Requirements for experimental activities on the coupling of an accelerator, a spallation target and a sub-critical blanket

compiled by

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Within EUROTRANS the Domain ECATS replaces the Domain TRADE-PLUS

Original Objectives:

Realisation and Operation of the experimental facility TRADE to demonstrate the coupling between proton accelerator, spallation target and sub-critical blanket at sizeable power (several 100 kWs) in presence of thermal reactor feedback effects. The expected outcomes of this domain – in terms of proof of stable operability, dynamic behaviour and definition of licensing issues of an ADS - are crucial for and give input to the Domain 1: Design.

Original Work Programme

- Design, follow-up of construction and commissioning of the specific modifications to the existing TRIGA reactor, including system transient analysis, safety and licensing.
- Target system design, realisation and qualification.
- Design, follow-up of construction and commissioning of the Beam Transport Line and of the Test Station for out-of-pile beam adjustment and final target qualification under irradiation.
- Shielding, dose and radiation damage analysis of the whole system from the accelerator complex to the reactor building.
- Development of instrumentation adapted to sub-critical systems for reactivity monitoring and control and sub-critical power diagnostics.
- Preliminary in-pile experiments for sub-critical core characterisation and instrumentation assessment.
- Commissioning tests of the whole system up to full power.
- Performance and assessment of in-pile sub-critical experiments under steady state and transient operational conditions of an ADS.

Preliminary Design Characteristics of the XT-ADS and EFIT Designs

	XT-ADS	**EFIT**
Design level	Advanced design	Conceptual design
Coolant	Pb-Bi	Pure Lead (backup: gas)
Primary System	Integrated	Integrated
Power	50 to 100 MWth	≥ 300 MWth
Core Inlet Temp	300°C (350°C)	400°C
Core Outlet Temp	400°C (430°C)	480°C
Target Unit Interface	Windowless	Windowless (backup: window)
Target Unit Geometry	Off-center / Centered	Centered
Fuel	MOX (a few MA)	(Pu, Am)O2 + MgO (or Mo)
Av. Fuel Power Density	700 W/cm^3	450 to 650 W/cm^3
Fuel pin spacer	Grid	Grid
Fuel Assembly type	Wrapper	Wrapper / Wrapperless
Fuel Assembly cross section	Hexagonal	Square (based on BREST/ PWR)

Preliminary Design Characteristics of the XT-ADS and EFIT Designs

	XT-ADS	**EFIT**
Fuel loading	Top / Bottom TBD	Top
Fuel monitoring	T and FF (per FA)	T and FF (per regions)
External fuel handling	RH oriented	TBD
Primary coolant circulation in normal operation	Forced with mechanical pumps	Forced with with mechanical pumps
Primary coolant circulation for DHR	Natural + Pony motor	Natural + Pony motor
Secondary coolant	Low pressure boiling water	Superheated water cycle
Structural Material	T91 and A316L	TBD
Accelerator	LINAC (power: 2 ~ 5 MW)	LINAC (power: TBD)
Beam Ingress	Top	Top

Preliminary Design Characteristics of the XT-ADS and EFIT Designs

- The proton beam specifications of the two designs show that the envisaged machines belong to the category of the so called HPPA (High-Power Proton Accelerators) with a proton energy ranging from about 350 MeV for the XT-ADS up to the range of 800 to 1000 MeV for the EFIT design with a maximum beam intensity of up to 20 mA CW on the target in case of the EFIT design.
- The proton beam structure recommended is a CW-based time structure with additional short and well defined (sharp edge) beam interruptions of about 200 µs with a repetition frequency in the order of 1 Hz. These beam holes, shutting down the neutron power source from time to time, should enable continuous and accurate on-line measurements and monitoring of the reactor sub-criticality.

Core Sub-criticality Level Monitoring

The simplest approach is based on a measurement of the current proton I and on the power level P (through a fission chamber)

Given the fact that the source strength is proportional to the beam current and the power level is proportional to the fission chamber responseone can get access to the reactivity.

