Feynman-alpha and covariance-to-mean methods for reactivity estimation in a SUR100 research reactor

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Introduction

- Subcritical measurements were performed in the RA-4 teaching reactor (SUR100)
- Application of α-Feynman and covariance-to-mean for the estimation of kinetic parameters: reactivity, prompt decay constant and reactor power
- Improvement in the implementation of the methods in order to reduce correlation in data
- Reactivity of some configurations were compared with another method based on the inverse kinetic equations
- These measurements will serve as a reference value to validate simulations of reactor noise experiments with Monte Carlo neutron code (MCNP6.2)

RA-4 reactor

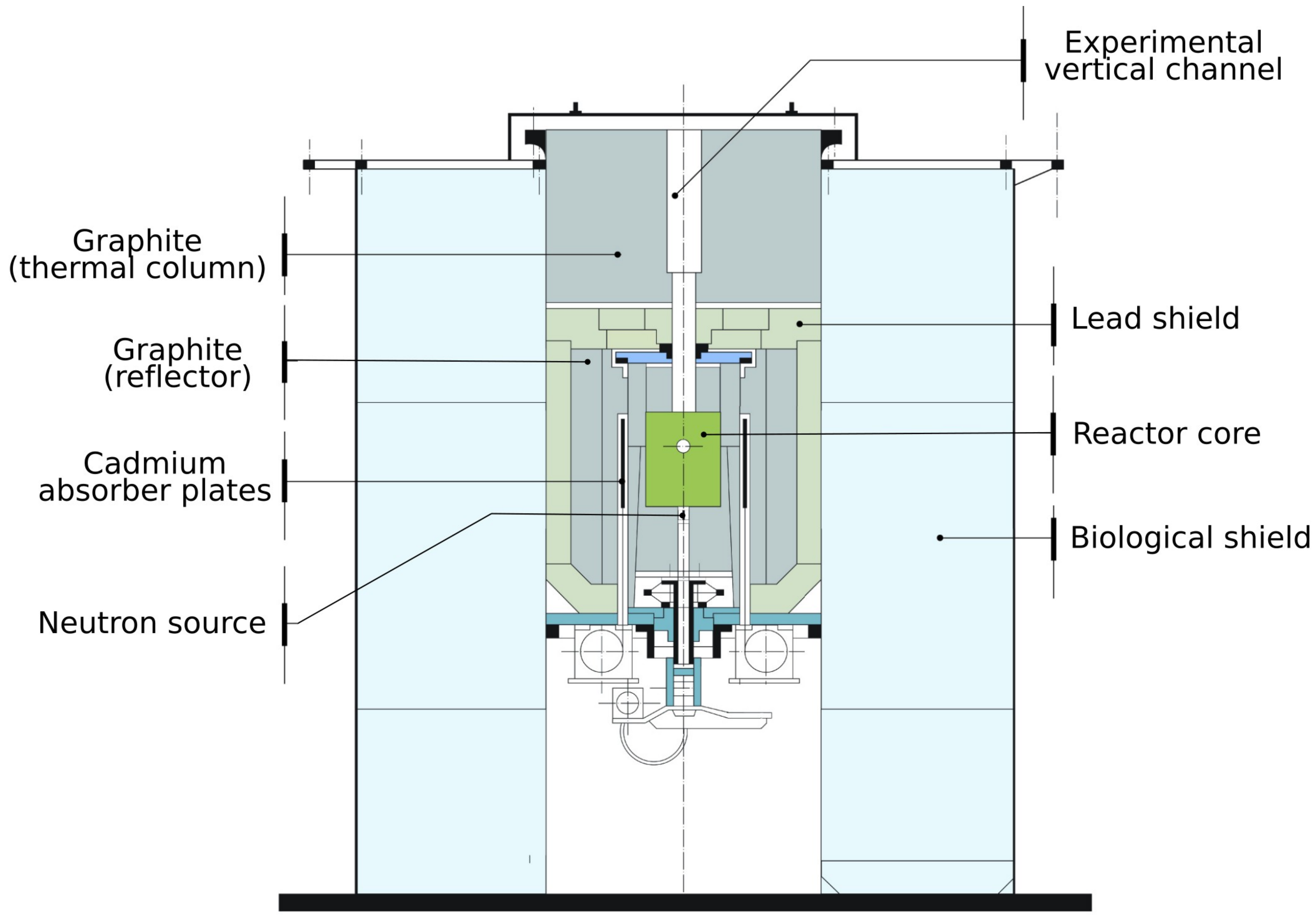
- The RA-4 (Argentinean Reactor 4) is a Siemens-Unterrichts-Reaktor of nominal power of 100 mW (SUR100)
- It is now licensed to operate up to a maximum continuos power of 1 W

- It is located in the main campus of the National University of Rosario (UNR), Santa Fe Province.

- The reactor is owned by the CNEA and the UNR is the primary responsible of its operation

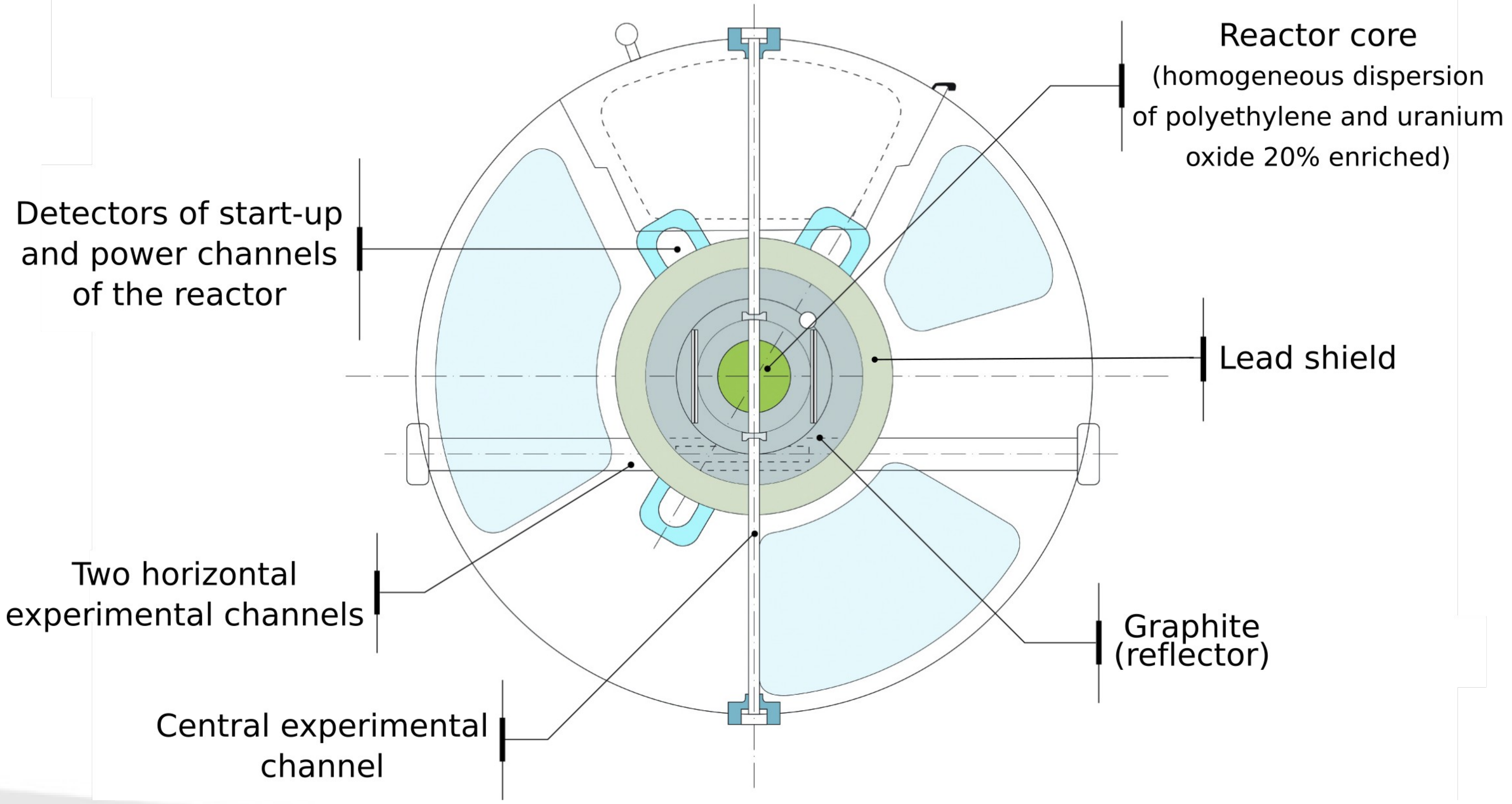
- Its main purpose is educations and training (students, NPP operators, technicians)
- Research activities from different fields: physics, electronics, control systems, material science, etc.

