Validation of ADS reactivity monitoring techniques in the Yalina-Booster subcritical assembly

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Abstract

The development of a reactivity monitoring system for subcritical reactors is a major task prior to industrial scale accelerator driven system (ADS) construction. Within the 6th European Framework Program, the IP-EUROTRANS project has performed a series of experiments at the Yalina-Booster subcritical assembly located at the Joint Institute for Power and Nuclear Research (JIPNR) of the National Academy of Sciences of Belarus, using a continuous (D,T) (fusion) neutron source in pulsed and continuous mode with short interruptions (beam trips). In this paper, the implementation and results of three different monitoring techniques intended to operate with continuous neutron sources will be presented, namely the source-jerk technique, the prompt decay constant technique and the current-to-flux technique. The results will be compared with the values of the reactivity obtained using the pulsed source in PNS experiments, discussed in detail in another paper.

Keywords: accelerator driven system (ADS), reactivity monitoring, current-to-flux, beam trip, Yalina-Booster

1. Introduction

Over the last decades, there has been considerable interest in accelerator-driven subcritical systems (ADS) due to their potential capability to stabilize or reduce the volume and radiotoxicity of high level nuclear waste and thus to contribute to make nuclear energy more sustainable (OECD-NEA (2002, 2006); Lensa et al. (2008)).

One of the requirements to license and operate an industrial ADS is the ability to monitor the reactivity of the system during operation (Baeten and Ait Abderrahim (2003)). Most of the techniques applied up to now to determine the reactivity of a subcritical system that cannot become critical are based on Pulsed Neutron Source (PNS) experiments. PNS experiments have been carried out in the MUSE (Soule et al. (2004); Villamarín (2004)), TRADE (Jammes et al. (2006)), RACE (Jammes (2007)), Yalina-Thermal (Persson et al. (2005)) or Yalina-Booster (Talamo et al. (2009); Berglof et al. (2010); Talamo et al. (2012)) subcritical assemblies to validate PNS techniques and therefore they are today well documented and can be taken as reference. However, during the normal operation of an industrial ADS, the power must be stable and continuous, and these techniques can not be applied. Hence, it is necessary to use other techniques compatible with a continuous or quasi-continuous operation of the accelerator.

In the final conclusions of the MUSE-4 experiments carried out during the 5th European Framework Programme (Mellier et al. (2005)) it was proposed to combine two independent techniques for continuously monitoring the reactivity of an ADS. The first of these techniques is the so-called current-to-flux technique. The current-to-flux technique is based on the modified source method (MSM), which is commonly used in the calibration of control rods (Bignan et al. (2010)), adapted to ADS characteristics. This method has the drawback that only provides relative measurements of the reactivity and therefore, it should be complemented with another technique that can provide absolute values for the reactivities. One possibility can be obtained using very short interruptions of the beam current (beam trips) and applying slightly modified PNS methodologies.

Two experiments have been included in the EUROTRANS project of the 6th European Framework Program IP-Eurotrans (2005) to explore this measurement scheme: a measurement campaign at the Yalina-Booster subcritical assembly, which has already finished, and the Guinevere experiment at the VENUS reactor, which has started in 2011. The EUROTRANS experiments at Yalina-Booster were carried out during 2008, with the

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Yalina-Booster subcritical assembly coupled to a (D,T) fusion source capable to produce 14 MeV neutrons in pulsed or continuous mode with beam trips.

The purpose of this paper is to present and discuss the results obtained during the Yalina-Booster experiments using continuous beam with short interruptions. The results of the reactivity monitoring will be presented in two parts. First, in section 4, the results obtained in experiments performed when the reactor was in steady state will be shown. In these experiments the reactivity and neutron source production remained constant or variations were slow compared with the delayed neutrons scale of time. Results are compared with those obtained using PNS techniques, already presented in Berglof et al. (2010) and Bécares et al. (to be published). Second, in section 5, the results obtained during fast variations of the reactivity of the assembly and the neutron source intensity are presented.

Finally, in section 6 the first beam trip measurements using current mode detectors will be discussed. This mode of operation of detectors is expected to be the most common one during normal operation in commercial plants.

2. Reactivity monitoring techniques

2.1. Current-to-flux

The current-to-flux technique to measure the subcriticality of an ADS is based on studying the relationship between the power level (or the neutron population) in the system and the external neutron source intensity. Let N be the total number of neutrons produced by multiplication in the system after the introduction of S source neutrons from an external source, then the neutron source multiplication, k_s, is defined by Herrera-Martínez (2004):

$$k_s = 1 - \frac{S}{N} \Rightarrow N = S\frac{1}{1-k_s} \tag{1}$$

In general, k_s is dependent on the neutron source characteristics and its position within the assembly.

By analogy with the MSM method, routinely used to evaluate rod worth in critical reactors, equation 1 is normally rewritten in terms of k_{eff} introducing the concept of *source efficiency*, defined as[3]:

$$\varphi^* \equiv \frac{1-k_{eff}}{1-k_s} \tag{2}$$

resulting in:

$$k_{eff} = 1 - \varphi^*\frac{S}{N} \tag{3}$$

From this equation it is possible to evaluate the k_{eff} of the system by measuring N and S or the ratio between them. However, this measurement requires that φ^* is calibrated at specific configurations. Furthermore, neither N nor S will be experimentally measured but some related measurable magnitudes M and R (e.g. detector counting rates or current intensities). M and R are respectively proportional to N and S and are related with them through the corresponding efficiencies, namely $M = \epsilon_D N$ and $R = \epsilon_S S$. Hence, in terms of M and R, equation 3 becomes:

$$k_{eff} = 1 - \varphi^*\frac{\epsilon_D}{\epsilon_S}\frac{R}{M} \tag{4}$$

The neutron source is expected to be deduced from a measurement of the intensity of the charged particle beam (typically protons) generating the neutrons in the spallation target. Consequently, the value of ϵ_S and φ^* depend on the beam position, energy, shape and density of the spallation target and probably other factors. ϵ_D will also be affected by the detector nature, position and other factors. Some of these parameters can be measured easily but others are very difficult to monitor, and hence a recalibration of the entire $\varphi^*\frac{\epsilon_D}{\epsilon_S}$ factor, with a technique other than the current-to-flux, is needed from time to time.

In any case, these factors usually evolve slowly and they can be considered constant during a period of time. Therefore, the current-to-flux method is useful for online monitoring of the reactivity. The difference of reactivity between two configurations of a system will be given by:

$$\Delta k_{eff} = k_{eff,2} - k_{eff,1} =$$
$$= \left(1 - k_{eff,1}\right)\left(1 - \frac{\varphi_2^* \frac{\epsilon_{D2}}{\epsilon_{S2}}}{\varphi_1^* \frac{\epsilon_{D1}}{\epsilon_{S1}}}\frac{M_1/R_1}{M_2/R_2}\right) \tag{5}$$

If both configurations are similar enough as to assume that $\epsilon_{D1} = \epsilon_{D2}$, $\epsilon_{S1} = \epsilon_{S2}$ and $\varphi_1^* = \varphi_2^*$, then equation 5 can be approximated by:

$$\Delta k_{eff} \simeq \left(1 - k_{eff,1}\right)\left(1 - \frac{M_1}{R_1}\frac{R_2}{M_2}\right) \tag{6}$$

In the case of the experiments at the Yalina-Booster assembly presented in this work, the requirement of source stability was generally not met (section 4) for long periods (minutes to hours range) and thus the application of the current-to-flux technique will be limited to monitor the reactivity during short periods (seconds to minutes range) (section 5). Some additional investigation on the applicability range of the current-to-flux technique was presented in Villamarín et al. (2009).

