GUINEVERE Program for the Reactivity Monitoring of an ADS System Using the GENEPI-C Accelerator

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Abstract*: One of the objective of the European Sixth Framework Program is to produce scientific and technical data for the feasibility assessment of an ADS-based transmutation strategy. Within the Integrated Project EUROTRANS, the Domain DM2 : ECATS – "Experimental activities on the Coupling of an Accelerator, a Target and a Sub-critical blanket" is devoted in particular to the sub-criticality monitoring of an ADS.*

After MUSE experiment, the analysis indicated that two important points were left open for significant improvement: validation of the methodology for reactivity monitoring by using a continuous beam and also a strong request for a lead core in order to have representative neutronics conditions of a lead-cooled ADS. Therefore, a large fast lead/uranium enriched core will be coupled to a specific GENEPI accelerator in the VENUS reactor at MOL. In the paper, the reactivity monitoring system using the specific GENEPI accelerator able to operate in pulse, continuous and "beam trip" modes is presented.

I. INTRODUCTION

It is generally agreed that Accelerator Driven Systems (ADS) can play a role in the transmutation of actinides for the reduction of radiotoxicity in long-term storage. In France, the law requires not only that storage in geological formations be studied, but also that the possibilities of long-term storage and reduction of the toxicity of the waste via separation-transmutation be explored. With the Third and Fourth EURATOM Framework Programs (1991-1998), studies were performed in the areas of partitioning processes allowing the extraction of the most radiotoxic elements in the waste stream, and also on the feasibility of transmutation by neutron irradiation of these radionuclides into elements that are stable or have a significantly shorter half-life or lower radiotoxicity. Since April 2001, the objective of the Fifth Framework Program was to produce a basis for evaluation of the feasibility of partitioning-transmutation at an industrial scale, and thus to develop effective and reliable processes of advanced reprocessing, and to produce scientific and technical data for conducting the future engineering studies for an ADS demonstrator. Three levels of validation can be presented:

First, validation of the different components, taken separately (accelerator, target, subcritical core, dedicated fuels and fuel processing methods).

Second, validation of the coupling of the different components in a significant environment.

Third, validation in an installation, explicitly designed for demonstration. The MUSE experiments [1] conducted at low power levels with the MASURCA reactor (CEA/Cadarache) were studying several subcritical configurations driven by an external neutron source provided by a pulsed neutron accelerator, GENEPI, built by the CNRS (French Centre for Scientific Research). The cores use MOX fuel with sodium or lead coolants at several levels of subcriticality (from Keff=0.95 to nearly 1.0).

Within the Sixth Framework Program, the Integrated Project EUROTRANS [2], the Domain DM2: ECATS – "Experimental activities on the Coupling of an Accelerator, a Target and a Sub-critical blanket" is devoted to neutronic experiments for the demonstration of the conceptual feasibility.

The DM2 objectives are specified in full consultation with the design-team of the "Domain1 DESIGN" which is developing a reference design for a long-term European Facility for Industrial Transmutation (EFIT) with a power of up to several 100s MW(th), together with a more detailed design of a short-term eXperimental demonstration of the technical feasibility of Transmutation in an Accelerator Driven sub-critical System (XT-ADS). These objectives concern:

- Qualification of sub-criticality monitoring
- Validation of the core power/beam current relationship
- Start-up and shut-down procedures, instrumentation validation and specific dedicated experimentation
- Interpretation and validation of experimental data, benchmarking and code validation activities
- Safety and licensing issues of different components and for the integrated system.

The different experiments that concern ECATS are:

- The RACE (Reactor Accelerator Coupled Experiment) experiments at Low Power operated in two different facilities : the TRIGA reactor of the ENEA/CASACIA named "RACE-T" and the RACE sub-critical assembly of the Idaho Accelerator Center named "RACE-LP/IAC" in the USA.

- The YALINA experiments in Belarus. These experiments are of the MUSE type, i.e. a neutron generator is coupled to a flexible zero-power sub-critical assembly
- And the recent GUINEVERE program proposed by SCK-CEN. There it is proposed to modify the critical facility VENUS located at Mol and to couple it with a modified GENEPI accelerator to perform the GUINEVERE experiment (Generator of Uninterrupted Intense NEutrons at the lead Venus Reactor).

