Reactivity monitoring of a subcritical assembly using beam-trips and current-mode fission chambers: The Yalina-Booster program

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Abstract. Transmutation of spent nuclear fuel in Accelerator-Driven Systems (ADS) is considered as a key technology for achieving sustainable nuclear energy. In the design of future ADS facilities, the reactivity monitoring system is of highest importance. An extensive experimental program devoted to reactivity monitoring of ADS has been carried out at the subcritical facility YALINA-Booster in the framework of IP-EUROTRANS. The main objective, besides the qualification of the reactivity monitoring techniques, has been to develop electronic chains that can be used in a full power ADS. For this purpose, YALINA-Booster couples a D-T neutron generator to a flexible zero-power subcritical assembly with a coupled fast-thermal neutron spectrum. The high intensity of the accelerator and the possibility to work in continuous or pulsed mode allowed the study of the current-to-flux relationship, beam-trip experiments and dedicated experiments for loading and start-up procedures. In addition, the experimental facility provided the opportunity to test electronic chains in current mode, which correspond to the most probable condition in a full power ADS. The experimental program has mainly been focused on the current-to-flux and beam-trip methodologies using detectors operating either in current or pulsed mode. However, in order to achieve the reference reactivity values of the different loading configurations, an extensive set of measurements based on pulsed neutron source techniques has been carried out. In addition, neutron noise measurements have also been performed. These studies are presented in separated papers within this conference. At present, the experimental campaign has been finished and, for the first time, the reactivity of a subcritical system has been measured within a single instantaneous beam trip (~20 ms) using fission chambers operating in current mode. The necessary electronic chains to operate the fission chambers in this mode have been developed at CIEMAT. The preliminary results of our analysis show that the reactivity values obtained applying the Sjöstrand method and the slope-fit method using data from current-mode detectors are compatible with those obtained when using standard pulsed-mode detectors (presented also in this conference). The validity of the reactivity determination methods using fission chambers operating in current mode has been stated.

1. Introduction

In the design of future ADS facilities, the reactivity monitoring system is of highest importance. Hence, an extensive experimental program devoted to reactivity monitoring of ADS has been carried out at the subcritical facility YALINA-Booster in the framework of IP-EUROTRANS [1]. Two main objectives focus these experiments, the qualification of the reactivity monitoring techniques and the development of electronic chains that can be used in a full power ADS. For this purpose, YALINA-Booster couples a D-T neutron generator to a flexible zero-power subcritical assembly with a coupled fast-thermal neutron spectrum. The high intensity of the accelerator and the possibility to work in continuous mode allowed the study of the current-to-flux relationship [2] and the beam-trips techniques. In addition, the availability of large fission chamber detectors (500 mg) provided the opportunity to test electronic chains in current mode detection, which correspond to the most probable detector operation mode in a full power ADS.

Although the main technique foreseen to monitor reactivity variations in a ADS is the current-to-flux relationship, it can only provide relative changes. Hence, in order to determine the absolute reactivity level of the system, we can take profit of short imposed beam interruptions in the millisecond scale, thus providing the possibility for applying the Source-Jerk method [2] and prompt decay constant method [2] to determine the reactivity within few milliseconds.

The standard pulsed electronic chains used in previous experimental campaigns such as MUSE-4 [3] will not be useful in a full power subcritical core due to dead time effects[1]. It is then a challenge to develop the necessary tools to measure the reactivity in a subcritical reactor using detectors operating in current mode and also to test whether the standard methods for reactivity determination can be also used in current mode.

2. Experimental set-up

The experimental set-up used in this work was made up by a subcritical fast-thermal reactor, a neutron generator feeding the nuclear core with the necessary neutrons and several detectors to determine the neutron flux intensity at several locations within the core. In what follows, each part of the experimental set-up will be briefly described.

2.1. Neutron Generator

For the experiments presented here, we have used the NG-12-1 neutron generator [4], which accelerates a deuteron beam impinging on a Ti-T target to produce a quasi-isotropic neutron energy spectrum of 14 MeV fusion neutrons. With a diameter of 45 mm, the target is located in the centre of the core. The neutron generator can be operated in both continuous and pulse modes and gives thereby the possibility of performing both pulsed neutron source (PNS) measurements and continuous wave measurements. Moreover, the continuous wave can be promptly interrupted (~1 µs) followed by a fast beam restart. In this way, short repeated beam trips can be induced intentionally with interruption times in the millisecond scale. The maximum beam current in continuous mode is around 1.5 mA giving a maximum neutron yield of approximately 10^{11} neutrons per second.

