Recent developments in neutron noise measurements based on the continuous signal of detectors

M. Szieberth[1], M. Boros[1],G. Klujber[1], L. Nagy[1,2],, T. Misawa[3], Y. Kitamura[3], I. Barth[1] , I. Pázsit[2]

[1] Institute of Nuclear Techniques, Budapest University of Technology and Economics (BME), H-1111 Budapest, Hungary

[2] Division of Subatomic, High Energy and Plasma Physics, Department of Physics, Chalmers University of Technology, SE-412 96 Göteborg, Sweden

[3] Kyoto University, Institute for Integrated Radiation and Nuclear Science (KURNS), Osaka 590-0494, Japan

MŰEGYETEM 1782

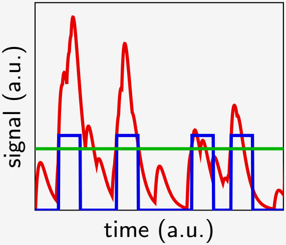
CHALMERS UNIVERSITY OF TECHNOLOGY

KURNS

31st International Meeting on Reactor Noise (IMORN-30), Delft University of Technology, Delft, The Netherlands, September 9-12, 2024

Introduction

- Based on L. Pál's stochastic model of the continuous current of fission chambers a theory was developed to extract information for neutron noise measurements.
- Measurements were performed to demonstrate the correctness of the theory and the practical applicability of the methods a the Kyoto University Critical Assembly (KUCA) and the BME Training Reactor.
- Simulations were perfomed to investigate the range of applicability of the method.



- Measurement of the detection rates:
  - traditionally: counting of **discrete pulses**
  - new approach: analysis of **continuous detector signal**
- Potential gain from the new method:
  - elimination of **deadtime** from pulse counting
  - application of state-of-the-art **digital** signal processing and analysis tools

Traditional version of the Rossi-α and Feynman-α methods

The reactivity ρ is indirectly obtained from the prompt neutron decay constant α:

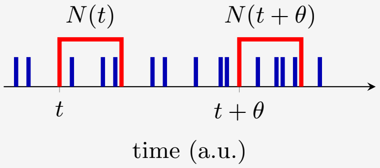
$$\alpha = \frac{\beta - \rho}{\Lambda} \quad (1)$$

β: delayed neutron fraction; Λ: prompt neutron generation time.

Rossi-α method:

Measuring the covariance of counts in two gates at various θ distances.

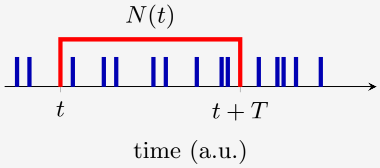
$$\begin{aligned} \mathrm{Cov}(\theta) &= \mathrm{Cov}[N(t), N(t+\theta)] \\ &= a\,\mathrm{e}^{-\alpha\theta} + b \end{aligned} \quad (2)$$



Feynman-α method:

Measuring the variance-to-mean ratio of counts in gates of various widths T.

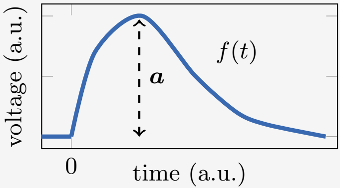
$$\begin{aligned} \mathrm{vtm}(T) &= \frac{\mathbb{D}^2[N(T)]}{\mathbb{E}[N(T)]} - 1 \\ &= c\left(1 + \frac{1 - \mathrm{e}^{-\alpha T}}{\alpha T}\right) \end{aligned} \quad (3)$$



The value of α **is obtained by fitting** the above functions to the measured data.

Stochastic model of the continuous signal of fission chambers

L. Pál proposed an alternative stochastic model of the continuous signal of fission chambers.



Advantages of this approach:

- simpler and more transparent derivation
- easy to extend the model

First step: describing the **distribution of a single** neutron induced **pulse**.

Each pulse has a:

- deterministic shape $f(t)$
- random amplitude $\boldsymbol{a}$ (prob. density $w(a)$)

The probability density function of the pulse value at time t:

$$h(x,t) = \int_0^\infty \delta[x - a\, f(t)]\, w(a)\, \mathrm{d}a. \tag{4}$$

Its characteristic function of the pulse value at time t:

$$\chi(\omega,\, t) = \int_0^\infty \mathrm{e}^{\imath\omega x}\, h(x,t)\, \mathrm{d}x = \int_0^\infty \mathrm{e}^{\imath\, \omega\, a\, f(t)}\, w(a)\, \mathrm{d}a \tag{5}$$

Pulses from subsequent detections form a continuous and fluctuating voltage signal $\boldsymbol{y}(t)$.

