THE EUROPEAN PROJECT PDS-XADS "PRELIMINARY DESIGN STUDIES OF AN EXPERIMENTAL ACCELERATOR-DRIVEN SYSTEM"

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Abstract

During the 1990s, in different European countries, the idea of using accelerator-driven systems as efficient tools for transmutation of radioactive wastes came to the forefront. At the national level, various concepts of accelerator-driven system have also been suggested. In 1998, a Technical Working Group was mandated by the Research Ministers of France, Italy and Spain, to identify the critical technical issues and to prepare a "Roadmap" for a demonstration programme.

The Roadmap, issued in April 2001, defines the main requirements of an experimental accelerator-driven system commonly accepted by the European countries.

Subsequently, certain European research centres, universities and nuclear industry companies decided to merge their efforts on this topic so as to propose a common European experimental accelerator-driven system. One of the first steps towards attaining this objective is to evaluate the different candidates previously developed in Europe in order to select the most appropriate concept. This led to the creation of the *P*reliminary *D*esign *S*tudies of an E*X*perimental *A*ccelerator-*D*riven *S*ystem (PDS-XADS) project performed within the Fifth Framework Programme and supported by the European Commission.

Introduction

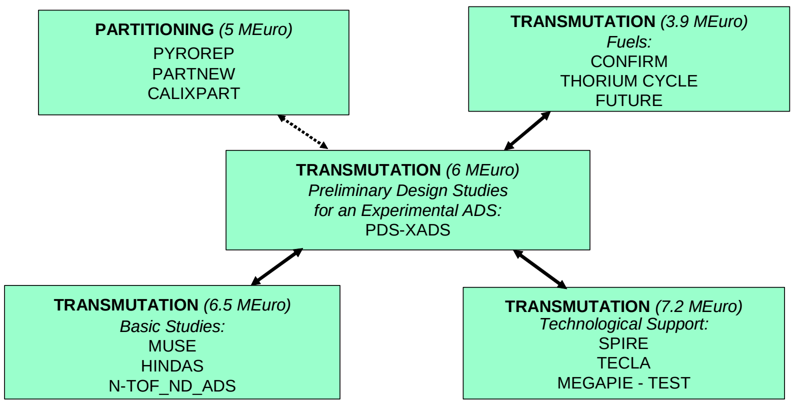
In 1998 the Research Ministers of France, Italy and Spain, set up a Ministers' Advisory Group on the use of accelerator-driven systems (ADS) for nuclear waste transmutation. This led to the creation of a Technical Working Group (TWG) consisting of representatives from Austria, Belgium, Finland, France, Germany, Italy, Portugal, Spain, Sweden and the European Joint Research Centres, whose task was to identify critical technical issues and to prepare a Roadmap [1] for a demonstration programme.

The goals of the Roadmap were to propose a technological route for the transmutation of nuclear waste in ADS; to prepare a technical programme which will lead to the realisation of an e*X*perimental *ADS* (XADS); to co-ordinate the human resources and experimental facilities in Europe and to identify the possible synergies in the scientific community.

In order to be able to define a consistent view of the programme needed for supporting the development of an XADS, it appeared necessary to establish a minimum detailed design of the XADS. The design activities initially performed in the European countries have been merged in a common European project named "Preliminary Design Studies of an XADS" (PDS-XADS), partially funded by the European Commission within the Fifth Framework Programme. The project rallies the main European organisations involved in partitioning and transmutation studies, both industrial companies and research institutes. The duration of the project is three years (2002-2004); its budget is 1 034 persons months.

The PDS-XADS project is consistent with various other activities performed within the framework of partitioning and transmutation studies supported by the European Commission (Figure 1).

Figure 1. Projects on *AD*vanced *O*ptions for *P*artitoning and *T*ransmutation (ADOPT)



In contrast to conventional nuclear reactors in which there are enough neutrons to sustain a chain reaction, subcritical systems used in ADS require an external source of neutrons to sustain the chain reaction. These external neutrons are provided by the spallation source in which high-energy protons produced by an accelerator interact with the spallation source.

