Experimental validation of reactivity monitoring techniques for power ads systems to incinerate radioactive wastes

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Introduction

- ADS (Subcritical Accelerator Driven Systems) are the main candidates for dedicated intensive transmutation of actinides.
- Reactivity monitoring is one of the critical topics for ADS feasibility.
- Industrial ADS will probably not be allowed to reach criticality at any time by design and regulation.
- A reactivity monitoring system has to be designed without use to the critical reference.
- A solution has been proposed in a series of EURATOM projects including MUSE, PDS-XADS and EUROTRANS by combination of a chain of several techniques, most of then based on kinetic behavior of subcritical systems.

Introduction

Chain of several techniques for the determination of reactivity

- During normal power operation
  - Current-to-power. Is based on the proportionality between reactivity and the ratio charged particle beam current to power.
  - Beam trips technique. Is based on the dependency of the neutron flux evolution with reactivity after the fast interruption of the charged particle beam (external neutron source).
  - Noise techniques. Are based on the statistical properties of the fission chains.
- During loading and start-up
  - Pulsed Neutron Source (PNS) technique. Is based on the kinetic response of the neutron flux in a series of periodical neutron pulses.
  - Noise techniques. With different sources.

Introduction

Current-to-flux	Beam trips (S.Jerk/Shape) + Noise techniques	PNS (Area/Decay shape) Noise techniques
• Used at full power • continuously	• Used at full power • Not conti. But frequently	• Used at zero or v. low power • When possible
• High sensitivity in relative changes • Sensitive to systematics • Not for the absolute value of reactivity	• Induced beam trips • Provide the absolute value of reactivity • Used to calibrate Current-to-flux	• Special pulsed proton/neutron source • Provide the absolute value of reactivity • Higher control of systematics

Introduction

- After corrections PNS can be used as a reference for the reactivity monitoring techniques based on Beam trips and Current-to-flux.
- The interpretation method for beam trips and current-to-flux is equivalent to the interpretation of PNS. The required corrections for local effects are better tested in PNS.
- In the frame of IP-EUROTRANS, a series of experiments have been performed in YALINA-Booster to investigate Beam trips and Current-to-flux reactivity monitoring techniques.
- The YALINA-Booster facility at JIPNR (Belarus) with a 14 MeV D-T source, both in pulsed or continuous mode, with a zero power coupled fast-thermal reactor, has provided unique conditions to test the full chain of reactivity monitoring systems.

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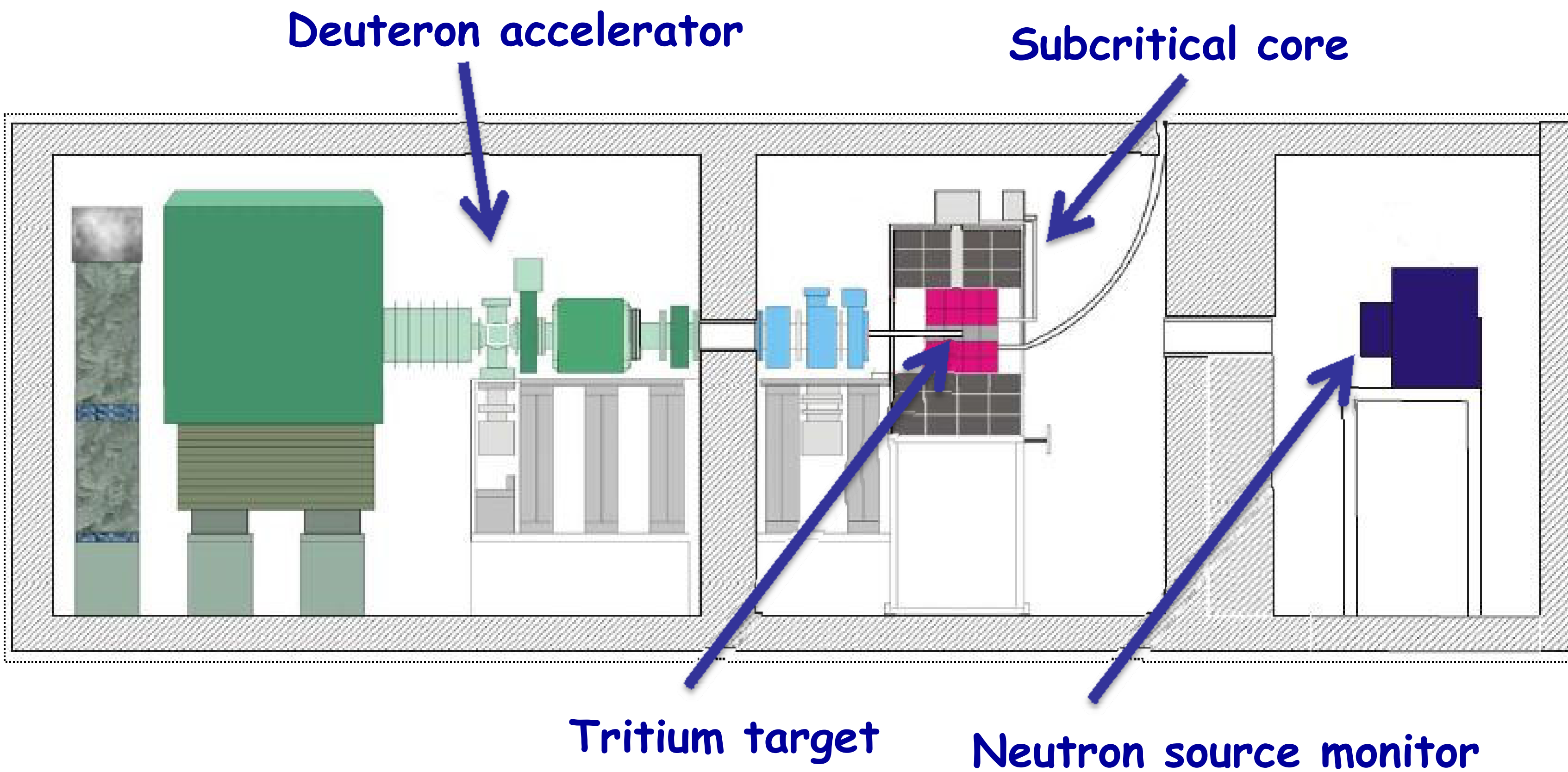
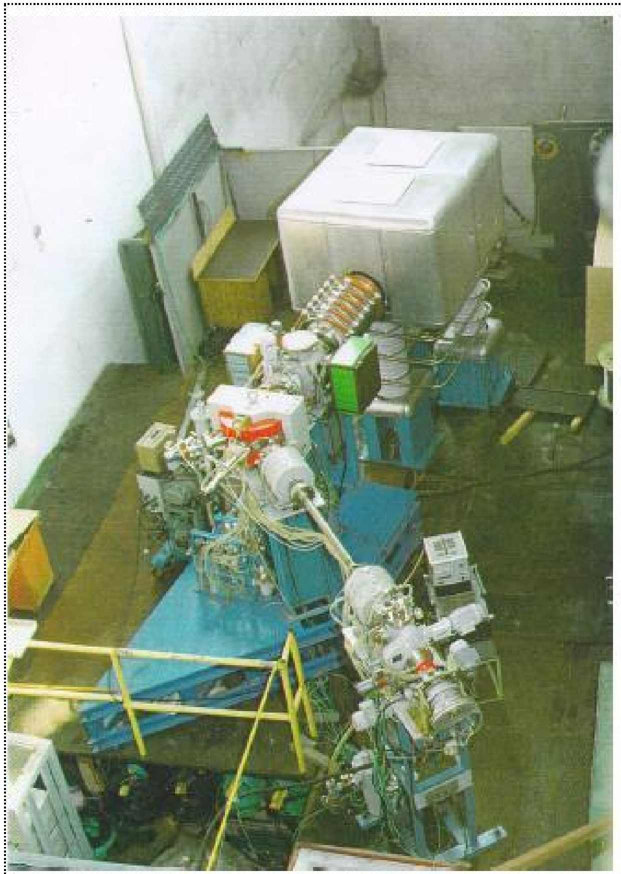
YALINA-Booster set-up



YALINA is a subcritical assembly located in JIPNR-SOSNY institute in Belarus used for this validation in the EURATOM IP-EUROTRANS project

YALINA-Booster set-up (cont.)