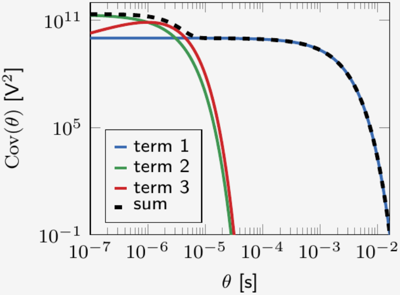
Continuous version of the Rossi-α method

To obtain a continuous Rossi-α formula, **we calculate the covariance function of the continuous signal**:

$$\mathrm{Cov}(\theta) = \lim_{t\to\infty} \langle y(t)\, y(t+\theta)\rangle - \langle y(t)\rangle\langle y(t+\theta)\rangle \tag{6}$$

The final result (for pulse shape $f(t) \sim t\,\mathrm{e}^{-t/\alpha_e}$) is:

$$\begin{aligned}\mathrm{Cov}(\theta) = &\frac{1}{2}\,\alpha\,\langle y\rangle\,\Phi\,e^{-\alpha\,|\theta|}\\ &+\frac{1}{2}\,\alpha_e\,\langle y\rangle\,\Psi_1\,e^{-\alpha_e\,|\theta|}\\ &+\frac{1}{2}\,\alpha_e\,\langle y\rangle\,\Psi_2\,\alpha_e|\theta|\,e^{-\alpha\,|\theta|}.\end{aligned} \tag{7}$$



For not too deep subcriticalities $\alpha \ll \alpha_e$, hence **the 1st term dominates for large θ**:

$$\mathrm{Cov}(\theta) \approx c\,\mathrm{e}^{-\alpha\theta} \tag{8}$$

Φ, Ψ_1 and Ψ_2 are algebraic combinations of the detector parameters, the parameters of the multiplying medium and the source.

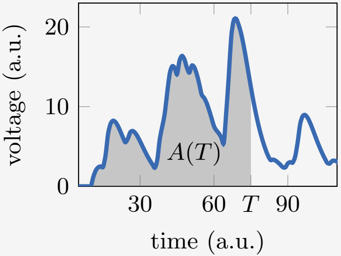
Continuous version of the Feynman-α method

To obtain a continuous Feynman-α formula, we **introduce the area under the signal**

$$A(T) = \int_0^T y(t)\,\mathrm{d}t \tag{9}$$

and **calculate its variance-to-mean ratio**

$$\mathbf{vtm}(T) = \frac{\mathbb{D}^2[A(T)]}{\mathbb{E}[A(T)]} \tag{10}$$



The denominator is easily calculated and yields

$$\mathbb{E}[A(T)] = T \lim_{t\to\infty} \langle y(t) \rangle \tag{11}$$

The numerator is obtained by integrating the covariance function (calculated earlier):

$$\mathbb{D}^2[A(T)] = \int_0^T \int_0^T \mathbf{Cov}(t_2 - t_1)\,\mathrm{d}t_2 \mathrm{d}t_1 \tag{12}$$

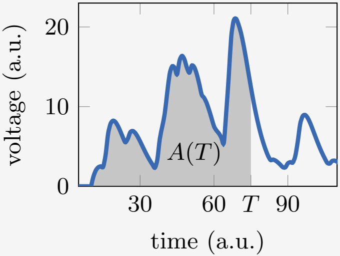
Continuous version of the Feynman-α method

To obtain a continuous Feynman-α formula, we **introduce the area under the signal**

$$A(T) = \int_0^T y(t)\,\mathrm{d}t \tag{9}$$

and **calculate its variance-to-mean ratio**

$$\mathbf{vtm}(T) = \frac{\mathbb{D}^2[A(T)]}{\mathbb{E}[A(T)]} \tag{10}$$



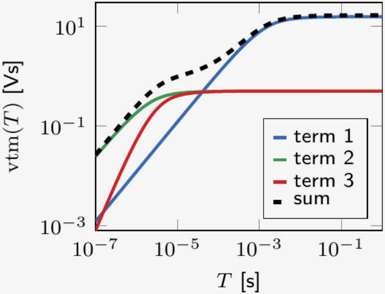
The final result (for pulse shape $f(t) \sim t\,\mathrm{e}^{-t/\alpha_e}$) is:

$$\mathbf{vtm}(T) = \Phi\, f_1(\alpha\, T) + \Psi_1\ f_1(a_e\, T) + \Psi_2\, f_2(\alpha_e\, T) \tag{13}$$