2.2. YALINA-Booster Core

The YALINA-Booster core [5], depicted in *FIG. 1*, consists of a central lead zone (booster), a polyethylene zone, a radial graphite reflector and a front and back biological shielding of borated polyethylene. The booster zone has been loaded with two different arrangements, which will be described below.
The fast-spectrum lead zone and the thermal-spectrum polyethylene zone are separated by a so called thermal neutron filter, or valve zone, consisting of one layer of 108 pins with metallic natural uranium and one layer of 116 pins with boron carbide (B_4C), which are located in the outermost two rows of the fast zone. Hence, thermal neutrons diffusing from the thermal zone to the fast zone will either be absorbed by the boron or by the natural uranium. In this way, a coupling of mainly fast neutrons between the two zones is maintained. The three B_4C-control rods that can be inserted in the thermal zone have allowed us to slightly change (-0.5$) the reactivity of the system. Hence, the sensitivity of the different reactivity monitoring techniques can be tested.
In this experimental campaign we have used two different core configurations with similar k_{eff} values, but very different source multiplications:

- SC3a configuration: using 695 36% enriched UO_2 pins while the polyethylene zone is loaded with 1077 fuel pins of UO_2 using an enrichment of 10%. This configuration has a k_{eff} ~0.95.

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[1] Results obtained with pulsed mode electronic chain are also presented in this conference [8].

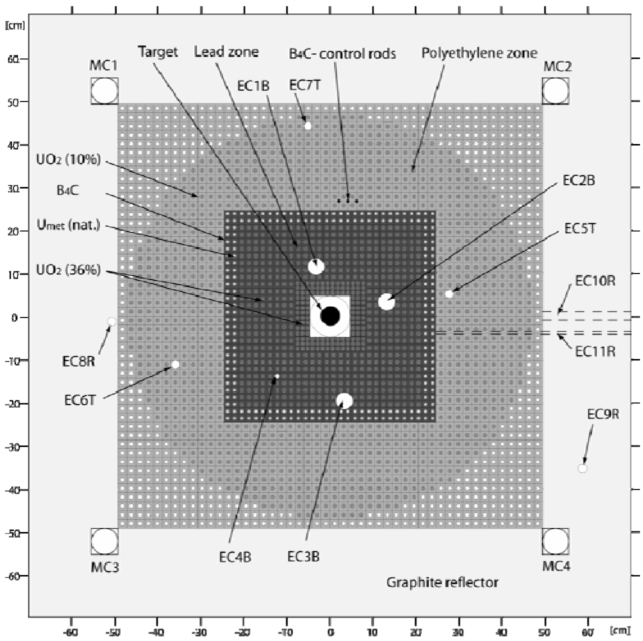

Fig. 1. Schematic cross-sectional view of the YALINA-Booster reactor core for the SC3a configuration. SC3b differs mainly in the inner booster, where no fuel pins are loaded.

- SC3b configuration: using 563 36% enriched UO_2 pins while the polyethylene zone is loaded with 1090 fuel pins of UO_2 using an enrichment of 10%. This configuration has also a k_{eff} ~0.95.

There are seven axial experimental channels (EC1B-EC4B and EC5T-EC7T) in the core, two axial (EC8R and EC9R) and two radial experimental channels (EC10R and EC11R) in the reflector. In addition, there is one neutron flux monitoring channel in each corner of the core (MC1-4) and outside the reactor (Y.T. not shown in the figure).

2.3. Neutron detectors

Two types of detectors were placed in these experimental channels to monitor the neutron flux, ^{235}U fission chambers and ^{3}He detectors. Both pulsed mode electronic chains and current mode electronic chains have been used throughout the experiments. Unfortunately, current mode measurements were only possible in the reflector region due to the strong pick-up noise induced by the accelerator in the booster region.

In order to measure the fast variations in the neutron population after a beam trip, the current in the fission chambers was sampled in the MHz range. Even more, to obtain a good uncertainty in the measurements, it was necessary to use 14-bit resolution. For this reason, it has not been possible to use the standard electronic chains used in power reactors, where the sampling rate is much lower. It has to be pointed out that to use this arrangement, the polarity of the fission chambers must be inverted in order to be able to use commercial fast current amplifiers. Due to this polarity inversion, the chambers are no longer shielded and the level of the pickup noise was not negligible. It is important to stress that due to the relatively low intensity of the source, the current in the 500 mg ^{235}U fission chamber was 1 μA at maximum, what obliged us to use amplification factors of 10^5-10^6 V/A in the current amplifier.

