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Kinetic parameters of the GUINEVERE reference configuration in VENUS-F reactor obtained from a pile noise experiment using Rossi and Feynman methods

Benoit Geslot, Frédéric Mellier, Alexandra Pepino, Jean-Luc Lecouey, Mario Carta, Anatoly Kochetkov, Guido Vittiglio, Annick Billebaud, Patrick Blaise

***Abstract*–Within the framework of the EURATOM FP7 FREYA project, a pile noise measurement campaign has been conducted by the CEA (France) in the VENUS-F reactor (SCK-CEN, Mol Belgium). The experiment took place in April 2011 in the reference critical configuration of the GUINEVERE experimental program. The experimental set-up made it possible to estimate the core kinetic parameters: the prompt neutron decay constant, the delayed neutron fraction and the generation time. A precise assessment of these constants is of prime importance. In particular, the effective delayed neutron fraction is used to normalize and compare calculated reactivities of different subcritical configurations, obtained by modifying either the core layout or the control rods position, with experimental estimators deduced from the analysis of measurements.**

This paper presents results obtained with a CEA-developed time stamping acquisition system. Data were analyzed using Rossi-α and Feynman-α methods. Results were normalized to reactor power using a calibrated fission chamber with a deposit of Np-237. Calculated factors were necessary to the analysis: the Diven factor computed by the ENEA (Italy) and the power calibration factor computed by the CNRS/IN2P3/LPC Caen.

Results deduced with both methods are consistent with respect to calculated quantities. Recommended values are given by the Rossi-α estimator, that was found to be the most robust. The neutron generation time is 0.438 µs +/- 2.0% and the effective delayed neutron fraction is 765 pcm +/- 1.1%. Discrepancies with the calculated value (722 pcm, calculation from ENEA) are satisfactory: -5.6% for the Rossi-α estimate and -2.7% for the Feynman-α estimate.

I. INTRODUCTION

THE GUINEVERE (Generator of Uninterrupted Intense NEutrons at the lead VEnus REactor) project [1] was launched in 2006, within the 6th European Framework Program IP-EUROTRANS [2], in order to study the feasibility of transmutation in Accelerator Driven subcritical Systems (ADS). This zero-power facility operated by SCK•CEN (Mol, Belgium) couples the fast subcritical (keff ~0.96) lead-moderated reactor VENUS-F with an external neutron source provided by the deuteron accelerator GENEPI-3C via $T(d,n)^4He$ fusion reactions.

Since 2011, this facility has been running for the FP7 FREYA (Fast Reactor Experiments for hYbrid Applications) project [3], which aims at solving the reactivity monitoring issue, but also at providing data in support to the MYRRHA project design and licensing.

This paper presents results obtained in April 2011 in the reference critical configuration. A CEA-developed time stamping acquisition system was used to acquire signals from two fission chambers (FCs). Acquisition setup is detailed in section II.

Data have been analyzed using Rossi-α (type I) and Feynman-α methods by taking advantage of the multiple measurement lines to analyze the signals cross-correlations. Results are presented and discussed in section III with an emphasis on uncertainty management.

Kinetic parameters are finally obtained using calculated factors:

- The Diven factor is equal to 0.863 +/- 0.65% (ENEA calculation [4]);
- VENUS power calibration factors have been calculated by CNRS/IN2P3/LPC Caen for two CEA miniature fission chambers (FC) used for monitoring the experiment (^{237}Np and ^{238}U) [5].

II. EXPERIMENTAL SETUP

A. Reactor configuration

The VENUS-F reactor was loaded with 93 square fuel assemblies (FA) arranged in a cylindrical geometry, composed of 30% ^{235}U enriched metallic uranium provided by CEA and solid lead rodlets that simulate a fast lead cooled system. The fissile zone is surrounded axially and radially by a reflector made of lead. For mechanical reasons, the 12x12 assemblies are contained into a square stainless steel casing. The reactor is equipped with six absorbent safety rods (SR) with fuel

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followers and two absorbent control rods (CR). The height of the CR can vary from 0 mm (fully inserted) to 600 mm (fully removed).