ADS is considered for the transmutation of minor actinides (Np, Am and Cu). Because of their characteristics, cores loaded with high contents of minor actinides could not be burnt in critical reactors. These characteristics are especially a low fraction of delayed neutrons and a low Doppler effect. Under critical conditions, the control of such cores could not be safely maintained.

Previous studies have concluded that the most efficient transmutation of minor actinides requires a fast neutron spectrum, for which the ratio between fission and capture is the highest.

The mission of XADS is to demonstrate the safe and efficient operation of the XADS concept dedicated to the transmutation of long-life highly-radioactive wastes. The demonstration requests a significant neutronic power of several tens of megawatts.

Concerning the accelerator, the studies conclude that the demonstration might be achieved with a proton beam of several hundreds MeV, up to one GeV, and a few milliamps. The main requirement concerning the accelerator is its reliability, which must be very much higher than that observed for existing accelerators dedicated to physic experiments. The objective for the accelerator is a number of beam trips, the duration of which lead to the shutdown of the plant, lower than a few per year. Beam trips of short duration might be acceptable if the thermal loadings on the reactor structure, the fuel and the spallation target are not penalising. A duration lower than some hundreds milliseconds has been assessed acceptable *a priori*. Both cyclotron and linac concepts are assessed.

The efficiency of the spallation target in term of neutrons generated per proton is maximum if heavy metal is used. The reference solution is to use liquid metal (e.g. the lead-bismuth eutectic), which tolerates high-power density. The window separating the accelerator-end and the spallation target is a very highly loaded structure. Therefore a spallation concept without a physical window is also considered.

The XADS concepts investigated in the PDS-XADS project

Research and engineering activities have been performed in the European countries to integrate basic aspects of the ADS and to define conceptual XADS configurations. Several technological options have been considered. These options are oriented to the basic characteristics of the ADS concept dedicated to the transmutation of nuclear wastes:

- Fast spectrum subcritical core leading to use gas or liquid metal as coolant.
- No requirement concerning the conversion of the generated energy (no need for electrical production).
- The objective of demonstration of the operability of the ADS concept need not use cores having a high content of minor actinides, therefore in order to be consistent with the time schedule defined in the European Roadmap, the investigated fuels of XADS are classical MOX fuels (e.g. similar to the Superphénix fuel).
- Due to the innovative technological aspects of XADS, the operational criteria (temperature, pressure…) are selected as low as possible, but consistent with the objective of operability demonstration.

Three XADS concepts are studied:

- Two lead-bismuth eutectic (LBE)-cooled concepts:
  - An 80 MW concept.
  - A smaller concept (50 MW): MYRRHA.
- A gas-cooled concept (80 MW).

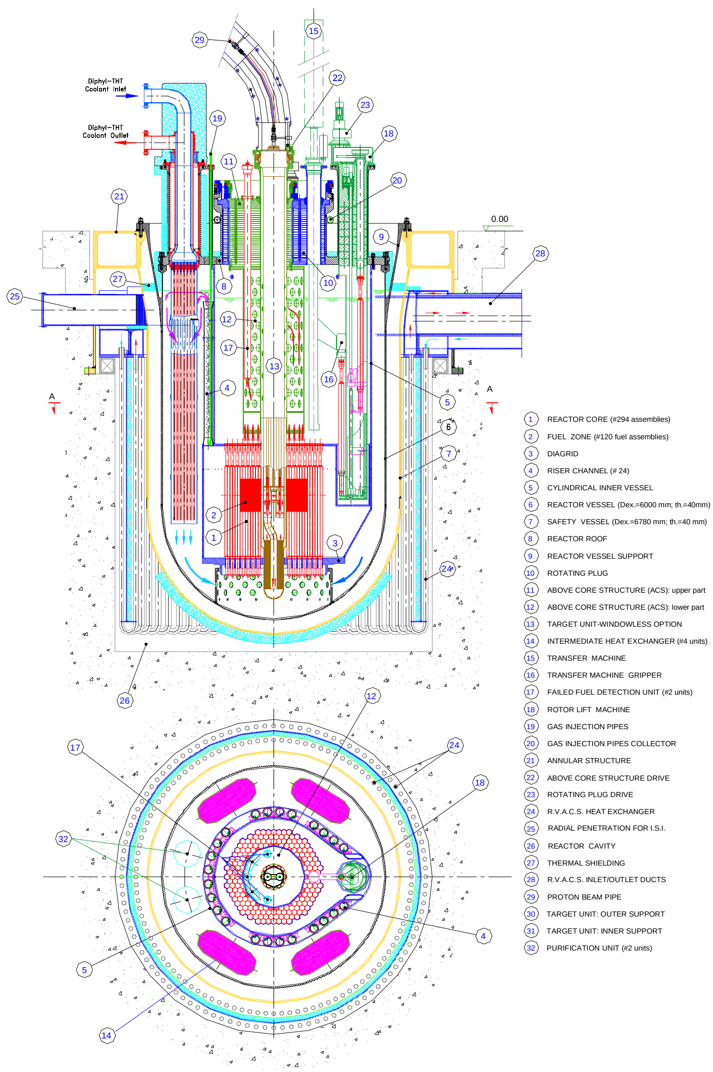
The main purpose of the PDS-XADS project is to develop the three concepts using common rules and objectives, to a level sufficient to precisely define the supporting R&D needs, to perform objective comparisons and eventually to recommend the solution to be engineered in detail and realised.