For not too deep subcriticalities $\alpha \ll \alpha_e$, hence **the 1st term dominates for large $\boldsymbol{\theta}$**:

$$\mathrm{vtm}(T) \approx \Phi\left(1 - \frac{1 - e^{-\alpha\, T}}{\alpha\, T}\right) \tag{14}$$

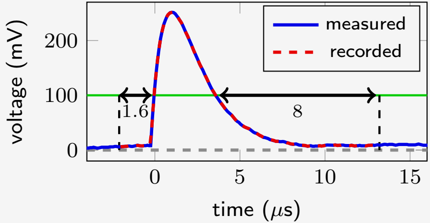
$$f_1(x) = 1 - \frac{1 - e^{-x}}{x} \quad f_2(x) = 1 + e^{-x} - 2\,\frac{1 - e^{-x}}{x}$$



Development of the data acquisition method

- Special data acquisition technique had to be developed to realize measurements based on continuous detector signals.
- A fast preamplifier was developed at BME which preserve the pulse shape and produces signal between ±1 V.
- High sampling rate is required for the accurate calculation of the signal moments

- Applied A/D converter
  - Red Pitaya STEMLab 125-14 type
  - embedded FPGA + CPU
  - 14 bit resolution between ±1 V
  - 125 MHz max. sampling frequency (8 ns resolution)
  - 2 parallel, synchronized analogue input

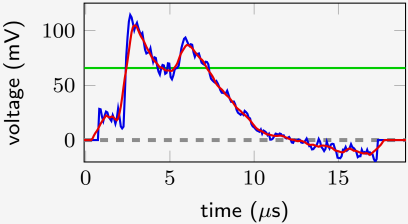


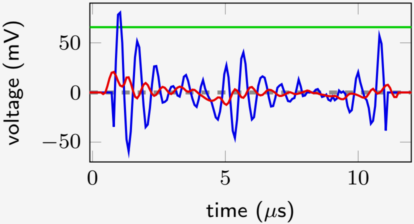
- Data storage was reduced by recording the signal only above **thresold** and some surrounding data.
  - Time between such signal section was also stored.
  - Discarded sections were replaced by an average background value during analysis.

- In parallel time-stamped data was also produced by conventional pulse counting.

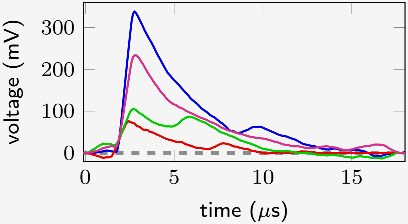
Data recording and processing

- Moving average **smoothing** was applied to reduce electronic noise ($0.84\,\mu$s window):

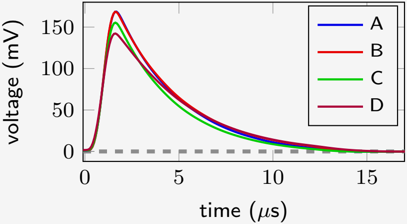




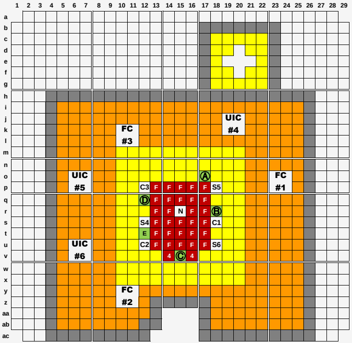
examples of pulses



mean pulses of detectors



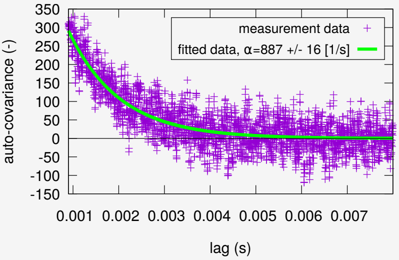
- Measurements were performed in September 2019 in a special configuration of the KUCA A core with a neutron source (N) in the middle and four fission chambers (A-D) at the periphery of the core.
- Two subcritical states and critical state at different power levels has been used.
- Low count rate cases served as reference for comparison with traditional pulse counting.