Subcritical assembly

Fast zone:

36% enriched UO_2 in Pb

Thermal zone:

10% enriched UO_2 in a polyethilene matrix

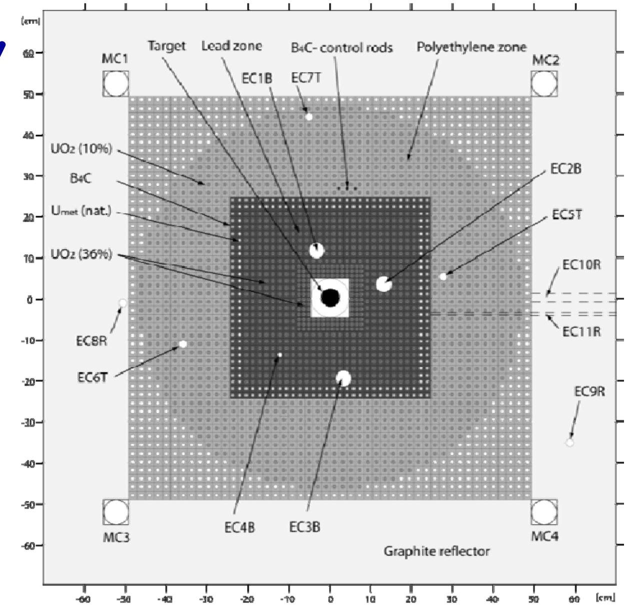
Valve zone:

108 pins of natural U

116 pins of B_4C

Reflector zone:

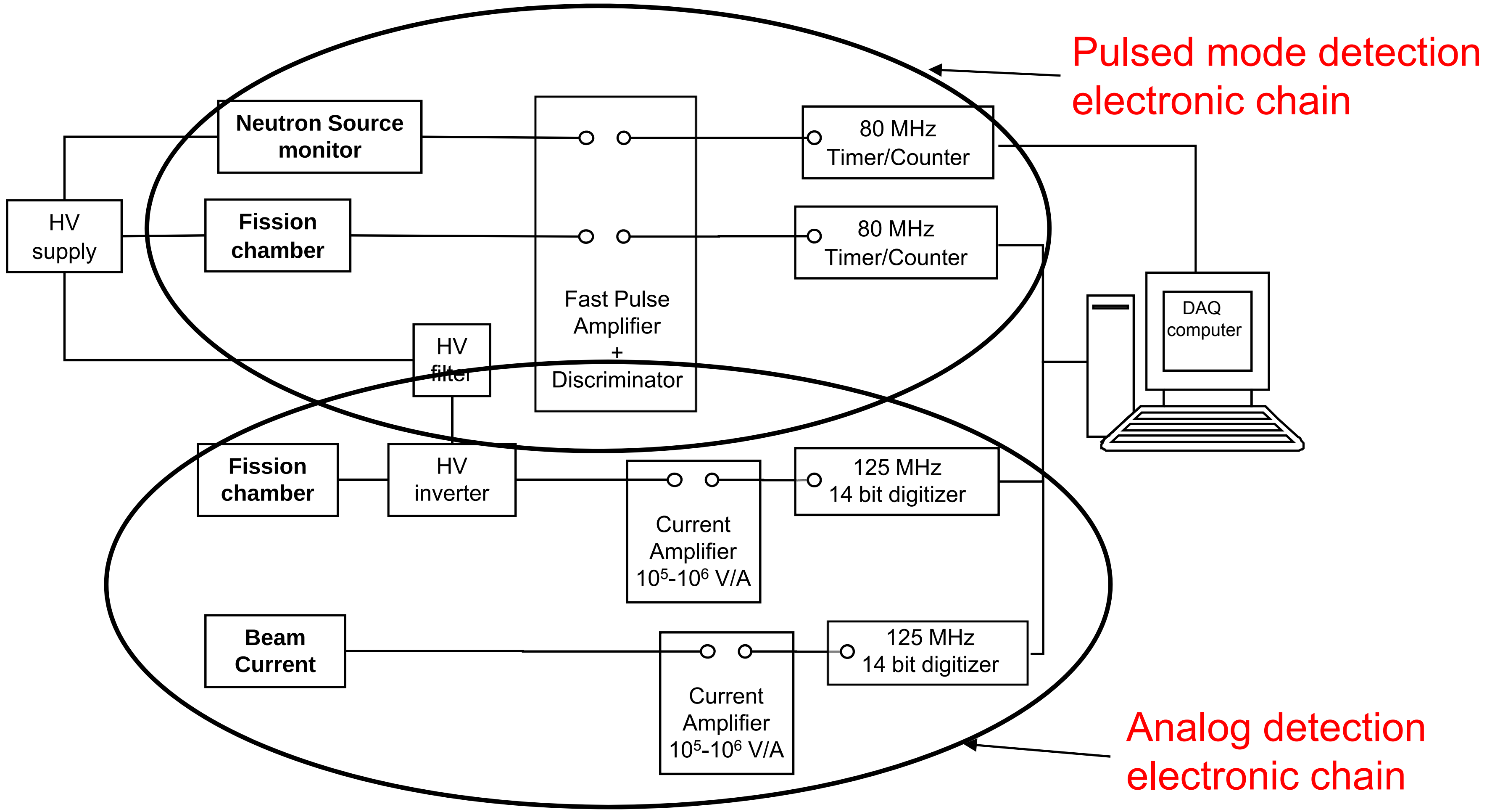
Graphite



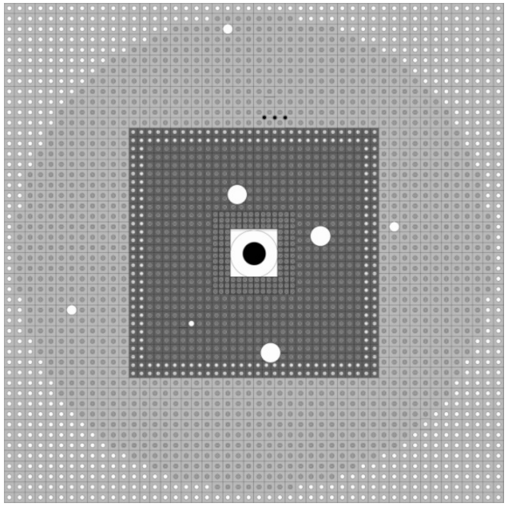
NG-12-1 neutron generator:

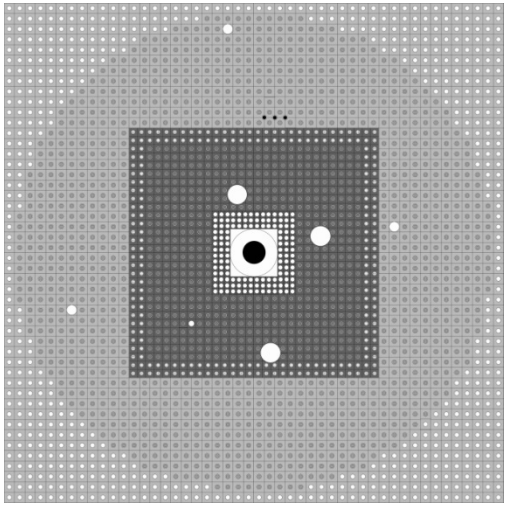
- Deuteron maximum current 1.5 mA.
- Neutron maximum intensity of ~10^{11} neutrons/s (4π).
- Can be operated in pulsed or continuous mode.
- The continuous wave can be interrupted for ~30-40 ms.
- The repetition rate of the beam trips was 1 Hz.

YALINA-Booster DAQ



Experimental Configurations





SC0: k_{eff} ~ 0.98

+

SC6: k_{eff} ~ 0.85

SC3a
k_{eff} ~ 0.95
Inner booster: 132
Outer booster: 563
Thermal zone: 1077

SC3b
k_{eff} ~ 0.95
Inner booster: 0
Outer booster: 563
Thermal zone: 1090

Small reactivity variations were introduced by movements of the control rods ($\Delta\rho$~350 pcm) for SC3a and SC3b

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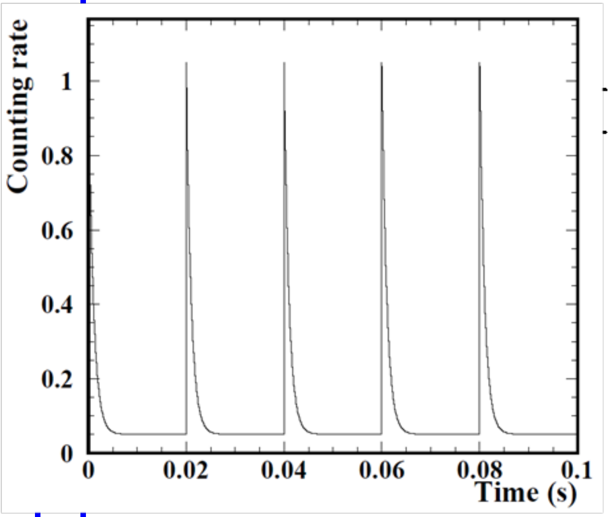
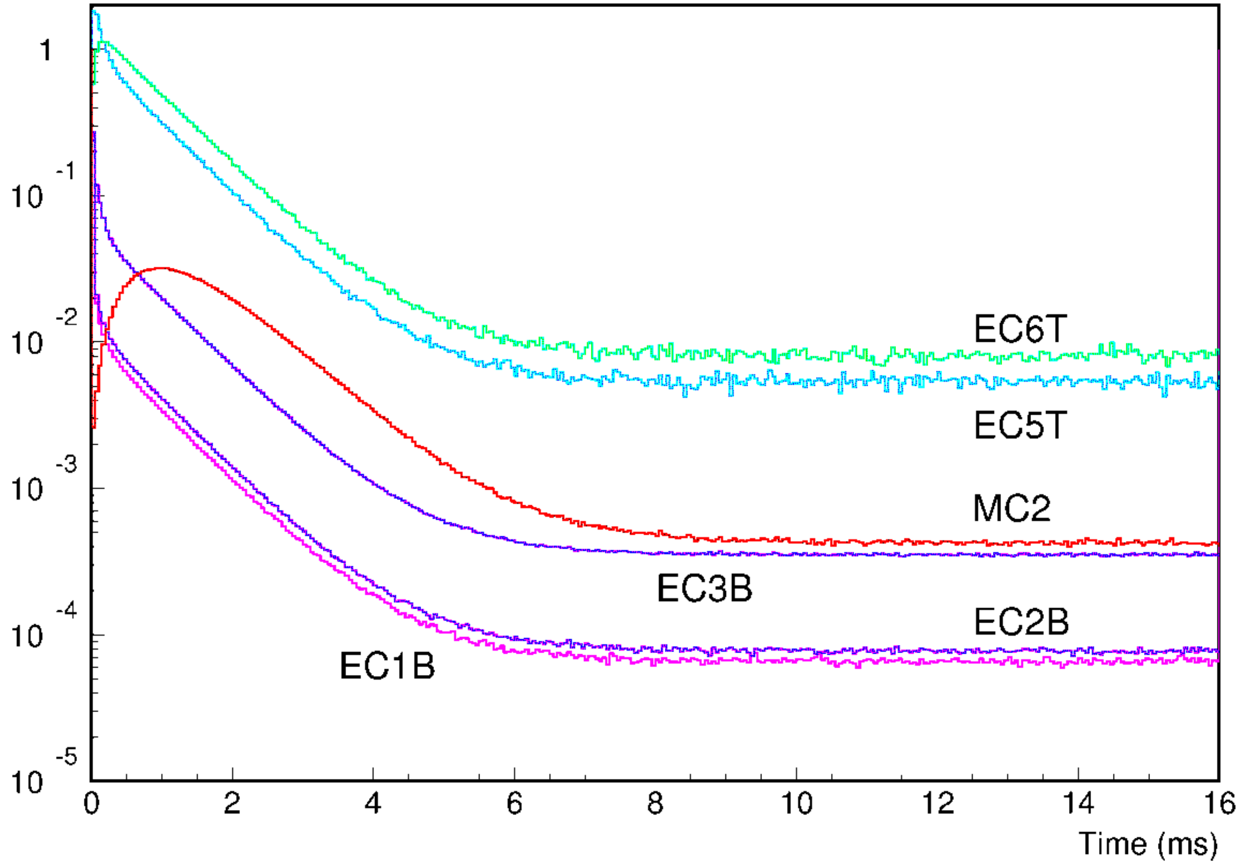
Experimental results