In the following sections we highlight the main characteristics of the different concepts studied as well as for the accelerator. More ample information on the XADS concept investigated in the PDS-XADS project can be found in the proceedings of the International Workshop on P&T and ADS Development (InWor), organised by SCK•CEN, Mol, Belgium on 6-8 October 2003 [2-5].

An 80-MW lead-bismuth-eutectic-cooled concept by Ansaldo

The primary system for this concept is a pool-type and the main characteristics can be found in Figure 2. A peculiarity in this concept is the argon gas lift system for primary coolant circulation to avoid rotating parts (mechanical pumps) immersed in Pb-Bi.

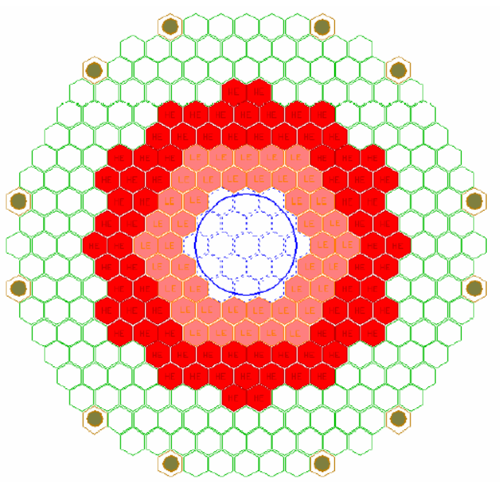
Figure 2. Primary system – main sections



The LBE target containing the spallation products is kept confined within the target unit in order to prevent the contamination of the primary LBE coolant. The target unit is a removable component of slim cylindrical form, positioned co-axially with the reactor vessel which also serves as an inner radial restraint of the core. Its component parts are the proton beam pipe, the heat exchanger and the LBE circulation system, that can be designed with forced or natural circulation, depending on the two design options currently under study: windowless or window.

The core (Figure 3) consists of 120 fuel assemblies arranged in an annular array of five rows. The inner row surrounds the target unit. The assemblies are all alike, each loaded with 90 fuel pins, which have the same cross-section and fuel MOX composition with two different enrichments. The 42 fuel assemblies of the two innermost rows are enriched as the standard Superphénix reload fuel, the remaining 78 fuel assemblies are higher enriched at 28.25% Pu, to set an operational $k_{eff} = 0.97$ at nominal power and BOL.

Figure 3. Core cross-section



For this concept it is concluded that:

- The LBE-cooled XADS concept has been developed at a sufficient level as to allow the identification of critical issues; for most of them, in any case, suitable solutions have already been identified.

- An operational k_{eff} = 0.97 at beginning of cycle and full power guarantees an adequate subcriticality margin under any operational and accident conditions (DBC and DEC) without the need for shutdown or control rods. Compensation of fuel burn-up would be achieved by increasing the 600-MeV proton beam current up to 6 mA max at EOL.

- In spite of the large mass of Pb-Bi of the primary system, the main and safety vessels can resist seismic loads because the reactor assembly rests on horizontal anti-seismic supports.