2.2. Beam trips

Pulsed neutron experiments have shown that it is possible to determine the reactivity of the system using the kinetic response of the neutron flux after a short source injection (Soule et al. (2004); Villamarín (2004); Jammes et al. (2006); Persson et al. (2005); Talamo et al. (2009); Berglof et al. (2010); Mellier et al. (2005)). Conceptually, this situation is equivalent to a continuous source produced with an accelerator, where the beam is interrupted very quickly and restarted again after

[3]Other authors (Gandini and Salvatores (2002)) define the source importance alternatively as $\varphi^* \equiv \frac{1-k_{eff}}{1-k_s}\frac{k_s}{k_{eff}}$. In this paper the definition given by equation 2 is always used.

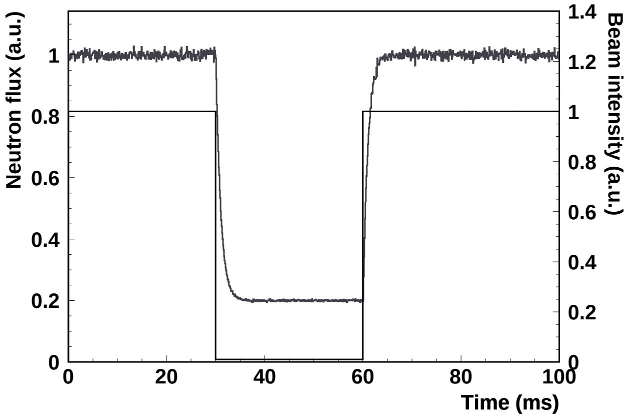


Figure 1: Graphical scheme of the point kinetics response of the flux (thick line) during a trip of the beam current (thin line).

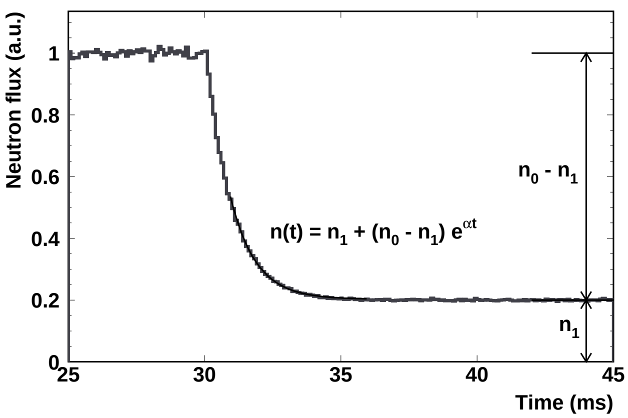


Figure 2: Graphical scheme of the source-jerk and the prompt decay constant techniques to determine the subcriticality during a beam trip.

a few milliseconds. These interruptions happen naturally during the operation of most accelerators and are called beam trips, but they can also be induced by the accelerator control system when needed (if designed to do so). This type of situation is presented in figure 1. It can be observed that after the beam interruption, the counting rate in the flux monitoring detectors shows a fast decay until a constant level is reached. The fast decay is due to prompt neutrons disappearing from the system while the constant level (in fact, also decaying, but very slowly in this time scale) is due to delayed neutrons.

There are two major techniques available to determine the reactivity of the system from the beam trip response, both derived from the well known point kinetic model (Keepin (1965); Ott and Neuhold (1985); Hetrick (1993)). In this model, prompt neutrons decay exponentially after the source loss with a prompt decay constant, α, which is related to the reactivity by the equation:

$$\rho(\$) \equiv \frac{\rho}{\beta_{eff}} = \frac{\alpha}{\beta_{eff}/\Lambda_{eff}} + 1 \tag{7}$$

This equation holds as well for PNS experiments, so the value of α should be similar in both situations. Notice that the determination of the reactivity with this technique requires the knowledge of the kinetic parameters of the system, $\beta_{\rm eff}$ and $\Lambda_{\rm eff}$, or the ratio of them to obtain the reactivity in units of dollars.

The other available technique to determine the reactivity with beam trip experiments is the source-jerk technique. It consists of comparing the counting rates in a given detector before the beam trip and after it, when the prompt neutron component has disappeared and the constant level of delayed neutrons, mentioned above, has been achieved. If they are denoted by n_0 and n_1 respectively (see figure 2), it can be derived from the point kinetic model (Keepin (1965); Ott and Neuhold (1985); Hetrick (1993)):

$$\rho(\$) \equiv \frac{\rho}{\beta_{eff}} = -\frac{n_0 - n_1}{n_1} \tag{8}$$

This technique is equivalent to the Sjöstrand (area-ratio) technique used to determine the reactivity in PNS experiments. The source-jerk has in principle two advantages over the prompt decay constant technique. The first is that it does not require Λ_{eff} but only β_{eff} to obtain the absolute value of the reactivity of the system. The second is that since n_0 and n_1 are determined by accumulating detector counts over a period of time, a larger statistics can be accumulated and hence it is applicable with lower counting rates.

It is important to remark that both techniques are derived from point kinetics, and hence any deviation from this simple model in a real system will lead to spatial and/or spectral dependence in the detector response. Consequently, the same corrections applied in the PNS experiments corresponding corrections will be usually needed to obtain the actual reactivity of the system from the experimental results. The application of such corrections for the case of the Yalina-Booster will be discussed later in this paper.

3. The Yalina - Booster subcritical assembly

A schematic view of the Yalina-Booster subcritical assembly (Bournos et al. (2007); Kiyavitskaya et al. (2005)) during the EUROTRANS experiments is presented in Figure 3. The facility consisted of a core with two well differentiated regions: a central fast zone with 36% enriched UO_2 embedded in a lead matrix (booster) with two packing densities and a thermal zone surrounding the booster consisting in polyethylene blocks with 10% enriched UO_2-Mg fuel. In addition, there are a radial graphite reflector and a front and back biological shielding of borated polyethylene.

The fast and the thermal-spectrum zones are separated by a thermal neutron absorber, or valve zone, consisting of one layer with pins of metallic natural uranium and another layer with pins of boron carbide, which are located in the outermost two rows of the lead buffer. Hence, only fast neutrons can be exchanged between the two zones.

Small changes of reactivity ($\Delta\rho \sim 300$ p.c.m) can be achieved using three B_4C-control rods that can be inserted in

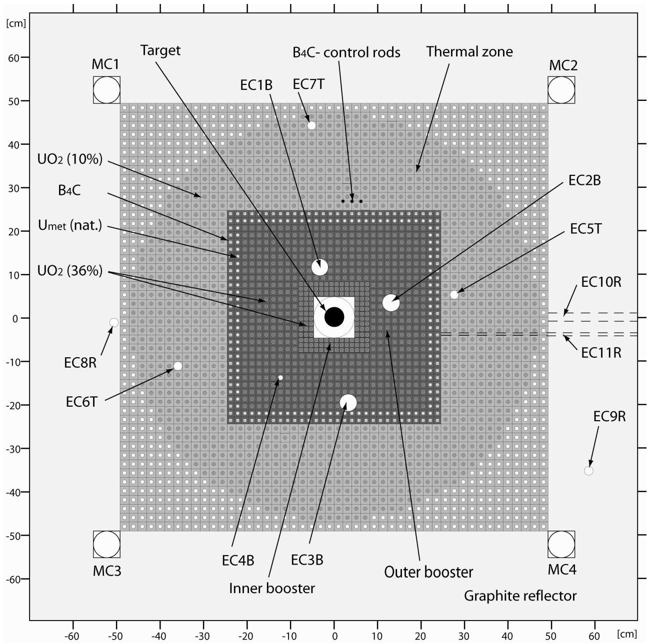


Figure 3: Schematics of the Yalina - Booster subcritical assembly in the SC3a configuration.

the thermal zone. This allows testing the sensitivity of the different reactivity monitoring techniques to reactivity changes of this magnitude.