RA-4 reactor



- Solid core with cylindrical shape (24 cm diameter and 26 cm height) divided in two separable sections
- The lower section is movable up to 4.7 cm from the upper section (shutdown condition)
- The fuel is a homogeneous dispersion of U_3O_8 (19.86% enriched) and polyethylene
- Average thermal flux: 3.4 10^7 n/(cm^2 s)
- Two cadmium absorber plates moving vertically in the reflector
- Cylindrical graphite reflector with a thickness of 20 cm

- One central experimental channel crossing the core
- Two horizontal channels (tangential) and one vertical channel coaxial with the core (thermal column)
- One start-up channel (BF_3) and two power range channel (CIC)



α-Feynman method

- The method was developed by Richard Feynamn in the 40's during the Manhattan Project
- Allows the determination of the prompt neutron constant (α) and fission rates at subcritical stationary states
- It is based on the statistical analysis of neutron counts in a certain time interval τ
- Due to the presence of a multiplying medium, the variance is greater than would be in a Poisson process:

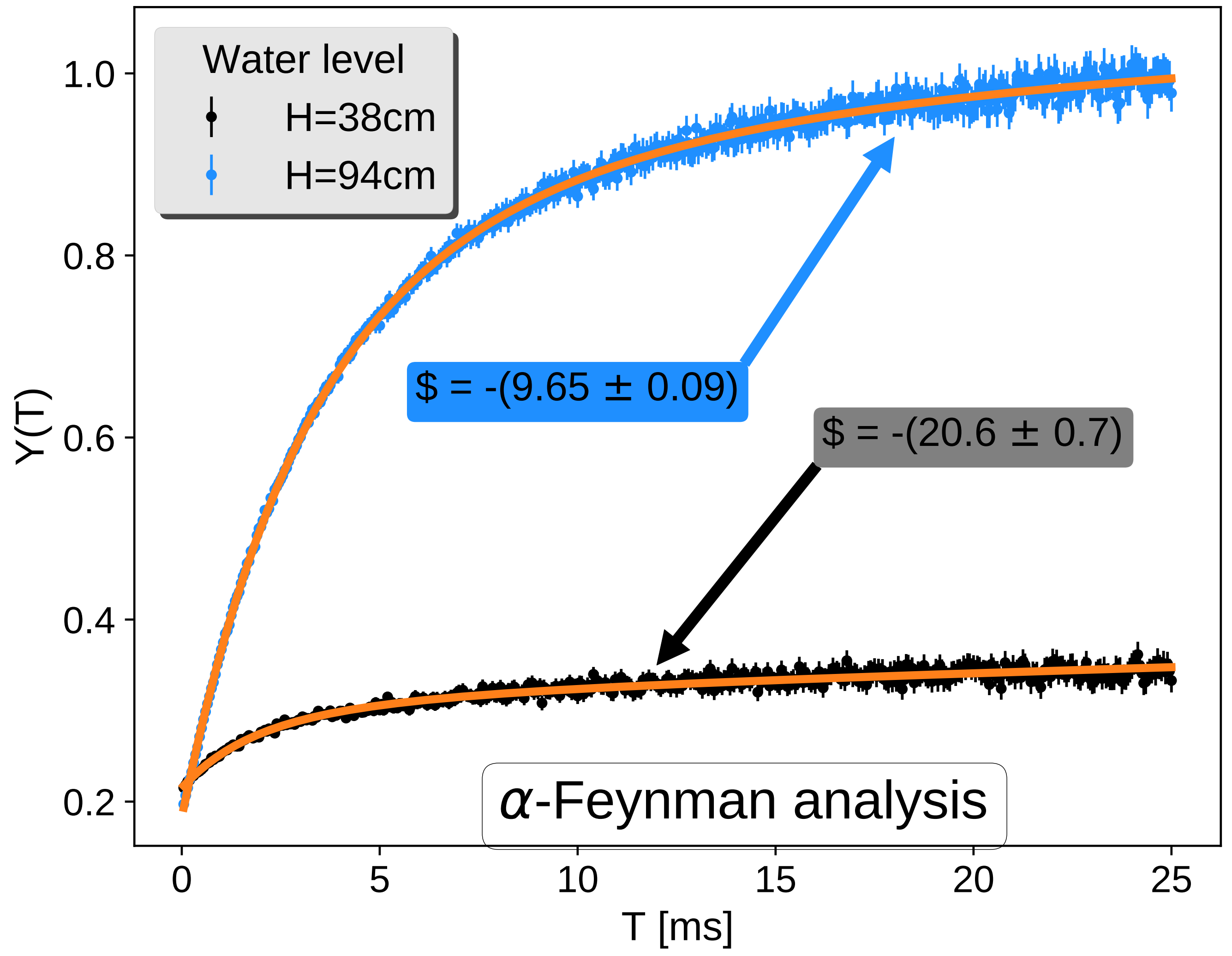
$$Y(\tau)=\frac{\langle N^2\rangle-\langle N\rangle^2}{\langle N\rangle}-1=\frac{\varepsilon D}{\alpha^2\Lambda^2}\left(1-\frac{1-e^{-\alpha\tau}}{\alpha\tau}\right)-2Rd$$

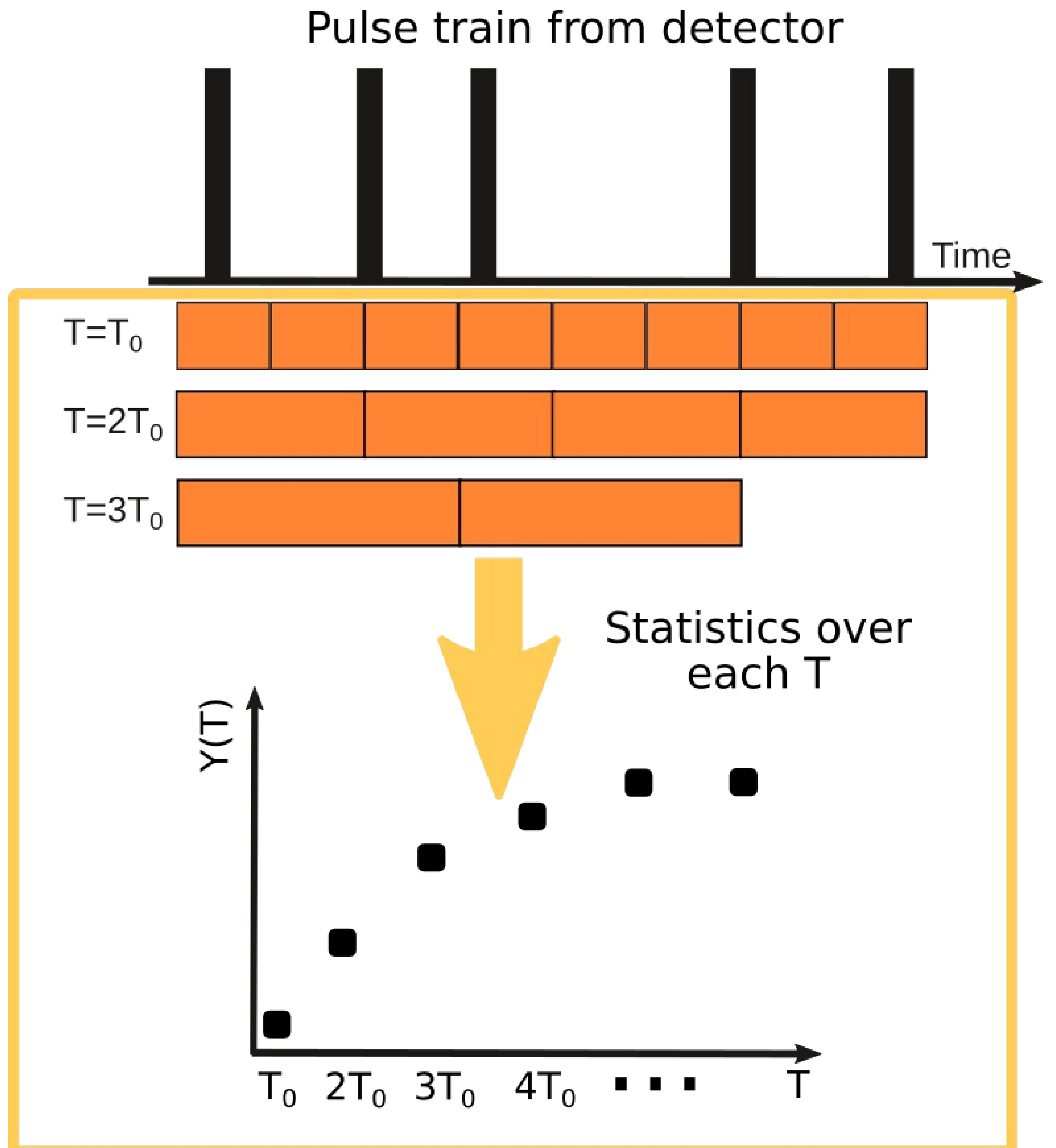
- If instead of the variance, the covariance from two detectors is computed, then we obtain the covariance-to-mean ratio:

$$\text{Cov-to-mean}(\tau)=\frac{\langle N_1N_2\rangle-\langle N_1\rangle\langle N_2\rangle}{\sqrt{\langle N_1\rangle\langle N_2\rangle}}=\frac{\sqrt{\varepsilon_1\varepsilon_2}D}{\alpha^2\Lambda^2}\left(1-\frac{1-e^{-\alpha\tau}}{\alpha\tau}\right)$$

