DM1 DESIGN: DEVELOPMENT OF A DETAILED DESIGN OF XT-ADS AND OF A CONCEPTUAL DESIGN OF EFIT WITH HEAVY LIQUID METAL COOLING

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Abstract

The domain DM1_DESIGN of the FP6 integrated project EUROTRANS has the mission to launch the conceptual design of a lead-alloy-cooled European Facility for Industrial Transmutation (EFIT) loaded with transmutation-dedicated minor actinide fuel to "prove" transmutation at the industrial level. EFIT would represent a modular unit of a large power system able to handle European high-level waste. In parallel to the EFIT design, DM1_DESIGN partners are developing a detailed design of the short-term XT-ADS (eXperimental demonstration of Transmutation in an Accelerator Driven System) that would serve the full-scale demonstration of the ADS concept and be able to accept up to a full MA fuel assembly. XT-ADS is also intended to serve as a test banc for some components of EFIT. The Work Plan of the domain DM1_DESIGN addresses the following main issues of EFIT and XT-ADS:

- Definition of the design parameters for the optimisation of the transmutation objectives in an economical way for EFIT and the short-term realisation for XT-ADS including the most essential features of EFIT.
- Development and assessment of the reference Pb design of EFIT and the back-up option based on gas. In parallel and in a synergetic way XT-ADS with only Pb-Bi reference design is developed in a more detailed manner.
- Further development of the high-power proton accelerator (HPPA) needed for both EFIT and XT-ADS and, in particular, qualification of the beam reliability, the development of the beam transport line and the demonstration of the prototypical components of the chosen HPPA.
- Proof of feasibility windowless spallation targets making maximum use of the existing work for defining the needed complementary experimental work for XT-ADS spallation targets.
- Evaluation of the safety performance and licensability of the three designs developed in the DOMAIN DM1.
- Cost estimates and planning issues for the deployment of the transmutation facilities.

In this paper we give the progress accomplished in these different work packages and present the first results obtained after 18 months of activity.

Objective

The objective of the Domain DM1_DESIGN is to proceed towards the demonstration of the industrial transmutation through the ADS route. This will be carried out with two interconnected activities. The first activity is to carry out a detailed design leading to a "short-term" experimental demonstration of the technical realisation of transmutation in an accelerator-driven system (XT-ADS). The total power level of the XT-ADS will range between 50 and 100 MW_{th}. This facility is intended to be as much as possible a test bench of the main components and of the operation scheme of the European Facility for Industrial Transmutation (EFIT), but at lower working temperatures thanks to the use of lead-bismuth eutectic (LBE) as a core coolant and spallation target material. The second activity is the development of a conceptual design of the EFIT with a power of up to several 100s MW_{th}. The reactor coolant and the spallation target material of EFIT will be pure lead. Both designs (XT-ADS and EFIT) bear the same fundamental system characteristics in order to allow for scalability considerations. Design features will be worked out to a level of detail which allows a cost estimate of XT-ADS and through parametric projections and the preliminary design of EFIT the cost estimate of the industrial scale ADS

The features of XT-ADS and EFIT

The EFIT is a full-scale transmutation *demonstrator*, loaded with transmutation-dedicated fuel. The machine becomes operational many years after the XT-ADS (around 2040) and takes into account all the experience gained from the already running R&D programmes on fuel and materials. On the other hand, the XT-ADS is to be *built and tested in a near future* (about eight years from the start of the IP_EUROTRANS project). The machine should be completely operational around 2017-2018 and fulfil three objectives: *demonstrate the ADS concept* (coupling of accelerator, spallation target and subcritical core) and its operability, *demonstrate the transmutation*, provide an *irradiation facility* for the testing of different EFIT components (samples, fuel pin, fuel assembly).

Based on these different objectives of EFIT and XT-ADS, the design teams have compared the respective designs, trying to merge when possible the characteristics. As EFIT is an industrial-scale transmutation facility, the characteristics were defined according to the efficiency of transmutation, the ease of operation and maintenance, and the high level of availability in order to achieve an economical transmutation. For XT-ADS on the other hand, the characteristics have been defined to get a flexible testing facility. Despite those sometimes contradictory definitions, some characteristics remain identical in the EFIT and XT-ADS machines and are listed here below.