Two calibrated FCs placed in the center of the core were used for core power monitoring. Measurements are achieved in Pulse Height Analysis (PHA) mode using a Canberra spectroscopy acquisition chain. Due to electronic perturbations, it was only possible to keep one detector signal (^{237}Np FC, n°2131), located in (1,1) to estimate the core integral fission rate.

The signals of two CFUL-01 fission chambers (with deposit of ~1g ^{235}U) located in the reflector, were acquired in time-stamping mode using X-MODE acquisition system (with a time resolution of 25 ns):

- CFUL-01 n°653 located in (6,-6): channel n°1 connected to cable X1,
- CFUL-01 n°658 located in (-6, -6): channel n°2 connected to cable X13.

The measurement took place on April 7th 2011. The reactor configuration was F01/27 (Fig. 1). Measurements were performed at ~5 W.

Experiment duration was 16118 s (around 4h28min). Although the power stability is not an issue for processing pile noise data, a good neutron flux stability was achieved (see Fig. 2, counting rates standard deviation is ~2%).

B. *Power monitoring*

Results obtained with a miniature ^{237}Np FC are given in TABLE I (uncertainties are given in percent at 1σ). Due to some random signal perturbations, the measurement duration was shortened to 600 s.

Fission chamber n°2131 has been calibrated during a dedicated measurement campaign in the BR1 reactor in 2010 [6]. Since then, a reevaluation of fissile cross sections in the calibration flux has been realized by the SCK•CEN in 2012 [7]. New cross sections have been calculated with MCNP by modeling the entire reactor and calibration device. For ^{237}Np it has been found a significant difference on the cross section compared to the one used in 2010 (around 8%). The detector calibrated mass has thus been reevaluated, as well as its associated uncertainty.

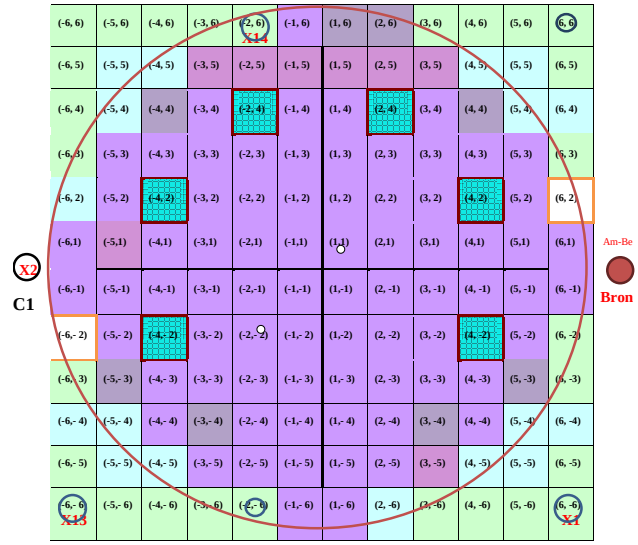
The reactor integral fission rate F_0 is required to obtain the delayed neutron fraction from a pile noise experiment. Knowing a calibration factor f_{Np7}, it is obtained using the following formula (C and m are the detector counting rate and calibrated mass, respectively):

$$F_0 = \frac{C}{m} \times f_{Np7} \tag{1}$$

Using the value calculated for ^{237}Np (f_{Np7} = 7.255 10^5 f/g), F_0 equals 1.96 10^{11} f/s. This corresponds to a reactor power of 6.2 W, consistent with the chosen power of 5 W. Estimated uncertainty on F_0 is 2.2%.

TABLE I. Counting Rates Measured with Monitor FC.

Measured Counting rate (c/s)	Calibrated mass (µg)	Corrected counting rate (c/s)
76.39 (0.5%)	283 (4%)	75.25 (1%)



		Amount	SCR,mm	PEAR	POAR
	- lead assemblies, PbA	45			
	- FA	91			
	- standard control rods "SCR"	2			
	- PEAR rod drop	0		NO	
	- safety rods, SR	6			

Fig. 1. VENUS core configuration F01/27.