- In order to reduce the measurement time, the α-Feynman method is usually implemented with the bunching technique:

  - Acquisition is made in a fixed time windows T_o
  - The rest of the τ are obtained bunching the original T_o interval

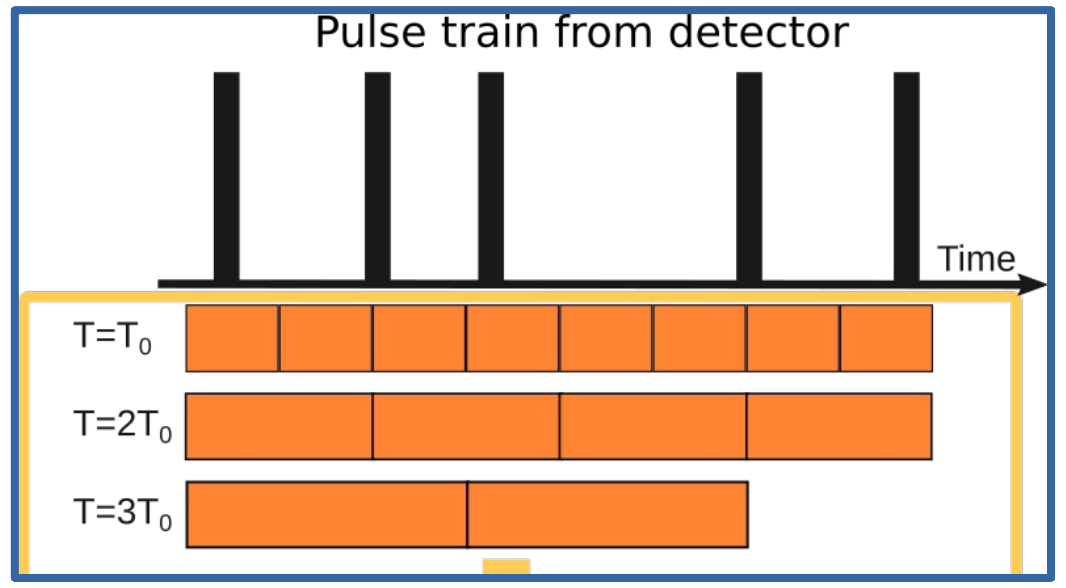


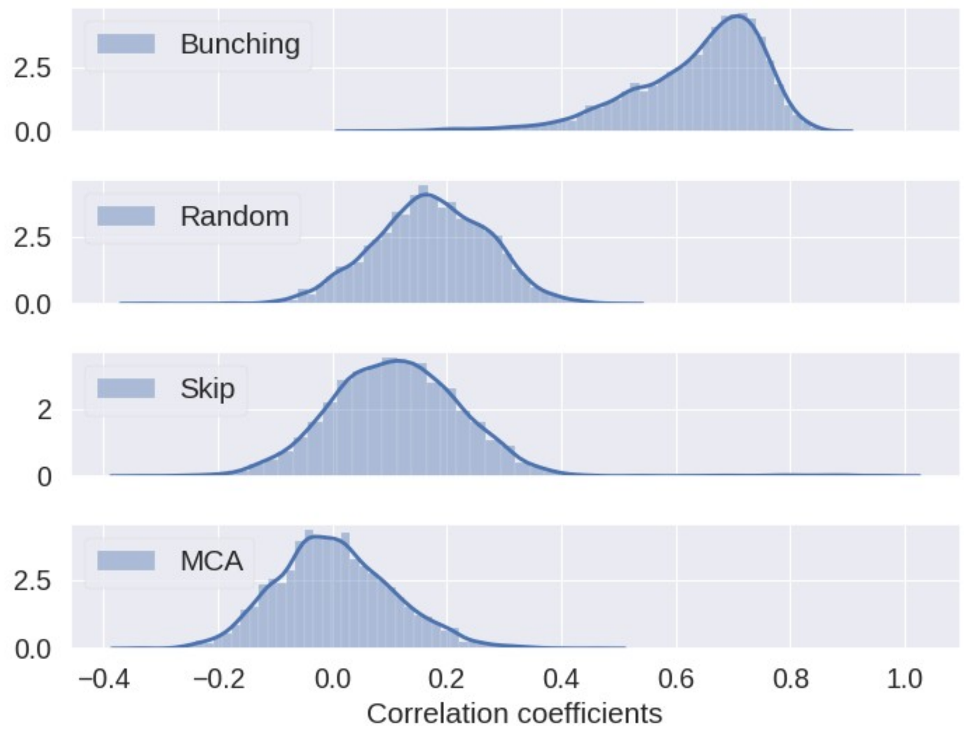


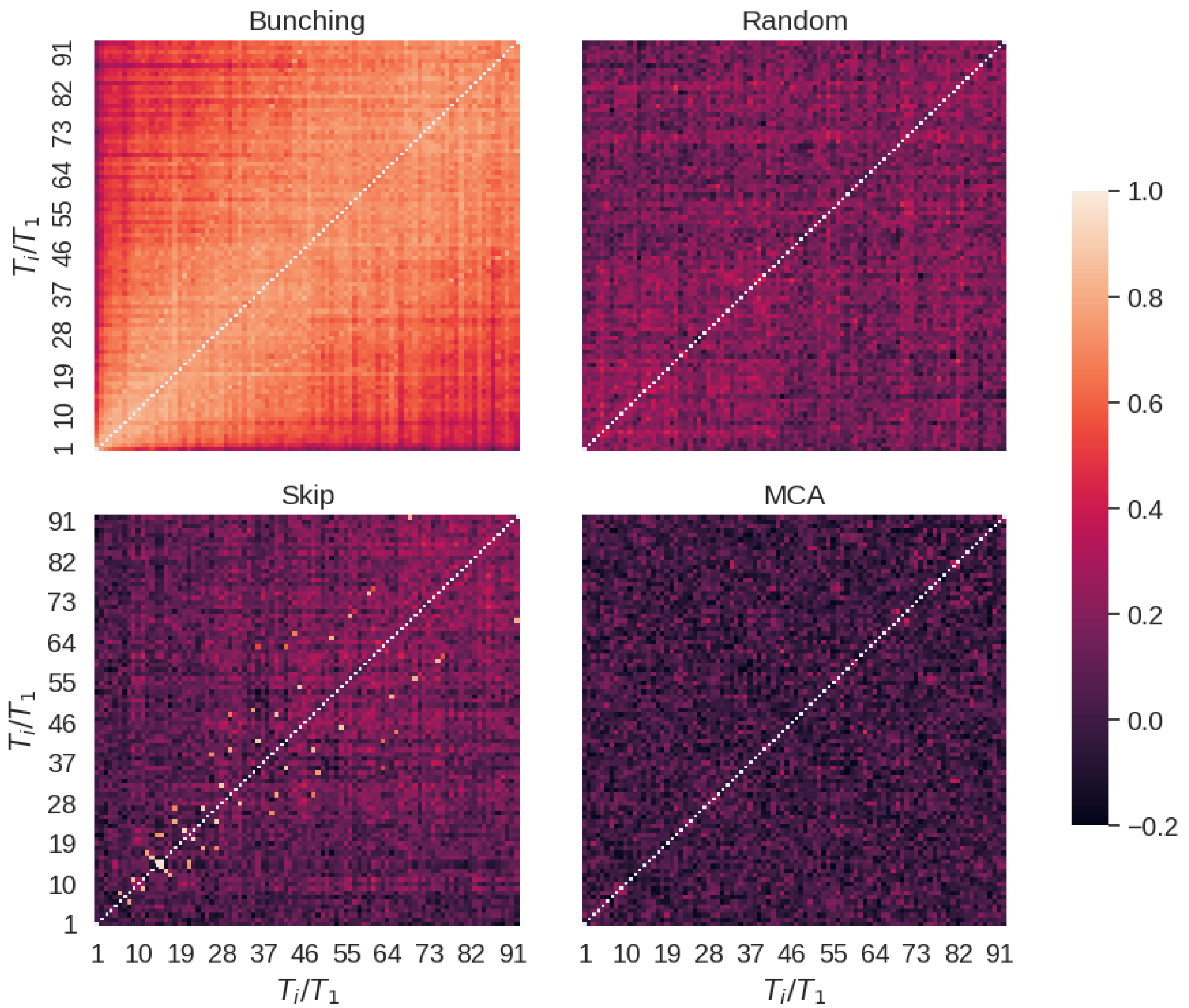
α-Feynman method with bunching technique