Evolution of the counting rate in different detector positions after an external source neutron pulse: SC3a





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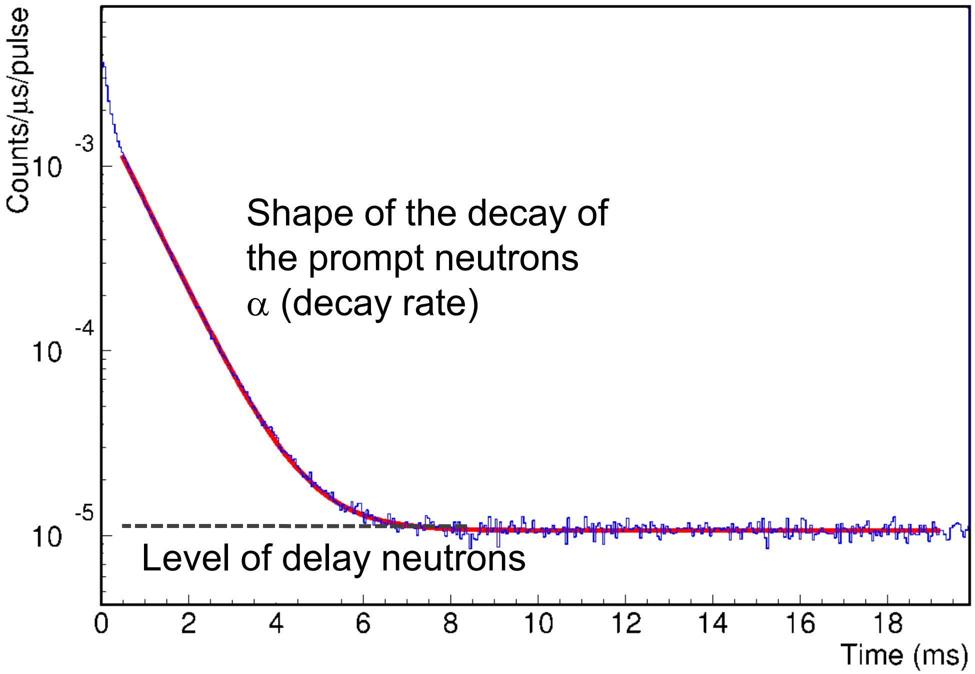
Prompt decay constant technique

Reactivity determination with the prompt decay constant tecnique



$$n_p(t) \propto e^{-\alpha t} \Rightarrow$$

$$\Rightarrow \alpha = \frac{\rho - \beta_{eff}}{\Lambda} \Rightarrow$$

$$\Rightarrow \rho = \alpha\Lambda + \beta_{eff}$$

$$\Rightarrow \frac{\rho}{\beta_{eff}} = \frac{\alpha}{\beta_{eff}/\Lambda} + 1$$

Simmons, B. E. and King, J.S., Nucl. Sci. Eng. 3 (1958) 595-608

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Spectral and space dependent effects

The local response of the neutron flux measured in a detector can behave far from point kinetics:

- different prompt decay constant and area ratios for different detectors.

Spectral and space dependent effects at each detector position must be taken into account in the evaluation of the experimental results.

Detailed simulations of the subcritical system, with MCNPX, provide the calibration constants and can be used in methods largely tolerant to inaccuracies of the model or nuclear data.

Interpretation and corrections to the prompt decay constant

1) In the first aproach we can use point kinetic with β_{eff} and Λ experimental or evaluated by detailed simulation.

Λ has been calculated with the methodology proposed in [Verboomen et al., Ann. Nucl. En. 33 (2006) 911-916]: Λ (μs) = 60.2 ± 1.0

2) To take into account the local spectral and geometrical effects one effective values of Λ^* is computed by MC for each detector.

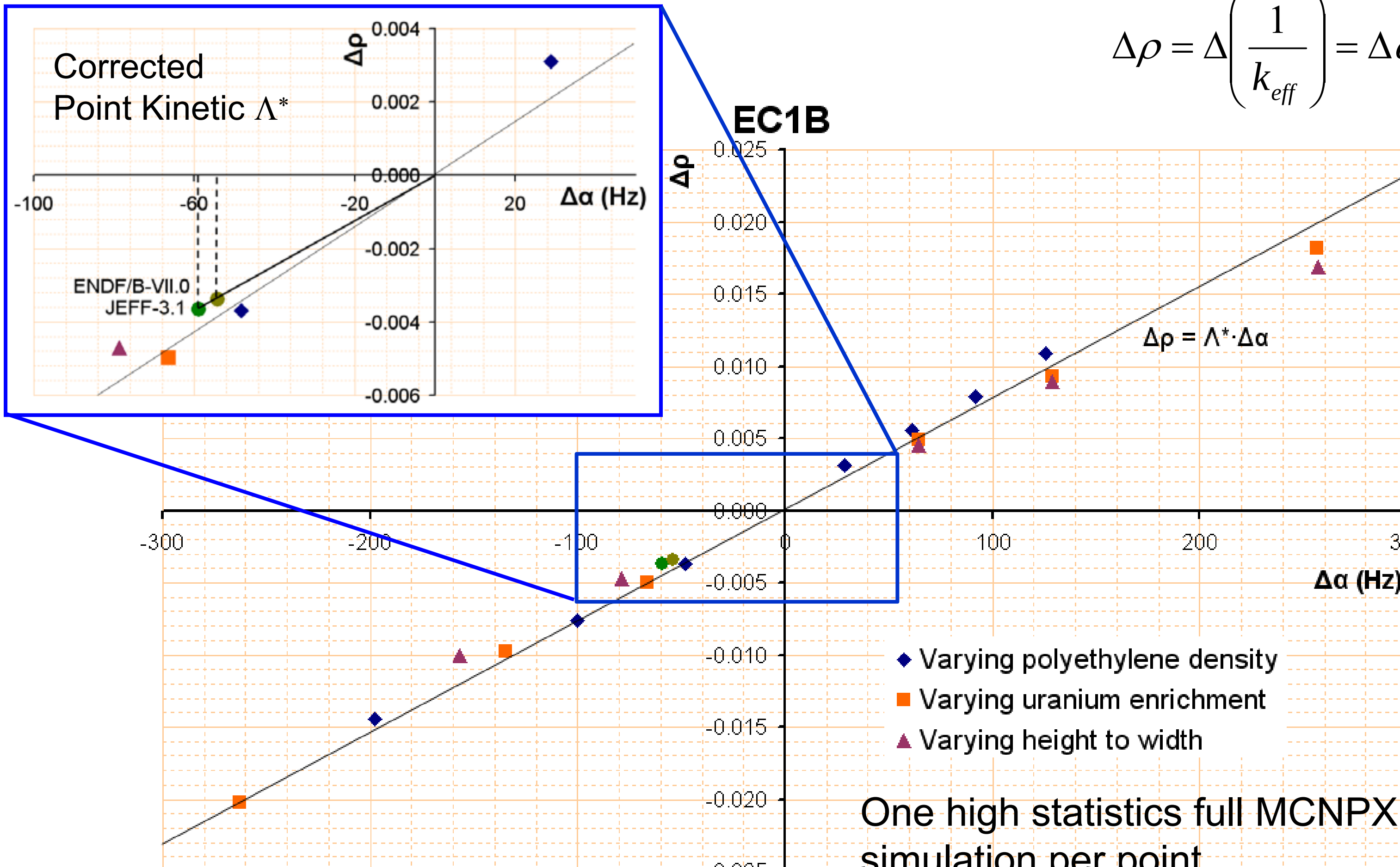
3) But, how sensible is the interpretation of the experimental data (the values of Λ^*) from the details of MC simulation? What if the description of the system in the simulation was not exact?

$$\frac{1}{k_{eff}} = 1 - \alpha_{eff}\Lambda^* - \beta_{eff} \qquad \Delta\rho = \Delta\left(\frac{1}{k_{eff}}\right) = \Delta\alpha\Lambda^*$$

So the question is equivalent to whether: there is a universal relation between $\Delta\rho$ and $\Delta\alpha$, for a given detector position in a given system. If so use it to correct the experimental data.