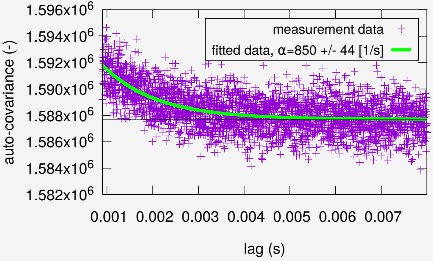
configuration	power [W]	detectors used
CR-1	5.46e-1	A
CR-2	1.84e-2	A, D
CR-3	1.84e-3	A, D

configuration	k_{eff}	detectors used	C1 position	C2 position	C3 position
SCR-1	0.9906	A, D	inserted	withdrawn	withdrawn
SCR-2	0.978	A, B, C, D	inserted	inserted	inserted

Rossi-α results

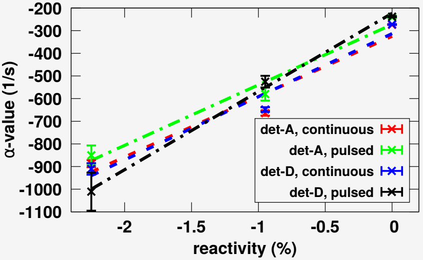


(a) Continuous signal.



(b) Time-stamped data.

- In the thermal system the prompt decay constant (α) separates well from the much higher time constant of the detector pulse.
- Good agreement observed in the low count rate SCR-2 case and with the estimated reactivity values.



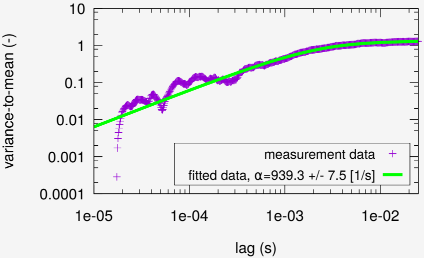
Rossi-α results

- In the higher count rate SCR-1 and CR-3 cases the continuous signal analysis tends to estimate higher values.
- Probably caused by dead time effects.

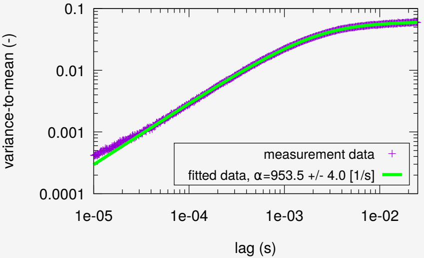
Configuration	Detector pair	$\alpha_{continuous}$ [1/s]	α_{pulsed} [1/s]
CR-3	A-A	274.4 ± 1.1	241.6 ± 2.1
	D-D	272.1 ± 1.1	238.2 ± 2.8
SCR-1	A-A	664 ± 11	579 ± 29
	D-D	648 ± 10	525 ± 26
SCR-2	A-A	887 ± 16	850 ± 44
	B-B	814 ± 20	777 ± 60
	C-C	961 ± 15	935 ± 36
	D-D	911 ± 25	1011 ± 84
	A-B	1000 ± 18	927 ± 42
	C-D	1010 ± 18	945 ± 39

Feynman-α results

- Variance-to-mean was impossible to evaluate due to a bias appearing in the curves
- Instead covariance-to-mean of detector pairs was evaluated, which shows good agreement with the pulse counting data.



(a) Continuous signal.

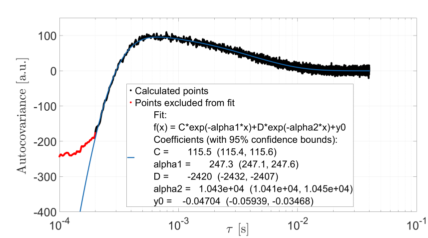


(b) Time-stamped data.

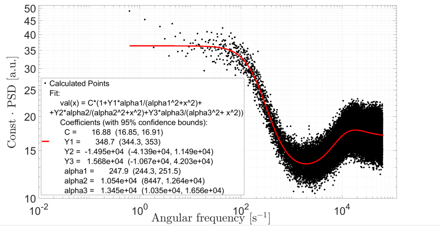
Configuration	Detector pair	$\alpha_{signal\ analysis}$ [1/s]	$\alpha_{pulse\ analysis}$ [1/s]
SCR-2	A-B	939.3 ± 7.5	953.5 ± 4.0
	C-D	926.3 ± 7.8	930.4 ± 4.0

Explanation of the bias in the KUCA measurements

- Anti-correlation (negative ACF) below 1 ms lag time
- Negative exponential term with $\alpha \approx 10000\ \mathrm{s}^{-1}$
- High-pass filter in the frequency domain (APSD)
- Originates from the frequency transfer of the measurement chain (pre-amplifier)
- Emphasizes the importance of the linearity of frequency transfer in continuous data acquisition



