

THE ACCELERATOR ACTIVITIES OF THE EUROTRANS PROGRAMME*

Paolo Pierini[†], INFN Sezione di Milano, LASA

Abstract

The objective of the EC Integrated Project EUROTRANS is the design and feasibility assessment of an industrial accelerator driven system prototype dedicated to the transmutation of high level waste from nuclear power plants. A part of the program is dedicated to the further development of the high power proton accelerator needed for both the short term experimental demonstrator systems and the long term large scale industrial realizations. In particular the accelerator program addresses the issues of the qualification of the beam reliability with respect to the spallation target requirements, the development of the beam transport line to the subcritical reactor, and the demonstration of the key prototypical components of the proposed linear accelerator. This communication will present an overview and status of the accelerator activities carried out by the partners of the EUROTRANS project.

INTRODUCTION

The European Research Programme for the Transmutation of High Level Nuclear Waste in an Accelerator Driven System is a research program funded by the European Commission in the 6th Framework Programme, involving 31 partners between research agencies and nuclear industries and with the contribution of 16 universities. EUROTRANS is a 4 year program extending previous activities (PDS-XADS, Preliminary Design Study for an eXperimental Accelerator Driven System) and paving the road towards the construction of an eXperimental facility demonstrating the technical feasibility of Transmutation in an Accelerator Driven System (XT-ADS) in the next EC framework programmes.

The main objective of EUROTRANS is to work towards a European Transmutation Demonstration (ETD) in a step-wise manner:

- to provide an advanced design of all components of an XT-ADS system at significant power levels of the subcritical assembly (50 to 100 MWth), driven by conventional MOX fuel, in order to allow its realization in a short-term (~10 years),
- to provide a generic conceptual design of modular European Facility for Industrial Transmutation (EFIT), with power levels exceeding several 100 MWth and operated with new fuel loaded with reprocessed waste. The EFIT is the long-term objective of the program.

TRANSMUTATION IN AN ADS

Transmutation in an Accelerator Driven System (ADS) intends to address the problem of the long term disposal of the nuclear waste. In particular its objective are to reduce the radiotoxicity of the waste, to minimize the volume and the heat load of the nuclear waste sent to the deep geological storage in underground repositories.

The EU has (2001 data [1]) 145 reactors, providing more than 125 GW of electrical power, with an 850 TWh yearly production (covering 35% of the total), and producing an yearly amount of 2500 tons of spent fuel, among which 25 are Pu.

The strategy aimed at solving this problem relies on partitioning and transmutation, i.e. to separate chemically the waste fuel - that is, isolate Pu, the Minor Actinides (MA) and the Long Lived Fission Fragments (LLFF) – and to recombine the chemically pure elements obtained in this way in proper assemblies that could fuel dedicated transmuter systems, aimed at disposing of them in times much shorter than the natural decay times.

In order to deploy a solution for the waste disposal problem, two main technological ingredients are needed for a transmutation system:

- a **subcritical reactor** (with a criticality factor k substantially smaller than 1) where the fission chain reaction is not self-sustained, and operating with U-free fuel, in order to avoid nuclear proliferation problems
- an **intense neutron spallation source** (i.e. a high proton flux on a liquid lead target) that provides the “missing” neutrons that are needed to keep the reaction going. The neutrons produced by a high energy proton beam by spallation have also the broad energy spectrum which is needed to “burn” the MA components, that are otherways accumulated in conventional critical reactors operating with a thermal neutron spectrum.

The radiotoxicity of the spent fuel decreases to the level of the starting raw uranium ore used to produce the fuel elements only after a period greater than a million years. In order not to release these toxic elements in the biosphere it is thus necessary to dispose of the waste in deep and stable geological repositories, ensuring proper containment and surveillance for this extremely long period. The Partitioning and Transmutation (P&T) goal is, via chemical separation and irradiation in a fast and intense neutron flux, to reduce this time to 700-1000 years (See Figure 1).