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

Any change in the reactivity is accessible through the current I and the power P

The theory associated to that type of measurement is

the **Multiplied Source (MS) method**

This method is a relative measurement and one needs an absolute measurement at first and then from time to time to verify that the other terms remains constant

Core Sub-criticality Level Techniques

The standard technique for acquiring absolute reactivity values in a critical core
i. e. the rod drop type measurement is no longer usable

Various other techniques are available for acquiring absolute reactivity values such as:

the **Prompt Neutron Decay method (PND)** and
the **Source Prompt Jump method (SPJ).**

which can be used in different stages of the start-up procedure
and during ADS operation

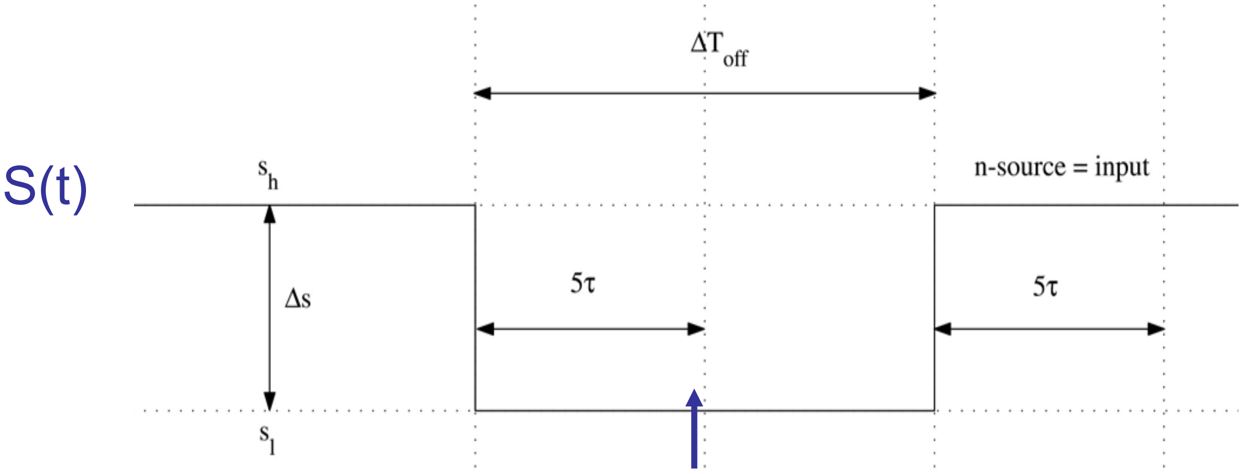
There are some feedbacks from MUSE experiments which demonstrate that
techniques still need need to be validated

In particular, all these techniques rely in fission chambers
and these fission chambers should be located within the core
(it has not been demonstrated that
signal bias in the reflector can be corrected)

What is the issue?