In this paper, the reactivity monitoring system using the specific GENEPI accelerator able to operate in pulse, continuous and "beam trip" modes is presented.

II. RESULTS AND OPEN ISSUES FROM THE MUSE EXPERIMENTS

The first coupling between MASURCA core and the GENEPI accelerator happened on November 2001. The experiments include the full characterization of the reference critical configuration with a large experimental program including: importance traverses using a 252Cf source; foil irradiations; spectral indices; numerous axial and radial traverses of fission rates; rod-drop experiments; measurements of kinetic parameters in view of the reactivity reference determination.

Since 2001 to 2004, three different levels of sub-criticality were studied in the core represented in the figure above: SC0 (near criticality core), SC2 (K_{eff} ~0.97) SC3 (K_{eff} ~0.956). With the Multiplication of Source Modified method (MSM), the different techniques used to determine subcriticality were: PNS (Pulsed Neutron Source), SJ (Source Jerk) techniques, the transfer function method as well as noise methods. An analysis of the MUSE experimental results is given [3].

Concerning the sub-criticality techniques, among the major conclusions of the MUSE-4 experiments [6], the common agreement is as following:

Demonstration is done that it is possible to determine the reactivity of a subcritical system without the need of a critical reference.

In a multiple regions system, there is a complicated distribution of flux in space and energy and the time evolution of a pulse is difficult to predict.

Because of the characteristics of the GENEPI accelerator, MUSE couldn't provide results concerning the on-line monitoring.

The consistency between MSM method and other sub-criticality techniques will be supervised one more time during the GUINEVERE program.

III. RATIONALE FOR EXPERIMENTS CONCERNED BY EUROTRANS

In view of XT-ADS and EFIT (see §I), The capability of the different experiments of ECATS (RACE-T, RACE-LP/IAC, YALINA and GUINEVERE) to contribute to a better knowledge of the physics of ADS systems is analyzed hereafter.

Qualification of sub-criticality monitoring

Hence, it is clear from the conclusions from MUSE (cf. §IIA) that very specific items were left opened and needed to be solved in order to be able to validate the subcriticality monitoring methodology. One of the items which needed to be investigated into more details was the so-called reference reactivity measurement technique: the rod-drop technique in combination with the MSM-technique. Especially, the MSM-technique did not yield the high precision results as was expected and further work is necessary to clarify the possible sources of bias. In this respect, the RACE-T programme will provide valuable results.

The RACE-LP-IAC programme consists in coupling an electron-accelerator to a W-Cu solid target to produce a neutron beam which can then be inserted into a thermal subcritical core (consisting of graphite and water). Due to the thermal nature of the core and the difficulty to obtain sufficient repeatable beam trips of an equivalent continuous neutron source, the added value of the RACE-LP-IAC programme with regard to MUSE in view of the objective stated here above is limited.

The YALINA-experiment which couples a continuous beam (with the possibility of beam trips) to a mixed thermal-fast core, allows to investigate several items which were left open after the MUSE-programme. Especially the current-to-flux reactivity indicator can be investigated and validated. Since in the YALINA-experiment there exists a large thermal spectral component in the core, the results which will be obtained from the investigation of the fitting techniques after beam trips with a continuous source in this spectrum, cannot be easily transposed to XT-ADS/EFIT where a fast spectrum exists. In the YALINA-experiment, it is impossible to make reference to the critical state which complicates the validation process and might lead to an increase in uncertainties.

In the GUINEVERE-project, the coupling of a modified GENEPI-accelerator (continuous, beam trips, pulsed) to a fast lead core VENUS is envisaged with the possibility of reaching the critical state for obtaining a reactivity reference. In this respect, the GUINEVERE-project will allow to validate the current-to-flux reactivity indicator, the prompt decay fitting techniques and the ADS prompt jump technique and hence will allow to obtain a validated methodology for reactivity monitoring.

Validation of the core power/beam current relation

In the RACE-LP/IAC, when the minimum break frequency of the core, around 220 Hz (for k_{eff}=0.94), and the maximum accelerator repetition frequency (180 Hz) are compared, one can argue that the core will see a semi-continuous neutron source, since the micro-structure of the accelerator pulses has disappeared before the typical time of neutronic processes characterised by the break frequency. In this way, first measurements for the investigation of the current-to-power reactivity indicator can be performed. However, one has to be aware that the electron accelerator is a commercial device which does not have the same performances as an accelerator designed for scientific purposes in terms of stability, precision and characterisation. Moreover, the neutron production in the target by the electron accelerator is subject to several sources of bias which makes it difficult to obtain an accurate determination of the neutron source and one has to note that the maximum k_{eff} is limited to about k_{eff}=0.9.