For the beam trip experiments two different core configurations have been used (table 1), denoted by SC3a and SC3b. The two configurations have been designed to have similar k_{eff} values but, in the SC3b configuration, part of the fuel in the booster was removed to explore possible differences due to changes in the source importance. The values of k_{eff} for each of these configurations as calculated with the Monte Carlo code MCNPX (Pelowitz et al. (2005)) are shown in Table 2.

The experiments presented here were performed with a (D,T) source, consisting of a tritium target coupled to a 250 keV deuteron accelerator (NG-12-1) impinging on a tritium target. The tritium in the target was embedded in a titanium disk, with 45 mm diameter and cooled by water. It was placed in the geometrical center of the assembly to maximize the source importance. It provides $\sim 10^{11}$ neutrons per second at maximum intensity. It must be pointed out that during operation some deuterium is implanted in the target, and hence, a fraction of the source neutrons are produced in (D-D) reactions. This effect may have implications for reactivity monitoring, as will be discussed later in the paper.

Several experimental channels are available at different locations throughout the assembly. They are depicted in figure 3. The experimental results presented in this work were measured with detectors at the locations EC1B and EC2B in the booster and EC5T in the thermal zone. Two different types of U-235 fission chambers operating in pulse mode were used, one containing 500 mg of U-235 (KNT-31) was used in the booster and other containing 1 mg of U-235 (KNT-5) was used in the thermal zone. The (D,T) neutron source was monitored with a BC501A liquid scintillator. Due to the high counting rates ($\sim 10^6$ counts/s) dead time effects were relevant. Therefore, measured counting rates were corrected to take into account this effect.

Table 1: Number of fuel elements in the different regions of Yalina-Booster during the beam trip experiments.

	Inner booster	Outer booster	Thermal zone
SC3a	132	563	1077
SC3b	0	563	1090

Table 2: Calculated values of k_{eff} (KCODE module of MCNPX) with different cross section libraries.

	SC3a	
	C.R. Out	C.R. In
ENDF/B-VII.0	0.94873 ± 0.00011	0.94588 ± 0.00015
JEFF-3.1	0.94905 ± 0.00004	0.94600 ± 0.00015
JENDL-3.3	0.94908 ± 0.00011	0.94593 ± 0.00011

	SC3b	
	C.R. Out	C.R. In
ENDF/B-VII.0	0.94851 ± 0.00011	0.94544 ± 0.00012
JEFF-3.1	0.94909 ± 0.00011	0.94584 ± 0.00012
JENDL-3.3	0.94891 ± 0.00011	0.94601 ± 0.00011

4. Steady-state reactivity monitoring

As mentioned in the introduction and in section 2.1, the current-to-flux technique is suitable only for relative reactivity measurements. Therefore, steady-state experiments have been only applied to validate the absolute reactivity determination techniques with beam trip interruptions. Steady-state experiments were performed in the two main configurations SC3a and SC3b and the two sub-configurations obtained by the insertion or extraction of the control rods. In addition, for the SC3a configuration, different intensities were explored to investigate possible effects of the neutron source intensity in the reactivity determination using beam trips. Beam trips were forced at a rate of one per second with a trip duration of about 40 ms.

It is important to notice that the accelerator beam during the experiments was not perfectly constant. As it can be observed in figure 4, a large 50 Hz oscillation in the neutron source could not be avoided. This oscillation was due to an oscillation in the deuteron beam impinging position. Nevertheless, since the period of this oscillation is much larger than the characteristic decay time of the prompt neutrons (about 1 ms) but still an order of magnitude shorter than the shortest of the decay periods of any of the delayed neutron families (between 0.23 and 55.72 s in a six group model (Hetrick (1993))), the oscillation is not expected to significantly affect the reactivity determination when it is properly time averaged.

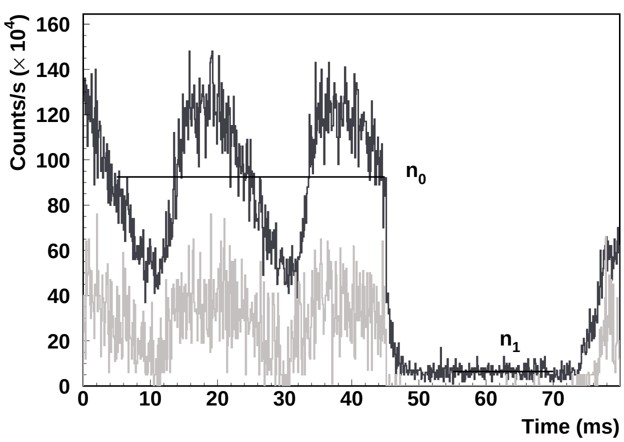


Figure 4: External neutron source (pale gray) and ^{235}U detector response (dark gray) before and during a beam trip. Both signals have been averaged over periods of 0.1 ms to reduce statistical fluctuations. Notice that the source has a strong 50 Hz oscillation, which drives the ^{235}U detector between beam trips.

4.1. Prompt decay constant method

First of all, it must be remarked that the accurate determination of the prompt neutron decay constants, that are used in the prompt decay constant method, requires large statistics. Hence, the histograms of counts per unit time after a large number of beam trips (∼ 1000) have been superimposed in order to have enough statistics. The prompt decay slopes have been obtained as shown in equation 7 simply by fitting the slope of the decay of the prompt neutrons after a beam trip to an exponential plus a constant. An adequate range for the fit must be chosen to get rid of the non point-kinetics effects present at the very first microseconds after the beam interruption. The 50 Hz oscillation described above is not expected to affect the results of the prompt decay constant method, which is only function of the neutron population just a few prompt neutron decay periods before the beam trip.

The results of the application of the prompt decay constant method are shown in Table 3, alongside with the values of the prompt neutron decay constants obtained in complementary PNS experiments in the same configuration of the system (Bécares et al. (to be published)). It must be remarked that the slopes have been found to be largely compatible, within errors, for different detector positions. There are only two exceptions that deviate considerably from the others (position EC1B with 1.2 mA beam intensity and position EC5T with 0.5 mA intensity, both in the SC3a configuration with the control rods inserted) and that can be considered spurious results.

The similarity of the prompt neutron decay slopes among different detector positions is a remarkable finding since it implies that, at least for the case of Yalina-Booster and for the detector positions investigated, the same values for the reactivity will be obtained at these detector positions, in spite of spatial effects (notice, however, that the similitude of the results at different detector positions remarked above does not necessarily imply that spatial or spectral effects are not present). Furthermore, the results are also compatible with the results obtained in PNS experiments.

From the prompt neutron decay slopes it is possible to compute the reactivity using equation 7, provided that Λ_{eff} and β_{eff} are known. However, a new methodology has been proposed (Bécares et al. (to be published)) that removes the need of knowing these two parameters and better takes into account the presence of local and spectral effects deviating from the point kinetic model. This methodology is based on the assumption that there exists a a universal relationship between the reactivity and the prompt decay slope, $\rho = \rho(\alpha)$, at least within a certain range of perturbations from a reference configuration. The existence of this functional relationship has been investigated through detailed simulations of the system with MCNPX. More specifically, we have started from a description of the assembly configuration (SC3a or SC3b), where we have calculated values for the reactivity, ρ_0, and the prompt neutron decay slope for every detector position, α_0. Then additional configurations varying some characteristic parameters (moderator density, uranium enrichment, height to width ratio) have been simulated in order to obtain a series of pairs $(\Delta\rho, \Delta\alpha)$ from which the shape of the relationship $\rho = \rho(\alpha)$ can be inferred.