- The reactor can accommodate either a window or a windowless target unit, both designed as retrievable components. The final choice can be postponed even if the windowless option appears to present more merit in terms of less reactor roof activation, longer lifetime and reduced need of material qualification.

- The low LBE temperature and velocity allow the use of proven stainless or martensitic steels, even if qualification is still necessary.

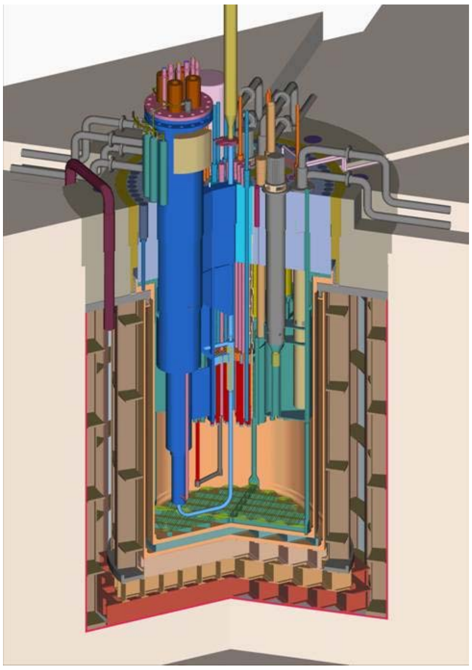
- Early results of the transient analyses indicate that the design exhibits a large safety margin on account of a combination of very favourable safety characteristics.

- The combination of good heat transfer properties, large thermal inertia and high boiling point of the primary coolant, with the design characteristics of the core, primary system, secondary system and reactor vessel air cooling system, all favourable for the promotion of natural circulation, prevents voiding within the core and fuel clad overheating even under the most severe transient conditions.

MYRRHA, a 50-MW lead-bismuth-eutectic-cooled concept by SCK•CEN

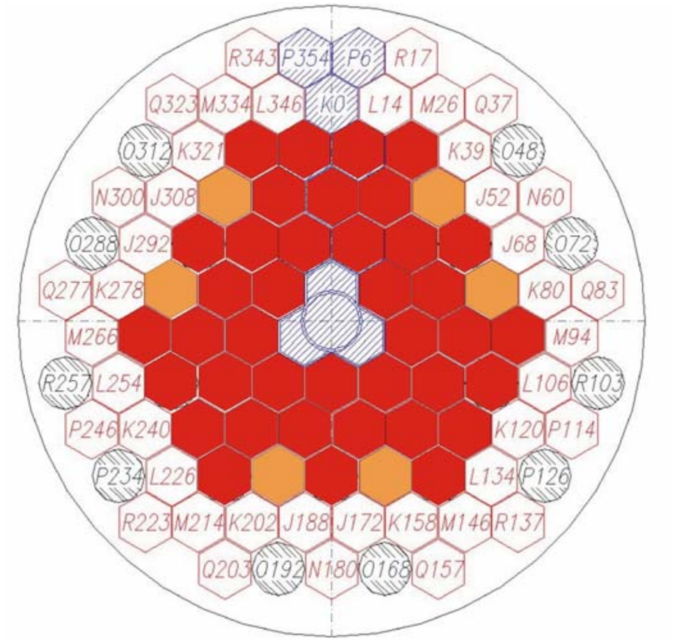
The MYRRHA project is based on the coupling of a proton accelerator with a liquid Pb-Bi windowless spallation target, surrounded by a Pb-Bi-cooled subcritical neutron multiplying medium in a pool-type configuration with a standing vessel (Figure 4). The spallation target circuit is fully immersed in the reactor pool and interlinked with the core but its liquid metal content is separated from the core coolant. This is a consequence of the windowless design presently favoured in order to use low-energy protons on a very compact target at high beam power density in order not to lose on core performance.

Figure 4. MYRRHA 3-D vertical view



The core pool contains a fast-spectrum subcritical core (Figure 5) cooled with Pb-Bi eutectic (LBE). The core is fuelled with typical fast reactor fuel pins with an active length of 600 mm arranged in hexagonal assemblies. The three central hexagons are left free for housing the spallation module. The core is made of fuel hexagonal assemblies of 85-mm flat-to-flat, composed of MOX typical fast reactor fuel (Superphénix-like fuel rods) with total Pu contents of 30% and 20%.