In YALINA-experiments, the fact that the spectrum in the core is a mixed thermal-fast one is less an issue for the validation of this current-to-flux reactivity indicator than for the qualification of the subcriticality monitoring, since the time variations to be followed are slower than the typical reactor time constants. Moreover, results from the YALINA-experiments can be expected at the end of 2007 which makes it the first real test-case for the applicability of the current-to-flux reactivity indicator as an on-line monitoring technique.

It is clear from the definition of the GUINEVERE-project (continuous beam, fast core) that it will allow to fully investigate the applicability of the current-to-flux reactivity indicator as an on-line indicator. In this way, we have two independent experiments GUINEVERE and YALINA to provide experimental results for the validation process of this crucial topic.

Start-up and shut-down procedures, instrumentation validation and specific dedicated experimentation

The proposed experimental programs of RACE-LP/IAC and RACE-T do not contain a dedicated effort to provide input for the study of start-up and shut-down procedures, since in comparison to the YALINA-experiments and GUINEVERE-experiments the accelerator and core characteristics are less representative and hence it was judged to be preferable to optimize the efforts with regard to the most representative systems. One has however to note that during the RACE-T experiments dedicated instrumentation such as the piccolo-micromegaz detector and that during RACE-LP/IAC, the X-mode advanced acquisition system for ADS were tested.

In the YALINA-experiment, a dedicated experimental programme is foreseen to be able to draft start-up and shut-down procedures for an ADS thanks to the fact that the accelerator can work both in continuous and pulsed mode. Moreover, the YALINA-experiment will make it possible to test to some extent current-mode electronic chains in on-line reactivity monitoring. The measurement of the accelerator beam current and the on-line neutron source monitoring represents also a specific objective of the YALINA experimental programme which provide input to this ECATS objective.

As for the YALINA-experiments, the GUINEVERE-project foresees a dedicated experimental programme for investigating start-up and shut-down procedures, thereby also investigating the shut-down by safety rods. It will also allow to test the same instrumentation issues as in YALINA and hence a more thorough validation of the dedicated instrumentation can be obtained.

Interpretation and validation of experimental data, benchmarking and code validation activities

The RACE-T will contribute to the generic validation of neutron codes for the calculation of MSM-factors which are essential for the determination of the reactivity by the reference measurement techniques nevertheless one should mention here that the TRIGA fuel is not a fresh fuel and thus its characterisation is not very precisely known. The RACE-LP/IAC was not specifically conceived to provide additional input to code benchmarking and validation due to the thermal characteristics of the core.

Since the spectral conditions in the YALINA-experiment are not fully representative of a future fast ADS, the added value of these experiments with regard to code validation is limited.

In the GUINEVERE-project, the reactor core consists of 30% enriched uranium rodlets and lead rodlets (to simulate the lead coolant in ADS) and hence a very representative neutron spectrum of a fast lead-cooled ADS e.g. XT-ADS/EFIT is obtained. The fact that the core contains enriched uranium instead of MOX fuel as envisaged in XT-ADS has only a minor and secondary effect on the neutron spectrum and hence does not have any impact on the capability of code validation for specific calculations needed in the interpretation of measurements for subcritical reactivity determination. Moreover, the approach to substitute 25% plutonium by 30% uranium without changing the moderator is the best approach to start.

Safety and licensing issues of different component parts as well as that of the integrated system as a whole

During the MUSE-programme, already valuable lessons were learned with regard to specific licensing aspects for the coupling of an accelerator to a reactor. Due to the different energy spectrum and the different accelerator technology, it is expected that RACE-T- and RACE-LP/IAC-projects will only contribute to this ECATS objective in a limited way in addition to the lessons learned during MUSE for the licensing of XT-ADS/EFIT.