Interpretation and corrections to the prompt decay constant

$$\Delta\rho = \Delta\left(\frac{1}{k_{eff}}\right) = \Delta\alpha\Lambda^*$$



One high statistics full MCNPX simulation per point

$$\Lambda^* = \frac{\Delta\rho}{\Delta\alpha} \qquad \varepsilon(\Lambda^*) = 8 - 13\%$$

(depending on the detector location) implies a systematic uncertainty in $k_{eff,exp}$ of ~ 80 pcm

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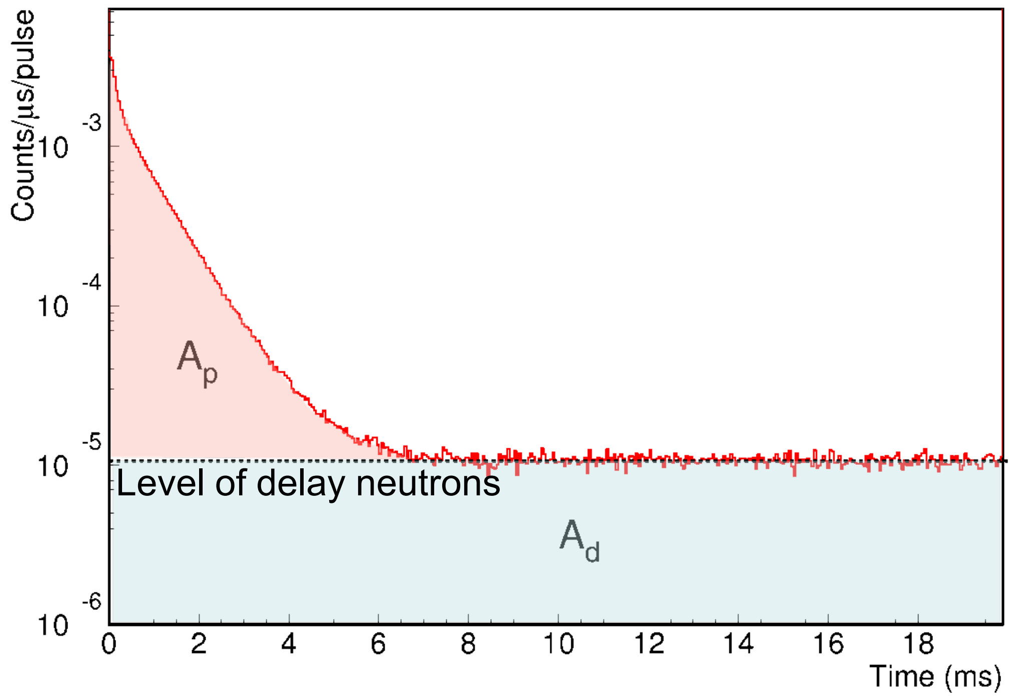
The area ratio technique

Reactivity determination with the area-ratio technique



$$\frac{\rho}{\beta_{eff}} = -\frac{A_P}{A_d}$$

Sjöstrand, N. G., Ark. Fys. 11 (1956) 233-246

Interpretation and corrections to the area-ratio technique

In point kinetics we have that:

1)

$$\frac{\rho}{\beta_{eff}} = -\frac{A_P}{A_d}$$

To take into account spatial kinetics, we introduce correction factors with MCNPX (for each detector position – i):

2)

$$-\frac{A^i_{p,MC}}{A^i_{d,MC}} = C^i_{MC}\rho_{MC} = C^i_{MC}\frac{k_{effMC}-1}{k_{effMC}} \Rightarrow C^i_{MC} = \frac{A^i_{p,MC}}{A^i_{d,MC}}\left(\frac{k_{effMC}}{1-k_{effMC}}\right)$$

And we use these factors to correct the experimental data:

$$\rho^i_{\exp} = -\frac{A^i_{p,\exp}/A^i_{d,\exp}}{C^i_{MC}} \Rightarrow k_{eff} = \left(1+\frac{A^i_{p,\exp}/A^i_{d,\exp}}{C^i_{MC}}\right)^{-1}$$

Interpretation and corrections to the area ratio technique

3) In a similar way to the prompt decay methodology we have to determine how sensible is the interpretation of the experimental data (the values of C^i_{MC}) from the details of MC simulation

What if the description of the system in the simulation was not exact?

$$\rho = -\frac{A_p^i / A_d^i}{C^i} \rightarrow \Delta\rho = \xi^i \, \Delta(A_p^i / A_d^i)$$

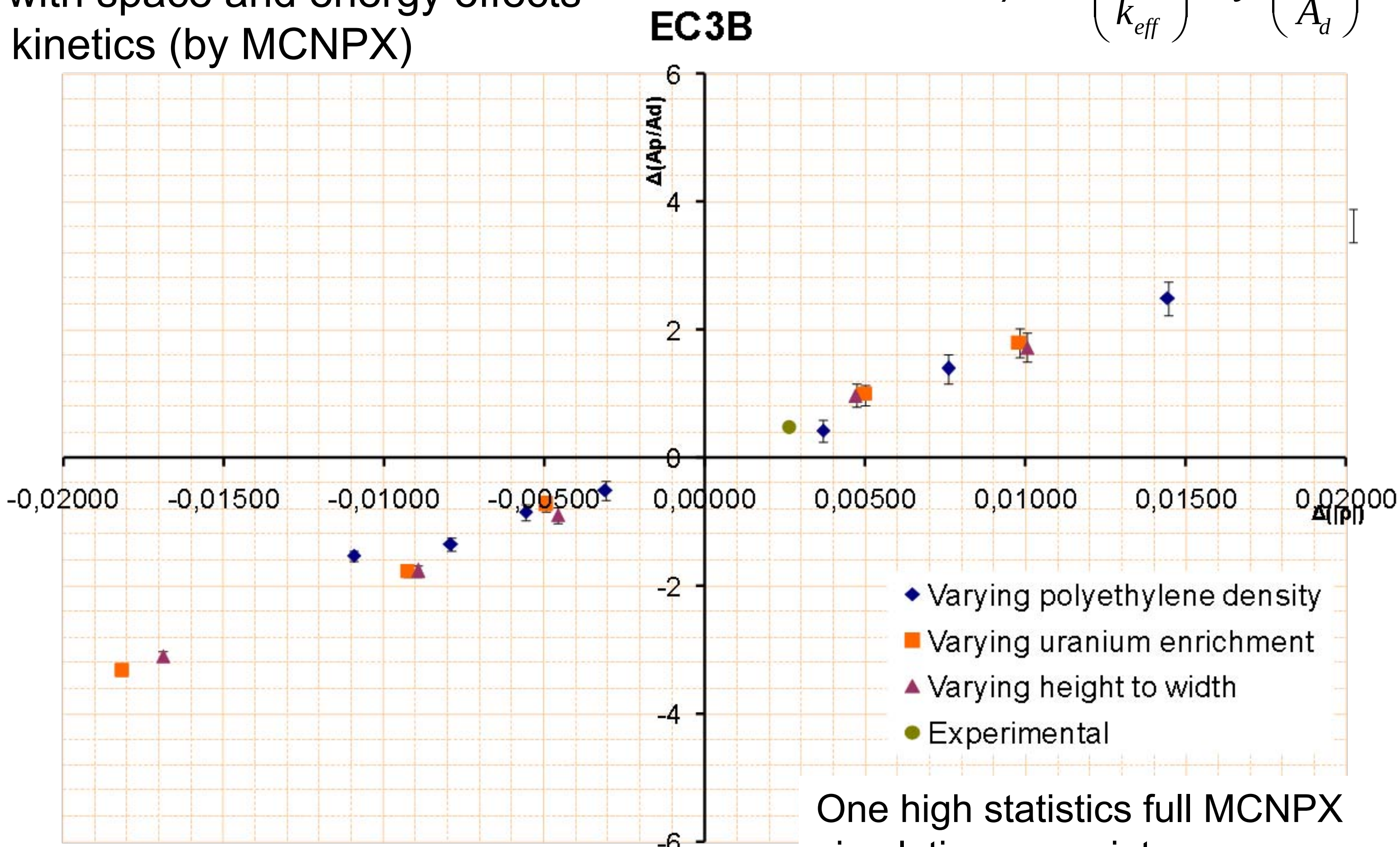
Again, the question is equivalent to: How universal is the relation between $\Delta\rho$ and $\Delta(A_p/A_d)$, for a given detector position in a given system.

A large number of MCNPX simulations with perturbations on the geometry/materials of the system and using different libraries were performed to investigate this universality.