Using this methodology, it has been found that, within uncertainties, the relationship $\rho = \rho(\alpha)$ can be described with a linear dependence of the shape $\rho - \rho_0 = \Lambda^* (\alpha - \alpha_0)$, with the values of α_0 and Λ^* being specific of each detector position. In particular, Λ^* is obtained from the linear fit of the pairs $(\Delta\rho, \Delta\alpha)$ obtained after perturbing several parameters from the reference configuration. An advantage of this procedure is that the dispersion of the results of Λ^* obtained from the variation of each parameter alone can be taken as a measure of the range of the systematic uncertainty in the value of Λ^*. Therefore the final error given for the reactivity (or alternatively the $k_{\rm eff}$) can include an estimate of the systematic uncertainty due to the local or spectral effects, in addition to the statistical uncertainties.

The values of $k_{\rm eff}$ thus obtained are shown in table 4, alongside with the values obtained in the PNS experiments, for comparison. As the values of α obtained in beam-trips experiments were largely compatible with the ones obtained in PNS experiments, the results of $k_{\rm eff}$ are also compatible. It can also be observed in table 4 that, with the exception of the two cases above mentioned, the results for $k_{\rm eff}$ are about 300-400 p.c.m. lower than the MCNPX results, with an uncertainty of the order of 100 p.c.m., taking into account both statistical errors and the estimated range of systematic uncertainties in Λ^*. Furthermore, the difference in $k_{\rm eff}$ due to the change in the control rods position is of the order of magnitude of the expected value (about 300 p.c.m).

4.2. Source-jerk method

The source-jerk method (equation 8) has been applied to the Yalina-Booster experiments. It is important to remark that thanks to the large statistics available for this method it was possible to determine the reactivity at every single beam trip with a precision better than 2$. An example of the distribution of the source-jerk results every beam trip for a given experiment

Table 3: Prompt decay constant results for SC3a and SC3b configurations, compared with the results of the PNS experiments

(a) SC3a configuration

Detector position	Beam intensity (mA)	Control rods extracted		Control rods inserted	
		α (s^{-1})	α_{PNS} (s^{-1})	α (s^{-1})	α_{PNS} (s^{-1})
EC1B	1.2 mA	-1059 ± 7	-1057 ± 3	-1053 ± 9	-1128 ± 4
	1.0 mA	-1042 ± 11		-1121 ± 14	
	0.5 mA	-1054 ± 10		-1126 ± 12	
EC2B	1.2 mA	-1066 ± 7	—	-1094 ± 8	-1124 ± 3
	1.0 mA	-1062 ± 9		-1105 ± 10	
	0.5 mA	-1055 ± 14		-1118 ± 15	
EC5T	1.2 mA	-1062 ± 18	-1094 ± 8	-1105 ± 21	-1134 ± 6
	1.0 mA	-1033 ± 23		-1116 ± 27	
	0.5 mA	-1050 ± 41		-1054 ± 10	

(b) SC3b configuration

Detector position	Beam intensity (mA)	Control rods extracted		Control rods inserted	
		α (s^{-1})	α_{PNS} (s^{-1})	α (s^{-1})	α_{PNS} (s^{-1})
EC2B	1.0 mA	-1035 ± 5	-1048 ± 3	-1085 ± 5	-1111 ± 3
EC5T	1.0 mA	-1034 ± 12	-1073 ± 6	-1073 ± 14	-1125 ± 6

Table 4: k_{eff} estimations from the prompt decay constant method for SC3a and SC3b configurations compared with the results of the PNS experiments.

(a) SC3a configuration

Detector position	Beam intensity (mA)	k_{eff} c.r. extracted		k_{eff} c.r. inserted		Δk_{eff} (p.c.m.)	
		BT	PNS	BT	PNS	BT	PNS
EC1B	1.2 mA	0.94545 ± 0.00063	0.94558 ± 0.00058	—	0.94119 ± 0.00103	—	438 ± 115
	1.0 mA	0.94651 ± 0.00078		0.94163 ± 0.00130		488 ± 152	
	0.5 mA	0.94579 ± 0.00078		0.94134 ± 0.00124		445 ± 146	
EC2B	1.2 mA	0.94501 ± 0.00070	—	0.94330 ± 0.00092	0.94151 ± 0.00103	171 ± 116	—
	1.0 mA	0.94529 ± 0.00076		0.94262 ± 0.00107		267 ± 131	
	0.5 mA	0.94571 ± 0.00097		0.94185 ± 0.00132		386 ± 164	
EC5T	1.2 mA	0.94513 ± 0.00117	0.94316 ± 0.00072	0.94249 ± 0.00139	0.94071 ± 0.00077	264 ± 182	245 ± 106
	1.0 mA	0.94695 ± 0.00143		0.94181 ± 0.00176		514 ± 227	
	0.5 mA	0.94587 ± 0.00258		—		—	

(b) SC3b configuration

Detector position	Beam intensity (mA)	k_{eff} c.r. extracted		k_{eff} c.r. inserted		Δk_{eff} (p.c.m.)	
		BT	PNS	BT	PNS	BT	PNS
EC2B	1.0 mA	0.94605 ± 0.00049	0.94523 ± 0.00043	0.94288 ± 0.00068	0.94123 ± 0.00067	317 ± 83	401 ± 80
EC5T	1.0 mA	0.94599 ± 0.00080	0.94354 ± 0.00055	0.94353 ± 0.00099	0.94032 ± 0.00073	246 ± 127	322 ± 92

Table 5: Source-jerk results for SC3a and SC3b configurations, compared with the results of the PNS experiments

(a) SC3a configuration

Detector position	Beam intensity (mA)	Control rods extracted		Control rods inserted	
		Source-jerk	Area-ratio (PNS)	Source-jerk	Area-ratio (PNS)
EC1B	1.2 mA	15.17 ± 0.03	15.31 ± 0.03	17.99 ± 0.03	17.64 ± 0.04
	1.0 mA	15.63 ± 0.03		18.26 ± 0.04	
	0.5 mA	16.12 ± 0.04		18.65 ± 0.05	
EC2B	1.2 mA	13.75 ± 0.02	—	15.37 ± 0.03	15.63 ± 0.03
	1.0 mA	14.02 ± 0.03		15.66 ± 0.04	
	0.5 mA	14.61 ± 0.04		16.31 ± 0.04	
EC5T	1.2 mA	8.89 ± 0.06	8.70 ± 0.06	9.68 ± 0.07	9.44 ± 0.04
	1.0 mA	9.01 ± 0.08		9.64 ± 0.08	
	0.5 mA	9.07 ± 0.09		9.99 ± 0.09	

(b) SC3b configuration

Detector position	Beam intensity (mA)	Control rods extracted		Control rods inserted	
		Source-jerk	Area-ratio (PNS)	Source-jerk	Area-ratio (PNS)
EC2B	1.0 mA	13.84 ± 0.02	13.92 ± 0.02	15.45 ± 0.02	15.28 ± 0.03
EC5T	1.0 mA	9.39 ± 0.04	9.26 ± 0.04	10.22 ± 0.04	10.07 ± 0.05

Table 6: k_{eff} estimations from the source-jerk method for SC3a and SC3b configurations, compared with the results of the PNS experiments.