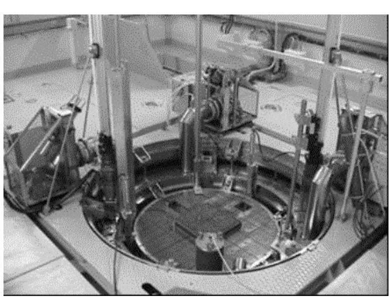
In the YALINA-experiment, the installation is coupled to an external accelerator source and is only licensed for a neutron multiplication factor lower than k_{eff}=0.98. Since this specific licensing aspect will also be encountered in the future XT-ADS/EFIT, this will represent an added value with regard to the safety analysis and licensing of XT-ADS/EFIT.

For the GUINEVERE-project, all the safety and licensing issues encountered in MUSE, RACE & YALINA will again be revisited, but now in front of the Belgian safety authorities. Since XT-ADS is intended to be built at the Mol-site in Belgium, the licensing of a fast subcritical assembly coupled to an accelerator provides a significant added value and allows to prepare the Belgian safety authorities for the licensing of XT-ADS.
In conclusion, the added value of each experimental programme with regard to each objective is summarized below.

IV. THE GUINEVERE PROGRAM [5]

To validate the methodology for reactivity monitoring, a continuous beam is needed. This request for a continuous beam was not anticipated in the definition of the MUSE-project, but lists on top of priorities for the ECATS programmes. In the definition of the MUSE-project, there was made from the beginning a strong request for a lead core in order to have representative conditions of a lead-cooled ADS. This request was only partly satisfied by the creation of a lead central part in the last configuration of the MUSE-programme. Due to programme limitations, the investigation of this core was strongly reduced. During the definition of the ECATS programme, it again appeared to be of significant importance to be able to perform measurements in representative conditions of a future ADS. Therefore, there is need for a lead fast critical facility connected to a continuous beam accelerator. Since such a programme/installation is not present at the international level, it is proposed to use a modified VENUS critical facility located at Mol and couple it to a modified GENEPI working in current mode: the GUINEVERE-project (**G**enerator of **U**ninterrupted **I**ntense **NE**utrons at the lead **VE**nus **Re**actor. In the following paragraphs, we will briefly describe the modifications to be performed on VENUS and GENEPI.

Top view of the VENUS reactor



Modifications at the SCK•CEN site: VENUS-F

The execution of this project will consist of two types of modifications at the SCK•CEN site. First of all, the modifications which are connected to the installation of the new GENEPI-C accelerator, working in continuous and pulsed mode, at the VENUS critical facility and its coupling to the core. The second type of modifications are linked with the adaptation of the VENUS critical facility to host a fast lead core, further on referred to as VENUS-F.
With regard to the "coupling" modifications, the following main items are identified:
- In the VENUS reactor hall there is not sufficient space to install the GENEPI accelerator
- Through-put of the beam-line through the vessel and the bunker already exist

Experimental programme	Qualification of subcriticality monitoring	Power/beam current relation validation	Start-up shutdown scram procedures	Benchmark and Code validation activities	Safety and licensing issues
MUSE	++	-	-	++	++
RACE-T RACE-LP/IAC	++	+	++	++	++
YALINA-B	+++	+++	++	++	++
GUINEVERE	++++	++++	+++	+++	+++

- Through-put of the beam-line through the existing the VENUS reactor hall to the neighbouring rooms.
- In these neighbouring rooms, largely sufficient space is available to install the GENEPI accelerator.
- A bending magnet of 2x45° or 1x90° in the VENUS reactor hall will be necessary

The authorization of the coupling of an accelerator to a subcritical system will be based on:
- The fact that the coupling of 14 MeV Pulsed Neutron Source was already performed in the past (1960-1970) at the VENUS reactor and several experiments have been carried out.
- The experience gained during the MUSE-project (and the YALINA facility)

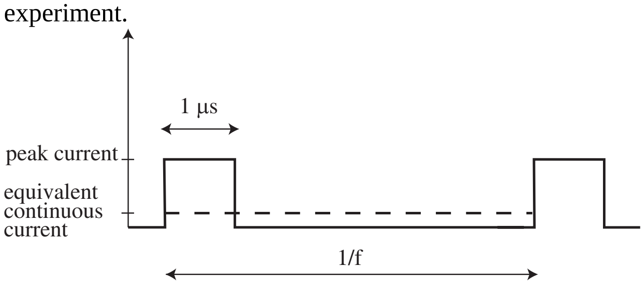
To modify the water-moderated thermal reactor in a fast lead reactor, the following main items were identified:
- A similar shut-down system, as in the first years of the VENUS facility, based on shut-down rods, will have to be installed.
- Construction of lead blocks for the core and the reflector (~ 10 t lead)
- Supporting structure to reinforce the structures to carry the lead
- Partially remote loading of fuel
- Repositioning of the neutron detectors
- New exploitation procedures
- New scram logic.