For the *accelerator* part of the system, both teams opt for a linac solution. The main reason for this choice is the improvement of beam reliability at such levels of proton energy. In both machines, the *beam ingress* is foreseen from the top of the vessel. One of the major reasons for that choice is strongly related the choice made for the target unit interface. The interface being windowless, a beam ingress from the bottom becomes simply unfeasible.

If the *cores* of both machines are significantly different, some characteristics are still identical: a grid will be used as fuel pin spacer, the fuel assembly (FA) will be of the wrapper-type and the FA cross-section will be hexagonal. If these options have been taken from the early beginning in the XT-ADS design, some FA alternatives have been envisaged in the EFIT, but not retained (wrapperless type, square cross-section).

Several characteristics are also identical in the *vessel* design: the primary system is integrated in the vessel, the primary coolant circulation in normal conditions is forced (with mechanical pumps) while in decay heat removal (DHR) conditions the primary coolant circulation is natural (with a pony motor, although full-natural circulation of all coolants is being considered for EFIT).

Besides these identical features, divergence has occurred in the choices of components or parameters of the two machines. This divergence, even necessary as the time scales of realisation of the two facilities are different, is listed below in tabular form. The XT-ADS has been largely inspired by the MYRRHA design [1,2] as offered by SCK•CEN and agreed by all DM1 partners.

	XT-ADS	**EFIT**
Proton energy	600 MeV × 2.5 mA / 350 MeV × 5 mA	800 MeV × 20 mA
Spallation target concept	Off-centred, windowless	Centred, windowless
Fuel	MOX, some minor actinide (MA) FA accepted	(Pu, AM)O_2 + MgO (or metallic Mo) matrix
Power (MW_{th})	50-100	395
Power density (W/cm³)	700	450-650
Reactivity swing compensation	No compensation as long as swing remains limited	The predicted small burn-up swing is to be compensated by proton current adjustment
Presence of absorbers	Yes	For refuelling only
Vessel structural material	316L	316 L
Vessel type	Not yet defined	Hung
Primary coolant	LBE	Pure lead
Primary system temperature range (°C)	Inlet: 300 Outlet: 400	Inlet: 400 Outlet: 480
Secondary coolant	Low pressure boiling water	Superheated water cycle
Fuel loading	From bottom (alternative from top has been reviewed)	from top
Fuel handling	Oriented remote handling	Extendible-arm handling machine and rotating plug
Seismic design	Seismic spectrum specific to the Mol site	Horizontal anti-seismic supports

At present, the designers have achieved already several results:

- A preliminary configuration of the EFIT reactor block (Figure 1 shows a vertical cut) with cylindrical inner vessel, primary pumps in the hot leg, free level of the cold pool outside the cylindrical inner vessel higher than the free level of the hot pool inside (the moderate free level difference is determined by the low pressure losses of the primary circuit), as well as functional sizing of the EFIT steam generators and DHR dip coolers.

- Core design studies of the XT-ADS have started from the "DRAFT-2" design of the MYRRHA project [1]. After several iterations between the partners, a fuel pin and fuel assembly reference design have been laid down. The "clean" core, i.e. the core without any irradiation devices, has been fixed at 72 fuel assemblies symmetrically placed around three emptied positions to make room for the spallation target. In another paper presented at this conference [3], we sketch the changes from the MYRRHA core to the XT-ADS core and propose a set of possible irradiation and transmutation facilities. These are very early designs and will mature during the remainder of the project. A preliminary EFIT core configuration has been established.

- Three options have been studied for the XT-ADS reactor block (Figure 2 shows the option "A" directly inspired by MYRRHA) and a reference design is under preparation:
  - A: MYRRHA, (DRAFT-2) version;
  - B: Modified MYRRHA: with fuel manipulation from the top;
  - C: EFIT-like design: the "cylindrical inner vessel" concept instead of the "diaphragm".