The acquisition system used in the YALINA experiments has been based on fast ADC modules. We have used 14-bit digitizers with 125 MHz sampling rate. However, detector signals were measured at 10 MHz sampling rate and filtered afterwards with a 100 kHz low-pass filter to reduce electronic noise introduced in the signal due to the large amplification.

This situation is unlikely to happen at high power, when the current in the detector is usually three orders of magnitude larger and the amplification of pick-up noise should become negligible.

3. Reactivity monitoring during the beam trips

The use of beam trips presents a powerful advantage as compared with the standard PNS methods, since we can take profit of the unavoidable (or forced) beam loses during the accelerator operation to determine the reactivity value. There exist two main methods to determine the reactivity value of a subcritical core after a beam trip. First, using the source-jerk technique; second, studying the prompt neutron decay after the source suppression [2].
In *FIG. 3* we can observe an example of a beam trip obtained during YALINA-Booster experiments. In this figure, the deuteron accelerator current (black line) is suddenly removed at a time t=40 ms and recovered again at a time t=72 ms. The evolution of the neutron density is measured with a ^{235}U fission chamber operating in current mode (blue line) and located in the MC4 experimental channel, in the reflector zone of the subcritical core. As can be observed, the decay of the neutron population follows point kinetic model and reaches a ground current level given by the delayed neutron population.

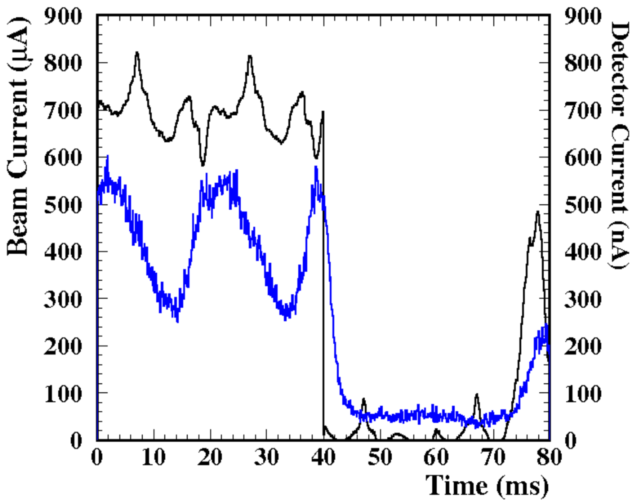

Fig. 3. Time evolution of a typical YALINA-Booster beam interruption (beam trip). The deuteron accelerator current (black line) is promptly interrupted. The time evolution of the current measured with a fission chamber is also shown within the same time interval (blue line).

3.1. Source-jerk results

The source jerk technique is based on the determination of the ratio between prompt neutrons and delayed neutrons after removal of the prompt neutron source. The theoretical basis of this method relies on the point-kinetic model. If we consider a sub-critical system which is maintained at equilibrium neutron density (n_t) by an external source S, the neutron balance equation of this system will be given by:

$$\left(\frac{\rho-\beta}{\Lambda}\right)n_t+\sum_{i=1}^{6}\lambda_i C_{i,0}+S=0$$

Where $C_{i,0}$ are the delayed neutron precursor population at equilibrium. If the external neutron source is suddenly removed, within a few prompt neutron lifetimes the system will adjust to a lower neutron density n_d. Immediately after the source jerk, the delayed neutron precursor population will still be the same as before the source jerk. Thus, the neutron balance equation after the source jerk will be given by:

$$\left(\frac{\rho-\beta}{\Lambda}\right)n_d+\sum_{i=1}^{6}\lambda_i C_{i,0}=0$$

Using both expressions, the reactivity (in units of β) can be expressed as follows:

$$\frac{\rho}{\beta}=\frac{n_d-n_t}{n_d}$$

The total and delayed neutron densities -n_t and n_d, respectively- have been determined from the best fit of the current in the detector to a line (*FIG. 4*). Despite of the large 50 Hz oscillation of the core power, the mean value of the oscillation is quite stable and it can be demonstrated that, actually, the main uncertainty source in the reactivity determination is given by the statistical fluctuations in the delayed neutron level n_d.

FIG. 4 corresponds to a fission chamber located in the reflector zone of the subcritical core, in the MC4 experimental channel for the SC3a configuration. In this particular case, the deuteron accelerator was prepared to produce a beam-trip of approximately 30 ms length, obtaining a reactivity value of 7.3 ± 0.6 $, being the first time that the reactivity of a subcritical core is determined within a single beam trip. This value can be compared with that obtained by means of standard PNS Sjöstrand method [6], also presented in this conference [7]. In that case we got a reactivity value of 7.23 ± 0.03 $. Although the uncertainty of the beam-trip method is larger than using the PNS technique, it must be taken into account that to obtain a PNS value several minutes are required, while just a few milliseconds are required for the beam trip method and the experiment can be repeated as much as one per second.