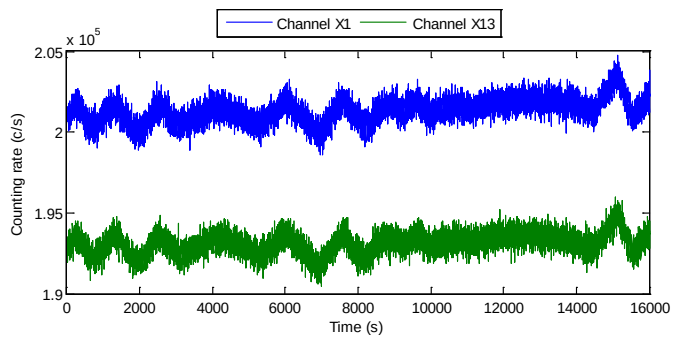


Fig. 2. Counting rates observed on CFUL-01 fission chambers.

III. MEASUREMENT ANALYSIS

A. *Feynman-α method*

The Feynman-α method is based on computing time average and variance of counts issued by fission chambers. For each time gate T, sample average and variance estimators are calculated using over the whole measurement.

When dealing with two detectors, the Feynman-α formula can be expressed using the covariance of the signals instead of the variance:

$$Y_F(T) = \frac{\langle C_1 \cdot C_2 \rangle - \langle C_1 \rangle \langle C_2 \rangle}{\sqrt{\langle C_1 \rangle \langle C_2 \rangle}} \tag{2}$$

The experimental curve was processed for 200 time bins linearly scaled between 5 µs and 1 ms. Notice that when using two detectors, the method is not impacted by detector dead time.

A theoretical model is to be fitted to the experimental curve in order to obtain estimators that can be linked to the kinetic parameters. This analytical model is as follows [9]:

$$Y_F(T) = C\frac{D}{\alpha^2 \cdot \Lambda^2 \cdot F_0}\left(1-\frac{1-e^{-\alpha T}}{\alpha T}\right) \quad (3)$$

In the previous equation, T is a time interval, α is the prompt decay constant $\alpha = (\beta\text{-}\rho)/\Lambda$, D is the Diven factor, and C is the detector average counting rate.

The model to be fitted to data is thus:

$$y(T) = A\cdot\left(1-\frac{1-e^{-B\cdot T}}{B\cdot T}\right) \quad (4)$$

This model shows only two parameters but a third one is necessary in order to derive the kinetic parameters: an estimate of the mean counting rate C (noted $\bar{C}$). $\bar{C}$ is estimated independently and its uncertainty is considered negligible as the counting rates are very high. Kinetics parameters are obtained using the following formulas:

$$\hat{\beta}_F = \frac{1}{1-\rho_\$}\sqrt{\frac{D}{F_0}\frac{\bar{C}}{\hat{A}}} \quad (5)$$

$$\hat{\Lambda}_F = \frac{1}{\hat{B}}\sqrt{\frac{D}{F_0}\frac{\bar{C}}{\hat{A}}} = \frac{\hat{\beta}_F}{\hat{B}}\left(1-\rho_\$\right) \quad (6)$$

An estimate of the fitted parameters covariance matrix is computed from the Jacobian matrix and using the input data covariance matrix (noted $V[Y_F]$):

$$Cov(\hat{A},\hat{B}) = \left(J_m^t \cdot V\left[Y_F\right]^{-1}\cdot J_m\right)^{-1} \quad (7)$$

The matrix $V[Y_F]$ is difficult to compute analytically because it is not a diagonal matrix as there are correlations between data points. An estimate of this matrix is obtained experimentally by splitting the measurement into 99 parts and processing a Feynman-α curve on each bunch of data. The experimental matrix shows high correlation between data points (Fig. 3): the closer the points are, the higher the correlation is.