Interpretation and corrections to the area ratio technique

Validation of the relation of ρ and A_p/A_d with space and energy effects in the kinetics (by MCNPX)

$$\Delta\rho = \Delta\left(\frac{1}{k_{eff}}\right) = \xi\Delta\left(\frac{A_p}{A_d}\right)$$



One high statistics full MCNPX simulation per point

Interpretation and corrections to the area ratio technique

Validation of the relation of ρ and A_p/A_d with space and energy effects in the kinetics (by MCNPX)

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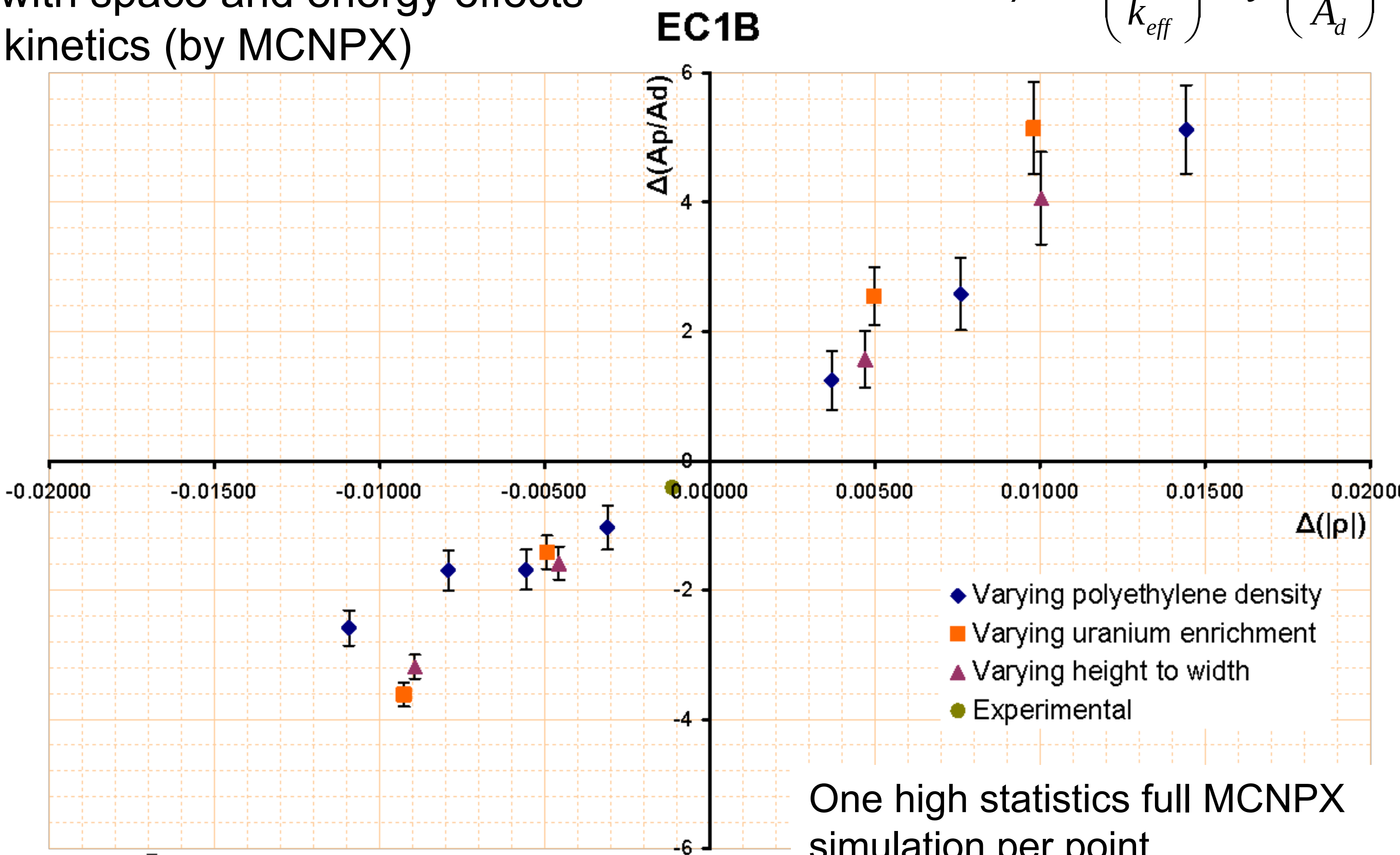
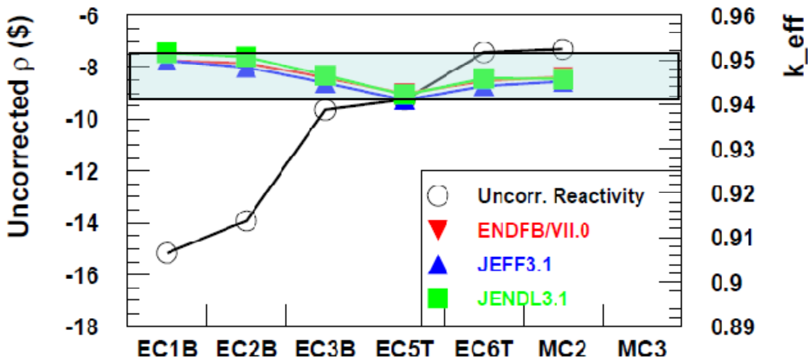


One high statistics full MCNPX simulation per point

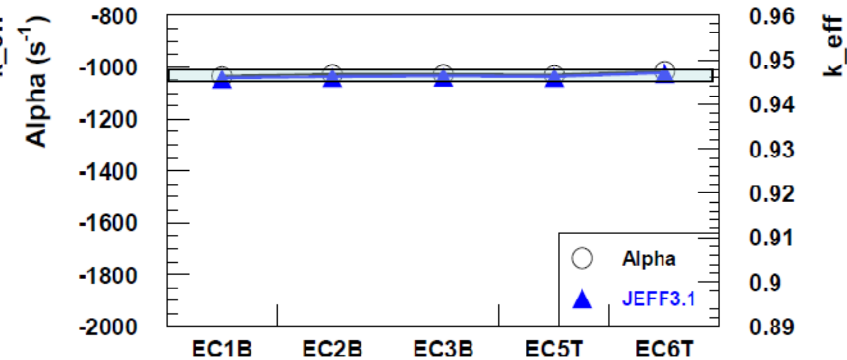
Raw and Corrected estimations of ρ (k_{eff}) for SC3b configuration