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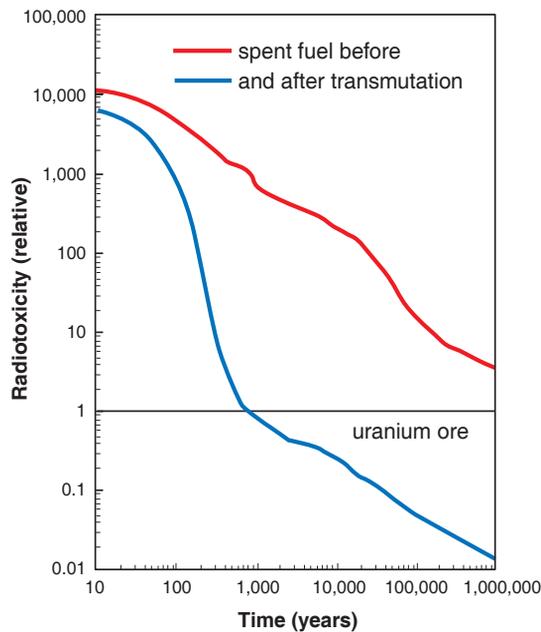


Figure 1: Ingestion radiotoxicity of spent nuclear fuel, before and after partitioning and transmutation, compared to the uranium ore level. From Ref. [1].

Within the EUROTRANS program the activities are carried in five main technical areas (called Domains):

- The first domain is dedicated to the **design** of the ADS systems (XT-ADS and EFIT), and subcomponents. The accelerator activities are carried in one workpackage of this domain.
- The second domain is devoted to experimental activities on the **coupling** of an accelerator, a neutron spallation target and a subcritical blanket. Experiments have been proposed using research reactors at low power levels driven by photofission generated neutrons by small electron accelerators.
- The remaining domains are concerned with the study of **advanced fuels** for transmuters, the investigation of structural materials for ADS systems and **heavy liquid metal technologies** (in particular the spallation target design), and nuclear data for transmutation.

EUROPEAN TRANSMUTATION DEMONSTRATION

EUROTRANS aims at proceeding towards the demonstration of the industrial transmutation through the ADS route, primarily with the design of the XT-ADS and EFIT systems. The first is intended to be as much as possible a test bench of the main components and of the operation scheme of the EFIT, but at the lower working temperatures allowed by the use of Lead-Bismuth Eutectic (LBE) as core coolant and spallation target material. The EFIT design will be detailed to a level which will allow a parametric cost estimate of the ADS-based transmutation process. The reactor coolant and the spallation target material will be pure lead. Both designs

(XT-ADS and EFIT) share the same fundamental system characteristics in order to allow for scalability considerations.

The basic features of XT-ADS and EFIT

The EFIT is intended as a full-scale transmutation demonstrator system, 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 programs on fuel and materials. On the other hand, the XT-ADS is meant to be built and tested in a near future (about 8-10 years from the start of the 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 sub-critical core) and its operability, demonstrate the transmutation, provide an irradiation facility for the testing of different EFIT components (samples, fuel pin, fuel assembly).

Even though the EFIT and XT-ADS have different objectives, they share as many designs characteristics as possible. As EFIT is an industrial-scale transmutation facility, the characteristics were meant to maximize the efficiency of transmutation, the easiness 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 deploy a flexible testing facility. Despite those sometimes contradictory definitions, many characteristics remain identical in the EFIT and XT-ADS machines:

- A superconducting linac solution has been chosen for both systems. The main reasons for that choice are the perspectives of improvement of beam reliability at such levels of proton energy [2-4].
- The cores of both systems are significantly different, but some characteristics are still identical.
- The vessel designs, which integrate the primary cooling system, share many design features.

Besides these identical features, divergence has occurred in the choices of components or parameters of the two machines. The following table resumes the main differences in the two concepts.

Table 1: Main differences in the two European Transmutation concepts

	XT-ADS	EFIT
Objective	Irradiation facility and EFIT test bench	Industrial waste burner
Power range	50-100 MWth	100 MWth
Subcriticality	~0.95	~0.97
Beam characteristics	5 mA@350 MeV or 2.5 mA@600 MeV	20 mA@800 MeV
Fuel	Conventional MOX	Minor Actinides loaded
Coolant	Lead-Bismuth Eutectic	Lead (gas as backup)

The reference accelerator

The ETD requires a high power proton accelerator operating in CW mode, ranging from 1.5 MW (for XT-ADS operation) to 16 MW (for the EFIT). Additional requirements at the neutron spallation target are a 2% beam power stability and 10% beam size stability, in order to provide a sufficiently stable neutron flux [2,3].