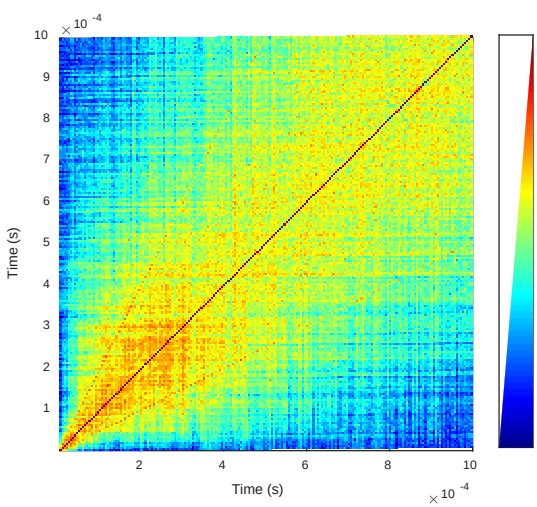


Fig. 3. Feynman curve experimental correlation matrix. Nearly 60% of the matrix has is above 50% correlation.

In order to introduce a reliable covariance matrix in the uncertainty calculations, it is required to use an analytical formula that models the measured covariance. Let T_m be the measurement duration and T_i the ith time interval of the curve, then $N(T_i) = T_m/T_i$ is the number of available samples. It can be demonstrated that the variance of the measurement, in the case of the variance to mean method, could be written [8]:

$$V\left[Y_F(T_i)\right] = 2\frac{\left(Y_F(T_i)+1\right)^2}{N(T_i)-1} \quad (8)$$

In the case of the covariance to mean method, the factor of 2 vanishes and the variance becomes:

$$V\left[Y_F(T_i)\right] = \frac{\left(Y_F(T_i)+1\right)^2}{N(T_i)-1} \quad (9)$$

On Fig. 4, it is shown that the previous equation gives a variance very close to the experimental one. The dashed line corresponds to the variance obtained from the residuals of a simple nonlinear fit of the curve. It is clear that the fit residuals drastically underestimate data uncertainty.

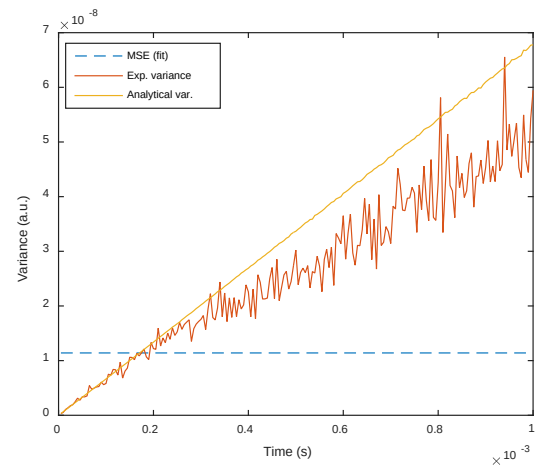


Fig. 4. Variance of the Feynman-α curve (experimental and computed).

By analogy and by adjusting the correlation level to fit the experimental covariance, the following formula can be used to model the non-diagonal element of the covariance matrix:

$$V\left[Y_F\right]_{i,j} = \sqrt{2}\times\frac{Y_F(T_i)+1}{\sqrt{N(T_i)-1}}\times\frac{Y_F(T_j)+1}{\sqrt{N(T_j)-1}},\quad i\neq j \quad (10)$$

The previous formula gives very satisfactory results when compared to the experimental matrix. Only the low level covariance elements in the computed matrix are significantly different compared to the experiment.

Finally, the covariance matrix of the kinetic parameters is obtained by:

$$Cov(\hat{\beta}_F,\hat{\Lambda}_F) = J_{\beta\Lambda}\cdot Cov(\hat{A},\hat{B})\cdot J_{\beta\Lambda}^t \quad (11)$$

Due to the high correlation for data points above a few hundred µs, it appears necessary to study the evolution of the results with the number of data points (i.e. the fit time range). As shown on Fig. 5, the estimated frequency tends to decrease when the time range increases. The parameter uncertainty reaches a minimum around T_{max} = 500 µs and above this value, the relative uncertainty increases steadily, showing that further data points do not bring relevant additional information.

Based on this study, the overall Feynman-α curve was fitted for 0<T<500µs (see Fig. 6). Results with associated uncertainties are given in Table 4 (uncertainties are given for 1 standard deviation). The total uncertainty also takes into

account uncertainties coming from the Diven factor and the integral fission rate. The correlation coefficient between β_F and Λ_F is -0.72, which indicates that their estimation is slightly anti-correlated.

