Current-to-flux experimental results in the YALINA-Booster subcritical assembly

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Abstract. As a part of the IP-EUROTRANS experimental program at YALINA-Booster, presented in this conference, a set of measurements concerning the current-to-flux techniques has been performed. In a subcritical assembly coupled to an accelerator operating in continuous mode, the power of the reactor is related to the accelerator beam current and the external neutron source strength. It is generally assumed that by monitoring the ratio between the accelerator beam current and the neutron source intensity as well as the ratio between the neutron source intensity and the core power, any change in the system can be detected. With this methodology, changes in the system caused by reactivity transients can be isolated. However, it has been observed that this is only true for transients in the time scale of seconds. At CIEMAT, an acquisition system capable of monitoring the core power, the accelerator beam current and the neutron source intensity in the millisecond scale has been developed. It has been observed that, in these short time ranges, the proportionality relationship between these three quantities is not always fulfilled.

1. Introduction

Transmutation of spent nuclear fuel (SNF) is a key technology for a sustainable nuclear energy, thus many efforts have been made worldwide in the frame of several R&D projects for its validation [1] – [3]. This technique consists on reducing the radiotoxic inventory of the high-level radioactive waste by fissioning the plutonium and minor actinides from the SNF. One of the explored concepts is developing fast neutron spectrum sub-critical reactors driven by a particle accelerator (ADS). Nowadays, the deuterium-tritium sources are reliable intense neutron sources also driven by an accelerator, being used in present experiments to improve our understanding on the kinetical properties of the ADS and to develop ADS control systems. The MUSE experimental program performed at the fast MASURCA facility in Cadarache, has used this kind of setup to study ADS kinetics in the Fifth Framework Program of the European Union [4]. Those studies will be continued in the YALINA facility [5] – [6] placed in Minsk. In this facility, one of the worldwide strongest deuterium-tritium source is coupled to a fast/thermal subcritical assembly. This work presents a set of experimental results measured in the YALINA-Booster facility concerning the reactivity monitoring of the system.

A key point of the future ADS facilities will consist of a robust on-line and continuous monitoring of the subcritical assembly reactivity. This monitoring system must yield valuable information concerning the rapid relative change of the reactivity, which in a subcritical assembly is given by:

$$-\rho = q\varphi^* \frac{S}{P}$$

Where q is the energy released per neutron fission, S is the source strength, P is the thermal power (neutron flux) and φ^* is the source importance. It is generally assumed that the source strength is proportional to the beam current and, hence, any change in the reactivity is accessible through the beam current ($S = \kappa \cdot I$) and the core power (neutron flux) P. The on-line determination of the reactivity, then, requires the monitoring of three quantities, the accelerator intensity (*I*), the neutron source intensity (*S*) and the core power (neutron flux) *P*. Actually two ratios must be determined, *S/I* and *P/S*. However, there exist several factors which can affect this proportionality as is the impinging position of the beam at the tritium target, the beam emittance, the beam oscillations or even the target consumption.

2. Experimental set-up

The experimental set-up used in the experimental campaign described in this work is schematically shown in *FIG. 1*.

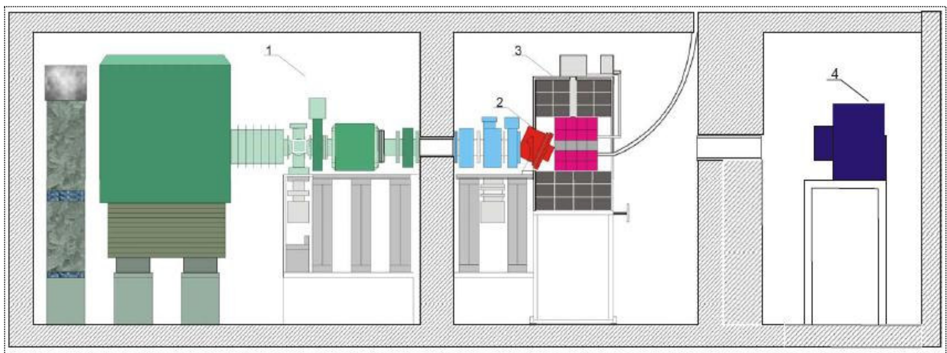

FIG. 1. Schematical view of the experimental set-up used in this work. 1) Deuteron accelerator, 2) Tritium target, 3) Yalina-Booster subcritical core and 4) BC501A liquid scintillator for neutron source monitoring.