Figure 5. MYRRHA core layout



Since access from the top is very restricted and components introduced into the pool will be buoyant due to the high density of the LBE, the loading and unloading of fuel assemblies is foreseen to be carried out by force feedback-controlled robots in remote handling from underneath. The pool also contains the liquid metal primary pumps, the heat exchangers presently using water as a secondary fluid and the two fuel-handling robots based on the well-known rotating plug of fast reactors.

The spallation circuit connects directly to the beam line and ultimately to the accelerator vacuum. It contains a mechanical impeller pump and a LM/LM heat exchanger to the pool coolant (cold end). For regulation of the position of the free surface on which the proton beam impinges (whereby this defines the vacuum boundary of the spallation target), it comprises an auxiliary MHD pump. Further on, it contains services for the establishment of proper vacuum and corrosion-limiting conditions.

By mid-2002, the MYRRHA pre-design file had been submitted to an International Technical Guidance Committee for reviewing the pre-design phase as achieved for the MYRRHA project. This international panel consisted of experts from research reactor designers, reactor safety authorities and spallation target specialists. The conclusions and recommendations of this panel were as follows:

- No show-stoppers are identified in the project.
- More attention should be paid to safety case studies and iterate to the pre-design before entering the detailed engineering phase.
- Address some R&D topics that can lead to timing bottlenecks very soon, such as fuel pin and assembly development and qualification.
- Make a decision on the accelerator option (cyclotron vs. linac) and eventually revisit beam parameters.

MYRRHA responds to the objectives of the XADS facility in terms of demonstration and performance, and also responds by design to some key issues related to the LBE ADS such as:

- The LBE corrosion by leaving the majority of the system at "cold" conditions and limiting the LBE velocity below 2.5 m/s.
- Criticality control during core loading by leaving the spallation target in position and loading from underneath.
- Avoiding spallation target window break by choosing the windowless design.
- Addressing the ISI&R and the O&M from the conceptual design by means of robotics and ultrasonic visualisation.

A 80-MW gas-cooled concept by FRAMATOME ANP

The reference basic features have been fixed by the PDS-XADS project global coherency:

Reactor power	80 MWth
First subcritical core	Classical FBR fuel U-PuO_2 (Pu < 35%)
Accelerator	Linac type
Core and target unit	Designed for E = 600 MeV, I < 6 mA,
Target	Physically separated from the reactor

The main parameters for this gas-cooled design are:

Primary coolant fluid	Pressurised helium at about 6MPa
Primary helium containment	Metallic vessels
Power conversion system	Heat exchanger and circulator

The overall reactor architecture is shown in Figure 6.

The spallation target consists of a 460-mm diameter, 25-mm thick tube submitted to external helium pressure bolted on the roof slab and guided at the core centre. The thimble houses the target unit located at core centre and composed of a vacuum tube, an internal tube for flow arrangement and the liquid lead-bismuth eutectic (LBE) spallation material container. The proton beam enters the beam tube at the upper end of the target unit, penetrates the beam tube window, located just above core centre line and impinges on the upward flowing target LBE below the window (spallation zone). The target LBE is circulated by pumps and cooled by an external heat exchanger located in the target cooling room, outside the reactor vessel. The LBE external circuit option is favourable with respect to both neutronic efficiency and maintenance of target unit and components.

The XADS gas-cooled core is built up from a ring of 90 fuel subassemblies (SAs) surrounding the spallation target which take up the central locations (Figure 7). Surrounding the core are steel reflector SAs in turn surrounded by shield SAs containing boron carbide to limit damage to the RPV. Six absorber rods, located at the core fuel zone periphery, are to be used only during shutdown conditions to bring sufficient reactivity margins mainly with respect to fuel handling error and accidental water ingress in the core. The design of the core has been based largely upon previous fast reactor experience.