Modifications for the continuous GENEPI-C accelerator designed for VENUS-F

Requirements

Based on the GENEPI 1-2 experience, a new GENEPI-C accelerator operating both in the continuous

and pulsed mode could be designed to be coupled to VENUS-F. In the pulsed mode it should work with characteristics as close as possible of that of the GENEPI 1-2. In the continuous mode, deuteron current to be reached should be in the 100 µA-1 mA range.
It is recalled that a 1 µs peak of 40 mA intensity at 4 kHz is equivalent to a continuous beam of 160 µA (see Fig.), bringing the same quantity of source neutrons per second (around 10^9-10^{10} n/s), conditions of the MUSE experiment.



Equivalence between pulsed current and continuous current.

To achieve the "beam trips" part of the experimental program prompt beam interruptions (transition time less than 1 µs) should be performed, with a repetition rate of a fraction of Hz, with a duration bounded by a few hundreds of microseconds and a few tens of milliseconds.
The different points to be re-studied for a new GENEPI-C accelerator are detailed below.

The source
The duoplasmatron source used at the present time is designed for a pulsed use. The CNRS has some experience of continuous sources obtained during the exploitation of the local SARA cyclotron in the 80-90's. Operating such a source in a continuous mode has to be tested and, in case of success, source and extraction parameters optimized to reach the beam intensity mentioned above. A source test bench will be installed at LPSC before July 2006. In case of limitations of the duoplasmatron, other types of source could be tested. Once the source chosen, the beam interruption operation will be tested: it could be performed by driving the source itself (if possible it is the easiest), or by a fast electrical deflexion downstream on the beam line (chopping). The versatile use (pulsed and continuous mode) of the duoplasmatron would be the easiest solution. If different sources are required for the two modes, the change of the source to achieve the different parts of the experimental program can be managed, a few days of technical intervention would then be needed.

The beam transport
The focalisation at the entrance of the acceleration field is strong and designed for an intense extracted beam, to handle the very high intensity of GENEPI1. In the case of a less intense beam it may become too strong and has to be studied. More generally, all the focusing structure has to be checked for the whole intensity range required now, and some modifications may be proposed. In the best case the same optics will be usable for both beam types with only a change in the tunings. Anyway, additional studies are required do adapt GENEPI-C to the VENUS-F geometry.

The target
At the present the maximum power on the target to be evacuated is around 40 W. The cooling is ensured by a compressed air flow. A continuous beam of 160 µA would bring the same power. At the maximum limit of a 1 mA beam, the maximum power to be evacuated is 250 W. The performances of the cooling system have then to be improved (without oil or water, hydrogenous material, close to the target), which does not seem to be a major problem.

The monitoring and controls
The monitoring and control system of GENEPI 1-2 is performed by a PC computer and electronics which are based on out of date items (it must be kept in mind that the first design of this system dates from 1998). Therefore a completely new system based on modern components and techniques has to be studied. The conception and achievement of the first system required about 1 manXyear.

The experimental program
The need to set-up an internal lead zone surrounding the neutron source was already studied during MUSE. This device can be considered as a mock-up of a spallation target. It is also devoted to decrease the energy of the neutrons source. During the GUINEVERE program, the sensitivity to the high energy part of the lead cross sections, especially for the (n,2n) and the inelastic cross sections will be emphasized and will be a new benchmark for a large fast core, cooled by lead. The comparison of the importance of the (D,T) and (D,D) neutron sources will be looked at carefully.
The use of the uranium enriched in a fast core, during the GUINEVERE program will also be interesting for improving the cross sections of U-235 in the fast region [4].
Concerning the basic core lay-out structure, it is determined taking into account:
- the fuel assembly design:
  - composition by fuel rodlets and lead blocks/lead rodlets
  - core height and presence of top axial reflector
  - number of fuel rodlets per assembly
  - grid structure square/hexagonal
- the presence of shut-down rods/control rods

- the penetration of the beam guide
- experimental traverse channels
- start-up source & detector locations.

Once the basic core lay-out defined, the different core configurations for the execution of the experimental programme were determined.