Area method

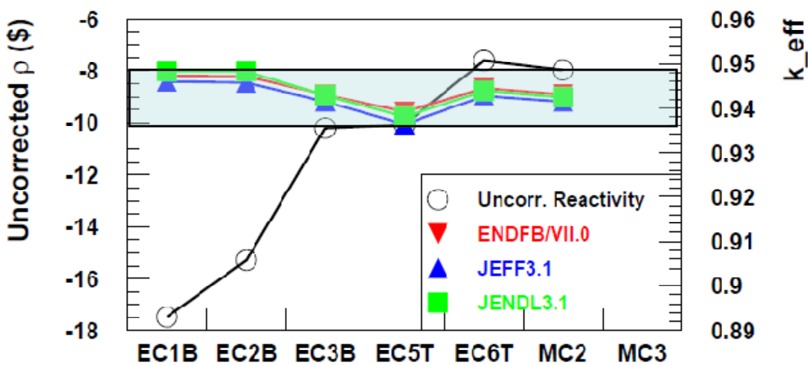


CR out Δk = 1000pcm

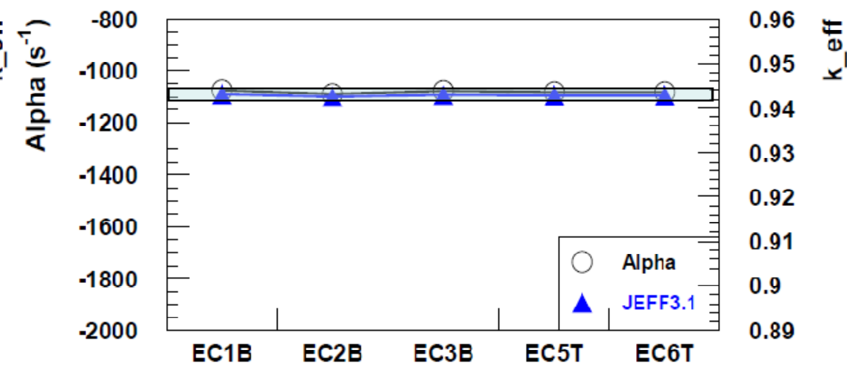
Prompt decay constant



CR out



CR in Δk = 1200pcm



CR in

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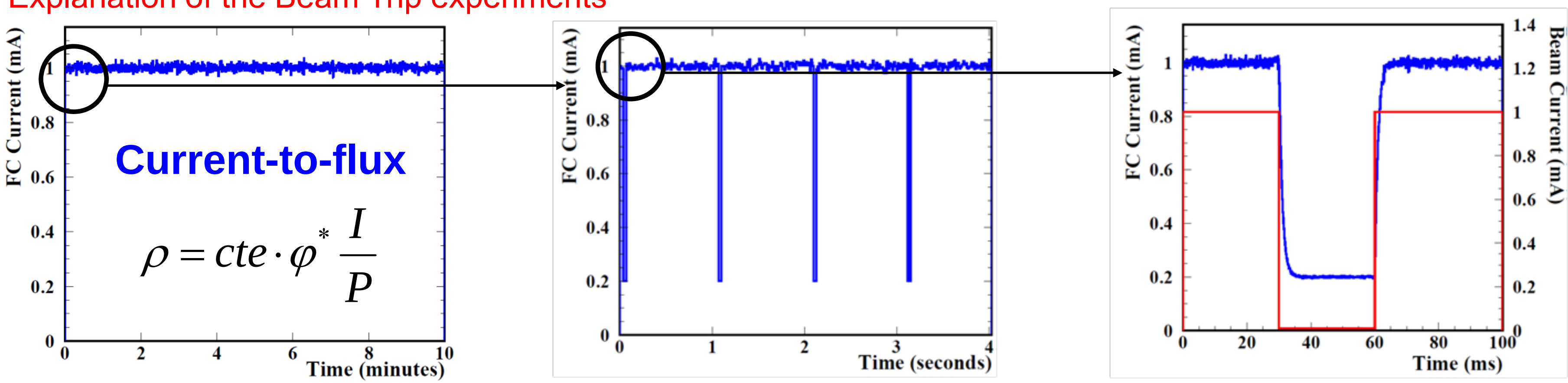
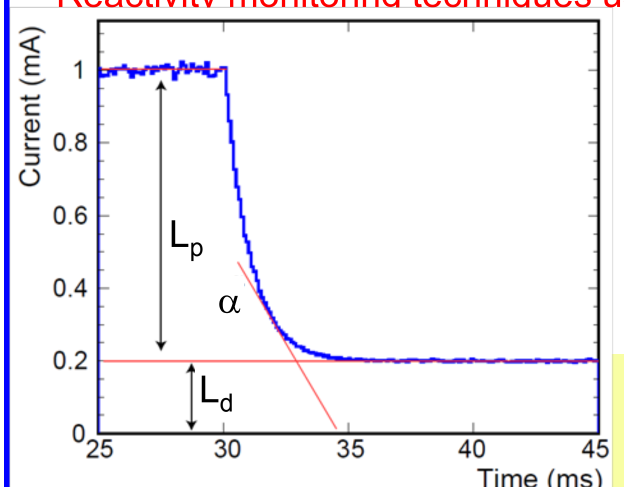
Continuous beam: Current-to-Flux & Beam trips

Explanation of the Beam Trip experiments



Reactivity monitoring techniques using Beam Trip experiments



Source-jerk

$$-\frac{\rho}{\beta_{eff}} = \frac{L_p}{L_d}$$

Prompt-decay constant

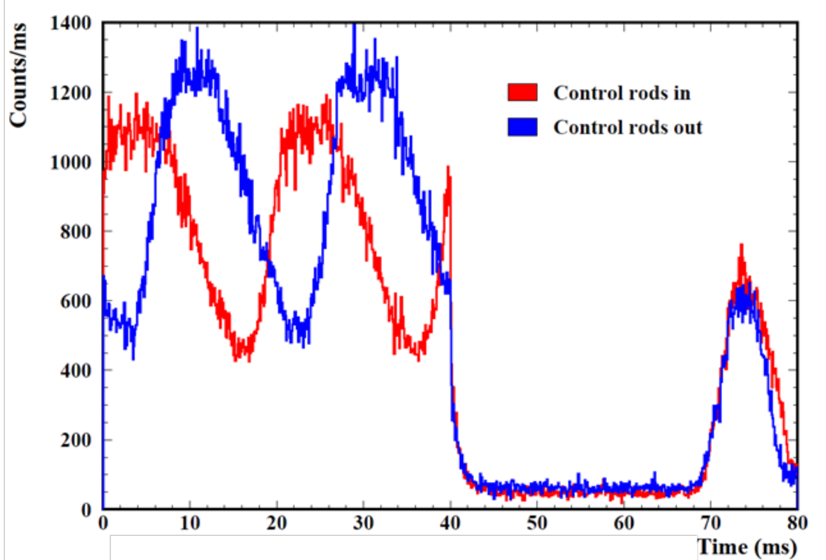
$$-\frac{\rho}{\beta_{eff}} = \frac{\alpha}{\beta_{eff}/\Lambda} - 1$$

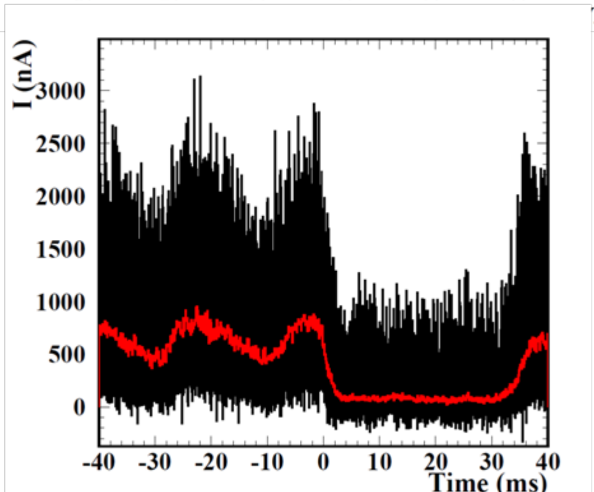
Equivalent to Area ratio and Prompt decay constant in PNS

One reactivity measurement every Beam Trip

Same corrections than in PNS experiments to get k_{eff}

The YALINA-Booster case

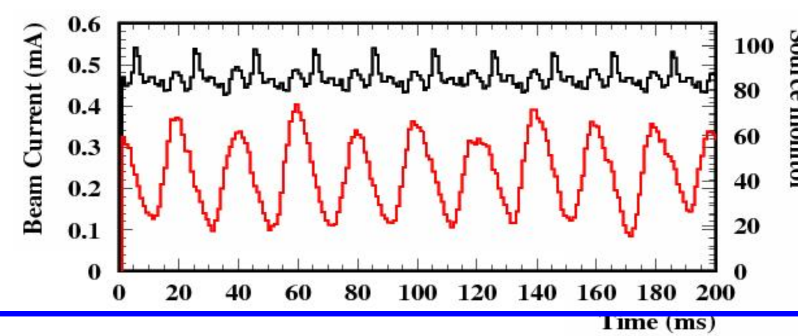




- Beam with a 50 Hz oscillation.
- Actual neutron source not proportional to the Beam current.
- **(Very) large dead time corrections in pulsed mode detection.**
- **Detectors in analog mode presented large electronic noise.**

In order to analyze we had to :

- *averaged over the 50 Hz oscillation,*
- *correct for Dead time,*
- *filter the Electronic noise,*
- *Use the Online Neutron Source Monitoring (14 MeV neutron detector).*



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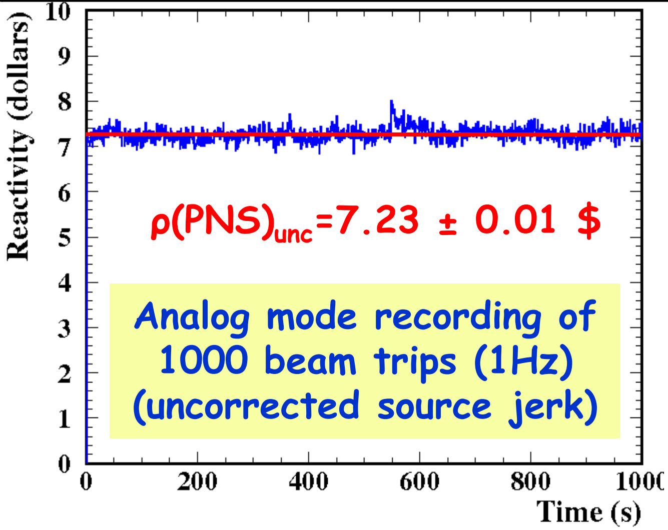
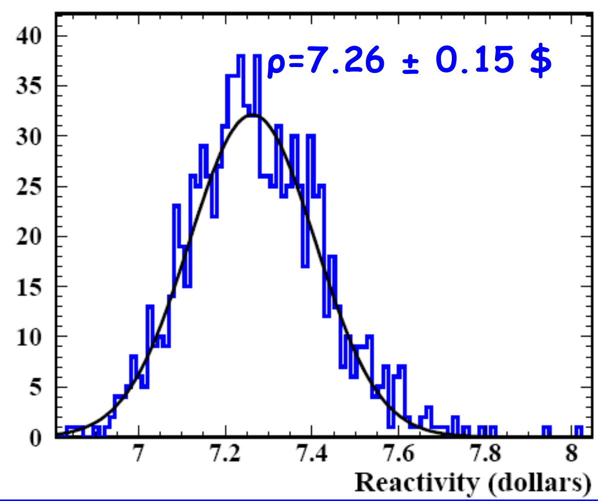
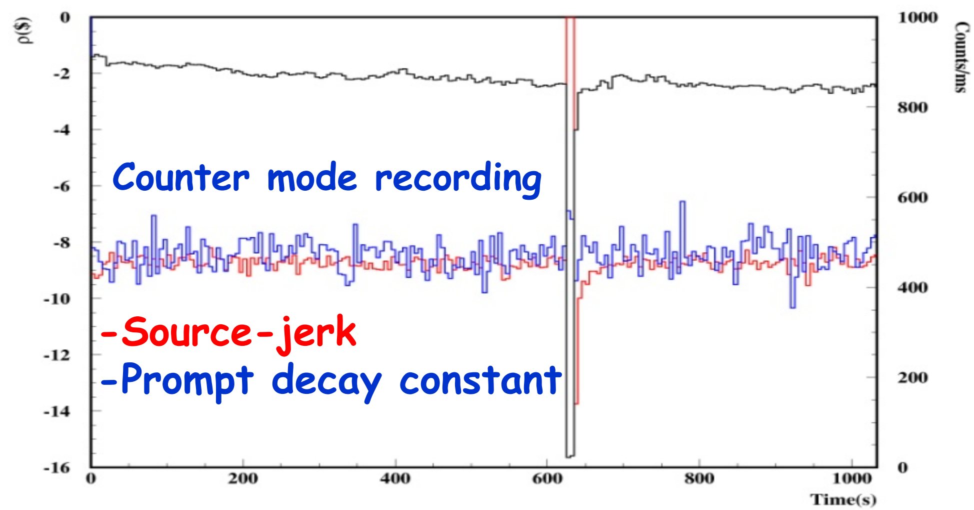
YALINA-B Beam trip results: stationary case





