly related to the Rossi-alpha for an intrinsic source, the same conclusions can be drawn. When for the Feynman-alpha method a pulsed neutron source is used as a driving source, the predicted theoretical behaviour is found experimentally, but the extraction of the alpha decay constant could not be achieved because of the characteristics of the pulsed source used during these experiments.

When the measurements obtained with the Feynman- α technique for a pulsed neutron source as a driving source are compared with the Rossi-alpha method for a pulsed neutron source as driving source, it can be concluded that the Rossi-alpha method allows a more simple interpretation and enables a much easier extraction of the alpha decay constant.

The recording of auto- and cross-power spectra at even small subcritical levels with a continuous intrinsic driving source based on the sampling of the detector current was not possible due to strongly reduced flux level. When a pulsed neutron source is used to drive the subcritical assembly, measurements with the CPSD techniques at larger subcritical levels will be possible, but anyway deep subcritical levels, as present in the operation of an ADS, will probably lead to a strongly reduced signal-to-noise ratio on the measured distribution due to the low current. Therefore, a high intensity for the external source will be required to obtain an acceptable signal-to-noise ratio.

The determination of the kinetic parameters Λ and β_{eff} can be achieved with the Rossi-alpha method or the CPSD technique when the subcritical facility is driven by the intrinsic source for subcritical levels smaller than 1β . To accomplish this with the CPSD technique in MASURCA a CH_2 embedded detector was needed to obtain a sufficiently high detector current. The introduction of the CH_2 material imposed a new interpretation model which renders the analysis more difficult. When the kinetic parameters can only be determined at larger subcritical levels as expected in ADS, spatial corrections are needed and a minimum signal-to-noise ratio on the determination of the kinetic parameters will imply higher efficient detectors and longer measurement times.

References

1. Williams, M. M. R., *Random Processes in Nuclear Reactors*, Pergamon Press, Oxford (1974)
2. R. E. Uhrig, *Random Noise Techniques in Nuclear Reactor Systems*, Ronald Press, New York (1956).
3. Paszit, I, Ceder, M., *Theory and analysis of the Feynman-alpha method for deterministically and randomly pulsed neutron sources*. PHYSOR Conference, Seoul, Korea, October 7-10 (2002)
4. Y. Yamane, Y. Kitamura, H. Yamauchi, *Derivation of variance-to-mean formula for periodic and pulsed neutron source*, Annals of Nuclear Energy, Volume 30, Issue 8, pp 897-909, May 2003, (2002)
5. Y. Rugama, J.L. Kloosterman and A. Winkelman, "Experimental Results from Noise Measurements in a Source Driven Subcritical Fast Reactor, Accepted for publication in Progress of Nuclear Energy (2003).
6. Y. Rugama, J.L. Kloosterman, and A. Winkelman, Preliminary Measurements of the Prompt Neutron Decay Constant in MASURCA, Progress in Nuclear Energy, 43:421-428, (2003)
7. F. Mellier, G. Perret, C. Jammes, C. Destouches, J.F. Lebrat, *MUSE-4 Experiment Progress at Subcriticality Levels Representative of ADS Operating*, Submitted to GLOBAL 2003 Atoms for Prosperity: Updating Eisenhower's Global Vision for Nuclear Energy, New Orleans, Louisiana, November 16-20 (2003).
8. P. Baeten, B. Verboomen, H. Aït Abderrahim, *Determination of the contribution of harmonics during transients in a cylindrical homogeneous reactor with a multigroup diffusion approximation in an ADS, Application to the MUSE subcritical experiments*, SCK•CEN internal note, 2003
9. Y. Rugama, J. L. Muñoz-Cobo, J.L. Kloosterman, *Application of the stochastic transport theory to reactivity measurements in a subcritical assembly driven by a pulsed source*, M&C 2003 Glatimburg April 6-9 (2003)
10. G. Perret, Y. Rugama, *Determination de la fraction de neutrons retardés b_{eff} et de la constante de décroissance prompte α par la technique du bruit de pile en mode courant dans le programme MUSE-4*, Internal CEA note NT-SPEX/LPE/03/002, 2003