The reference design for the accelerator has been developed during the PDS-XADS programme and is shown in Figure 2. For the injector, an ECR source with a normal conducting RFQ is used, followed by an energy

booster section which uses either a normal conducting IH-DTL or superconducting CH-DTL structures up to a transition energy still under optimization, around 20 MeV. This first part of the linac is duplicated in order to provide good reliability perspectives [4]. Then a fully modular superconducting linac (based on different RF structure) accelerates the beam up to the final energy.

The design of such a linac configuration has been motivated by the specific reliability requirements imposed to the ADS accelerator, which are summarized in the following paragraphs.

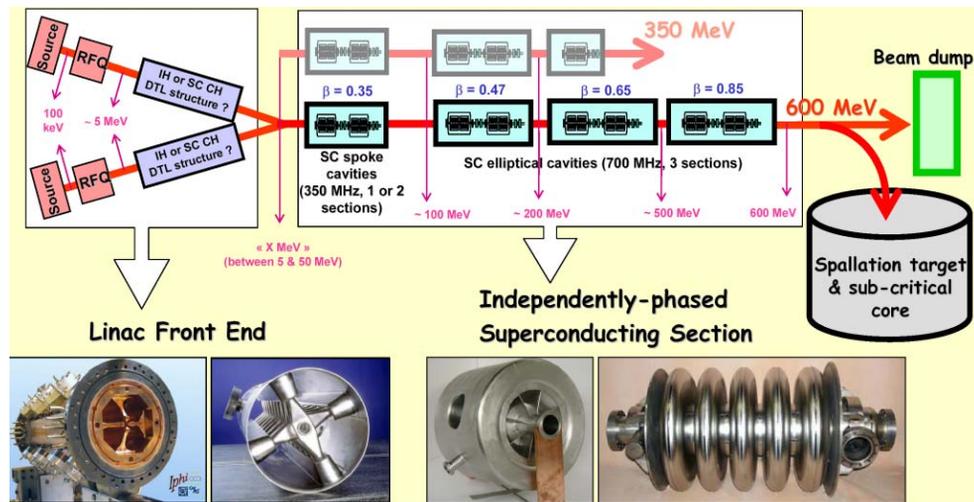


Figure 2: The reference accelerator scheme for the ETD/XT-ADS.

Issues and challenges for an ADS driver

The ADS accelerator is expected - especially in the long term EFIT scenario - to have a very limited number of unexpected beam interruptions per year which cause the absence of the beam on the spallation target for times longer than a second. This requirement is motivated by the fact that frequently repeated beam interruptions can significantly damage the reactor structures, the target or the fuel elements, and also decrease the plant availability. Therefore, it has been estimated that beam trips in excess of one second duration should not occur more frequently than five times per year (EFIT). To provide such an ambitious goal, which is lower than the reliability experience of typical accelerator based user facilities by many orders of magnitude, it is clear that reliability-oriented design practices need to be followed from the early stage of component design. In particular, “strong design” practices (based on component derating with respect to limiting performances) are needed, a rather high degree of redundancy needs to be planned and fault tolerance capabilities has to be introduced [4].

The chosen strategy to implement reliability relies on over-design, redundancy and fault-tolerance. Redundancy at the low energy stage has been obtained by duplicating the source, RFQ and booster stage, while a superconducting linac, with its modular and repetitive design, consisting in accelerating sections grouped in “cryomodules”, naturally meets this reliability strategy.

A second requirement on the operation of the CW ADS linac comes from the requirement to perform on-line reactivity measurements of the subcritical assembly. For this reason, the accelerator, while the RF operates in CW, needs to provide zero current beam “holes” with durations up to 200 μ s and sharp rise and fall times of few μ s, at a very low duty cycle, with a repetition rate ranging from 10^{-3} to 1 Hz.

The accelerator workpackage of EUROTRANS is dedicated to the design, operation and experimental characterization of the reliability characteristics of each of the major linac component in the various energy sections.

Design for reliability

As previously mentioned, the fundamental reliability guidelines have been extensively used in the linac design, in terms of:

- component derating,
- inclusion of redundancies,
- capabilities of fault tolerance operation..

During the PDS-XADS program a preliminary bottom-up reliability analysis (Failure Mode and Effects Analysis, FMEA) has been performed [4] in order to identify the critical areas in the design in terms of impact on the overall reliability. This activity suggested to provide a second, redundant, proton injector stage (composed of the source, RFQ and low energy booster), with fast switching capabilities.