- Online reactivity monitoring of a subcritical reactor driven by an external neutron source feasible.
- Source-jerk and PNS area method compatible within uncertainties.
- Pulsed mode detection and analog mode detection.
- Source-jerk lower statistical uncertainties but needs 50s to stabilize after long beam interruption
- Prompt decay constant immediate response but with larger statistical uncertainties.



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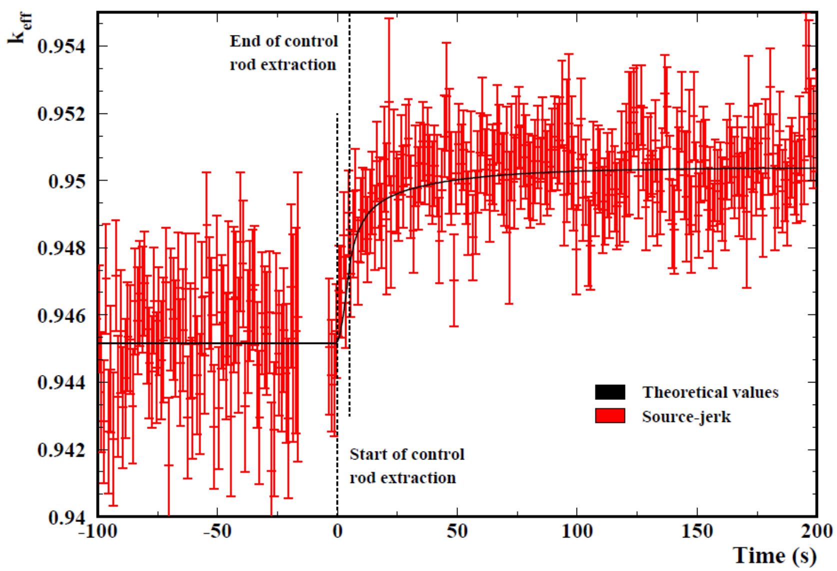
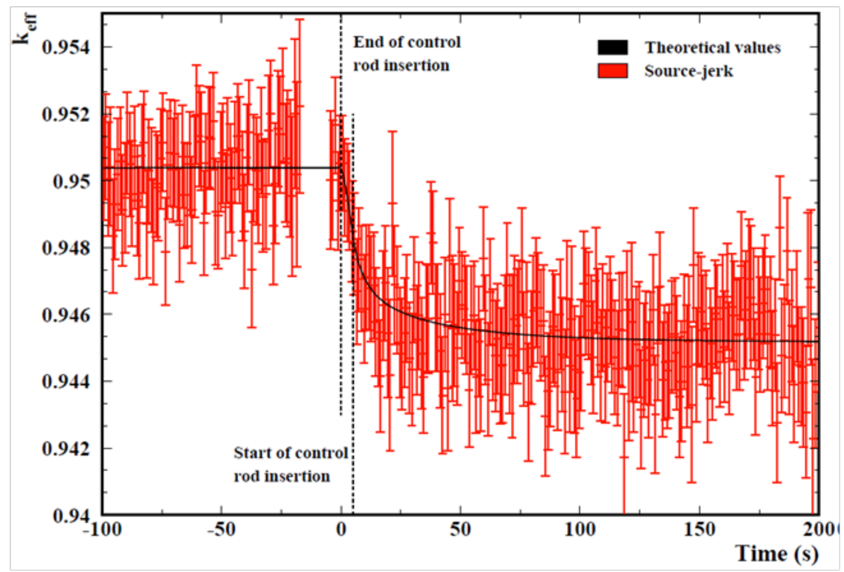
YALINA-B Beam trip results: control rod movement

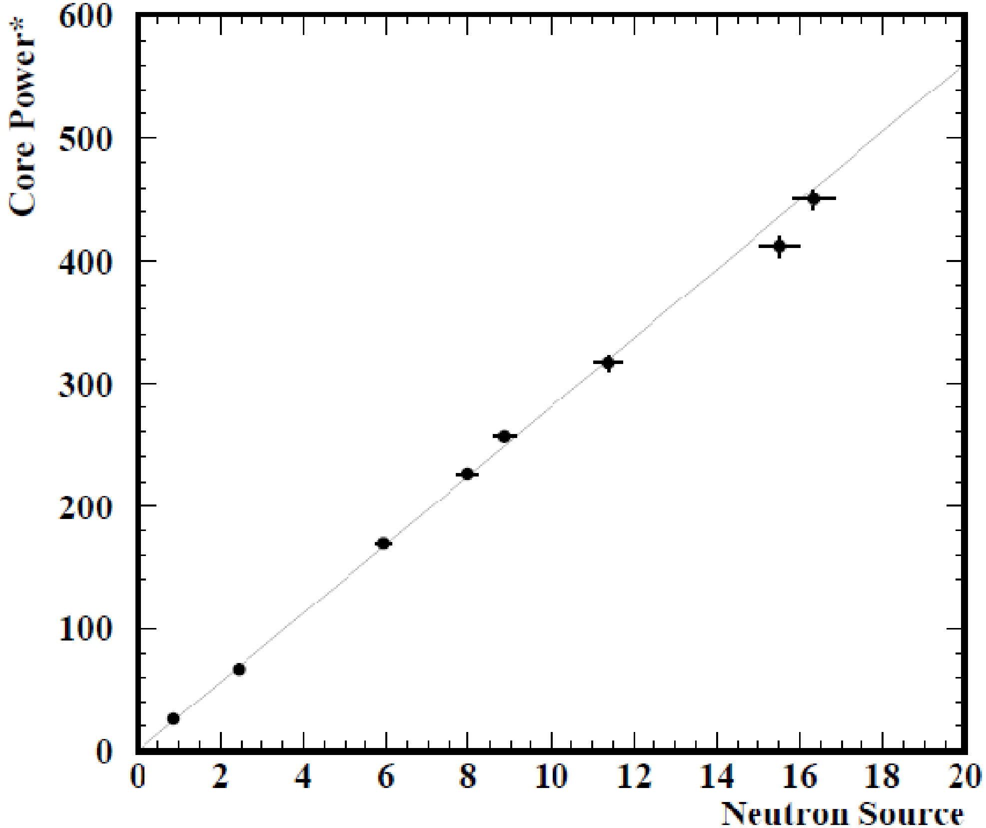
Reactivity monitoring during a control rod movement using source-jerk method





- The source-jerk technique can detect reactivity variations as small as 350 pcm.
- Source-jerk estimation of reactivity requires to wait for the delayed neutron stabilization before providing the actual reactivity.

