ACCELERATOR DRIVEN SYSTEMS*

D. Vandeplassche and L. Medeiros Romão, SCK•CEN, Mol, Belgium

Abstract

Accelerator Driven Systems are widely considered as promising devices for the transmutation of nuclear waste, as well as useful schemes for Th-based energy production. This paper aims at giving an overview of the accelerator requirements for successful ADS operation. It then highlights the most significant activities worldwide in this domain. Common features are: superconducting proton linacs and Pb-Bi cooled reactors.

INTRODUCTION

Among the applications of particle accelerators, the production of neutrons by hitting a target made of heavy elements with a proton beam is well known. Such a spallation reaction requires a proton energy above a few hunded MeV. Above around 1 GeV the neutron yield per incident proton scales with energy, and the optimum energy cost per neutron lies in the proton energy range 1–2 GeV, where roughly 20–30 neutrons are produced per incident proton.

On the other hand it is also well known that, under specific conditions, a neutron population may be multiplied through a fission process, which is the basis of the nuclear reactor. In the case of a critical reactor with a *critical* assembly there is an equilibrium between the increase due to multiplication and the losses, leading to a steady state with a non-zero neutron population.

Such a steady state may also be obtained in a *subcritical* assembly, provided there is an external source of neutrons. In this case the subcritical assembly multiplies the source neutron population by a factor $1/(1-k_{\text{eff}})$, where $k_{\text{eff}} < 1$ is the subcriticality level. The total neutron population (i.e. the power level of the reactor) is then controlled by the intensity of the external source. A typical external source would be a spallation target — this is both the principle and the conceptual advantage of the ADS, of which the power is soleley determined by the intensity of the proton beam (at constant subcriticality level). A few remarks:

1. In practice, k_{eff} levels are kept in the 0.95 to 0.98 range. k_{eff} stands for the net number of neutrons remaining after 1 generation in the fission process when starting with 1 neutron. Therefore criticality is obtained for $k_{\text{eff}} = 1$.
2. Besides the beam intensity, the operation of an ADS requires a quasi-constant monitoring of the reactivity in order to compute its power.

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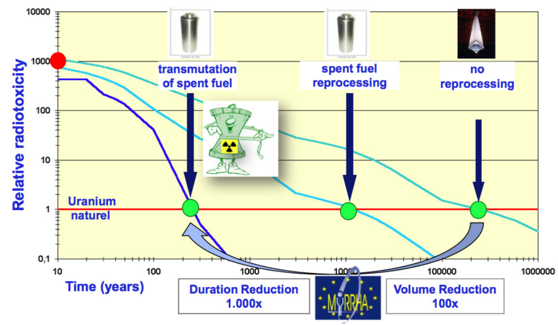

Figure 1: Schematic overview of the nuclear waste problem

3. The required beam intensity is obtained as

$$I_{\text{b}} = \frac{(1-k)P_{\text{th}}}{n\ f\ E_f}$$

where P_{th} is the reactor's thermal power, n the neutron multiplicity, f the fraction of neutrons causing fission, E_f the energy release per fission. Inserting typical numbers gives a beam power $\approx \frac{1}{2}(1-k)P_{\text{th}}$. The high power nature of the required accelerator is thus readily apparent by considering a typical 100 MW_{th} experimental reactor.

The consideration of ADS is much indebted to the concept of the Energy Amplifier by Carlo Rubbia [1].

The nuclear waste problem is presented in a very simplified and schematic way in fig. 1. It represents the 2 main issues:

1. the accumulated waste generates a very high level of radiotoxicity for an extremely long time, and therefore puts an intolerable burden upon the geological disposal
2. spent fuel must be reprocessed for a sizeable reduction of the amount of waste and for an efficient use of the energy content of the initial fuel.

Solutions are identified. The fundamental requirement for their applicability is Partitioning. Thereby the constituents of the spent fuel may be separated, and each resulting fraction may be dealt with in a specific way. Basically a fraction may be reused as fuel, be considered as waste, or be taken for Transmutation. By applying transmutation to the minor actinides and certain long lived fission products it is conceivable to reduce the decay time to radiotoxicity level of natural uranium ore by several orders of magnitude. Although partitioning is an absolute prerequisite for transmutation, it will not be highlighted any further in this paper. The link transmutation – ADS will be considered.