Figure 6. Gas-cooled XADS overall architecture

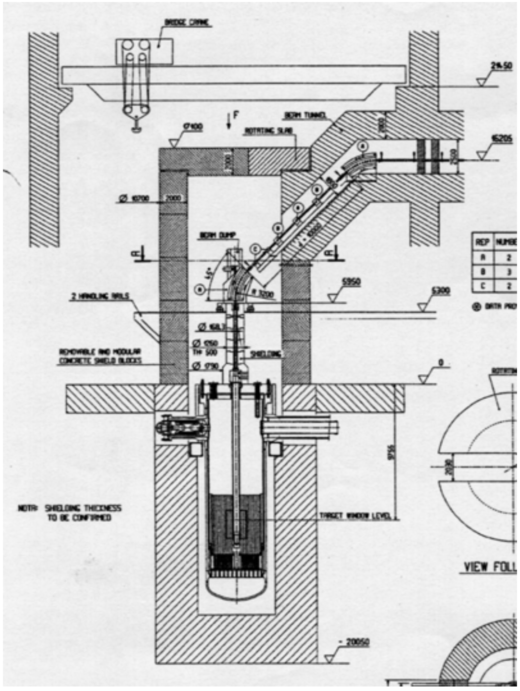
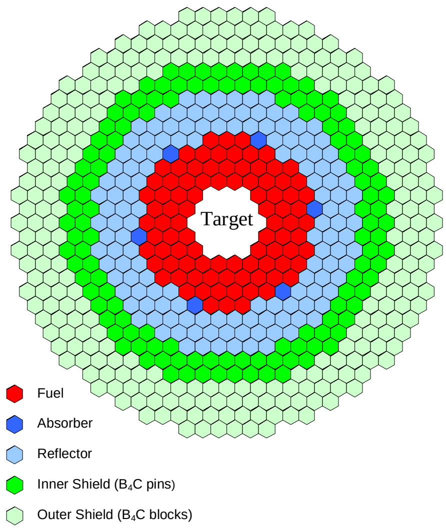


Figure 7. Gas-cooled XADS core layout



The XADS gas-cooled system has reached the end of the preliminary studies devoted to the definition and the justification of a reference and consistent reactor design. The basic options, sub-systems and components are described and ongoing analysis did not reveal major feasibility issues. Some important features are to be checked further such as:

- Selection of a core reference between single and multi-batch concepts and optimisation of core thermal-hydraulics.

- Confirmation of core subcriticality levels and associated measurement system.

- Reactor transient analysis (accelerator beam trip, transition between nominal and cold shutdown conditions, loss of flow and loss of coolant accidents) and consequences on structural mechanic analysis.

- Feedback on DHR system operating conditions and design.

- Evaluation of mechanical integrity and resulting residence time of beam tube and target unit.

- Confirmation and improvement of radiation dose rates outside and inside the reactor vessel, shielding design and definition of core instrumentation and ISI&R provisions.

- Reactor containment specification and design.

The PDS-XADS reference accelerator

The main technical specifications for the XADS accelerator are summarised in Table 1. These characteristics clearly show that this machine belongs to the category of the so-called high-power proton accelerators (HPPA). HPPA are presently very actively studied (or even under construction) for a rather broad use in fundamental or applied science. The overall performance of the subcritical system will be critically determined by a strict adherence of the XADS accelerator to its specifications. Compared to other HPPA, many requirements are similar, but it is to be noted that the reliability specification, i.e. the number of unwanted "beam trips", is rather specific to the use as driver for an ADS. The reference design had to integrate this stringent requirement from the very beginning, taking into account that this issue could be a potential "show-stopper" for ADS technology in general.

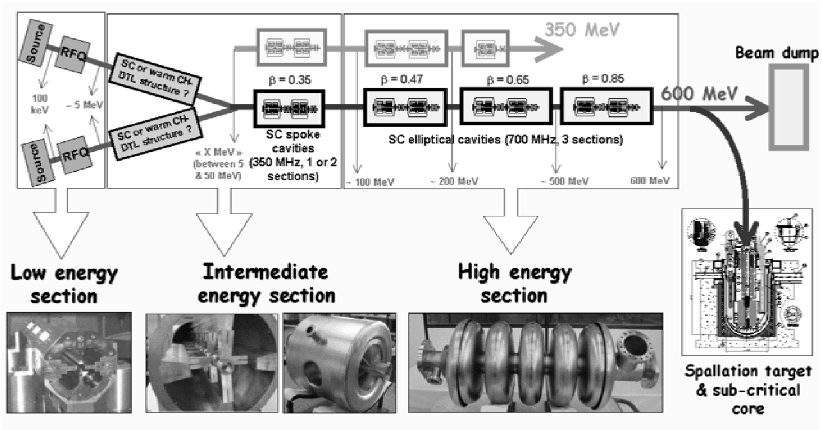
Table 1. XADS proton beam specifications