Such a sequence is shown in *FIG. 5*. The deuteron accelerator was prepared to produce a beam-trip of approximately 30 ms length with 1 Hz repetition rate. Hence, the absolute reactivity value was measured every second. In the figure, 1000 beam trips are presented. These reactivities have been measured using a 500 mg ^{235}U fission chamber operating in current mode and located in the MC4 experimental channel of the reflector region, although this time for the SC3b configuration. All these reactivity values measured during 17 minutes are located around 7 $, being compatible with the reactivity values obtained using standard PNS methods (see Reference [7] also presented in this conference).

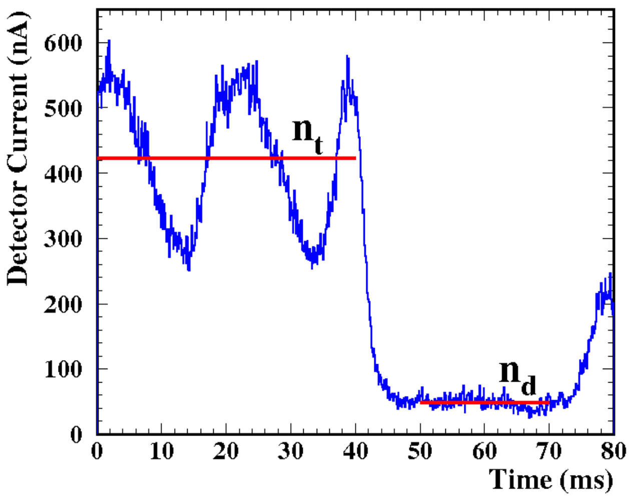

Fig. 4. Time evolution of the current for a typical beam-trip measured with a fission chamber. The level of current due to the total number of neutrons when the neutron source is operating is denoted by n_t. The level of current due to the delayed neutrons when the beam is promptly interrupted is denoted by n_d.

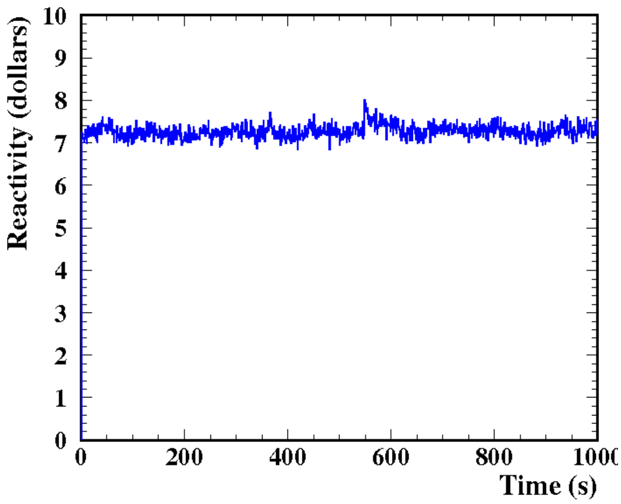

FIG. 5. Time evolution during 1000 seconds of the reactivity values (in dollars) measured with a fission chamber operating in current mode located in the MC4 experimental channel in the reflector region of Yalina-Booster for the SC3b configuration.

It must be pointed out that the fluctuations observed in the reactivity values can be largely reduce in a higher power subcritical core, where the neutron density would be larger, increasing the current in the fission chambers and also improving the signal-to-noise ratio on the detectors. As a naive approximation to a higher neutron density within the reactor, we have accumulated the current for 300 beam-trips measured in the reflector region for the SC3a configuration, as shown in *FIG. 6*. The amplitude of the 50 Hz oscillation is greatly reduced with this procedure. As the beam-trip has a fixed frequency, it can take place at any time position of the 50 Hz oscillation. Thus, each beam-trip is time shifted respecting to the rest of beam-trips and, when they are accumulated, the oscillation part is greatly reduced.