(a) ACF

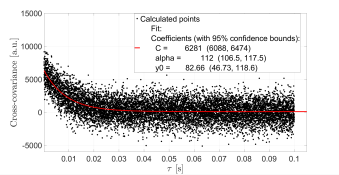
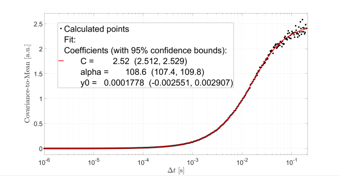
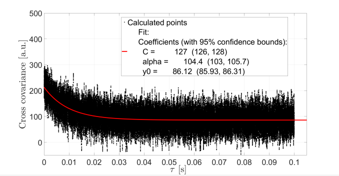
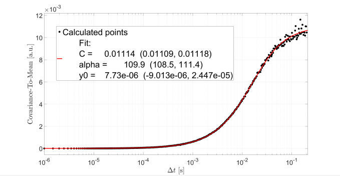
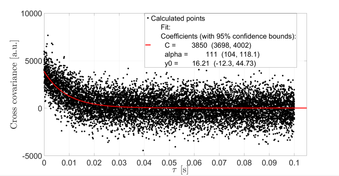
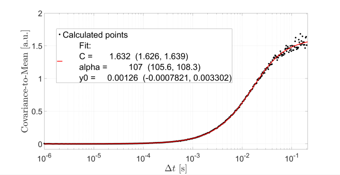


(b) APSD

Simulations

- **Reference signal**: time-stamped data of detections from a Monte Carlo point reactor model with one delayed neutron group
- **Continuous signal**: produced from the reference signal by adding average pulse shape and random amplitude variation
- **Pulsed signal**: time-stamped signal produced from the continuous signal with simulated data processing
- Goal: compare the methodologies in different conditions
  - source intensity (dead time)
  - α-value (influance of the detector pulse shape)

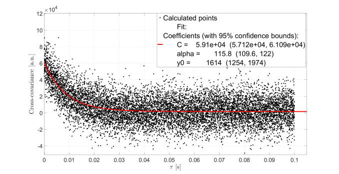
Simulation results with source of intensity of $5 \cdot 10^6$ s^{-1}

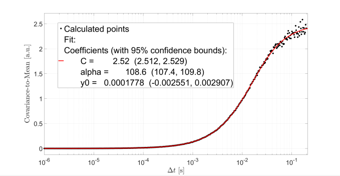
	CCF	Feynmann-α
reference		
continuous		
pulsed		

Simulation results with source of intensity of $5 \cdot 10^7$ s^{-1}

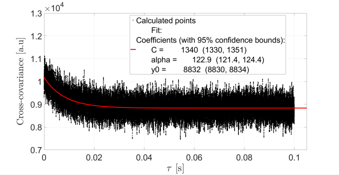
CCF | Feynmann-α

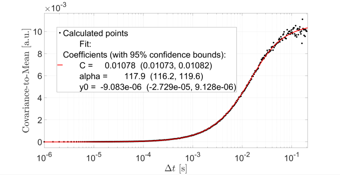
reference



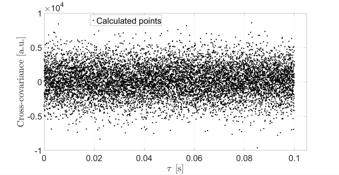


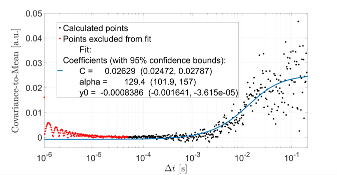
continuous





pulsed

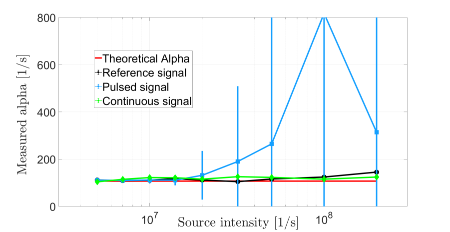




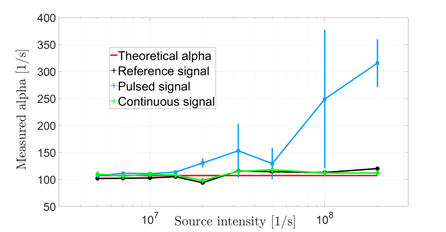
Simulation results for varying source intensity

- The method based on the continuous signal proved to be more tolerant to high count rates (i.e. dead time effect) than the pulse counting method.