Max. beam intensity	6 mA CW on target (10 mA rated)
Proton energy	600 MeV (includes 800 MeV upgrade study)
Beam entry	Vertically from above preferred
Beam trip number	Less than five per year (exceeding 1 second)
Beam stability	Energy: −1%, Intensity: −2%, Size: −10%
Beam footprint on target	Gas-cooled XADS: Circular ˘ 160 LBE-cooled XADS: Rectangular 10 · 80 MYRRHA: Circular, "donut" ˘ 72
Intensity modulation	0.2 ms "holes" in CW beam for neutronics measurements, repetition frequency 0.01-1 Hz

The proposed reference design for the XADS accelerator, optimised for reliability, is shown in Figure 8. It is composed of a "classical" proton injector (ECR source + normal conducting RFQ structure). Additional warm IH-DTL or/and superconducting CH-DTL structures are used up to a transition energy. At this point a fully modular superconducting linac accelerates the beam up to the final energy.

Up to the transition energy, fault tolerance is guaranteed by means of a "hot standby" spare. Above this energy, "spoke" and, from 100 MeV on, "elliptical" cavities are used. Beam dynamic calculations for this part have shown that an individual cavity failure can be handled at all stages without loss of the beam. Besides this fault tolerance, another remarkable feature of the concept is its

Figure 8. XADS reference accelerator layout; a doubled injector accelerator is followed by a fully modular spoke and elliptical cavity superconducting linac



validity for a very different output energy range: 350 MeV for the smaller-scale XADS requires nine cryomodules of b = 0.65 elliptical cavities; in order to obtain 600 MeV, 10 more cryomodules simply have to be added (seven with b = 0.65 and three with b = 0.85) and 12 additional (b = 0.85) boost the energy to 1 GeV. Therefore, the small-scale XADS accelerator is already fully demonstrative not only of the 600-MeV XADS (and could be converted to it), but even for an industrial machine.

The chosen superconducting cavities are the subject of important R&D programmes presently underway. The performance of the prototypes has been measured to exceed the operational characteristics for the XADS by a very comfortable safety margin that ensures the “over-design” criteria imposed by the reliability strategy.

Within a period of less than two years, it has been possible to develop a generic and robust technical solution for the XADS accelerator and its associated beam line. This solution, based on a superconducting linear accelerator, can fulfil *a priori* the specifications for the XADS. This linac can be used for all different versions of XADS studied within the 5th FP, and it is also representative of an industrial machine.

The proposed machine is reliable through the rigorous implementation of a highly modular system with de-rated components operated in a fault-tolerant manner. The continuation of the vigorous R&D programme presently underway, with a focus on the reliability aspect within the 6th FP, places the XADS accelerator on a roadmap in line with the TWG recommendations.

Conclusion

Within the PDS-XADS project, supported by the European Commission, are performed design studies for the three XADS concepts. The accelerator study has shown that it is possible to develop a generic and robust technical solution for the XADS accelerator and its associated beam line. The PDS-XADS project will be finalised at the end of October 2004.

The first R&D needs resulting from the design studies have been identified and described on specific R&D questions sheets. These sheets have been issued and distributed to the organisations involved in the ADOPT network on P&T activities within the Fifth Framework Programme. The sheets constitute a valuable input for the preparation of the P&T-related projects for the Sixth Framework Programme.

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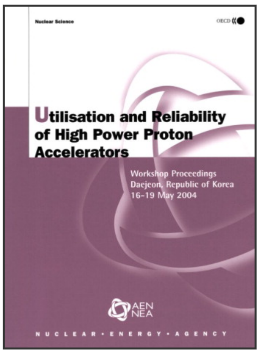

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