ACCELERATOR R&D FOR THE EUROPEAN ADS DEMONSTRATOR*

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Abstract

An Accelerator Driven System (ADS) for transmutation of nuclear waste typically requires a 600 MeV - 1 GeV accelerator delivering a proton flux of a few mA for demonstrators, and a few tens of mA for large industrial systems. Such a machine belongs to the category of the high-power proton accelerators, with an additional requirement for exceptional reliability: because of the induced thermal stress to the subcritical core, the number of unwanted beam-trips should not exceed a few per year, a specification that is far above usual performance. This paper describes the reference solution adopted for such a machine, based on a so-called "fault-tolerant" linear superconducting accelerator, and presents the status of the associated R&D. This work is performed within the 6th Framework Program EC programme EUROTRANS.

INTRODUCTION

The basic purpose of Accelerator Driven Systems (ADS) is to reduce – by orders of magnitude – the nuclear wastes' radio-toxicity, volume and heat load before their underground storage in deep geological depositories [1]. This issue is particularly significant in the European Union, where about 2500 tons of used fuel are produced every year, containing 25 tons of plutonium, 3.5 tons of minor actinides (Np, Am, Cm) and 3 tons of long-lived fission products.

"Partitioning & Transmutation" (P&T) has been pointed out in numerous studies as the strategy that can relax the constraints on the geological disposals, and reduce its monitoring period to manageable time scales. Within the P&T process, the different elements of the spent fuel are chemically separated, isolated and recombined to obtain new assemblies to be used and burnt either in (certain types) of critical Generation-IV reactors or into dedicated, sub-critical ADS "transmuter" facilities, therefore also limiting nuclear proliferation risks.

An ADS transmuter system is composed of two main parts: an "intrinsically safe" sub-critical reactor ($k_{eff} < 1$), in which the chain reaction can not be self-sustained, and an intense spallation source that provides the missing neutrons needed to keep the reaction going on. Such a neutron source, composed by a target subjected to a high energy proton flux, also produces the suited broad energy spectrum required to "burn" the minor actinides components, that are otherwise accumulated in conventional thermal spectrum critical reactors.

* Work supported by EU FP6 through the EUROTRANS programme
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∀ The PDS-XADS project was supported by EU FP5
∍ The CDT project is supported by EU FP7

THE EUROPEAN ADS DEMONSTRATOR

The EUROpean research programme for the TRANSmutation of high-level nuclear waste in accelerator driven systems (EUROTRANS) is funded by the European Commission within the 6th Framework Programme, and involves more than 40 partners (research agencies, universities and nuclear industries). It is a 5-year programme (2005-2010), extending previous R&D (e.g. the PDS-XADS project∀), and which activities are split into five main domains, respectively devoted to:

- DM1: the advanced design of a transmuter demonstrator including all its sub-components, together with a generic conceptual design of an industrial transmutation facility (see Table 1);
- DM2: experiments dealing with the coupling of an accelerator, a spallation target and a sub-critical core, like the zero-power GUINEVERE experiment [2];
- DM3: studies on advanced fuels for transmuters;
- DM4: investigations on suited structural materials and heavy liquid metal technology;
- DM5: collection of nuclear data for transmutation.

Table 1: European Transmuter Main Specifications

Transmuter demo (XT-ADS / MYRRHA project)	**Industrial transmuter (EFIT)**
50 – 100 MWth power	Several 100 MWth power
k_{eff} value ~ 0.95	k_{eff} value ~ 0.97
Highly-enriched MOX fuel	Minor Actinide fuel
Pb-Bi Eutectic coolant & target	Pb coolant & target

The main objective of the EUROTRANS programme is actually to pave the road towards the construction of an eXperimental facility (MYRRHA) willing to demonstrate the technical feasibility of Transmutation in an Accelerator Driven System (XT-ADS concept).

SCK.CEN (Mol, Belgium) has initiated the MYRRHA project in 1998 [3]. Its purpose is to design and later to build a flexible irradiation facility as suitable replacement for the existing Material Testing Reactor BR2 that is operating since 1962. The new facility would serve both as a test-bed for transmutation and as a fast-spectrum facility for material and fuel developments. It would operate first as a sub-critical (accelerator driven) system and later as a critical reactor. The Central Design Team (CDT∍) project is presently being settled to further develop the engineering design of such a facility, which should be fully operational in 2020.