(a) SC3a configuration

Detector position	Beam intensity (mA)	k_{eff} c.r. extracted		k_{eff} c.r. inserted		Δk_{eff} (p.c.m.)	
		SJ	PNS	SJ	PNS	SJ	PNS
EC1B	1.2 mA	0.94710 ±0.00041	0.94674 ±0.00056	0.93961 ±0.00183	0.94053 ±0.00199	749 ± 188	621 ± 172
	1.0 mA	0.94587 ±0.00063		0.93890 ±0.00197		697 ± 207	
	0.5 mA	0.94457 ±0.00087		0.93786 ±0.00217		671 ±234	
EC2B	1.2 mA	0.94713 ±0.00044	—	0.94225 ±0.00149	0.94147 ±0.00199	488 ± 155	—
	1.0 mA	0.94631 ±0.00060		0.94139 ±0.00168		492 ± 179	
	0.5 mA	0.94452 ±0.00099		0.93944 ±0.00212		508 ± 234	
EC5T	1.2 mA	0.94422 ±0.00072	0.94534 ±0.00078	0.93964 ±0.00111	0.94104 ±0.00112	459 ± 132	430 ± 114
	1.0 mA	0.94353 ±0.00082		0.93991 ±0.00112		362 ±138	
	0.5 mA	0.94319 ±0.00089		0.93789 ±0.00129		530 ± 158	

(b) SC3b configuration

Detector position	Beam intensity (mA)	k_{eff} c.r. extracted		k_{eff} c.r. inserted		Δk_{eff} (p.c.m.)	
		SJ	PNS	SJ	PNS	SJ	PNS
EC2B	1.0 mA	0.94930 ±0.00032	0.94908 ±0.00035	0.94474 ±0.00083	0.94521 ±0.00088	456 ± 89	386 ± 80
EC5T	1.0 mA	0.94160 ±0.00083	0.94236 ±0.00093	0.93671 ±0.00127	0.93759 ±0.00146	489 ± 152	477 ± 143

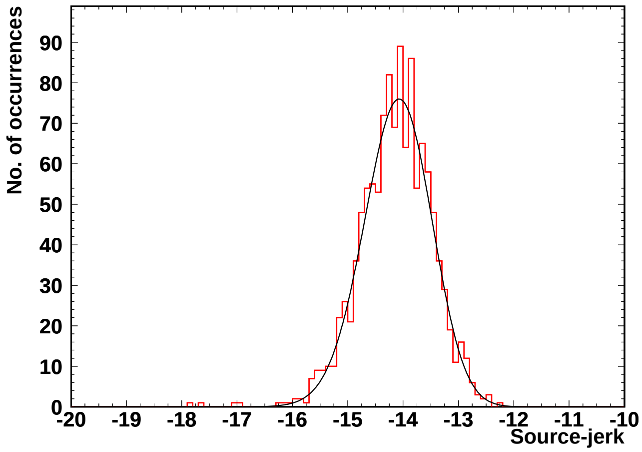


Figure 5: Distribution of source-jerk results every beam trip for a given experiment (SC3a configuration with the control rods extracted; EC2B position). The fit to a lognormal distribution is plotted alongside.

is presented in figure 5. This might be an advantage with respect to the prompt decay constant method, that needs much higher system power to allow single beam trip determination of the reactivity with the same precision.

The 50 Hz oscillation in the beam already mentioned should not affect the results of the source-jerk technique, since the half lives of the different families of delayed neutrons are much longer than the period of the oscillation. Thus the delayed neutron level n_1 is determined by the average neutron flux. Consequently, the prompt neutron level n_0 will be determined by the average neutron flux over one or several oscillation cycles before the beam trip.

Other aspect to take into account when applying the source-jerk technique is that beam interruptions reduce the effective neutron source. In the case of the experiments at Yalina-Booster presented here, there was a beam trip of about 40 ms every second, that is, the source is down 4% of the time. To take this effect into account, a duty cycle factor ξ is defined as the fraction of time the accelerator is working at average intensity. Equation 8 then becomes:

$$\rho\,(\$) = -\xi\frac{n_0 - n_1}{n_1} \qquad (9)$$

with an estimated value, from the previous argument, of $\xi \simeq 0.96$.

In table 5, the experimental results obtained with the source-jerk technique are presented. It also includes, when available, the results obtained with the PNS area-ratio technique for comparison purposes. Comparing the results from different detectors, it is found that the differences between results at different detector positions can reach a factor of up to two. These large differences are due to spatial effects. Spatial effects are expected to affect any subcritical assembly to a greater or lesser extent and in the case of Yalina-Booster they have already been found to largely affect the area-ratio technique in PNS experiments (Berglof et al. (2010); Bécares et al. (to be published)). Hence, the application of corrections methods to obtain values for the reactivity of the system becomes mandatory. Since the source-jerk technique is equivalent to the area ratio technique applied to a source interruption instead of a source pulse, the same correction method described in Bécares et al. (to be published) has been used for the source jerk experiments.

Therefore, a linear relationship between the variations of the reactivity and the source-jerk result has been considered, $\rho - \rho_0 = \beta^* \left((n_0/n_1) - (n_0/n_1)_0\right)$ for configurations close enough (small $\Delta(n_0/n_1)$) to the reference configuration with $((n_0/n_1), \rho_0)$. As in the prompt decay constant method, the parameter β^* is evaluated from the linear fit of the pairs $(\Delta(n_0/n_1), \Delta\rho)$ obtained after perturbing several parameters from the reference configuration. The systematic uncertainty due to spatial or spectral effects can be estimated from the dispersion of the results of β^* obtained after the individual variation of each parameter.

The results of the application of this method are presented in table 6. It can be observed that after this correction the dispersion in the k_{eff} results is considerably reduced.

The k_{eff} values obtained are largely compatible with the PNS area-ratio method. Still, the results obtained with the source-jerk technique show systematically a larger variation between detector positions than the results of the prompt decay constant method.

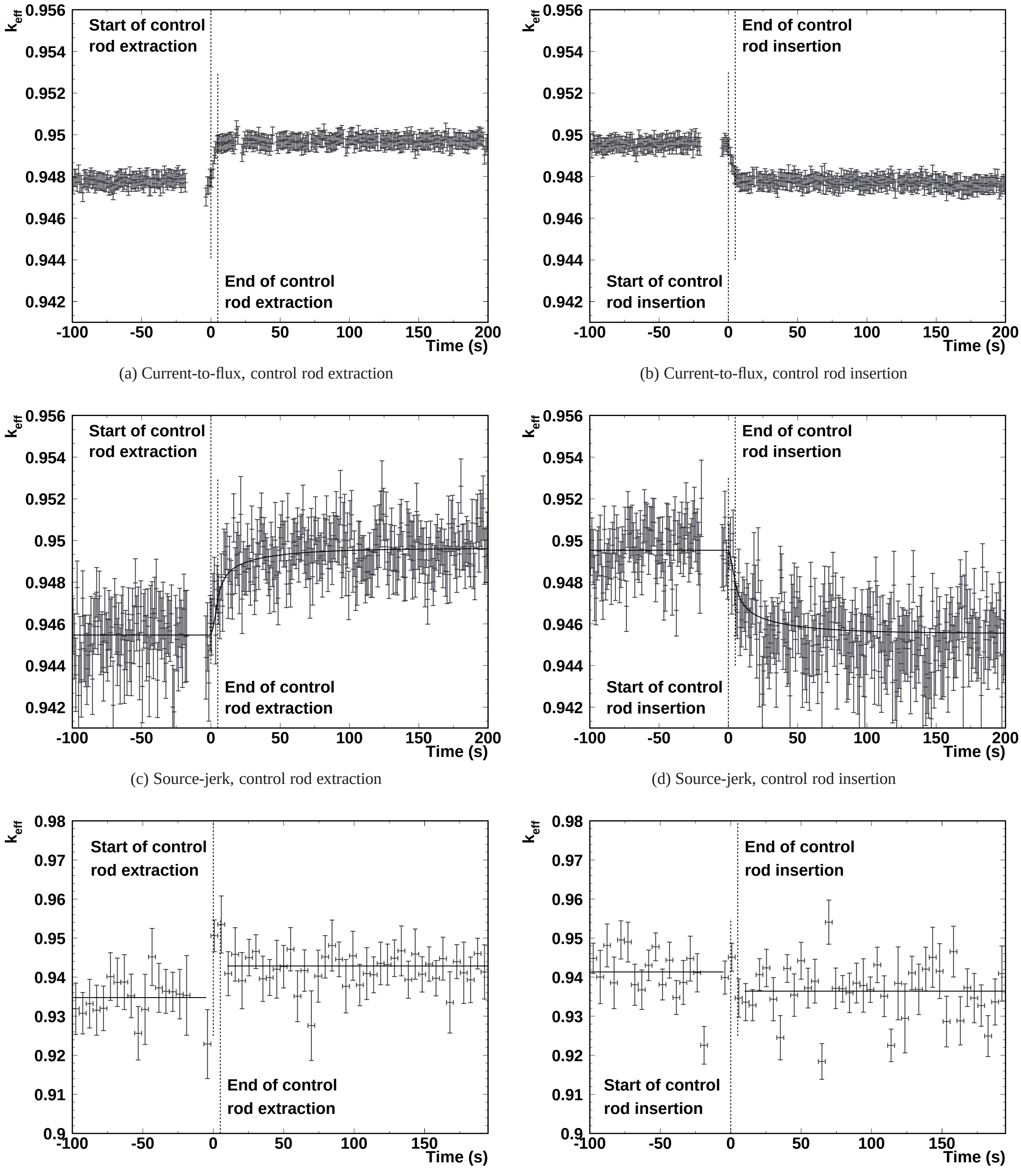
The difference in reactivity between the results with the control rods inserted and extracted for a certain detector (about 400-500 p.c.m in most cases) is somewhat larger than the expected value from the MCNPX simulations (300 p.c.m) and from the prompt decay constant method. However, the uncertainty in the results is too large for being conclusive (considering both statistical errors and uncertainties in β^*).