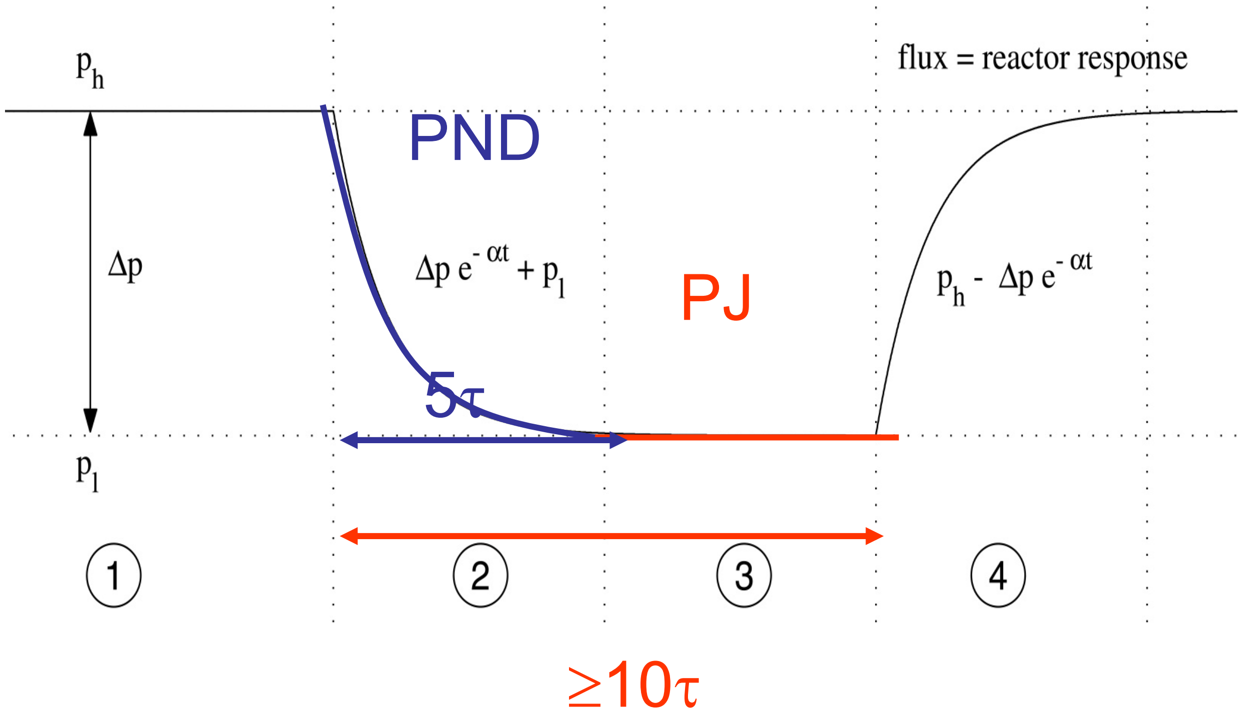
Can we take advantage of a short break of the neutron source for reactivity monitoring?

Accelerator signal:



Short break ≈ 50μs

PND (Prompt **N**eutron **D**ecay method) **or PJ (P**rompt **J**ump method) **methods**



(In practical P1 level could be difficult to assess at low power level)

Sub-criticality approach when loading the core

When loading the core, **a protocol should be designed in order to prevent the overshoot of the reactivity limit at which one has to operate the system**.

Issues of particular importance for an ADS during the core loading are:

- **Implementation of absorbing sub assemblies before any fuel handling** inorder to decrease the reactivity; this is associated both to the level of accuracy for reactivity measurement and the need to move to a higher criticality level (from 0.95 to 0.97 around)

- **Reliable and accurate measurement of the sub criticality level** during refuelling,

- **Subcriticality approach** when loading the core.

XADS shut-down conditions

In **shutdown conditions**,
an absolute measurement of the sub-criticality level (Keff) is rather difficult.

A **relative measurement of the subcriticality level (MS method)** might be sufficient during the refuelling period (e.g. a comparison of the relative efficiency of fuel and absorber S/As can be measured and the absolute reactivity could be a calculated one with relatively large uncertainties).

The measurement methods are also linked to the fuel handling operation:
during fuel handling, the beam tube is disconnected and the sub-criticality level is very low (lower than 0,95).

Consequently, **very sensitive fission chambers are required and this in the core** (e. g. fission chambers out of the vessel cannot be used).

Consequence:
Uncertainty on reactivity level during refuelling could be large (0.01 ?)
but acceptable

XADS start up operation

Absolute reactivity measurement with the accelerator (by low power pulses) will be performed before the reactor starts or restarts.

At the reactivity level requested **for the operation of the XADS, absolute reactivity measurements using the accelerator in a pulse mode can be used (PNS method,**

but MUSE has demonstrated that the AREA method is more accurate).

Consequence: **Uncertainty on reactivity during start up operation (at low power)**

could be reduced (0.007 ?)