After the injector stage, the superconducting linac has a high degree of modularity, since the whole beamline is an array of nearly identical “periods”. All components are operating well below any technological limitation in terms of potential performances, and therefore a high degree of fault tolerance with respect to cavity and magnets can be expected in the superconducting linac, where neighbouring components have the potential to provide the functions of a failing component without affecting the accelerator availability. Clearly this approach implies a reliable and sophisticated machine control system, and in particular a digital RF control system to handle the RF set points to perform fast beam recovery in the case of cavity failures.

THE ACCELERATOR ACTIVITIES

The accelerator workpackage is split in several tasks, focussed to identify the design of the main subcomponents of the ADS linac in the different energy areas and to identify their reliability characteristics.

Activities are dedicated to:

- the experimental evaluation of the proton injector reliability, performed at the CEA IPHI injector,
- the assessment of the reliability performances of the intermediate energy accelerator component, with particular attention to the comparison of different accelerating structures proposed,
- the design and the experimental qualification of the reliability performances of a high energy cryomodule tested at full power and nominal temperature,
- the design and testing of a prototypical RF control system intended to provide fault tolerance operation of the linear accelerator,
- the update of the accelerator design - including beam dynamics issues and investigation of control strategies for fault tolerance – and the development of further reliability analyses and cost estimations for the XT-ADS and EFIT.

Proton injector reliability tests

The IPHI injector (see Figure 3), developed in France by CEA and CNRS, fulfils the specifications of the ADS proton injector, with wide margins in term of beam current capabilities. IPHI is composed by the SILHI ECR ion source, a 3 MeV RFQ under completion, the associated beam lines and diagnostics, that are being assembled at Saclay. The IPHI injector, once completed, will be used for a long run test (several months), to demonstrate and assess, on a real scale, the reliability characteristics of this accelerator subcomponent.

In the past years the SILHI source has been successfully used for several week-long reliability tests at currents of 30 mA, showing no beam stops and occasional sparks in the extraction region, causing no beam interruptions. These tests will be extended to a few months and will include acceleration in the RFQ and propagation in the beam lines.

The possibility to achieve the sharp “beam holes” required for reactivity measurements, already tested at the source SILHI, will be extended to the full beam from the IPHI injector, at 3 MeV.

RF structures for intermediate energy

For the intermediate energy region after the RFQ and up to approximately 100 MeV, several cavity types are considered as valid “candidates”. Studies and test of prototypes are being developed in order to evaluate their feasibility and assess their potential reliability performances.

In particular, activities concentrate on:

- high shunt impedance copper DTL structures of the IH type, with “Konus” focussing scheme, i.e. elements outside the drift tubes.
- superconducting multi-gap CH structures, with “Konus” focussing scheme.
- superconducting spoke cavities which can operate at very low energies (around 5 MeV), and can be efficiently used up to 100 MeV and more.