It is interesting as well to remark that a dependence of the reactivity with the source intensity can be noticed, particularly in the detector at the EC1B position, which was the one with the highest counting rate. Although this dependence is rather small (less than one dollar), it is always in the same sense, showing lower values of the reactivity as the source intensity increases, making it unlikely to be only statistical fluctuations. Several explanations for this behavior are being evaluated. In principle, the most likely explanation seems to be an incomplete correction of the dead time effects, but there are other possible causes, such as spectral effects due to different relevance of the D-D reactions with the beam intensity (due to different distribution of the tritium or the implanted deuterons in the target, for instance). The lack of information on the neutron generator target components does not allow to confirm or reject any of these explanations, but it can be worth mentioning it to help in future experiments such as the FREYA experiment at the VENUS facility of the Belgian SCK-CEN.

5. Reactivity monitoring during system perturbations

5.1. Fast variation of the system reactivity

To determine the capability to measure the reactivity and detect changes during a fast variation in the reactivity of the system, a series of experiments have been performed in the SC3b



(a) Current-to-flux, control rod extraction

(b) Current-to-flux, control rod insertion

(c) Source-jerk, control rod extraction

(d) Source-jerk, control rod insertion

(e) Prompt neutron decay constant, control rod extraction

(f) Prompt neutron decay constant, control rod insertion

Figure 6: Reactivity values measured using the current-to-flux, source-jerk and prompt neutron decay constant techniques during the fast movement of the control rods in SC3b configuration. The detector is located in the EC2B position in the booster region.

Table 7: Estimates of the k_{eff} changes due to control rod movement (p.c.m.) observed by different techniques (SC3b configuration; detector position EC2B (booster zone)).

	Control rod extraction	Control rod insertion
Current-to-flux	194 ± 8	-194 ± 8
Source-jerk	416 ± 81	-399 ± 80
Prompt decay constant	808 ± 182	-492 ± 182
MCNPX (ENDF/B-VII.0)	307 ± 16	

configuration inserting and extracting the control rods. During these experiments, a beam trip per second was still produced. Hence, it was possible to apply both the current-to-flux and the beam trip techniques (source-jerk and prompt decay constant) to determine the reactivity during control rods movement. For the cases of the source-jerk and the prompt decay constant methods, the same methodologies described in section 4 have been applied to translate the experimental results into criticality constant and the uncertainties given include statistical as well as an estimate of the error due to systematic effects. The current-to-flux technique, for its part, has been applied using the approximate equation 6 (i.e., considering that the factor $\frac{\epsilon_D \varphi^*}{\epsilon_S}$ does not change as a result of the change of configuration caused by the movement of the control rods) and using as reference k_{eff} for calibration the source-jerk results before the control rod insertion.

The results are shown in Figure 6. With the current-to-flux and the beam trip techniques the reactivity has been monitored with a resolution of 1 second, corresponding with the beam trip frequency, while with the prompt decay constant method data of five consecutive beam trips have been accumulated to reduce statistical fluctuations. All three techniques allow detecting the change of k_{eff} before and after the control rods movement and allow having estimates of Δk_{eff} (table 7) compatible with the values measured in steady state (tables 4 and 6) and of the order of magnitude of the MCNPX estimate.

The current-to-flux technique is less affected by statistical fluctuations than the other two techniques, which allows higher monitoring frequencies. This is due to the large statistics that can be accumulated with both the flux and source monitoring detectors. In the present case of Yalina-Booster, the current-to-flux technique allows following the control rods during their movement with good statistical uncertainty, as it is evident in figures 6a and 6b. In a power ADS with larger statistics higher monitoring frequencies may be possible. The measured k_{eff} change between the two control rods positions has been found to be about 200 p.c.m., lower than the MCNPX result (300 p.c.m) and the changes measured with the source-jerk and the prompt decay constant technique (table 7). It must be taken into account that in addition to the statistical errors, systematic errors due to local effects are also present. These local effects have been neglected by assuming that the factor $\frac{\epsilon_D \varphi^*}{\epsilon_S}$ remains constant during the control rod movement.

Actually, it is possible to estimate the variation of the factor $\frac{\epsilon_D \varphi^*}{\epsilon_S}$ with the control rod position using MCNPX. If we consider that ϵ_S does not depend on the control rod position (which is normally true), equation 5 becomes:

$$\Delta k_{eff} = \left(1 - k_{eff,1}\right)\left(1 - \frac{\epsilon_{D2}\varphi_2^*}{\epsilon_{D1}\varphi_1^*}\frac{M_1/R_1}{M_2/R_2}\right) \tag{10}$$

The factor $\frac{\epsilon_{D2}\varphi_2^*}{\epsilon_{D1}\varphi_1^*}$ can be determined with MCNPX using equation 4, expressed in terms of M_1/M_2:

$$\left(\frac{\epsilon_{D2}\varphi_2^*}{\epsilon_{D1}\varphi_1^*}\right)_{MCNP} = \frac{(1 - k_{eff,2})}{(1 - k_{eff,1})}\frac{M_2/S_2}{M_1/S_1} \tag{11}$$

Using equation 10 it has been observed that the variation in Δk_{eff} measured with the current-to-flux method increases in 60 p.c.m, which is enough to explain most of the difference with the expected value of about 300 p.c.m.

The source-jerk technique also allows obtaining an estimate of the reactivity every trip, although the low statistics in the determination of the delayed neutron level n_1 causes larger uncertainties than the current-to-flux technique. Another important remark is that the source-jerk technique requires some time for the delayed neutrons level to stabilize after a reactivity change. From the figure it can be observed that while the control rod extraction takes about 6 seconds to complete, the source jerk estimation of k_{eff} takes more than 50 seconds to fully adapt to the new value, due to the time required by delayed neutrons to stabilize to their new level. The continuous line represents the theoretical evolution of the source-jerk results obtained solving the point kinetics equation, where the initial and final value of the k_{eff} have been fixed to the experimental values. The experimental data follow closely the theoretical model. Hence, it is necessary to stress that the source-jerk technique will underestimate the k_{eff} for some time after a k_{eff} increase and it will overestimate it for some time after a decrease, which has to be taken into account for safety analysis.