Following *FIG.1*, the set-up consists of an accelerator (1) which drives the deuteron nuclei onto a tritium target (2) located in the center of a subcritical core (3). The fusion neutrons generated in the D+T reactions are feeding the core and, some of them are flying forward reaching a liquid scintillator used as a neutron detector (4).

2.1. Neutron Generator

The neutron generator (NG-12-1) uses a deuteron ion accelerator impinging on a Ti-T or Ti-D target to produce fusion neutrons. With a diameter of 45 mm, the target is located in the centre of the core. In the experiments presented here only the Ti-T target was used, thus providing a quasi-isotropic neutron energy spectrum of 14 MeV. 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 Subcritical Core

The core [6], depicted in *FIG. 2*, 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 of 36% enriched UO_2 pins while the polyethylene is loaded with 10% enriched UO_2 fuel pins. The subcriticality of our system was k_{eff} ~0.95.

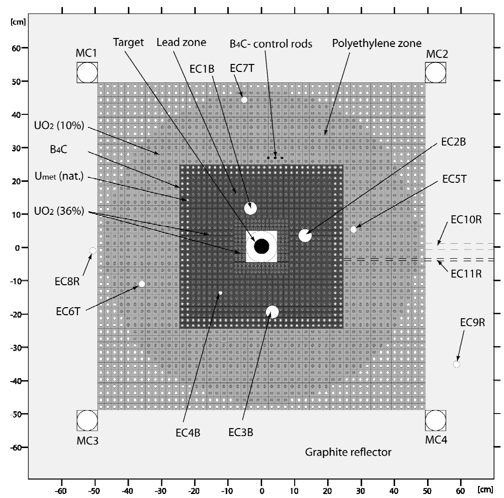

FIG. 2. Schematical view of the YALINA-Booster reactor core.

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.

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). In these current-to-flux measurements we have used several ^{235}U fission chambers, located at several places within the reactor core.

2.3. The Neutron Source Monitoring System

In this work we have used a BC501A [7] liquid organic scintillator acting as a veto detector to measure high-energy neutrons coming from the D-T source. The determination of the neutron source intensity relies in measuring neutrons coming directly from the D-T fusion reactions (14 MeV), which have energies larger than the fission neutrons created within the reactor. We have selected a detection energy threshold, fixed by using a typical neutron fission spectrum from a ^{252}Cf source. In this sense, using a constant fraction discriminator (CFD) we were able to neglect any neutron with energy below ~7 MeV. All the neutrons with deposited energy in the BC501A larger than 7 MeV can be considered as fusion neutrons coming directly from the D+T source.

3. Reactivity monitoring in the time scale of seconds.

The main goal of the current-to-flux measurements is answering the following question: Is it possible to develop a system to monitor rapid relative changes in the reactivity of a subcritical core? In *FIG. 3*, we plot the time evolution of the three relevant quantities monitored in our experiments: the deuteron accelerator current, the neutron source intensity and the core power (neutron flux). This plot is constructed as follows: the intensity of the deuteron current is fixed at a given value (the starting point is 1.5 mA) and the mean values of I, S and P are determined at intervals of 3 seconds. Then, the intensity of the deuteron beam current is decreased to 1.2 mA and the mean values of I, S and P are determined again.

As can be observed in the *FIG. 3* -in the time-scale of seconds- the deuteron current, the core power and the 14 MeV neutron source intensity are proportional to each other. Hence, if a proportionality loss is occurring between these variables in the system, it would be in principle possible to determine where this effect is coming from.

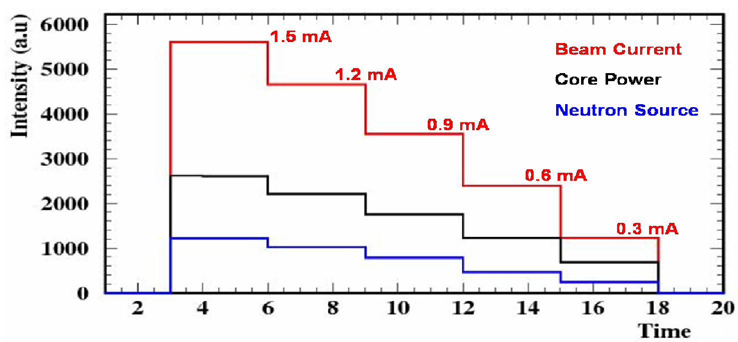

FIG. 3. Evolution of the deuteron beam current (red), core power (black) and the 14 MeV neutron source intensity (blue).