Conclusion: **The change in reactivity from 0.95 to 0.986 at cold state**
is associated to a change in measurement mode
requiring the use of the accelerator (in a pulse mode)

XADS operation

From a safety point of view, **the core control system should be able to detect any significant reactivity change (and particularly the increase** which might lead to an overshoot of the reactivity margins set by design) ;

Reactivity change however appears for some normal reasons (in particular associated to change in temperature) and for some abnormal ones

Consequence: **Reactivity should be measured frequently** during the ADS operation (for instance with the PJ method which has never been tested) and the feedback coefficients (which interfere with the measurement) should be under control

Conclusion: **The change in reactivity up to 0.97 at hot state**
(down from 0.986 at cold state)
is associated to a change in the measurement mode
using the accelerator with short time break signals

Important: Reactivity level is very much associated to a core state
and this is being developed in the following viewgraphs

Experimental proof of ADS technology

The experimental study of the transient dynamics of sub-critical systems will validate the current theoretical simulation capabilities.

The transient dynamics (safety) of sub-critical systems is significantly different from critical systems.

The study of transient characteristics implies the study of the combined transient behavior of:

a. source neutrons, and
b. prompt fission neutrons, and
c. delayed fission neutrons, and
d. influence of target design and target/core coupling issues as well as temperature dependent core reactivity feedbacks

Required are experiment series that allows the study of the combined dynamic behaviour of

the target,
the target/core coupling and
the core configuration with temperature dependent reactivity feedback effects

Experimental proof of ADS technology

Why evaluating the dynamics of sub-critical systems ?

1. Experimental facilities with a meaningful and well qualified temperature dependent reactivity feedback effects are needed.

2. Any well defined temperature dependent reactivity feedback effect is sufficient (does not necessarily have to correspond to a specific temperature reactivity effect associated with an actual transmuter) because :
   - in the set of Kinetic Equations,
   - that describe the dynamic behaviour of sub-critical systems,
   - the coupling term, that describes the combined effect of all the different temperature dependent reactivity feedbacks is universal,
   - i.e.; not plant specific !!

Approach for ADS technology demonstration

Specific Dynamic Issues of sub-critical systems to be studied

1. We know that the shutdown characteristics are significantly different from critical systems, depending on the level of sub-criticality

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2. Transient dynamics at various levels of sub-criticality assuming different initiators for reactivity insertion rates into the reactors. For example:

   a. Unprotected transient behaviour :

   large positive reactivity insertions (> 1 $ in reactivity)

   b. Unprotected transient behaviour :

   insertion of negative reactivities into the reactor (how far does the power level drop in comparison to a critical reactor)

Approach for ADS technology demonstration

Specific Dynamic Issues of sub-critical systems to be studied

3. Transient dynamics at various levels of sub-criticality assuming different initiators for reactivity insertion rates into the reactors (continued):

   c. Unprotected transient behaviour :

      large source strength increases and decreases, respectively (+/- 30 to 50 %)

   d. Unprotected transient behaviour :

      impact of differences in target/core coupling design solutions

   e. Unprotected transient behaviour :

      impact of core cooling transients as inlet temperature increases or coolant mass flow decreases and/or increases, respectively

Input data base validation required for the ADS feasibility study

1. Qualification of sub-criticality monitoring,
2. Validation of generic dynamic behaviour of an ADS in a wide range of sub-critical levels, sub-criticality safety margins and thermal feedback effects,
3. Validation of the core power/beam current relationship,
4. Start-up and shut-down procedures, Instrumentation validation and specific dedicated experimentation,
5. Interpretation and validation of experimental data, Benchmarking and code validation activities etc
6. Qualification of the proton beam reliability and the beam transport line,
   Pb-Bi or Pb-spallation target design in association with relevant proton beam and the effects of spallation residues including that of polonium,
7. Safety and licensing issues of different component parts as well as that of the integrated system as a whole
8. Shielding of high energy neutrons