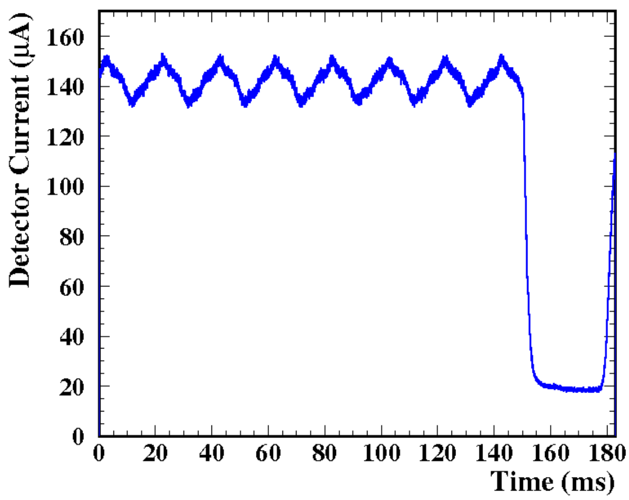

Fig. 6. Accumulated current for 300 beam-trips measured with a fission chamber located in the MC4 experimental channel at the reflector region of Yalina-Booster for the SC3a configuration.

3.2. Prompt decay constant results

As mentioned above, during a beam-trip, we can also apply the prompt decay constant method to determine the reactivity value. Also from the point kinetic model we can extract the following expression for the reactivity expressed in β-units:

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

where α is the prompt neutron decay constant that can be determined experimentally by fitting the decay of the prompt neutron population as shown in *FIG. 7*. The values of Λ and β can be computed using the appropriate code. We have used MCNPX 2.5.0 with the JEFF 3.1 libraries [7]. The values obtained for these magnitudes were Λ=59.7±0.6 μs and β=683±9 pcm. The analysis of the prompt decay constant data is still on progress and the results are very preliminary. As an example, the value of the decay constant obtained in the case of the MC4 channel for the SC3a configuration was α=870±56 s-1. This value differs from that obtained using standard PNS techniques (973±6 s-1). We think that these discrepancies are related to the phase of the 50 Hz oscillation, which is affecting the beam-trip and hence the fit of the decay. This effect is being studied and needs to be clarified.

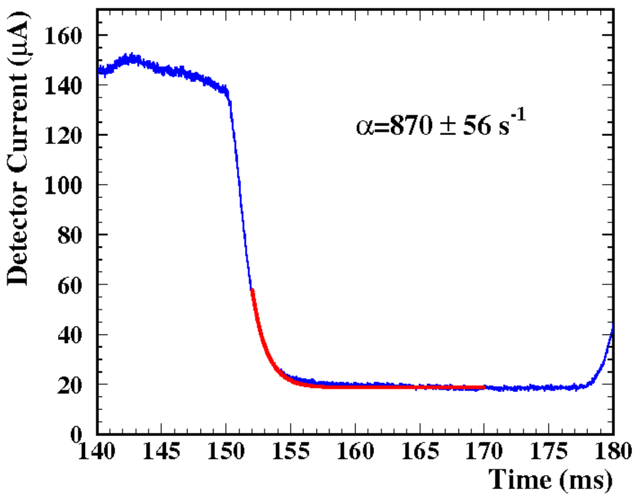

Fig. 7. Prompt decay constant method for reactivity determination. The best fit to the experimental data is shown on the figure by the red line. Data measured with a fission chamber located in the MC4 experimental channel at the reflector region of Yalina-Booster for the SC3a configuration.

4. Conclusions

In this work we have presented a preview of the preliminary experimental results obtained during the EUROTRANS experiments at YALINA-Booster facility using current mode detectors. The main objective has been to demonstrate the possibility to determine the absolute reactivity of the system using short beam trips measured with fission chambers operating in current mode, which seems to be the most realistic situation in high power ADS.

Special and dedicated electronic chains were developed in order to operate the fission chambers in current mode. The experiments were performed on a high-noise environment that affected especially the analogue measurements, like the beam current and the fission rate from the detectors operated in current mode. Despite of the adverse experimental conditions we were able to make useful recordings of these fission chambers, with current levels below 1 μA.

Using the source jerk techniques we were able to estimate the reactivity of the system in a single beam-trip and even more, to monitor during more than 15 minutes the reactivity at a measurement rate of one per second. To our knowledge, it is the first time that detectors in current mode are used to determine the reactivity values in a subcritical assembly using this technique.
In addition to the source-jerk method, the prompt decay constant method can be also applied while using the beam-trip technique. The results presented in this work are very preliminary and the uncertainties of the results could be reduced by exploring the nature of the 50 Hz oscillation.
Finally, it is important to note that the results obtained with the source-jerk method were compatible with those obtained by standard pulsed neutron source techniques, demonstrating the capabilities of the beam trip technique to calibrate the absolute reactivity for a subcritical core.

5. Acknowledgments

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