CCF

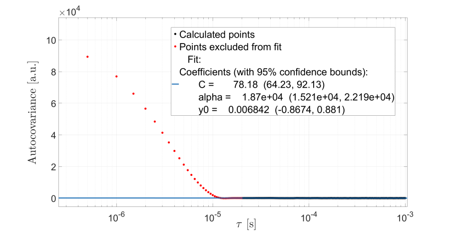


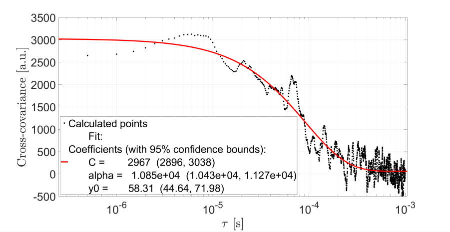
Feynmann-α

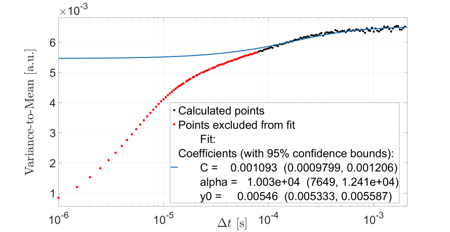


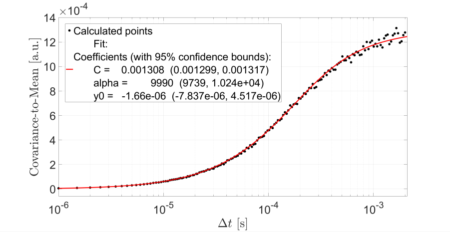
Simulation results for continuous signal with $\alpha = 10000\ \mathrm{s}^{-1}$

- Auto-covariance (ACF, Rossi-α) and variance-to-mean (Feynmann-α) methods are influenced by the large contribution from the pulse shape
- Cross-covariance (CCF) and covariance-to-mean (cross-Feynmann-α) diminishes the contribution from the pulse





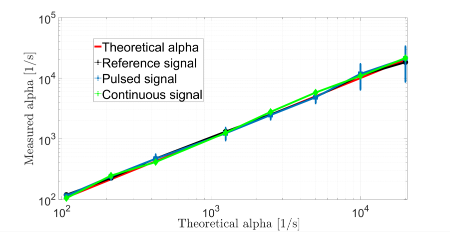




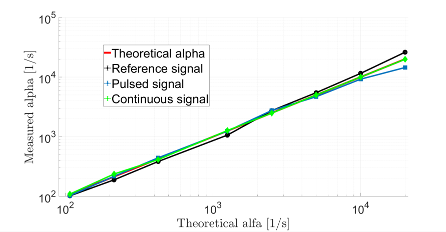
Simulation results for varying α-value

- With the cross-covariance and covariance-to-mean methods the α-values can be obtained from the continuous signal with high accuracy.
- Pulse counting provides high α-values with higher uncertainty due to the dead time effect

CCF



Feynmann-α



Deconvolution of the detector pulse shape from the signal

- The continuous signal is described as average pulse shapes $f(t)$ with a random amplitudes a_i at detection times t_i:

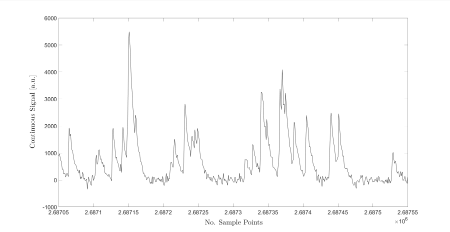
$$y(t) = \sum_{i=1}^{N} a_i f(t - t_i)$$

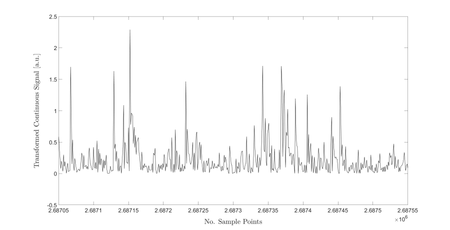
- This can be written as the convolution of $a_i f(t)$ and Dirac delta functions at t_i δ_{t_i}:

$$y(t) = \int_{-\infty}^{\infty} f(x) \sum_{i=1}^{N} a_i \delta(t - t_i - x) \mathrm{d}x$$

- In the Fourier-space $f(t)$ can be deconvolved from the signal, and the Dirac delta pulses remain:

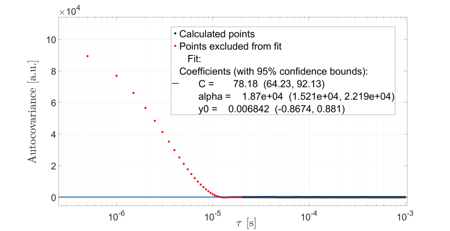
$$y_{\text{pulsed}}(t) = \mathcal{F}^{-1}\left\{\frac{\mathcal{F}\{y(t)\}}{\mathcal{F}\{f(x)\}}\right\} = \sum_{i=1}^{N} a_i \delta(t - t_i)$$