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ADS APPLICATIONS

Transmutation

Efficient transmutation of minor actinides requires a fast neutron spectrum ($E > 0.75$ MeV). It may be obtained in critical or subcritical assemblies. However, actinides exhibit a small delayed neutron fraction, causing problems with the control and safety in critical assemblies. So only small quantities of actinides can safely be mixed with standard fuel. The scenario of transmutation in the critical circuit also suffers from the need of a double transport activity, given the fact that partitioning will be performed at dedicated sites.

The ADS concept provides useful alternatives. A subcritical assembly is intrinsically safe and is only controlled through the intensity of the external source, not through a reactivity adjustment. Therefore a much higher minor actinide content may be envisaged from a safety point of view, and this content may then be chosen in function of optimal neutronic performance. Furthermore, installing the transmuter ADS at the partitioning site removes the necessity of further transports.

The Thorium cycle

There is worldwide interest for the use of Thorium for fission power generation. It may be applied as a solid fuel or in molten salt systems, and both alternatives may be considered in a critical reactor or in a subcritical, accelerator driven device. Today the experimental evidence allowing for an argumented choice between these possibilities is missing. An up-to-date overview of the matter is given in [2].

A conceptual design of a Pb cooled ADS with solid Th fuel (600 MW_e) has been produced under the name ADTR® [3], based on a version of the Energy Amplifier [4].

A molten salt-based ADS might present an advantage in terms of allowable beam trips (see the discussion in the next section) because there is no fuel cladding. Such a proposal is made by the Accelerator Driven Neutron Applications Corporation under the name GEM*STAR [5].

THE ACCELERATOR FOR ADS

The basic accelerator requirement is an operational mode that is compatible with the steady state character of the reactor operation, i.e. the beam has to be delivered in CW mode. However, the steady state has to be perturbed at regular intervals in order to monitor the absolute level of reactivity. To this end it is foreseen to have beam interruptions of typically 200 μs in order to monitor the decay of the prompt neutron population, giving access to the prompt multiplication factor [6]. The duration of the interruptions corresponds to 4–5 times the prompt decay period. These interruptions have to occur with a repetition rate > 1 Hz.

The beam power needed is in the MW range for experimental demonstration units; for industrial units it will be an order of magnitude larger. The beam energies will lie in the typical spallation neutron range (600 MeV – 1.5 GeV), and beam currents will range between ~ 4 mA (demo) and ~ 20 mA (industrial). These requirements place the ADS driver accelerators in the High Power Proton Accelerator domain. Although the Energy Amplifier considered a cyclotron as a driver, today the predominant choice in this domain is a superconducting linac. The main arguments in favour of the linac are beam current handling capacity, possibilities of upgrading, modularity. The main arguments for superconductivity are compactness, power consumption in CW operation, large beam apertures for small beam losses. Note that Neutron Spallation Sources use almost identical technological solutions [7, 8].

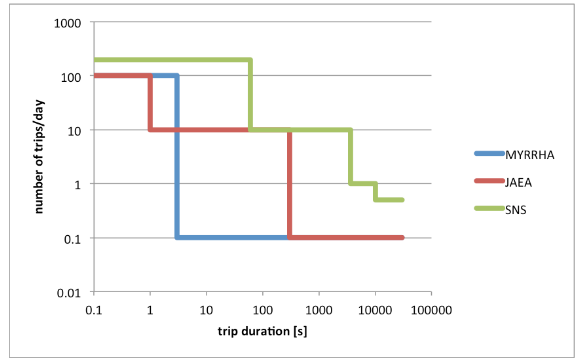

Figure 2: Beam trip frequencies: recorded in SNS, allowed by JAEA, accepted for MYRRHA

A particular issue with regard to the accelerator for ADS, and a heavily debated one, concerns the acceptable spectrum of unwanted beam interruptions, commonly called beam trips. The issue having been acknowledged by all ADS studies, analyses have been made in order to evaluate the effect of repeated beam trips on structural materials (beam window, inner barrel, reactor vessel), e.g. by Areva [9] and by JAEA [10].

Fig. 2 compares the experimental evidence from SNS [11] with the accepted levels by JAEA and by MYRRHA [12, 13]. As far as the structural materials are concerned there appears to be a consensus to accept a beam trip spectrum as shown by JAEA. With regard to the cladding material, and in particular under Pb-Bi, the risks are still being evaluated [14, 15], but they point to possible issues regarding the integrity of the protective oxide layer. A recent re-evaluation considers the FP6 EUROTRANS information [16] plus all the past experience with the French PHENIX fast reactor, and advocates the limit of 10 trips longer than 3 s per operational period of 3 months [17]. Two side remarks are explicitly added:

- more experimental work is needed, and a new set of experiments is planned
- minimizing the number of beam trips is anyway essential for the plant's availability.