It is important to note that the uncertainty computed using the analytic covariance matrix does not gives consistent results (compare columns 3 and 4 in TABLE II). The uncertainty is still under-estimated and additional study is required to solve this issue. The recommended global uncertainty is derived from the empirical uncertainty, obtained from the independent fits as discussed above.

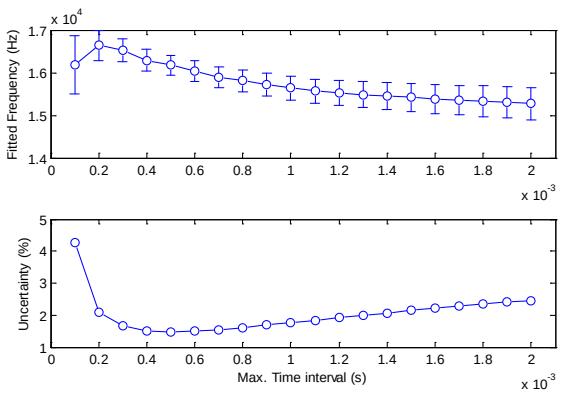


Fig. 5. Fitted frequency versus data time range (up) and associated uncertainty (bottom).

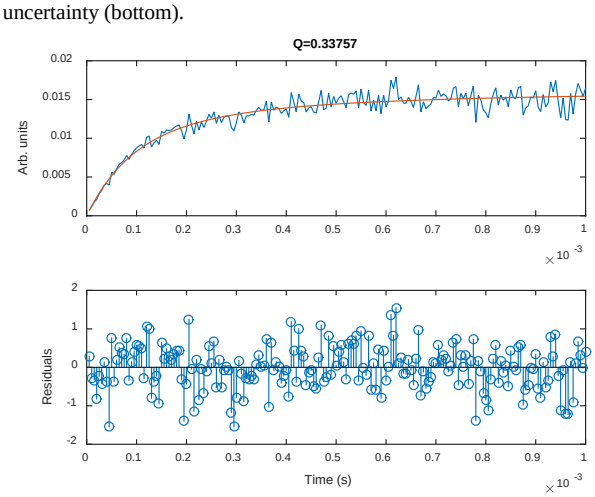


Fig. 6. Results of the Feynman-α fit (R-square=0.33).

TABLE II. ESTIMATED PARAMETERS BASED ON THE FEYNMAN-α.

Parameter	Value	Uncertainties (%)		
		Fit	Exp.	Total
$\hat{A}$	1.576 10^{-2}	0.4	1.0	
$\hat{B}$	1.56 10^{4} s^{-1}	1.2	1.7	
$\hat{C}$	197226 c/s			
$\hat{\beta}_F$	741.8 pcm	0.2	0.5	1.1
$\hat{\Lambda}_F$	0.480 µs	0.2	1.4	1.8

B. *Rossi-α method*

In the Rossi-α technique, correlations between pulses occurring in neutron detectors are analyzed. As previously, experimental correlations curves are then fitted by an analytical model with parameters that depend on the physical quantities (noted β_R and Λ_R). Based on the raw time-stamped signals obtained from the fission chambers, the inter-correlation histogram is computed by processing the time intervals between detected neutrons.

The theoretical formula of the Rossi-α function reads [9]:

$$Y_R(T) = C_1 \cdot C_2 \cdot \left(\frac{D}{2\alpha \cdot \Lambda^2 \cdot F_0} e^{-\alpha.T} + 1 \right) \tag{12}$$

where C_1 and C_2 are the average counting rates during the experiment and the other notations are the same as above. The experimental curve is thus fitted by a 1st order exponential model $y(T) = A.\exp(-B.T) + C$.