Reducing the data correlation

- The bunching technique produces highly correlated data that in turn, produce an overestimation of the uncertainties at each point of the α-Feynman curve

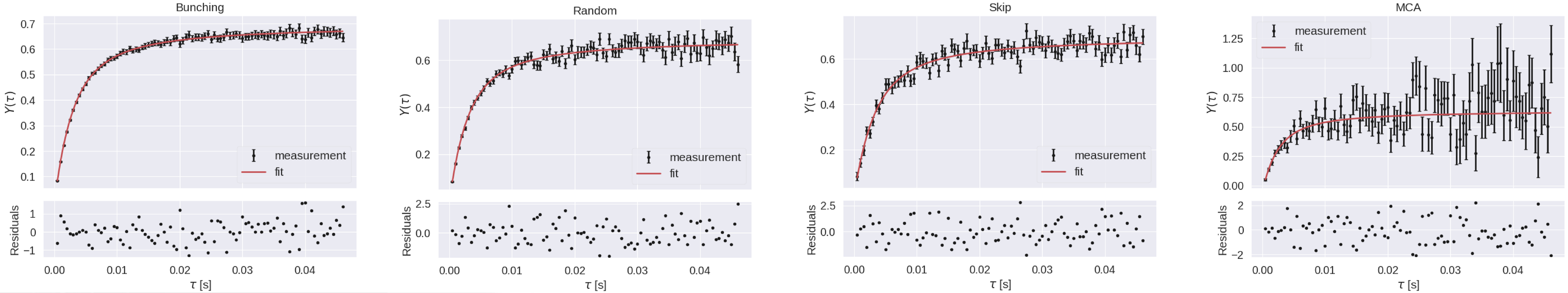






- The **random sampling** takes a random numbers of intervals at each τ (25 %). It was found to be a good trade off between correlation and uncertainties of the curve