The proportionality between the deuteron current and the 14 MeV neutron source intensity was already empirically demonstrated in the GENEPI-2 neutron generator [8]. In *FIG. 4* we present some experimental data from Yalina-Booster. It is shown the proportionality between the counting rate of the 14 MeV neutron source intensity and the neutron counting rate of a fission chamber located in the EC1B experimental channel to monitor the neutron flux within the reactor core. Each point in this figures correspond to the mean value of several seconds of measurements. The dead-time in the fission chamber has been corrected using a non-paralyzable model.

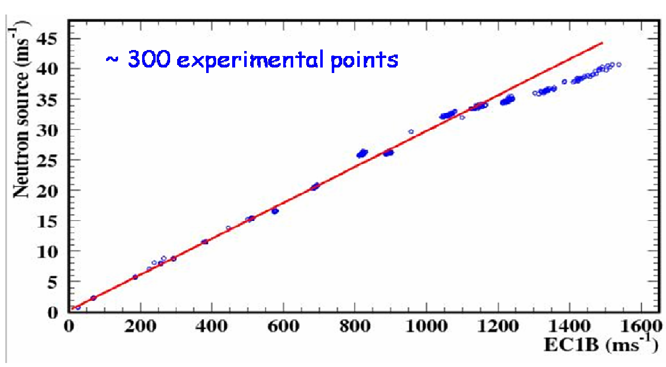

FIG. 4. Counting rate in the neutron source monitor versus the neutron counting rate measured with a fission chamber located in the EC1B experimental channel in the booster region.

As can be observed in the *FIG. 4*, we have stated the proportionality between the 14 MeV neutron source intensity and the core power (neutron flux) ranging in more than two orders of magnitude. It should be also noticed that, at high intensities, this linearity is lost. This behavior could be related to dead time effects in the BC501A liquid scintillator. The interpretation of this effect needs further analysis and discussions.

4. Reactivity monitoring in the time scale of milliseconds.

The acquisition system used in the YALINA-Booster experimental program made it possible to monitor the values of I, S and P in a much shorter time ranges. The values of these three variables were monitored at intervals as short as 1 ms, allowing the study of their evolution in the millisecond scale. Measurements in such a short time ranges, at our present knowledge, was not performed before in a subcritical assembly.

In *FIG. 5* and *FIG. 6* we represent the evolution of I, S and P in during a time interval of 200 milliseconds. In *FIG. 5* we show the time evolutions of the deuteron accelerator intensity (black line) and the 14 MeV neutron source intensity (red line). As can be observed in the figure, there is a strong oscillation in the 14 MeV neutron source. This oscillation has a frequency of 50 Hz and is not observed in the signal of the deuteron beam.

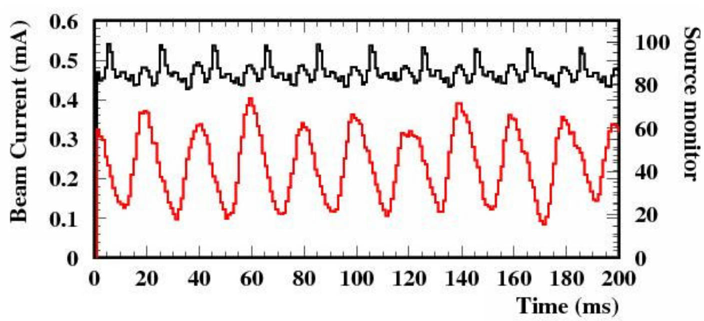

FIG. 5. Time evolution of the deuterium accelerator current (black) and the 14 MeV neutron source intensity (red).

We think that this oscillation could be related with the impact position of the deuteron beam on the tritium target. It could be possible that the last dipole magnet in the accelerator would be bending the deuteron beam with 50 Hz frequency. This would make the deuteron beam impinging outside the tritium target and, hence, the number of 14 MeV neutron created within the target would also be oscillating. This effect stresses the importance, for future ADS projects as GUINEVERE [9], to develop a stable and reliable system to monitor the beam impact position.