Three estimators (noted $\hat{A}$, $\hat{B}$ and $\hat{C}$) are obtained from the fit. They are linked to the delayed neutron fraction and prompt generation time as follows:

$$\hat{\beta}_R = \frac{1}{1-\rho_\$} \sqrt{\frac{D}{2 \cdot F_0} \frac{\hat{B} \cdot \hat{C}}{\hat{A}}} \tag{13}$$

$$\hat{\Lambda}_R = \sqrt{\frac{D}{2 \cdot F_0} \frac{\hat{C}}{\hat{A} \cdot \hat{B}}} \tag{14}$$

The covariance matrix is obtained from the Jacobian matrix J_m (i.e. the matrix of the partial derivatives of the model with respect to the parameters) and from the covariance matrix of input data (noted $V[Y_R]$):

$$\mathrm{Cov}(\hat{A}, \hat{B}, \hat{C}) = \left(J_m^t \cdot \mathrm{V}\left[Y_R\right]^{-1} \cdot J_m \right)^{-1} \tag{15}$$

Because Rossi-α curve being a histogram of poissonian counts, each data point also follows a Poisson statistics. Moreover, data points are independent (uncorrelated). The best estimate of the covariance matrix is then a diagonal matrix which element i is given by:

$$V\left[Y_R\right]_{i,i} = Y_R(i) \tag{16}$$

Finally, the covariance matrix of the kinetic parameters is obtained:

$$\mathrm{Cov}(\hat{\beta}_R, \hat{\Lambda}_R) = J_{\beta\Lambda} \cdot \mathrm{Cov}(\hat{A}, \hat{B}, \hat{C}) \cdot J_{\beta\Lambda}^t \tag{17}$$

where $J_{\beta\Lambda}$ is the jacobian vector of estimators $\hat{\beta}_R$ and $\hat{\Lambda}_R$ with respect to $\hat{A}$, $\hat{B}$ and $\hat{C}$.

As it shown in Fig. 7, correlations between data points are note significant. This means that the fit can be performed easily without calculating a data variance matrix, which is flat, but using the theoretical (Poissonian) estimation of the variance (see Fig. 8).

Moreover, no significant trend on fit estimation is observed when changing the data time range (Fig. 9). We chose the same time range as above (500 µs).

Final fit results are shown in Fig. 10. Adjusted parameters and their uncertainties are given in TABLE III (uncertainties are given for 1 standard deviation). The total uncertainty also takes into account uncertainties coming from the Diven factor and the integral fission rate. The correlation coefficient between β_R and Λ_R is -0.55, indicating a loose correlation between the estimated parameters.

The signal to noise ratio of the measurement (calculated as $\hat{A}/\hat{B}$) is around 0.065%. This value is independent on the reactor power, but is linear with the measurement duration.

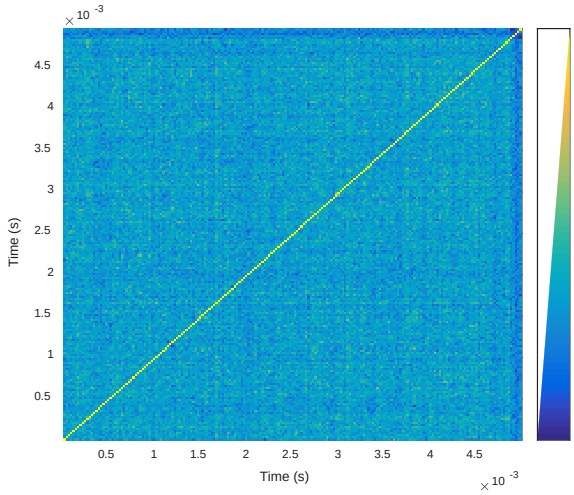


Fig. 7. Experimental correlation matrix of Rossi-α curves.

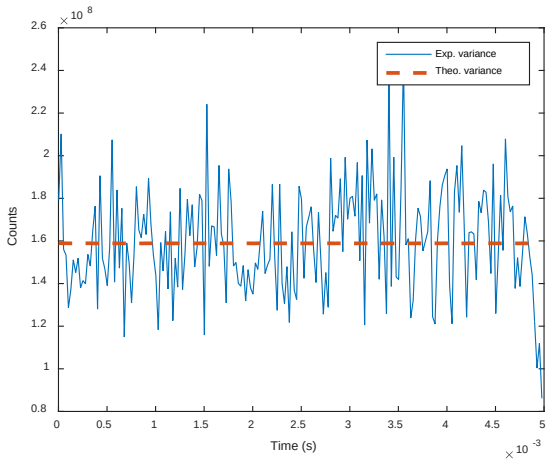


Fig. 8. Experimental and theoretical variance of Rossi-α curves.