Finally, the prompt decay constant technique has much larger statistical errors than the source jerk technique, even averaged over 5 seconds time intervals, and it is difficult to distinguish the effect of the control rod position due to statistical fluctuations. This limits the maximum frequency of reactivity monitoring, although this may not be an issue in a power ADS, where much larger statistics will be available. However, as it is based on prompt neutrons only, the prompt decay constant method should not be affected by the slow adaptation to a new value of k_{eff} after a reactivity change as it was the case of the source-jerk technique and therefore it should be capable of providing a fast monitoring capacity. Nevertheless, the statistics of the Yalina-Booster experiments do not permit to confirm it.

5.2. *Fast variation of the neutron source*

In addition to the fast movement of the control rods, during the Yalina-Booster experiments it was also possible to determine the capabilities of the reactivity monitoring techniques to measure the reactivity after a long (several seconds) beam trip interruption. This is equivalent to a fast variation of the beam power.

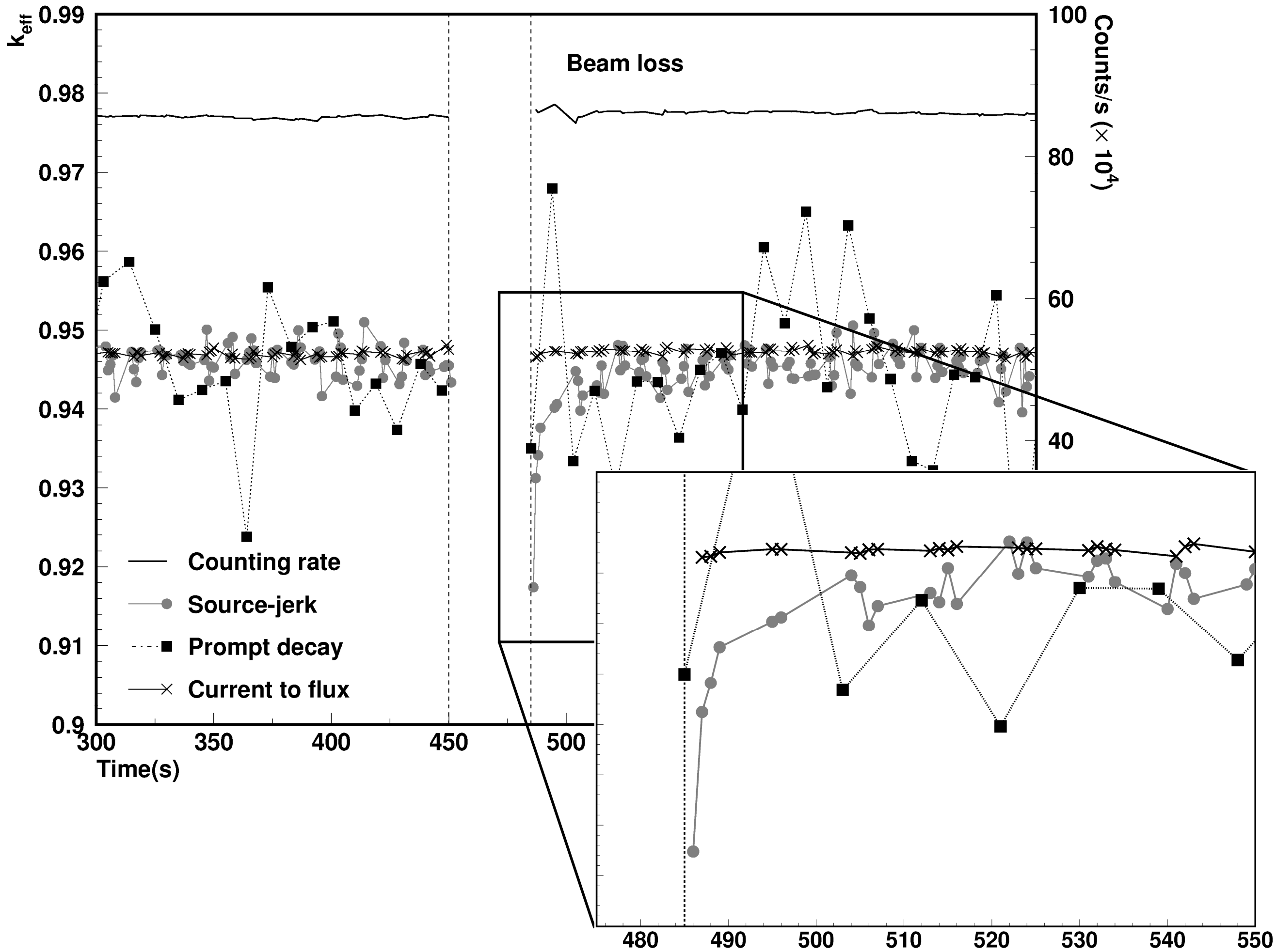


Figure 7: Corrected values of the reactivity obtained by the source jerk method and the prompt decay constant method during one experiment, alongside with the counting rate during these periods and the current-to-flux reactivity monitoring. The reason why the points are not equidistant is because the data acquisition system required some time to write the measured data in the hard disk during which additional data could not be measured.

In Figure 7 it is shown the reactivity monitoring during more than 1000 seconds of the Yalina-Booster reactor in the SC3a configuration. In the experiment, the beam was lost for approximately 30 seconds and recovered afterward. It can be observed that both the current-to-flux and the prompt neutron decay constant techniques (in the last, beam trips every 10 seconds have been accumulated to increase statistics) continue providing the same estimation of the k_{eff} after the beam recovery following the interruption. On the other hand, as it was already explained in section 5.1, the delayed neutrons require about 50s to stabilize after a modification of the reactor conditions or the power level and hence the source-jerk method requires this time to provide correct values for the reactivity. This effect must be taken into account if it is intended to apply the source-jerk technique for monitoring the reactivity in non-steady conditions.

6. First measurements of a beam trip experiment using current mode detection

As we have seen in previous section, in order to have an acceptable statistical uncertainty during a single beam trip experiment, very high counting rates are required. In fact, it would be desirable that for a single beam trip, the prompt decay method uncertainty, which in general will be affected by a larger uncertainty than the source jerk method, remains below 0.5 dollars.

However, above a given counting rate, dead time effects become important and achieving this uncertainty is not feasible using pulsed mode electronic chains. A typical solution to avoid dead time effects while increasing the detection rate consists in the use of detectors operating in current mode detection. In this mode, instead of identifying single detection events, the overall electric current is measured.

In this section, the description of the electronic chain developed to perform the first measurements, to our knowledge, of a beam trip using a current mode electronic chain will be presented.

6.1. Experimental setup

Due to the very short time interval of a beam trip, usually a few milliseconds, the current-mode electronic chain for the Yalina-Booster experiments was designed keeping in mind the following minimum specifications:

1. Bandwidth of 10 MHz to ensure that all the effects at the mean neutron generation lifetime level are respected.
2. A sampling rate of at least 1 MSample/s, which is required to have enough points for fitting the prompt decay.
3. 12-bit ADC resolution, which ensures a 1% precision for samples in the lower part of the beam trip.