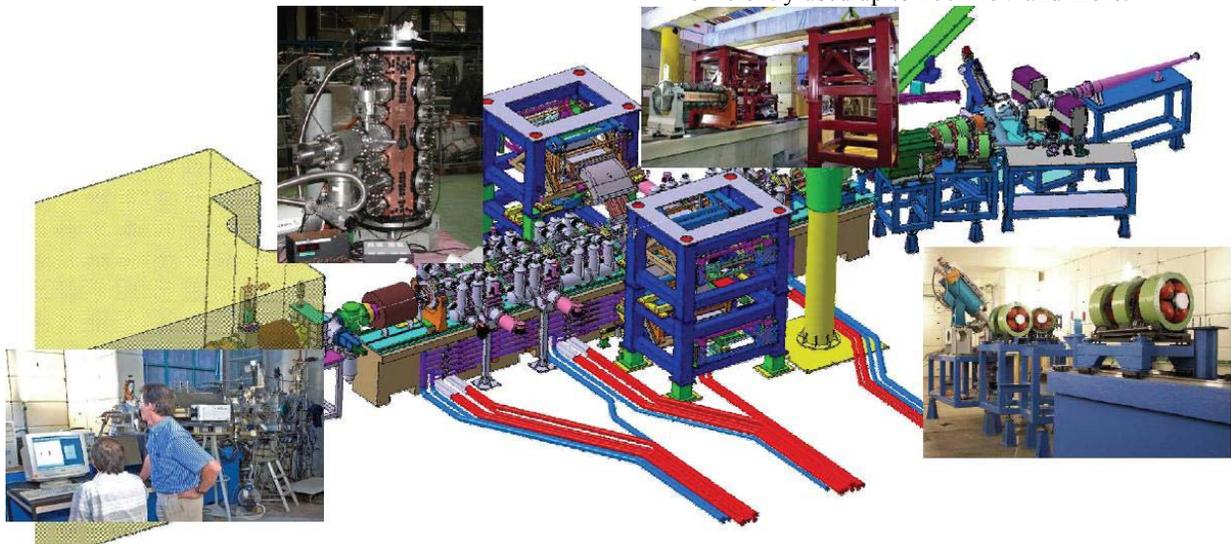


Figure 3: Scheme of the IPHI injector, and pictures of the components during their installation at Saclay.

The first activity is carried out at IBA, while the 19 gap SC CH structure has been successfully tested at IAP-Frankfurt and is ready to be installed in an existing cryostat, with an external driven mechanical tuner [5]. In addition, CNRS/Orsay is equipping an existing cryomodule with a $\beta=0.15$ spoke cavity, fully dressed with its stainless steel helium reservoir, the cold frequency tuning mechanism and the high power (20 kW) RF coupler [6]. The cavity, which has already reached the design goals in vertical tests, once completed with its ancillary RF components, will be operated at nominal operating conditions in long tests to determine the reliability characteristics of the components. Figure 4 shows the tests of the tuning mechanism on the cavity.

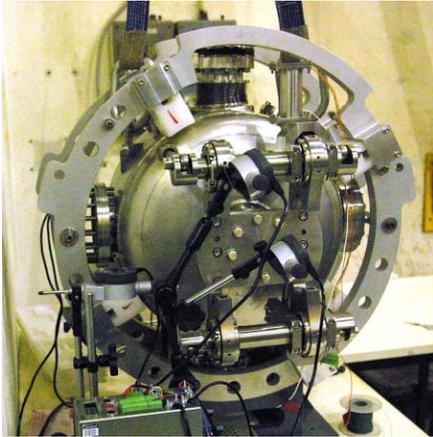


Figure 4: The spoke cavity equipped with the cold frequency tuner in the support frame of the cryostat.

The high energy cryomodule

For the high-energy part of the linac, using low beta elliptical cavities from an energy of approximately 100 MeV, one of the existing $\beta=0.47$ TRASCO cavities [7], equipped with a cold frequency tuner and a high power RF coupler, will be installed in a prototype cryomodule, under development at INFN and CNRS, to be tested in Orsay under nominal operating conditions. Figure 5 shows a conceptual layout of the module.

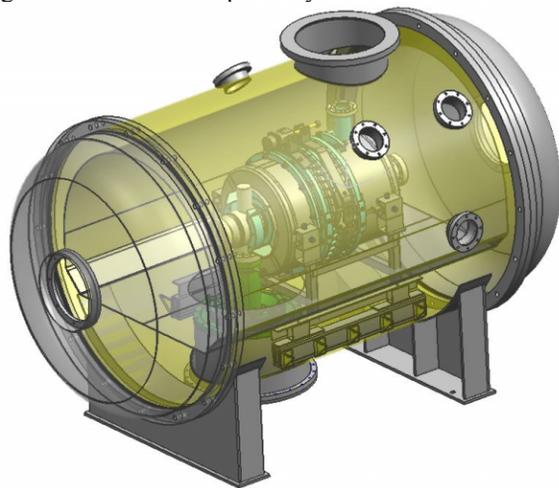


Figure 5: Conceptual layout of the single cavity module for the testing of the high energy components.

RF control system for fault tolerance

The scope of this activity, mainly carried out by CEA, CNRS and IBA is to develop a digital RF control system intended to provide the necessary field and phase stability and to identify and handle fast recovery scenarios for cavity failures in the superconducting linac, by means of local compensation at neighbouring cavities.

Accelerator design

The last task in the accelerator workpackage deals with the progress of the accelerator design and the characterization of its reliability goals. In particular, start to end beam dynamics simulations are performed for the different options for the intermediate energy structures. The modelling includes the effect of the beam transients induced by RF faults and explores the possible recovery scenarios needed to provide the necessary beam availability to the ADS application. Furthermore, an integrated reliability analysis is being performed to predict the reliability characteristics of the proposed accelerator, following the standard practices used in the nuclear energy applications (mainly failure mode and effects analysis and reliability block diagrams).

ACKNOWLEDGEMENTS

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