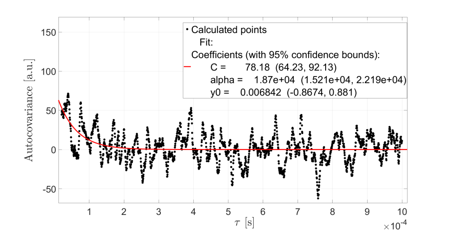




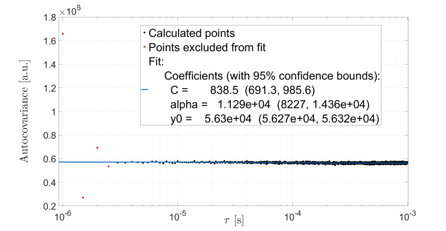
Rossi-α of the continuous and deconvolved signal with $\alpha = 10000$ s^{-1}

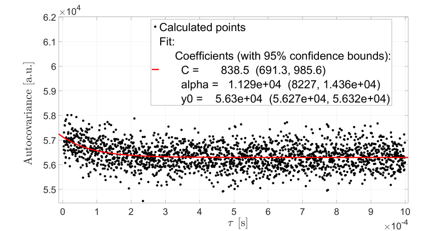
original





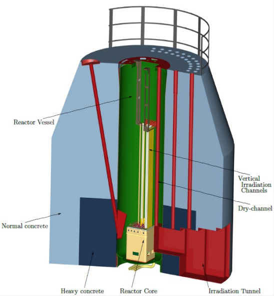
deconvolved

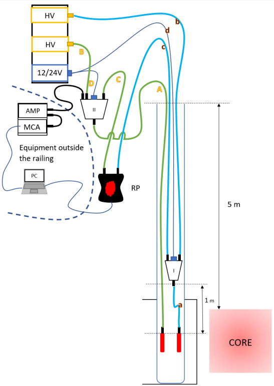




Measurement set-up at the BME Training Reactor

- 2 pieces of KNT-31 fission chambers in the dry channel next to the core
- 1 slightly sub-critical and 3 critical configurations at 0.01-10 W power
- 1 preamplifier close to the detector to reduce electronic noise

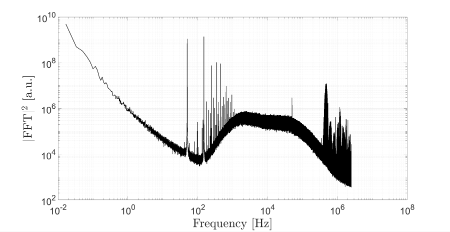




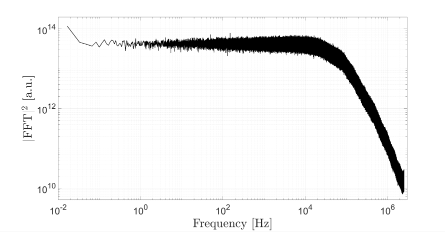
Name	ρ [¢]	A. rod [mm]	M. rod [mm]	Power [W]	Count rate [s^{-1}]
SCR	-10	502	360	$\sim$ 0.01	$\sim$ 500
CR1	0	505	385	$\sim$ 0.1	$\sim$ 5000
CR2	0	507	385	$\sim$ 1	$\sim$ 50000
CR3	0	509	385	$\sim$ 10	$\sim$ 500000

Problems with electronic noise

- Low and discrete frequency noise disturbs the measurements
- The measurements chain shows non-linear behaviour in the frequency domain
- Compressed recording filters the noise but is limited by the count rate

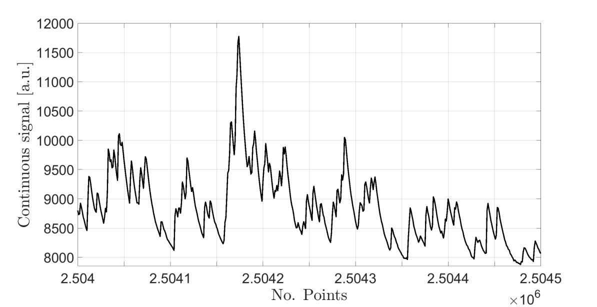


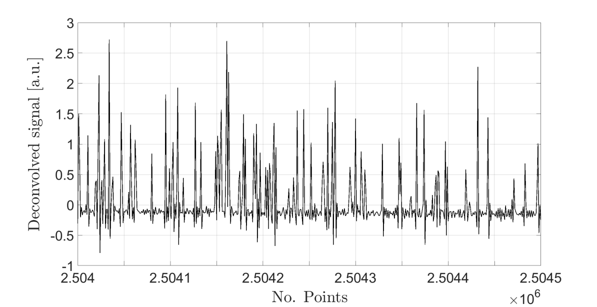
compressed



Deconvolution in measurement data

- Deconvolution of the pulse shape performs well even with the highest power measurement
- Evaluation was limited by the file size