α-Feynman method using some variations from the bunching technique



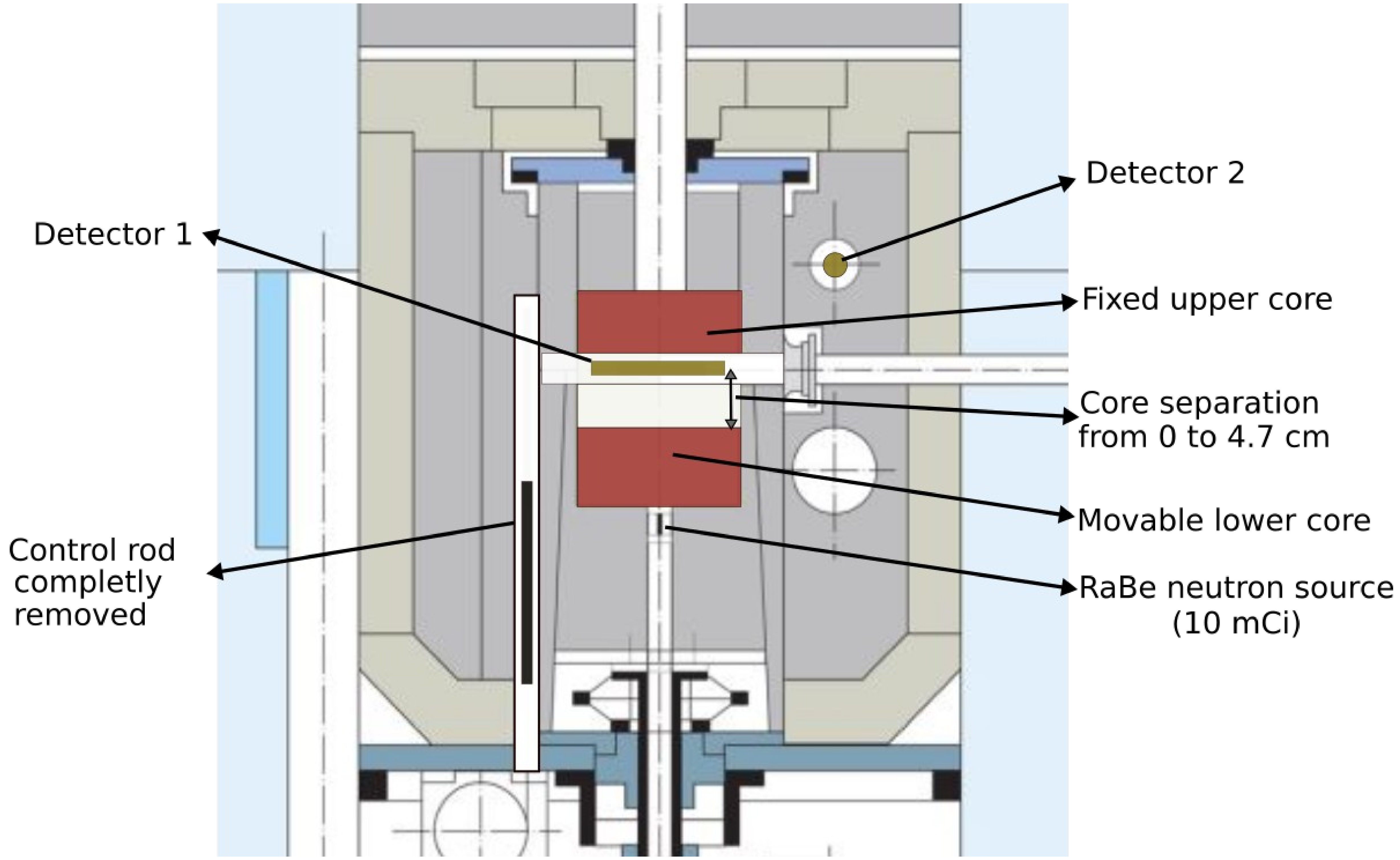
α = 572 (5) 1/s
X^2 / dof = 0.366

α = 575 (10) 1/s
X^2 / dof = 0.890

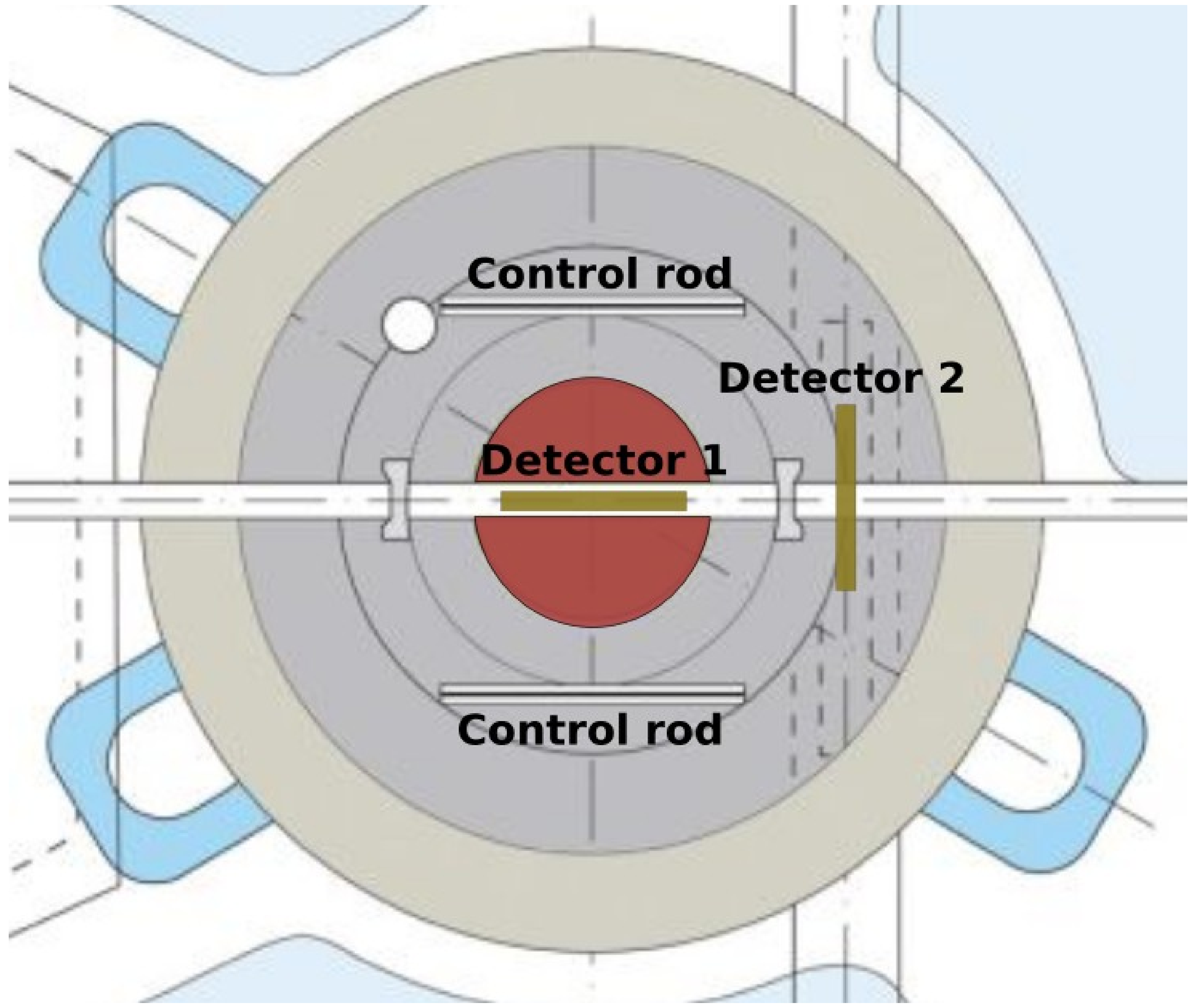
α = 508 (40) 1/s
X^2 / dof = 1.114

α = 672 (90) 1/s
X^2 / dof = 1.027

Experiment description



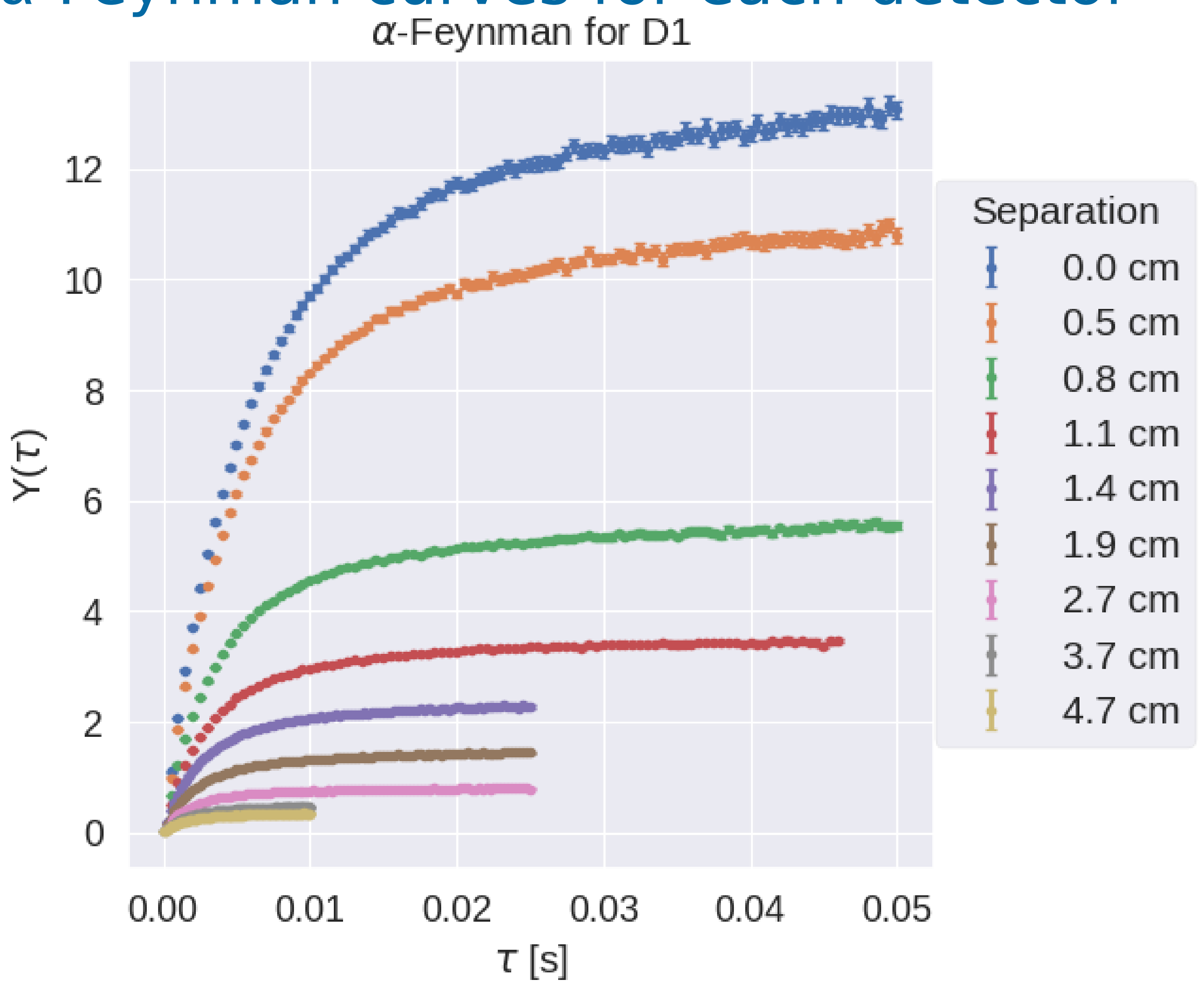
- Two ^{3}He neutron detectors (with sensitivity of 6 cps/nv), one located in the core region and the other in the reflector
- Reactor neutron source of Ra-Be with activity of 10 mCi (~1.5 10^5 n/s)
- The two control plates remained fully extracted during the measurements
- Measurements were performed at nine core separation distances
- The reactor could not achieve criticality with this detectors configuration

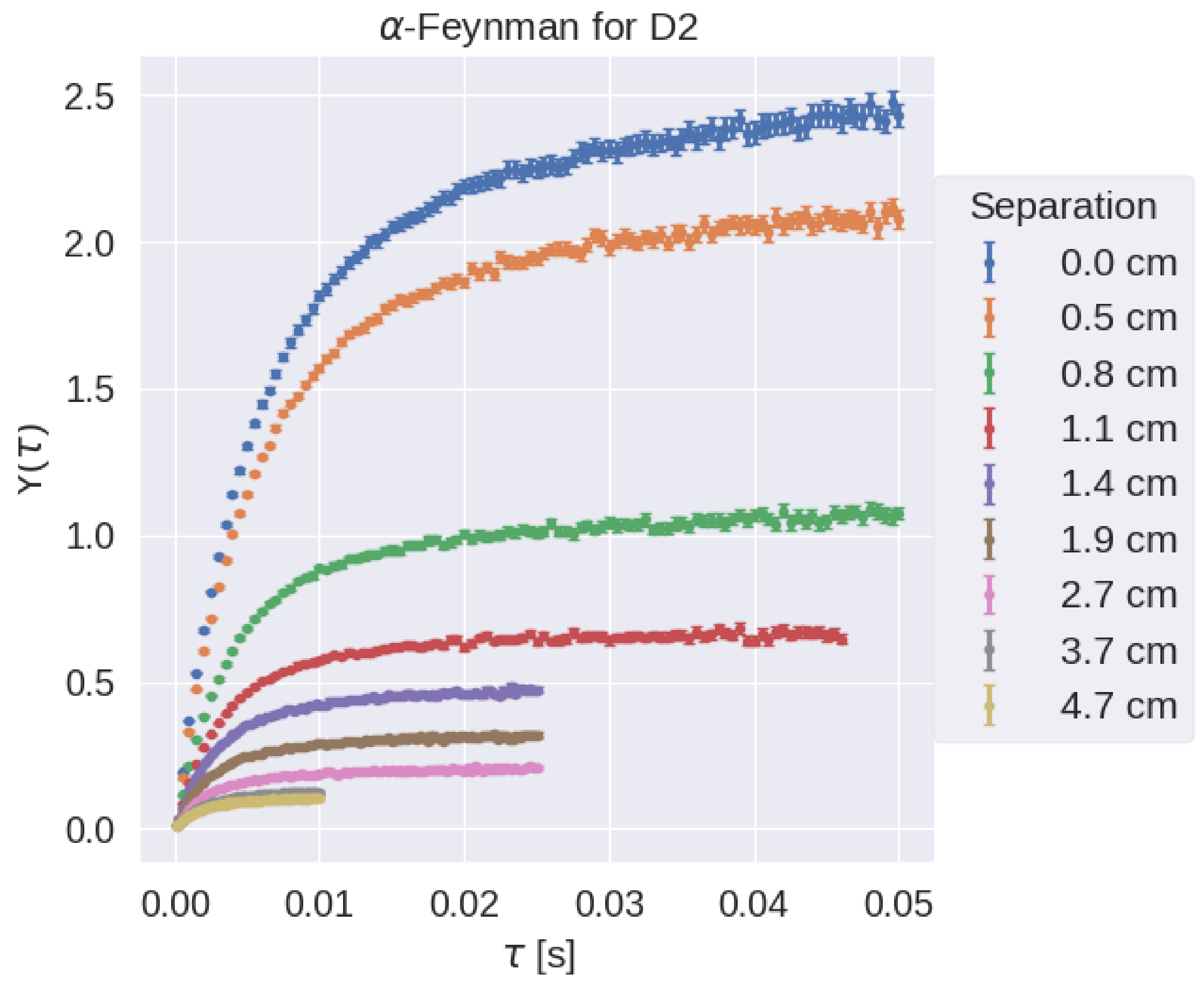


- Each measurement consisted in registering detected pulses in time windows of 50 μs
- The measurement time at each configuration took approximately 30 minutes
- Due to high count rates, listmode acquisition was not possible (α-Rossi method was excluded)