Table 2: Proton Beam General Specifications

	Transmuter demo (XT-ADS / MYRRHA project)	Industrial transmuter (EFIT)
Proton beam current	2.5 mA (& up to 4 mA for burn-up compensation)	~ 20 mA
Proton energy	600 MeV	~ 800 MeV
Allowed beam trips (> 1sec) number	~ < 5 per 3-month operation cycle	~ < 3 per year
Beam entry into the reactor	Vertically from above	
Beam stability on target	Energy: ± 1% - Current: ± 2% - Position & Size: ± 10%	
Beam time structure	CW (w/ low-frequency 200µs zero-current beam holes for sub-criticality monitoring)	

THE REFERENCE ADS ACCELERATOR

The European ADS concepts requires a high-power proton accelerator operating in CW mode, ranging from 2.4 MW (XT-ADS operation) up to 16 MW for the industrial EFIT. The main beam specifications are shown in Table 2. At first glance, the extremely high reliability requirement (beam trip number) can immediately be identified as the main technological challenge to achieve.

The conceptual design of the accelerator has been developed during the PDS-XADS project [4]. It is a superconducting linac-based solution (see Figure 1), leading to a very modular and upgradeable machine (same concept for demonstrator and industrial scale), an excellent potential for reliability (see dedicated section here after), and a high RF-to-beam efficiency thanks to superconductivity (optimized operation cost). A more advanced reference design is presently under final definition – to be frozen by mid 2010 – in the MYRRHA context. The main characteristics, still subjected to slight changes, are detailed below. The investment cost for such a machine has been assessed around 200 M€ (manpower included, buildings and general utilities excluded).

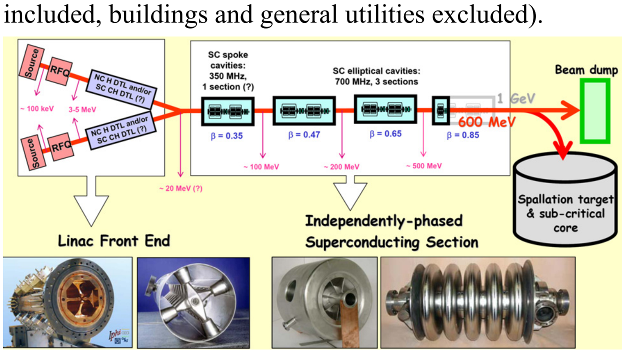

Figure 1: European ADS accelerator conceptual scheme.

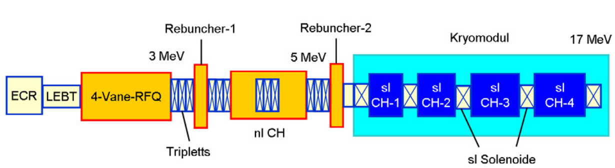

Figure 2: The reference linac front-end.

The Linac Front-End

The linac injector is composed of a 50 kV ECR proton source, a short magnetic Low Energy Beam Transport line and a 3 MeV 4-vane copper RFQ operating at 352 MHz. This RFQ, designed to handle up to 30 mA CW beams with close to 100% transmission for all currents, is about 4.5 metres long, and operates with moderated Kilpatrick factors (~1.7).

This "classical" injection section is then followed by a more "exotic" but promising energy booster [5], that is a combination of normal conducting and superconducting CH (Crossbar H-mode) DTL structures as shown in Figure 2, bringing the beam up to 17 MeV. Focusing is ensured by quadrupole triplets and superconducting solenoids inside the cryomodule containing the 4 superconducting CH cavities, and a couple of re-bunchers is used to perform the longitudinal beam adaptation. The design of the DTL structures is based on the KONUS beam dynamics concept [6], which allows to exhibit excellent accelerating efficiency at these low energies with a net energy gain of 14 MeV in 7.5 metres, while having very low power consumption in CW operation. Multiparticle beam-dynamics simulations of the whole front-end show very good beam behaviour, with moderate emittance increase (~10%), and low sensitivity to errors.

In this front-end line, the beam beta-profile is frozen by design, so that any accelerating section failure will inevitably lead to a beam interruption. For this reason and in order to enhance the machine reliability, it is proposed to duplicate the injector (at least the ion source, at most the whole 17 MeV front-end) to provide a hot stand-by injection line able to relieve the main one in case of failure.