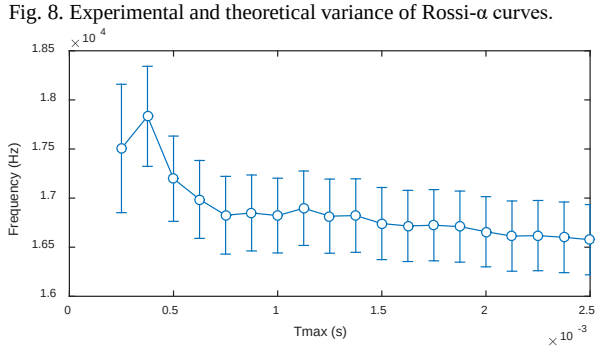


Fig. 9. Evolution of fitted frequency with data time range.

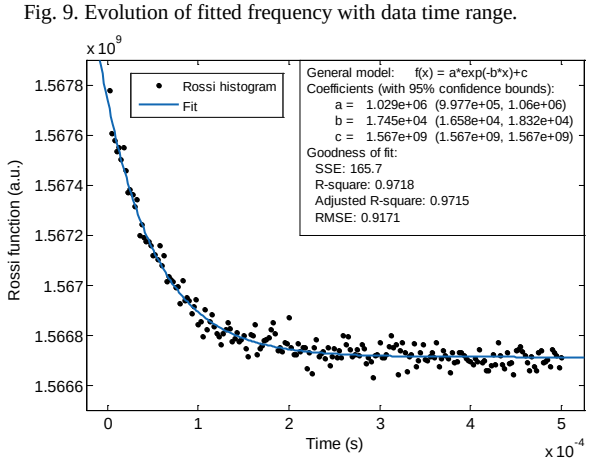


Fig. 10. Fit of Rossi-α histogram (RMSE=0.92).

TABLE III. ESTIMATED PARAMETERS BASED ON THE ROSSI-α.

Parameter	Value	Fit unc. (%)	Exp. unc. (%)
$\hat{A}$	1.01 10^6 c²/s²	1.5%	1.7%
$\hat{B}$	1.72 10^4 s^{-1}	2.5%	3.0%
$\hat{C}$	1.57 10^9	0.0002%	1.6%
$\hat{\beta}_R$	764.9 pcm	1.1%	1.2%
$\hat{\Lambda}_R$	0.438	1.9%	2.1%

IV. CONCLUSION

A pile noise measurement has been conducted in the VENUS-F reactor within the frame of the FREYA project. Measurements were performed and analyzed using Rossi-α and Feynman-α methods. Taking advantage of the two measurement lines, the analysis was focused on the correlations and covariance between detectors signals.

A discrepancy between the two methods is observed between the prompt decay constants (-9%) which cannot be explained by the uncertainties. On the contrary, the difference between the estimates of delayed neutron fraction (-3%) and neutron generation time (4%) are consistent with the associated uncertainties.

The delayed neutron fraction calculated value is 722 pcm (ENEA calculation). Discrepancies with the experimental values (C/E-1) are satisfactory: -5.6 % for the Rossi-α estimate and -2.7% for the Feynman-α estimate.

Based on the quality of the data analysis and also on the issues associated with both methods (especially correlation issues with the Feynman-α estimator), it is recommended to use the Rossi-α values. Indeed, this method allows a robust analytical uncertainty estimation, with lesser impact on the results of the data time range and eventually with a smaller correlation factor between the two parameters.

Parameter	Rossi-α		Feynman-α	
	Value	Std (calc.)	Value	Std (exp.)
$\hat{\beta}$	764.9 pcm	1.1%	741.8 pcm	1.2%
$\hat{\Lambda}$	0.461 µs	1.9%	0.480 µs	2.1%

V. ACKNOWLEDGMENT

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