In *FIG. 6* we represent the time evolutions of the neutron flux within the reactor core measured in the booster region EC2B (blue line) and the 14 MeV neutron source intensity (red line). As can be observed in the figure, the 50 Hz oscillation is present in both signals and is really remarkable, reaching relative values close to 50 % in the neutron intensity.

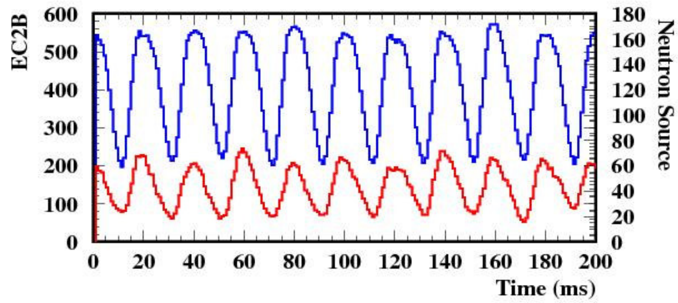

FIG. 6. Time evolution of the 14 MeV neutron source intensity (red) and the neutron flux measured in the EC2B experimental channel (blue), located in the booster region of the core.

To explore the linearity between both signals we make use of *FIG. 7*, where the values of the neutron source intensity on each millisecond of measurement is plotted versus the neutron flux measured in EC2B. This plot corresponds, approximately, to 10 seconds of measurements. As can be observed in the figure, there is a clear proportionality between the core power and the neutron source intensity, meaning that the neutron flux within the reactor is driven by the intensity of the 14 MeV neutron source. It is worth to say that, as seen in the *FIG. 7*, if the neutron source is switched off, the neutron flux within the core is not zero. This is due to the population of delayed neutrons, present in the reactor after the 14 MeV source neutrons have disappeared.

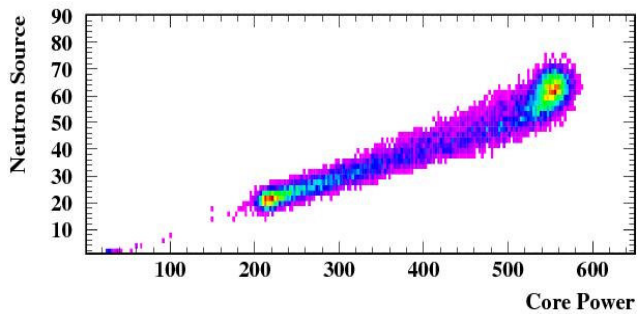

FIG. 7. Correlation between the 14 MeV neutron source intensity and the neutron flux measured in the EC2B experimental channel, located in the booster region of the core.

5. Conclusions and Outlook

In this work we have described some of the preliminary experimental results for the online reactivity monitoring of a subcritical core coupled to an external neutron source. As the reactivity is a direct function of the accelerator intensity, the core power (neutron flux) and the source strength, the necessary acquisition system to monitor these three quantities has been developed.

In the time scale of seconds, the three relevant quantities under study in this work (I, S and P) follow a linear relationship. However, the electronic chains used in this work made it possible an on-line monitoring of the core reactivity within time intervals as short as 1 millisecond. In this time scale some unexpected behaviours –not observed in the time scale of seconds- appeared. Exploring the reactivity in such a short time ranges allowed the observation of an oscillation in the neutron source intensity and the core power. This oscillation, with a frequency of 50 Hz, seems to be due to an oscillation in a bending magnet of the deuteron accelerator. This oscillation makes the deuteron beam to hit outside of the tritium target with a 50 Hz frequency.

Exploring the time range of milliseconds, there exist a clear correlation between the 14 MeV neutron source intensity and the core power (neutron flux). However, this correlation is not fulfilled in the case of the core power and the accelerator intensity. With the experimental set-up used in this work we were able to identify these situations where the proportionality between the three quantities is lost.

For future projects, as GUINEVERE, it will be very important to have a stable beam system and also to develop a system to monitor the beam impact position on the target.

6. Acknowledgements

This work was partially supported by IP-EUROTRANS contract FI6W-CT2005-516520, by the ENRESA-CIEMAT agreement for the Transmutación Aplicada a los Residuos Radiactivos de Alta Actividad and by the Swedish Institute.

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