The Independently-Phased SC Linac

From 17 MeV, a fully modular superconducting linac then accelerates the proton beam up to the final energy (600 MeV), through ~230 metres including MEBT. It is composed (see Table 3) of an array of independently-powered spoke and elliptical cavities with high energy acceptance and moderate energy gain per cavity – low number of cells and conservative accelerating gradients (around 50 mT and 25 MV/m peak fields nominal operation point) – in order to increase as much as possible the tuning flexibility and provide sufficient margins to allow the implementation of fault-recovery scenarios.

The linac design is based on the use of regular focusing lattices, with not-too-long cryostats – easy maintenance and fast replacement – and room-temperature quadrupole doublets. The beam tuning has been performed with great care, e.g. keeping a constant longitudinal acceptance, and limiting phase advances below 90° per lattice, while tuning them as continuous as possible, especially at the frequency jump [7]. This "conservative" optical design leads to very safe beam behaviours, with low sensitivity to mismatched conditions or current fluctuations, and producing very low emittance growths (below 5%).

Table 3: Independently-Phased Linac Overview

SC cavity type	#Cav. #Cryom.	Energy range	Section length
352 MHz 2-gap β0.35 Spoke	60 cav 20 cryo	17 ~ 90 MeV	~50 m
704 MHz 5-cell β0.50 Elliptical	30 cav 15 cryo	90 ~ 190 MeV	~60 m
704 MHz 5-cell β0.65 Elliptical	42 cav 14 cryo	190 ~ 450 MeV	~80 m
704 MHz 6-cell β0.85 Elliptical	16 cav 4 cryo	450 ~ 600 MeV	~35 m

The Final Beam Transport Line

The objective of the final transport line is to safely inject the proton beam with the specified footprint – donut-shaped – onto the spallation target located inside the reactor (~30 metres deep). The line is composed of two non-dispersive 2×45° achromats, so that the beam spot position and size at the target is independent from energy jitter and spread. In the dispersive region of the last achromat, position and size monitors will be able to provide information on proton energy variations, and to trigger a feedback system. Natural defocusing is used in the last straight line to get the desired beam spot size, and the footprint is then obtained by raster scanning (see Figure 3), using a redundant set of fast steering magnets operated at frequencies of 50 to a few hundreds Hz, and acting in the two transverse directions.

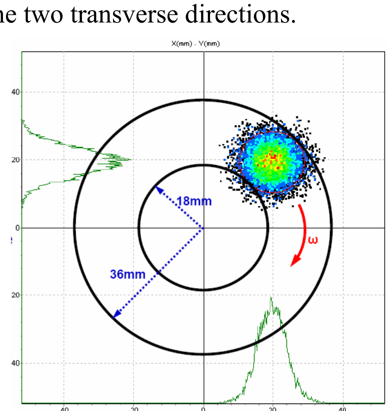

Figure 3: Beam footprint on target.

THE RELIABILITY ISSUE

The ADS accelerator is expected – especially in the industrial scenario – to have a very limited number of unforeseen beam interruptions per year. This requirement is motivated by the fact that frequently-repeated long enough beam interruptions induce high thermal stresses and fatigue on the reactor structures, the target or the fuel elements, with possible significant damages especially on the fuel claddings; moreover these beam interruptions decrease the plant availability, implying plant shut-downs of tens of hours in most of the cases. The present rough requirement in the XT-ADS/MYRRHA case is therefore that beam trips in excess of one second duration should not occur more frequently than five times per 3-month operation period.

Reliability-Oriented Design

To reach such an extremely ambitious goal, it is clear that reliability-oriented design practices needed to be followed from the early design stage. In particular:

- "strong design" is needed: every linac main component has to be de-rated with respect to its technological limitation ("over-design");
- a high degree of redundancy needs to be planned in critical areas; this is especially true for the identified "poor-reliability" components like the linac injector area, which is duplicated, or the RF power systems, where solid-state amplifiers should be used as much as possible;
- the accelerator should be able, to the maximum extent, to pursue operation despite some major faults in basic components ("fault-tolerance" capability); it has been shown in [8] that a solution based on a modular independently-phased SC linac is indeed capable to easily adapt its nominal tuning in the case of a loss of any RF cavity or power loop unit (see here after), and even of a quadrupole doublet, while keeping beam dynamics and beam properties on target into specifications.