Figure 1. Pb-EFIT primary system, vertical cut

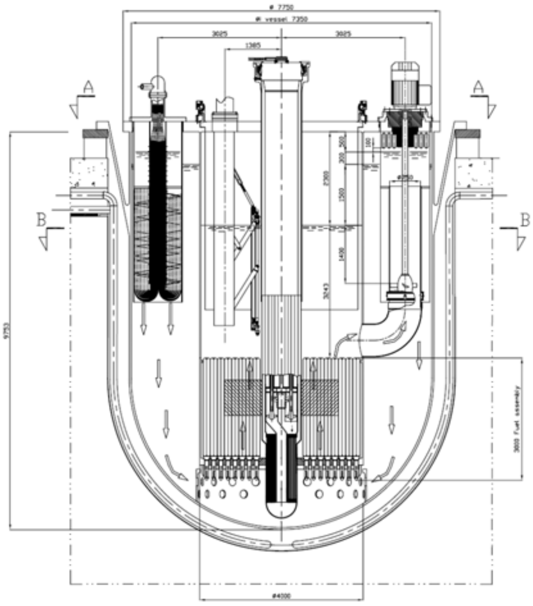
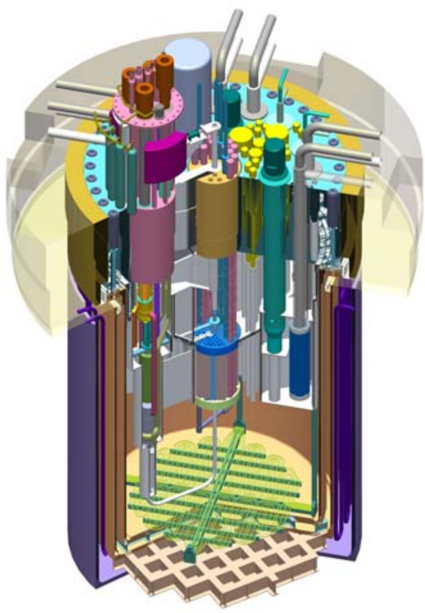


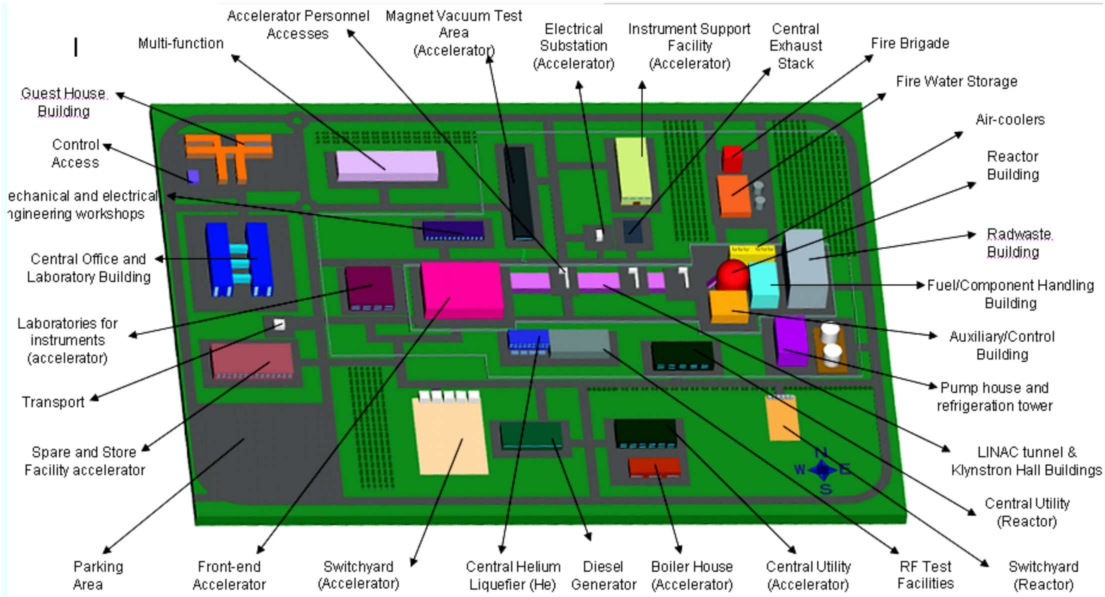
Figure 2. XT-ADS primary system (variant "A", vertical cut)



Possible plant layout

A first layout for the XT-ADS has been proposed for discussion (Figure 3) starting from a virgin site. If Mol is selected as host for XT-ADS, several utility buildings can be re-used and the layout can be adapted accordingly.