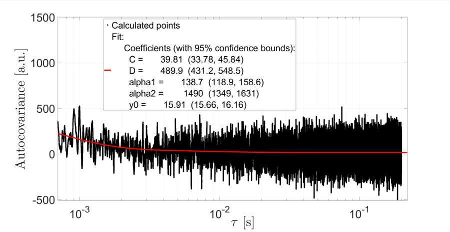


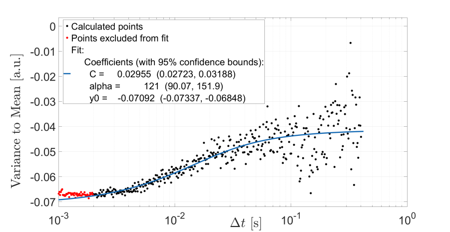


Measurement results

- The compressed continuous signal and the deconvolved pulsed signal of the CR1 configuration return the expected $\alpha \approx 100\ \mathrm{s}^{-1}$ value the best
- In some cases another component with $\alpha \approx 1000\ \mathrm{s}^{-1}$ appears

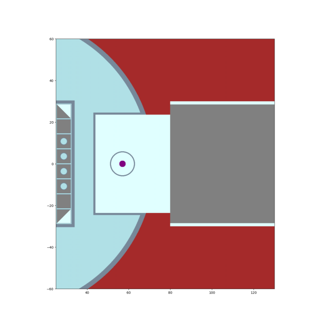
	CR1 #1	CR1 #2	CR2 #1	CR2 #2	CR3
Uncompr. ACF	Compressed signal used		**1508±100**	**1260±52**	**1314±57**
Compr. ACF	**1546±73** 51.8±16	**1490±141** **138.7±20**	Compression not feasible due to high detection rate		
Pulsed ACF	480±306	254.7±196	Unsuccessful evaluation due to too many lost counts		
Pulsed VTM	219±90	274.3±260			
Deconv. ACF	**1177±249**	Unsuccessful	174.8±188	315.4±281	file size limited
Deconv. VTM	839.1±68	**121±31**	163.1±41	345.3±115	

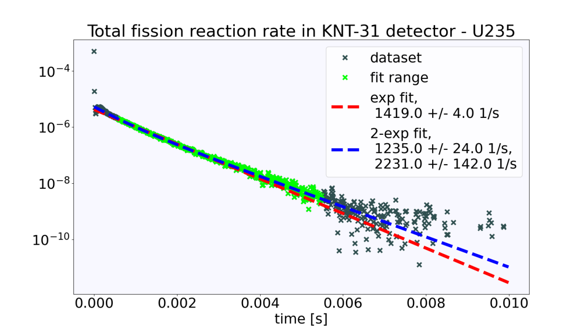




Effect of secondary neutron emission from fission chambers

- Monte Carlo (OpenMC) simulation of the surroundings of the dry channel shows that fission neutrons emitted in the fission chamber have a considerable probability to return and induce fission in the detector
- Time distribution of such secondary fissions has a decay constant of $\sim 1200 - 1400$ s^{-1}





Conclusions

- Methodology of neutron noise evaluation for continuous detectors signals has been developed based on the stochastic model of the signal.
- Simulations showed that the new method is more tolerant to high count rates than the traditional pulse counting methods.
- Successful measurements were performed to demonstrate the applicability of neutron noise measurements based on continuous detectors signals with the help of a data acquisition system developed for this purpose.
- In reactor noise analysis preliminary results show good agreement for lower count rate case with Rossi-α and covariance-to-mean methods. Further analysis to find reasons for discrepancies are in hand.
- New methodology has been developed to deconvolute the contribution of the pulse shape from the continuous signals.
- Electronic noise and non-linearities in the data acquisition system poses challenges for the continuous signal based measurements.
- A high-end data acquisition system has been purchased to overcome the limitation of the present one and further develop the new methodologies toward practical applications.
- Continuation of the measurement campaign at the BME Training Reactor is planned.

Thank you for your kind attention!