Tolerance to RF Faults in the SC Linac

Because we deal with a non-relativistic proton beam, any RF cavity fault implying beam energy loss will also lead to a phase slip along the linac. It will increase with distance, and thus push the beam out of the stability region: the beam will be completely lost.

To recover such RF faults conditions, the philosophy is to re-adjust the accelerating fields and phases of some non-faulty RF cavities to recover the nominal beam characteristics at the end of the linac, and in particular its transmission, phase and energy. A simple way to perform it is to react on the accelerating cavities neighbouring the failing one. This so-called "local compensation method" (see Figure 4) has the advantage of involving a small number of elements, and therefore of being able to compensate multiple RF faults in different sections of the machine at the same time.

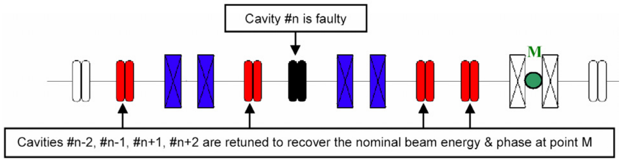

Figure 4: The local compensation method.

Beam dynamics simulations show that nominal beam parameters at the target can always be restored using such a retuning method, given the condition that a 20 to 30% rise in accelerating field and RF power can be sustained in the few (4 to 8) retuned elements [8]. This method is of course rather demanding in terms of linac length and installed RF power budget, but is on the other hand totally in-line with the ADS over-design criterion, and in any case required to try to reach the required reliability level.

Transient beam dynamics have been performed to better analyse what happens to the beam during such retuning procedures, keeping in mind that they have to be performed in less than 1 second ideally. A new simulation tool has been developed, based on the TraceWin code [9], allowing analysing the effect of time-dependent perturbations on the beam through RF control loop modelling. From this work [10], a reference "fast failure recovery scenario" has been defined, that consists in stopping the beam for 1 sec maximum while achieving the retuning. The following sequence (~100ms duration) is proposed:

- the RF fault is detected (or anticipated) via suited dedicated diagnostics and interlocks, and a fast beam shut-down is triggered;
- the new correcting field and phase set-points (previously stored in the low level RF cards' memory during the commissioning phase) are updated;
- the failed cavity is quickly detuned (using piezo-actuators) to avoid the beam loading effect, and the associated failed RF loop is cut off;
- once steady-state is reached, beam re-injection is triggered.

A conceptual design of a suitable Low Level RF (LLRF) system has been performed [11], based on the use of an integrated digital board containing a FPGA chip able to process the feedback control algorithms, several ADCs and DACs to convert the received and produced signals, a RAM memory used to store set-points or save operating parameters, a serial bus to communicate with the general control/command system, and a fast serial bus to communicate with boards of adjacent cavities.

Reliability Analysis and Discussion

Two independent integrated reliability analyses have been performed so far to try to estimate the number of malfunctions of the XT-ADS accelerator that could cause beam/plant shutdowns per 3-month operation cycle, and to analyze the influence of MTBFs (Mean Time Between Failures), MTTRs (Mean Time to Repair), and of the whole system architecture on the results.

These studies have been respectively performed by means of a reliability block diagram analysis using the Relex© software [12] and by home-made Monte-Carlo simulations [13] with slight differences in the hypotheses. In both cases, the results show that such linacs have a high potential for reliability improvement if the system is properly designed with this particular objective: from about 100 unexpected beam shut-downs per 3-month operation period for a "classical "all-in-series" SC linac, this figure falls around 5 beam interruptions – which is actually the XT-ADS goal – in the case where a second redundant injector stage with fast switching capabilities is used, and when fault-tolerance is included in the independently-phased linac via fast fault-recovery scenarios. Nevertheless, the obtained absolute figures remain highly questionable, because of the somewhat crude modelling used for such a complex system, and because of the lack of a well-established component reliability figures database.

Having a look at present high-power hadron facilities – like the SNS, not specifically designed for reaching a high reliability – it appears that the experienced number of beam trips longer than 1 second is much higher, by at least one order of magnitude [14], showing that there is still a long way to go on this topic. But on the other hand, facilities like ESRF, which is very much concerned by the reliability issue, prove that overall MTBF of several days can already be obtained routinely [15], leading to an equivalent of about 20 beam interruptions per 3-month operation.