Current-to-flux results: stationary case

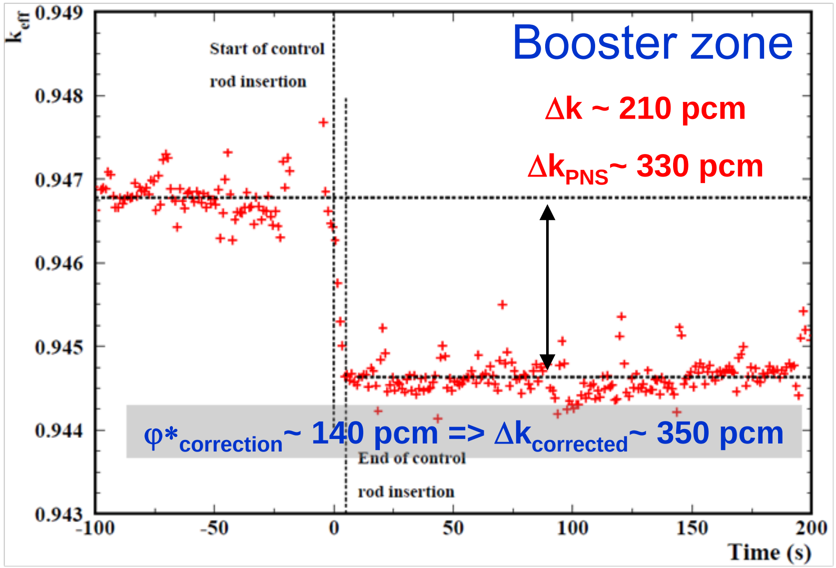


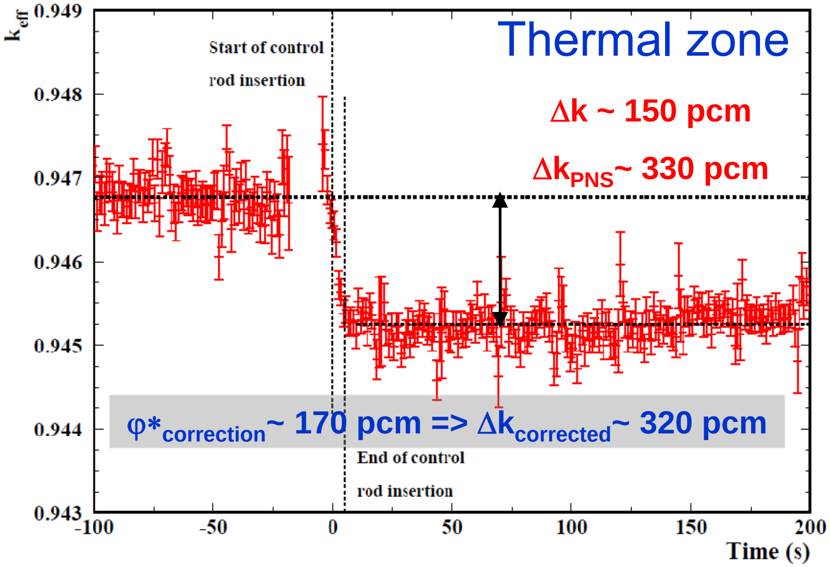
20 counts/ms in Neut. Source
≈1 mA D beam

Proportionality between neutron source and neutron flux is maintained: from 0.03 mA to 0.8 mA beam intensity. Less proportionality for larger intensities

Current-to-flux results: control rod movement

Current-to-flux reactivity monitoring during a control rod insertion

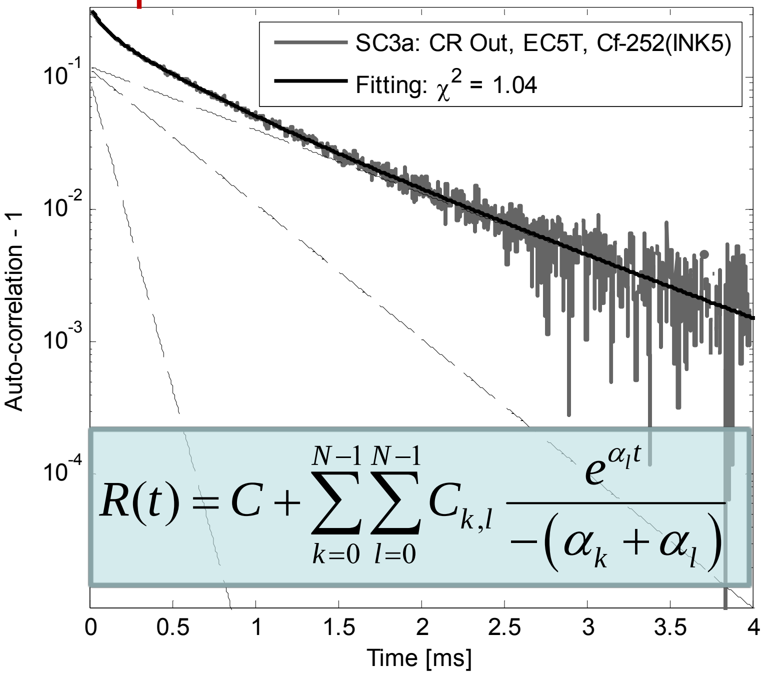




- The current-to-flux technique can detect reactivity variations as small as 330 pcm.
- Variations in the source importance + detector efficiency have to be taken into account to obtain the correct Δρ.
- The correction is similar to the MSM correction factor

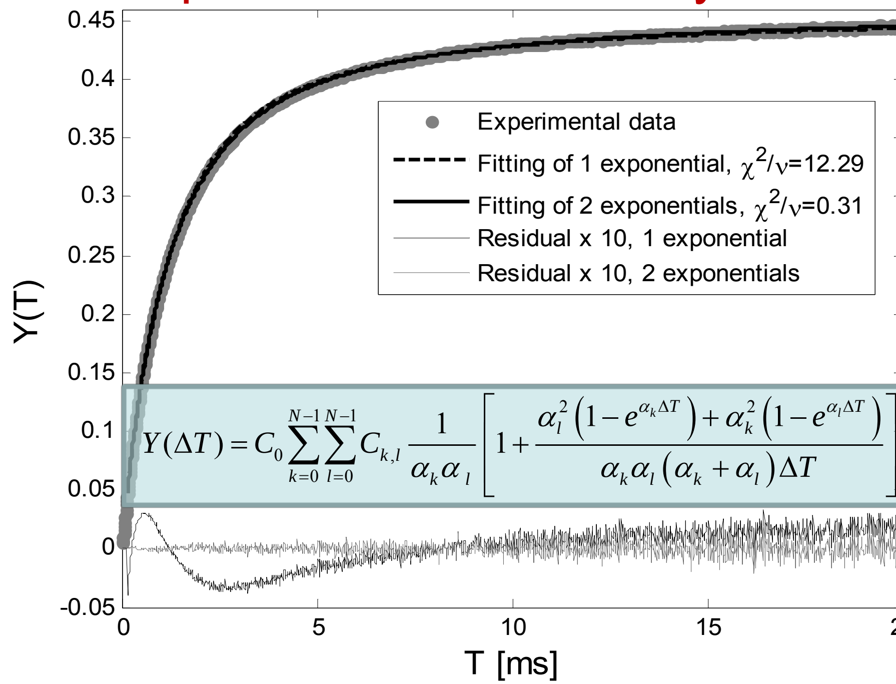
Noise experiments

Experimental results: Rossi-α



$$R(t) = C + \sum_{k=0}^{N-1}\sum_{l=0}^{N-1} C_{k,l} \frac{e^{\alpha_l t}}{-(\alpha_k + \alpha_l)}$$

Experimental results: Feynman-α



$$Y(\Delta T) = C_0 \sum_{k=0}^{N-1}\sum_{l=0}^{N-1} C_{k,l} \frac{1}{\alpha_k \alpha_l}\left[1 + \frac{\alpha_l^2\left(1-e^{\alpha_k \Delta T}\right) + \alpha_k^2\left(1-e^{\alpha_l \Delta T}\right)}{\alpha_k \alpha_l \left(\alpha_k + \alpha_l\right)\Delta T}\right]$$

Pos	Conf	CR	Rossi-alpha				Feynman-alpha	
			α_2 [s^{-1}]	α_1 [s^{-1}]	α_0 [s^{-1}]	α_{PNS} [s^{-1}]	α_1 [s^{-1}]	α_0 [s^{-1}]
EC5T	SC0	Out	-11340 ± 426	-2442 ± 50	-674 ± 10	-638 ± 3	-2300 ± 100	-647 ± 26
	SC3a	Out			-1094 ± 77	-1053 ± 9	-2290 ± 50	-1127 ± 13
		In			-1114 ± 8	-1081 ± 15	-3500 ± 400	-1165 ± 39
	SC6	Out		-	-3094 ± 113	-2614 ± 13	-	-3140 ± 270

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Conclusions

Control rods			SC3a		SC3b	
			Out	In	Out	In
PNS	Area ratio	ENDF/B VII.0	0.94580 ± 0.00020	0.94260 ± 0.00050	0.94680 ± 0.00100	0.94420 ± 0.00110
		JEFF 3.1	0.94510 ± 0.00050	0.94110 ± 0.00040	0.94590 ± 0.00110	0.94250 ± 0.00120
		JENDL 3.3	0.94600 ± 0.00060	0.94240 ± 0.00040	0.94760 ± 0.00130	0.94420 ± 0.00140
	Prompt decay	JEFF 3.1	0.94570 ± 0.00050	0.94280 ± 0.00020	0.94630 ± 0.00030	0.94300 ± 0.00020
Beam trip		JEFF 3.1			0.94630 ± 0.00040 ± 0.00400 (syst)	0.94250 ± 0.00050 ± 0.00500 (syst)
Δk (max-min)			90 pcm	170 pcm	170 pcm 400 (syst)	170 pcm 400 (syst)

Excellent coherence of k_{eff} monitoring techniques after corrections (for set of complementary detectors the uncertainty < 200 pcm)

Up to 400 pcm systematics for beam trips with present analysis.

Conclusions

- YALINA-Booster results have validated PNS techniques (Prompt decay constant and Area methods) in a complex system (very different systematics than MUSE).
- It has been necessary to develop new methods implemented with MCNP to calculate the corrective factors to the raw data to obtain the reactivity.
- After correction, the different kinetic reactivity monitoring methods are consistent. For a single detector with prompt decay constant method <150 pcm and with area-ratio method <1200 pcm. For a set of complementary detectors <170 pcm (for $K_{eff} \approx 0.95$).

Conclusions

- First validation test of:
  - Current to Power monitoring and analysis for an ADS.
  - Beam trips reactivity calibration techniques for an ADS.
- First monitoring of a fast reactivity variation (control rod movements) by current-to-flux and beam trip reactivity measurement.
- First estimation of the accuracy of the beam trip calibration techniques established.

The ADS scheme of the reactivity monitoring has been validated for YALINA (coupled fast-thermal reactor)

Current-to-flux	Beam trips (analog/pulses)	PNS (Area/Slopes/MCNP corr.) Noise techniques