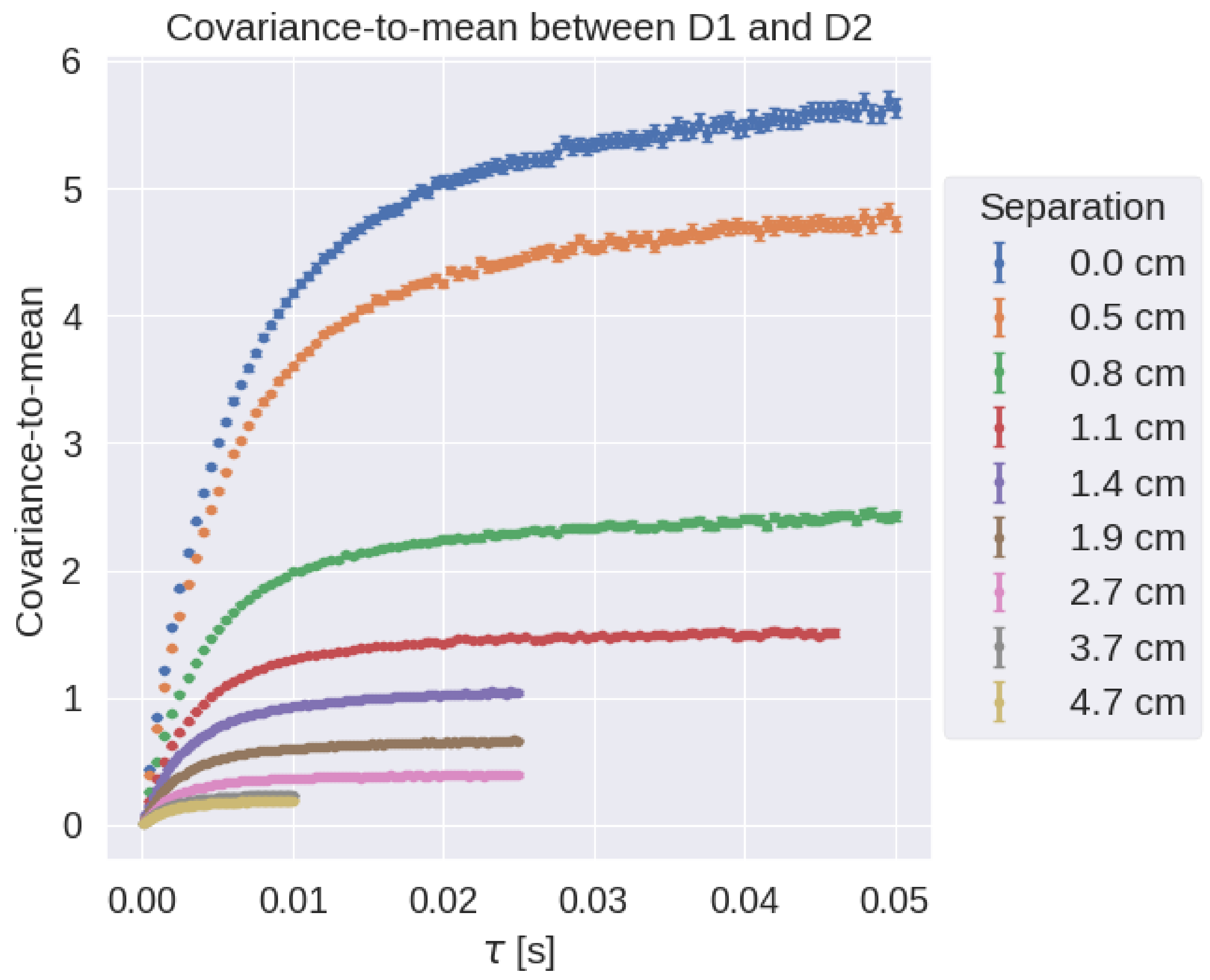
Results

- α-Feynman curves for each detector





- Covariance-to-mean curves



No significant improvement as the dead time (~ 1μs) is low compared to the low count rates and high detector efficiencies

Summary of the main features of each level

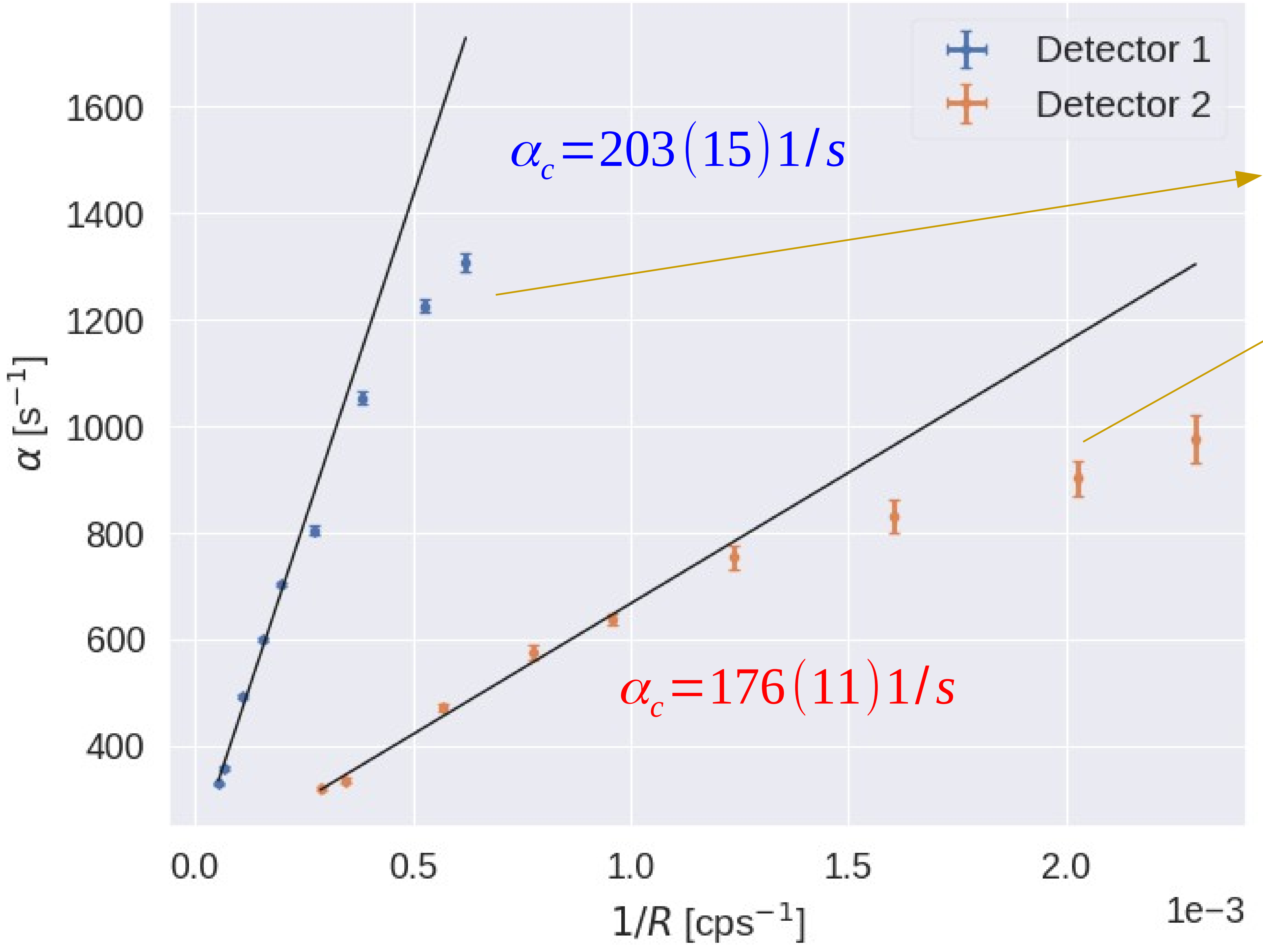
d [cm]	R_1 [kcps]	R_2 [kcps]	α [1/s]	p [mW]
0.0	18.5	3.5	322(3)	0.129(3)
0.5	15.4	2.9	336(4)	0.115(3)
0.8	9.1	1.8	472(7)	0.070(2)
1.1	6.4	1.3	575(14)	0.055(3)
1.4	5.0	1.0	637(12)	0.051(2)
1.9	3.7	0.81	753(22)	0.043(2)
2.7	2.6	0.62	831(30)	0.042(3)
3.7	1.9	0.49	902(32)	0.044(3)
4.7	1.6	0.44	975(44)	0.040(3)

Reactivity estimation

- It is possible to extrapolate the data to obtain the prompt neutron decay constant at critical state α_c

$$\alpha = \frac{\tilde{Q}}{R} + \alpha_c$$

$\tilde{Q}$ is the effective neutron source strength (detector dependant)