Figure 3. Possible XT-ADS plant layout on a virgin site



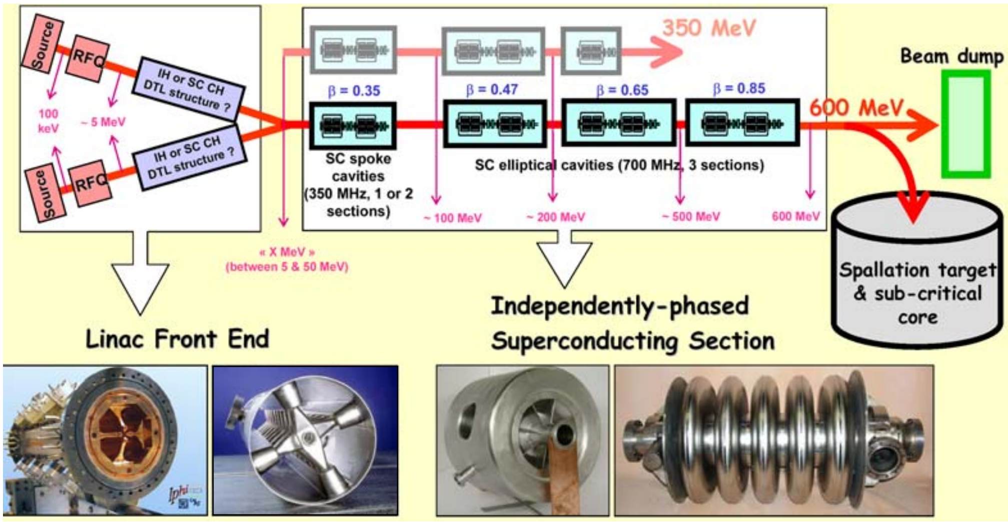
Accelerator developments

The accelerator considered here belongs to the category of high-power proton accelerators (HPPA), which are presently very actively studied (or even under construction) for a rather broad use in fundamental or applied science. Compared to other HPPA, many specifications are similar: 600 MeV final energy (for the smaller-scale XT-ADS), 6 mA CW beam, 2% beam power stability, 10% beam size stability on target, etc. [4]. But it is to be noted that the reliability requirement, i.e. the number of unwanted beam-trips, is rather specific to ADS. This reliability requirement is essentially related to the number of allowable beam trips, because, frequently repeated, they can significantly damage the reactor structures, the target or the fuel, and also decrease the plant availability. Therefore, beam trips in excess of one second duration should not occur more frequently than five per year. The studies integrated this stringent requirement from the very beginning, as this issue could be a potential "show-stopper" for ADS technology in general.

The strategy chosen to implement reliability depends upon over-design, redundancy and fault tolerance [5]. This approach requires a highly modular system where the individual components are operated substantially below their performance limit ("de-rating" principle): in contrast to a cyclotron, a superconducting linac, with its many repetitive accelerating sections grouped in "cryomodules", conceptually meets this reliability strategy.

The proposed reference design for the accelerator, optimised for reliability, is shown in Figure 4 [6]. For the injector, an ECR source with a normal conducting RFQ is used, followed by warm IH-DTL or/and superconducting CH-DTL structures up to a transition energy still to be optimised around 20 MeV. Then a fully modular superconducting linac accelerates the beam up to the final energy.

Figure 4. The reference accelerator



The accelerator design can profit from the good synergy existing between the many laboratories currently working in the field. The machine can even be built quite directly. However, a dedicated R&D programme is needed for the requirement of an extremely low number of beam trips. In this spirit, such a programme has been launched in DM1_DESIGN, focused on reliability and fault tolerance design. The five main tasks of this programme are discussed below.

Evaluation of the injector reliability

Concerning the injector section, a thorough campaign to test the reliability of every component of the injector, operated over a long period of time (e.g. a continuous run of many weeks), will be performed "full-scale" with IPHI. Presently under construction in France [7], IPHI, consisting of an already operational ECR source and a 6-m long RFQ, will deliver, in 2006, its 3 MeV high intensity beams (10-100 mA). The experimental results are expected before mid-2008.