As a conclusion, it seems at least not completely unrealistic to approach and ultimately reach the ADS accelerator reliability goal. It will imply, as underlined before, to include in the linac design de-rating, redundancy and fault-tolerance, and to have a few years of commissioning and training to identify and fix the weak elements. Approaching the goal "from the other side", i.e. relaxed specifications on beam trip numbers and their durations by appropriate design measures in the target/reactor system, would also help.

RELATED R&D ACTIVITIES

Source and RFQ Long-Run Beam Tests

In the past years, the CEA Saclay 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 [16]. In the EUROTRANS context, these tests are planned to be extended using the 3 MeV IPHI RFQ [17], still presently under final construction, for a 2-month long-run reliability beam test.

Development of SC CH-Cavities

A 19-gap superconducting 352 MHz low energy CH prototype has been successfully built and tested at IAP Frankfurt in vertical cryostat. Excellent effective gradients of 7 MV/m [18] have been reached so far, and the cavity is now ready to be tested in a horizontal one with its associated slow and fast tuners. In parallel, a new optimized prototype cavity, more suited to the XT-ADS linac layout, has been designed and will shortly enter in its construction phase. In the long run, this cavity will be able to be tested with beam.

Development of SC Spoke Cavities

IPN Orsay is presently testing at 4K and 2K a β 0.15 spoke cavity [19] in an "accelerator-like" horizontal cryostat configuration; i.e. fully equipped with its tuning system, magnetic shield, RF power coupler, and fed by a 10 kW 350 MHz solid-state amplifier and its associated digital LLRF loop. RF couplers have been successfully conditioned up to 10 kW in TW mode, with only a few easily processed multipacting barriers above 7.5 kW [20]. During previous low-power cold tests, the tuning system, newly equipped with two piezo-actuators, has been validated together with the digital low level RF control system, reaching a field and phase stability respectively better than 1% and 0.5° at 2 σ. In the fault-recovery scenario context, preliminary experiments have also been performed to test the fast cavity detuning procedure, with very good results (~1 kHz detuning in less than 5ms).

700 MHz Cryomodule Prototyping

A prototypical 700 MHz cryomodule [21], funded by the EUROTRANS project, is presently being built and will be installed end 2009 in a former cyclotron pit at IPN Orsay. A 5-cell β 0.5 elliptical superconducting, equipped with its blade tuner system, will be fed by a 80 kW Thales Electron Devices® IOT by means of a 150 kW power coupler and its associated door-knob transition (see Figure 5). The main goal of the experiment is to evaluate the efficiency, but above all the reliability, of such an accelerating device. In particular, the capability of the piezo-based tuning system coupled with the digital LLRF I/Q feedback loop will be evaluated, while microphonics influence on the cavity resonance frequency will be estimated. Experimental results will be compared to MATLAB Simulink® simulations of the cavity's behaviour. In the long run, the experiment will also be able to provide a testing bench for specific sequences of the XT-ADS fast fault-recovery reference scenario.

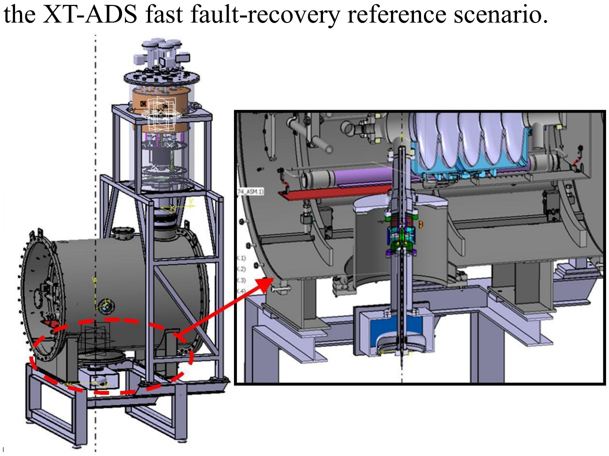

Figure 5: The prototypical EUROTRANS cryomodule.

CONCLUSION

A reliability-oriented superconducting linac has been identified as the reference solution for the European ADS demonstrator project MYRRHA. An advanced design of the machine is proposed, and will be frozen by 2010. R&D activities will be pursued after the EUROTRANS contract, especially on the very challenging reliability issue, before a possible construction start by 2012-2015.

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