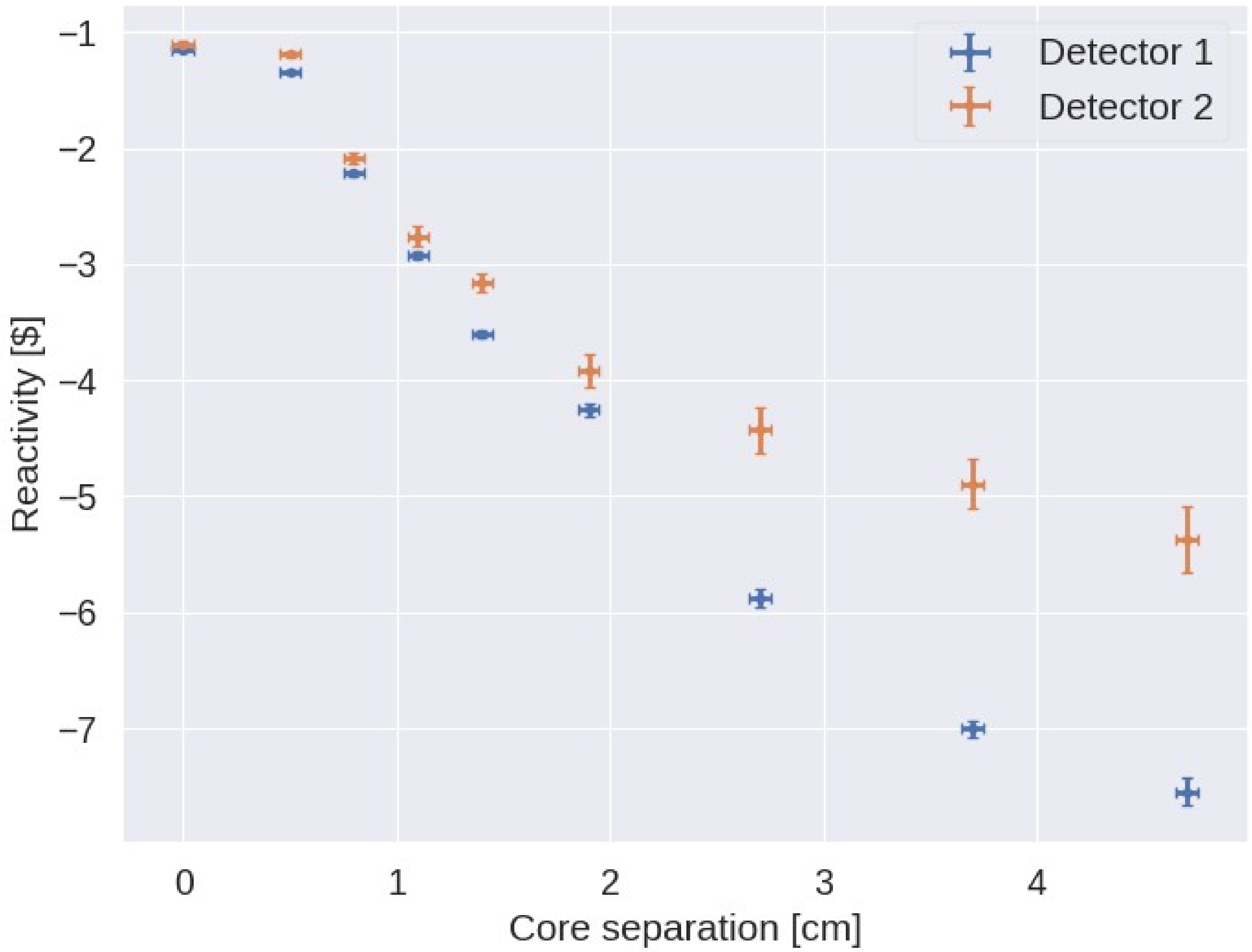


For deeply subcritical states, the point reactor model does not hold

Measured at critical state with a CIC (in the reflector) using spectral analysis:
α_c = 153 (2) 1/s

- The reactivity of each state can be calculated using the relation:

$$\$ = 1 - \frac{\alpha}{\alpha_c}$$

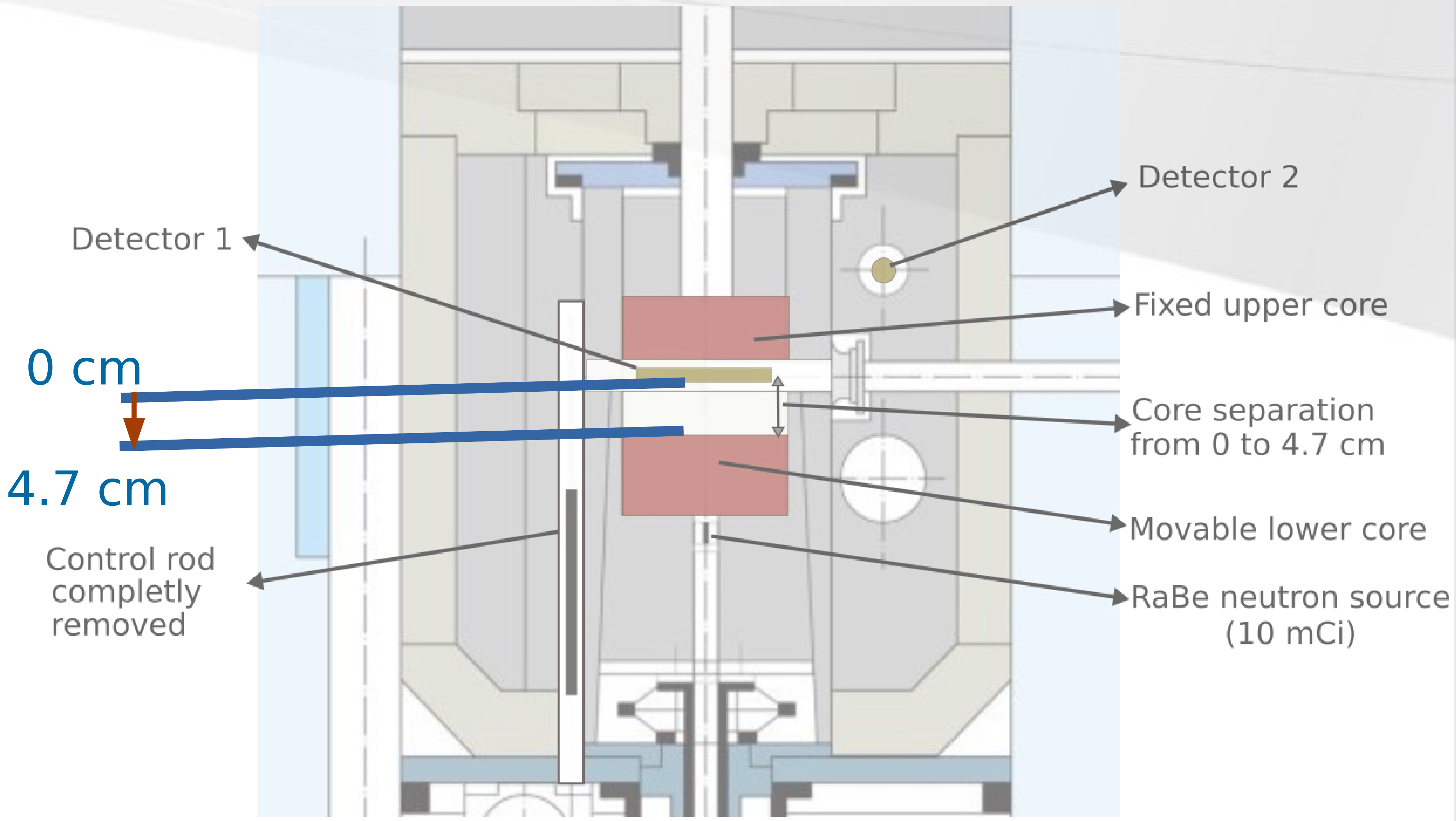


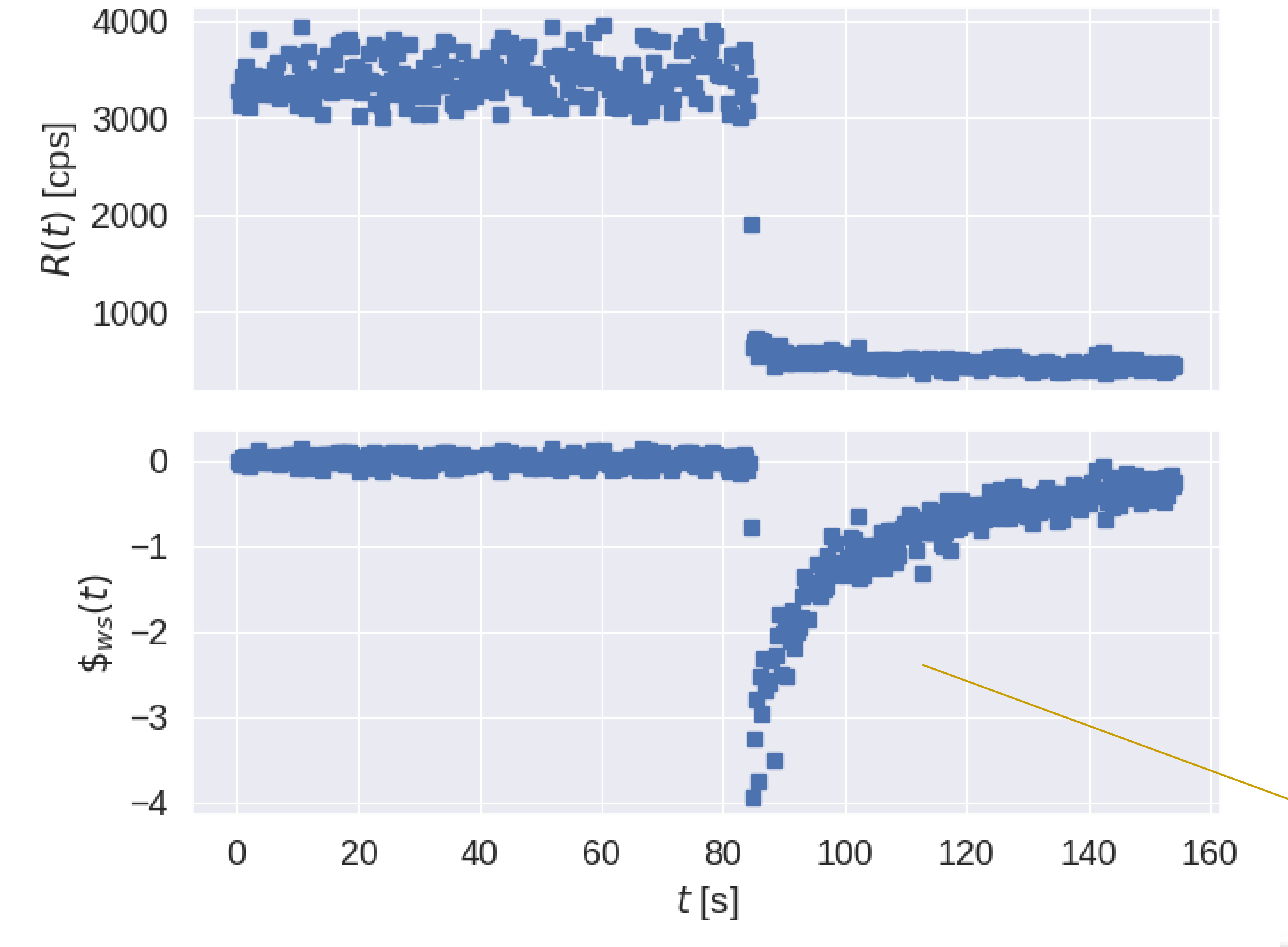
Reactivity worth of the lower part of the core:

$ = 6.4(1) Detector 1
$ = 4.3(3) Detector 2
$ = 6.83 Reference value

Reactivity worth of the lower core

- For comparison purposes, the reactivity worth of the lower part of the core was estimated with an alternative method
- The reactor has a shut-down mechanism in which the lower core section fall by gravity in less than 100 ms (core-drop)
- As the core-drop is done between two subcritical levels, the Least Squares Inverse Kinetic Method was applied





- It allows determination of the strength of the neutron source, allowing the implementation of a subcritical reactimeter:

$$\$(t)=1+\frac{\Lambda^*}{R(t)}\left[\frac{dR(t)}{dt}-\sum_{i=1}^{6}\lambda_i\tilde{C}_i(t)-\tilde{Q}\right]$$

Reactimeter without the source term

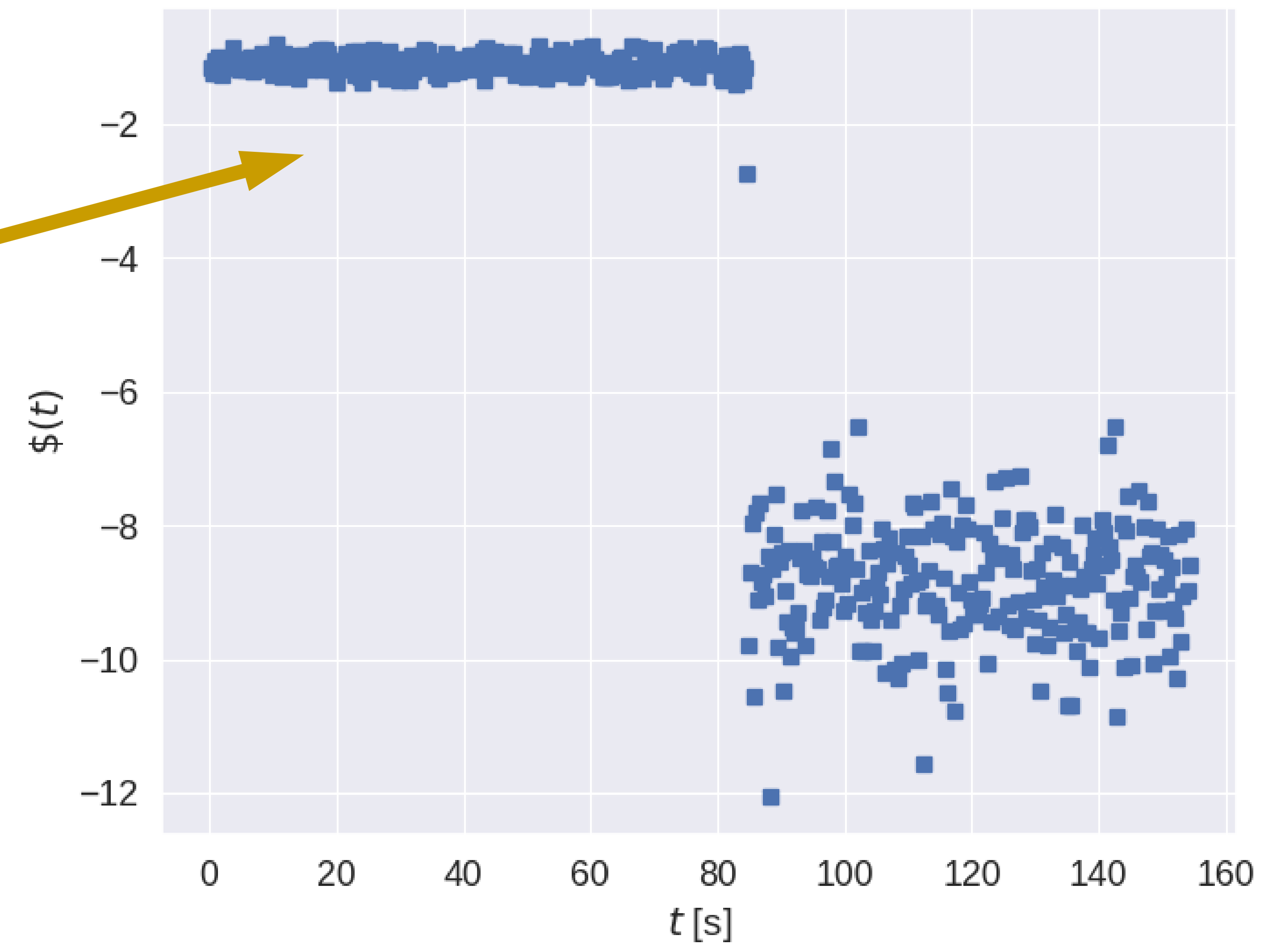
Least Squares Inverse Kinetic Method

- Using a clever combination of variables during the transient of the core-drop, a linearized equation can be found:

$$R(t)=\frac{\Lambda^*}{\$_f-1}D(t)-\frac{\Lambda^*\widetilde{Q}}{\$_f-1}$$

$$D(t)=\frac{dR(t)}{dt}-\sum_{i=1}^{6}\lambda_i\widetilde{C}_i(t)$$

Source term is found



Reactimeter with the source term

- Comparison for reactivity estimations using α-Feynman and LSIKM (initial separation of 0 cm and final separation of 4.7 cm)

	Detector 1		Detector 2		Reference
	α-Feynman	LSIKM	α-Feynman	LSIKM	
$\$_i$	-1.15(2)	-1.1(1)	-1.10(2)	-1.1(1)	-
$\$_f$	-7.5(1)	-8.8(8)	-5.4(3)	-13.6(8)	-
$\Delta\$$	6.4(1)	7.7(8)	4.3(3)	12.5	6.83

Conclusions

- Successful implementation of neutron noise techniques in the RA-4 reactor (for the first time)
- Reduction of the data correlation of the bunching technique for a better assessment of the uncertainties in the estimated parameters
- Further analysis Is needed in order to fully explain the different behaviour of detectors placed in the core and reflector regions (two regions models)
- The result of this measurement campaign could be used for validating simulations of neutron noise experiments

Thank you very much for your attention

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