The different configurations foreseen are:

- SC0 I and II: critical configurations, clean core and voided central zone for the beam tube
- SC1: basic subcritical configuration (Keff=0,97)
- SC2: subcritical configuration (Keff=0,99)
- SC3: subcritical configuration (Keff=0,95)
- SCL: deep subcritical configurations for verification of loading operations
- SCR: configurations with different reflectors
- SC-XT: configurations for XT-ADS mock-up.

One of the main task of the experimental program will consist in the preparation of the different experimental tools (devices, counters, electronics) to be used during the program and the set-up of the experimental programme for the critical configuration SC0 and the subcritical configuration SC1. Special attention will be paid on the investigation of on-line reactivity monitoring techniques and experimental techniques used at beam trips for the determination of the reactivity.

The on-line current-to-flux reactivity indicator

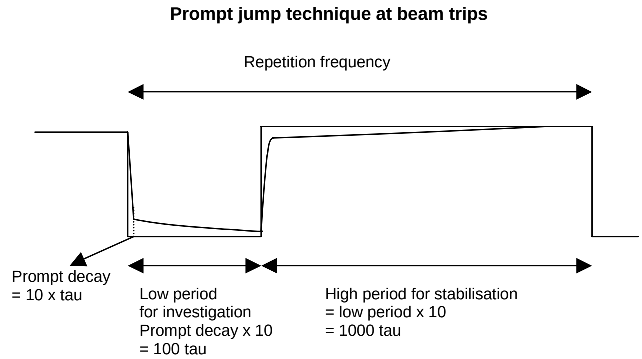
The on-line current-to-flux reactivity indicator has to be validated primarily in static, but also in kinetic conditions. With regard to measurements in static conditions, excellent precision can be reached in minimal measurement times. In kinetic conditions, small variations (0.1 s) can be followed with a high precision (1% uncertainty for a count-rate of 10^5 cps). Rapid variations can also be followed but with higher uncertainties. These are typical requirements existing in critical reactors. Shutdown systems responses take about a second.

Beam trip techniques

Dynamic reactivity measurements require specific signals from the accelerator. The time structure of the beam is based on a periodic structure (T is the period) in which the normal stabilized level of the beam is interrupted during the duration time (δt); as a result, the duty cycle (DC) of the beam is DC=1-δt/T. δt is depending on the measurement technique used for the reactivity measurement and T is depending on δt and on the delay necessary to recover the equilibrium of all the neutrons: prompt and delayed neutrons. The accuracy of the measurement depends on the counting statistics and the on the number of beam trips.

The analysis of the measurements is based on two main techniques: the prompt neutron decay fitting and the area ratio method (ratio of the delayed neutrons number to the prompt neutrons number). The relations between the two measurements (prompt neutron decay fitting, area ratio) and the reactivity are:

- Prompt neutron decay time: $\tau=1/\alpha=L/(\beta-\rho)$ (where L is the prompt neutron life time)
- Area Method: $-\rho/\beta$=(prompt neutron area)/(delayed neutron area)



In a typical fast reactor the characteristic values are for L=1 µs, β = 300 pcm and ρ = -5000 pcm, we obtain: τ= 20 µs.

With the prompt decay fitting technique, the duty cycle should be DC=1-10/1000=0,99, with the area method technique DC=1-110/1000=0,989 (the low period is necessary to measure the delayed neutrons).

During the GUINEVERE program different characteristics of the duty cycle will be analyzed (different values of δt, T). The associated uncertainties are also in this case depending on the time duration of the measurements. The transposition of all these results to a powerful ADS are of first interest and the considerations on the power level of the neutrons source created by the beam in different operational conditions will be simulated.

V. CONCLUSION

In view of XT-ADS and EFIT, the five objectives of ECATS (see §I) concerning the sub-criticality management are covered.

After MUSE, it appears that the major topics still to be analysed are: the use of a continuous beam to monitor the sub-criticality and the neutronic of a fast lead core.

The GUINEVERE program will produce these important validations necessary for the next step of development in EUROPE. RACE experiments brought already lot of results of comparisons of experimental techniques in moderated spectrum and also at low level of Keff; YALINA will be a first test of the beam trip technique to determine the sub-criticality. The analysis of the harmonics of flux will also be continued in this coupled fast/thermal sub-critical blanket.

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