R&D for the intermediate-energy section

Some basic R&D is required for the subsequent sections, up to 100 MeV, in order to assess a solution simultaneously reliable and economical. While SC components should in principle be deployed from the lowest possible energies on, room-temperature structures have nevertheless to be studied and prototyped: the transition energy to the superconducting structures might be higher than the RFQ output and, while room-temperature structures have large RF losses, their development risk is low (well established technology). The superconducting resonators considered here are CH structures before the transition energy, because of their very promising efficiency, and spoke cavities after, because they are short and modular in view of the fault-tolerance strategy. The first SC cavity prototypes are presently successfully tested, showing performance exceeding the specifications by a very comfortable over-design safety margin [8,9]. It is therefore important to push these developments by adding helium tanks and power couplers. The final aim of all these developments is to assess the best technical option for the intermediate section of the accelerator based on established, demonstrated performance. It might well be a combination of several technologies.

High-energy section cryomodule

While the R&D on 704 MHz superconducting elliptical cavities is well advanced in Europe, the demonstration of the full technology is not yet accomplished. Besides the development of the bare superconducting cavity, it is important to prototype each auxiliary system needed for the cavity operation in a real environment (power coupler, RF source, power supply, RF control system, cryogenic system, cryostat…). The construction of a full-scale module with a given beta value ($\beta = 0.5$) can be considered as a rather general proof-of-principle of the technology, since the higher beta modules are very similar. The construction and test with RF at nominal power (although without beam) of such a module should be done before end 2008.

Digital LLRF control system

The performance of the RF control system procedures in case of a cavity failure is a major key to reach the reliability requirement. Indeed, the reaction speed for retuning the whole accelerator to nominal beam conditions must be less than 1 second for fault tolerance. Digital techniques are necessary to meet the speed and software configuration requirements. It is planned in this task to perform a full conceptual design of such a specific low-level RF system for the 704 MHz elliptical section.

Accelerator design

This last task will ensure the overall coherence of the accelerator design. Beam dynamics simulations will be performed, in close collaboration with the LLRF task, to assess the adequate transient procedure while dealing with a cavity failure. An integrated reliability analysis of the whole linac will also be made, the final goal being to obtain in 2009 a frozen detailed design of a linac, with assessed reliability and costing.

The spallation source module

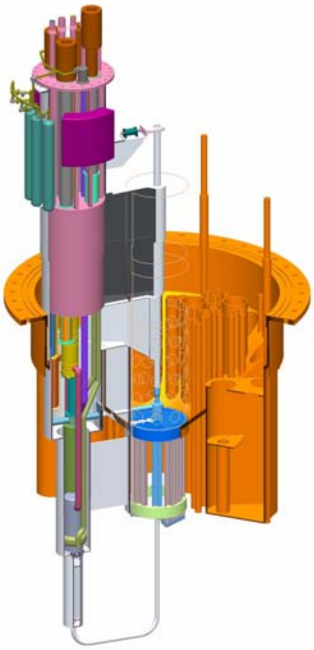
The MYRRHA spallation target module (Figure 5), is serving as the starting point for the target design of the XT-ADS. With respect to the MYRRHA case, modifications of the spatial constraints within the XT-ADS core and incorporation of the 600 MeV, 2.5 mA option for the proton beam energy and current, triggered relatively small design changes. More fundamental design alterations are currently being studied. These include the investigation of a spallation target configuration featuring flow detachment, the introduction of swirl, and a detailed study of the three-feeder option. In addition a modification of the vacuum system to simplify the spallation product confinement is being investigated. Finally, the interface with the different variants of primary system has been reviewed. More details are found in [10].

Safety challenges

The safety approach previously developed in the FP5 PDS-XADS project is updated to cope with the new situation induced by the presence of large amount of MA in the core of EFIT and high pressure water heat exchangers in the primary systems of both EFIT and XT-ADS.

An integrated safety approach has been developed for the designs of XT-ADS and is being extrapolated to the case of EFIT. Scoping safety analyses have been performed for the design base

Figure 5. XT-ADS spallation target, inspired by MYRRHA design



conditions (DBC) and the design-extension condition (DEC) transients of XT-ADS and EFIT, and any shortcomings in the designs with respect to safety have been identified. A scoping assessment of the source term and the containment has been performed to determine if there are any show-stoppers.

Conclusions

Several academic, research and industrial partners are working together on the development of two accelerator-driven systems, XT-ADS and EFIT, within the framework of the 6th European Framework Programme. XT-ADS is to serve as a prototype ADS, a fast neutron irradiation facility in which critical components of the large scale EFIT waste burner can be tested. EFIT, a several hundreds megawatt machine, will be the first European industrial-size nuclear waste burner.

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