The requisites enumerated above excluded usual nuclear power plant electronic chains, with bandwidths in the kHz range. Hence, it was necessary to design a whole new electronic chain to be used in Yalina-Booster. The system consisted of a modified large 500 mg ^{235}U fission chamber, a linear fast current amplifier and a 14-bit 125MSample/s fast ADC (Gage Octopus) connected to a PC.

The main challenge of this setup was the current to voltage conversion. It was necessary to design a specifically dedicated module interposed between the high voltage source and the detector. This module derived the high voltage of the fission chamber to the carcase of the detector instead of the wire, which remained at 0 V, and therefore, it could be connected to a the commercial fast current amplifier (Femto DHCPA-100).

It is worth noting that this solution presents many problems that had to be solved. First, since the high voltage is in the carcase of the detector, we had to use an isolator surrounding the detector. Second, the electronic pick-up noise increases drastically due to the antenna effect. As we will show next, at the current level generated in the detector, 1 μA, this last effect reduced largely the signal-to-noise ratio.

6.2. Results

Figure 8 shows a single beam trip measured with a 500 mg ^{235}U current mode detector in the MC2 position (reflector region) in SC3a configuration. The deuteron accelerator was prepared to produce a continuous 1 mA deuteron current with beam trips of about 40 ms duration. It can be observed that the average current level in the detector is approximately 0.5 μA, which, according to detector specifications, corresponds to 5×10^5 fissions/s, in agreement with the fission rate at this position.

The detector current was measured using a 1 MHz low pass filter in the current amplifier and a sampling rate of 10 MSample/s. The low pass filter was necessary to reduce the large pick-up noise that can be appreciated in figure 8. In addition to the hardware filter, two types of data processing filtering have been tested, a median average filter and a simple average filter. It has been observed that both filters provide compatible results. The result of a 100 kHz simple average filter is shown in figure 8. As expected, the large oscillation of the neutron source is clearly appreciated. It is important to remark that in a power reactor the detector current is expected to be three orders of magnitude larger while the electronic noise remains basically constant.

To compare the result obtained using the current mode detector with the pulsed mode detectors, we have performed a source-jerk estimation of the reactivity. The total and delayed neutron densities have been determined from the best fit of the current in the detector to a constant level. In a similar way than for pulsed mode detectors, the large 50 Hz oscillation of the core power has been averaged for a complete cycle so it is not affecting significantly the mean value. In this particular case, the source jerk ratio value was 7.3 ± 0.6$ before spatial corrections, being the first time that the reactivity of a subcritical core is determined within a single beam trip using current mode detectors. This value is compatible with the standard PNS area-ratio method 7.23 ± 0.01$ (Bécares et al. (to be published)) for MC2 detector. It is worth noting that gamma background on the detector can bias the result of the source jerk. However, the effect in Yalina-Booster experiments is much lower than the uncertainty of the measurement.

In the case of the prompt decay constant method, the result of the fit is highly affected by the 100 kHz filter, so no conclusion can be obtained.

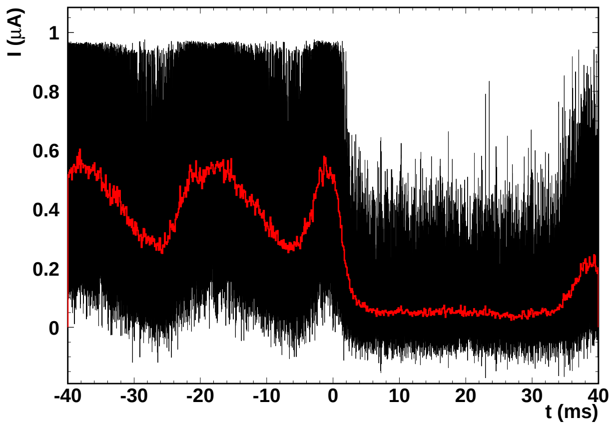


Figure 8: Beam trip measured with a detector in current mode located at the reflector region in SC3a configuration. The detector current was measured using a 1 MHz low pass filter and a sampling rate of 10 MS/s. We can appreciate the large fluctuations produced by the pick-up noise and the result of a 100 kHz first order filtering.

7. Conclusions

One of the requirements to license and operate an industrial ADS is the ability to monitor the reactivity of the system during operation. In this work the experimental demonstration of different techniques to determine the reactivity of a quasi-continuous accelerator driven subcritical core carried at the Yalina-Booster facility has been presented.

Yalina-Booster is a partially coupled fast-thermal assembly which allows testing reactivity monitoring techniques in a practical assembly where spatial effects are present. Two different situations have been analyzed: when the system is in a steady state and during system perturbations.

Three different techniques for reactivity determination have been applied: the current-to-flux technique, the prompt decay constant technique and the source-jerk technique. The current-to-flux technique is the most likely to be used for continuous reactivity monitoring in a large-scale ADS since it only requires the system operating in a steady state. However, this technique can not provide absolute reactivity measurements and it is largely dependent on having a stable external neutron source. Furthermore, to measure the reactivity difference between two different configurations, it requires that either the parameter $\frac{\epsilon_D \varphi^*}{\epsilon_S}$ is conserved between the two configurations or that it is possible to determine its variation between these two configurations (e.g. through detailed Monte Carlo simulations). Hence, this technique has been applied only to monitor the change in the reactivity during system perturbations, more specifically, during the fast movement of the control rods and fast variations of the neutron source. The current-to-flux technique has been found to be able to precisely track the control rod movement within one-second intervals and should work even at higher rates.

The other two techniques, namely the prompt decay constant technique and the source-jerk technique, are both capable to provide absolute reactivity measurements and hence they are able to complement the relative reactivity measurements with the current-to-flux technique. Hence, in addition to for monitoring the reactivity during system perturbations, they have been applied to obtain absolute reactivity values with the system in a steady state.

The prompt decay constant technique and the source-jerk technique are based in analyzing the system response to short beam interruptions (beam trips or induced interruptions). Both techniques are based on the point kinetic model and are, respectively, equivalent to the prompt neutron decay constant and the area ratio and techniques applied in PNS experiments. Because both techniques are based on the point kinetic model, they will be affected by spatial and spectral effects in a practical system. The same correction techniques based on detailed Monte Carlo simulations already validated in PNS measurements have been used to take into account these effects. Once corrected, both the prompt decay constant and the area-ratio techniques provide largely compatible results for the reactivity and compatible with the values obtained with the PNS experiments.

In comparing the source-jerk and the prompt decay constant techniques, it has been found that for the neutron flux of level of Yalina-Booster the source-jerk technique provides more precise data than the prompt-decay constant technique and thus allows monitoring the reactivity during fast variations of the reactivity or the assembly power. In the case of Yalina-Booster, the source-jerk method is precise enough to monitor the reactivity every second. However, for more powerful ADS with higher flux levels both the source-jerk and the prompt decay constant techniques could reach similar levels of precision. The drawback of the source-jerk technique is that it requires some time for delayed neutrons to stabilize after fast variations of the reactivity or the assembly power and hence it requires some time to provide correct reactivity values after a system perturbation while the current-to-flux and the prompt neutron decay constant method can be applied during and immediately after the perturbation. Hence, our recommendation is to use both the source-jerk and the prompt decay constant methods for the interim calibration of the reactivity, and use the current-to-flux technique for the continuous monitoring of the reactivity.

Finally, the first results of a beam trip experiment measured with a current mode detector have been presented. This mode of operation is more likely to be used during ADS power operation since the detector can operate at much higher detector rates, which reduces the uncertainty in the source-jerk and prompt decay constant estimations of the reactivity. Our estimations indicate that operating at $\sim$ 500μA (1000 times more than in Yalina-Booster) could be enough for determining the reactivity per beam trip with sufficient accuracy. This will ensure that the current-to-flux method can be re-calibrated instantaneously.

8. Acknowledgments

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