The specification set by MYRRHA upon its accelerator is based on this recommendation. It is expressed as a beam

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MTBF > 250 h, with a beam failure being defined as a trip longer than 3 s.

Again, in this debate one should not omit the operational aspect of availability. Recovery of what is considered as a long beam trip may be lengthy due to the event being assimilated to a reactor scram. In general, the availability of the facility will severely suffer from a high beam trip frequency, geopardizing the very credibility of ADS.

Considering these aspects there is no doubt that controlling the beam trip spectrum and bringing it in accordance with the ADS requirements is the outstanding challenge of the accelerator development, and the permanent focus point of the associated R&D.

Implementation

The fundamental key to realizing the expected reliability of the accelerator was already identified during the FP5 PDS-XADS project[1]: fault tolerance. The realistic possibility of its implementation is strongly linked to the modular layout of a superconducting linac with individually controlled RF cavities. Beam dynamics calculations have clearly established this possibility by providing a retuning scheme in case of a cavity failure, recovering nominal beam characteristics at the output of the linac [18]. An experimental confirmation has been given by SNS [19]. On the other hand, LLRF simulations have shown the feasibility of such a retuning in a fast way (< 3 s) by making use of up-to-date digital techniques [20]. However, this serial redundancy scheme is not effective at low energy because the condition of modularity cannot be satisfied. Fault tolerance is then retained by parallel redundancy. This is the concept used in the accelerator for MYRRHA [13], where the injector (17 MeV) is doubled: one in operation, one hot spare.

Besides the fundamental requirement of fault tolerance, the practical realization of a highly available linac will have to satisfy these rules:

1. obtain the highest achievable/affordable MTBF-values at the level of all the linac components and of their ancillary equipment (power converters, readout electronics, connections)
2. install auxiliary systems and services of which the availability performance matches the actual linac availability requirement
3. do all the engineering design with a strong emphasis on the repair aspect, such that the MTTR-values are small with respect to the corresponding MTBF-values
4. design the control system along the same guidelines as the linac itself (including fault tolerance), and use it to obtain predictive capabilities of the diagnostics systems
5. find and set the right compromises for the Machine Protection System, and for all interlock systems in general, such that unwanted interlocks are minimized while keeping absolute protection.

[1]EURATOM FP5 Programme Grant no. FIKW-CT-2001-00179

It is useful to note, and significant, that many industrial developments are presently going on in the field of power electronics based on the principles of modularity and fault tolerance. These developments lead to high availability power converters, including RF power generators, that appear to be particularly attractive. If the application voltage is low enough, hot swap capability further extends the high availabilty concept by reducing the MTTR to practically zero.

The need for R&D effort around the accelerator for ADS is mainly driven by rule #1 of the above list, but the R&D activities should maximally address the full list.

PROJECTS

Europe

A common effort of several European countries in view of defining a reference layout of an experimental ADS demonstration plant at one hand (XT-ADS), of an industrial transmuter ADS demonstration at the other (EFIT) has been supported by the European Commission during the 5th and 6th Framework Programmes . In the course of FP6 the preliminary reactor design of the Belgian MYRRHA project, borne by the Belgian Nuclear Research Center SCK•CEN, was taken as the base design for XT-ADS [16].

In FP7, the effort on EFIT is not pursued. The further design of the XT-ADS/MYRRHA reactor, its buildings and its beam delivery is dealt with by the CDT project[2], accelerator aspects by the MAX project. Besides that a sizeable R&D effort is funded by the Belgian Federal Government and is being set up at SCK•CEN in order to address technological issues on one hand, licensing, financing and managing issues on the other hand. Again, many of these activities have a strong national and/or international collaborative structure.

The latest characteristics of FASTEF[3]/MYRRHA in ADS mode are[4]:

coolant and target	Pb-Bi eutectic (LBE)
thermal power	~ 70 MW$_{th}$
target interface	beam window
fast neutron flux	10^{15} n/(cm^2 s) at $E_n > 0.75$ MeV
proton beam	600 MeV, 4 mA

A description is found in [21].

Concerning its superconducting linac [13], a collaborative R&D program has been defined around 3 main lines of activity: (i) global coherence, (ii) low energy section, (iii) cryomodule prototyping. This program should be seen in the context of SCK•CEN itself having very limited accelerator-linked resources. Strong partnerships are in particular set up with IN2P3 (CNRS, France) and IAP (University of Frankfurt, Germany).

[2]EURATOM FP7 Programme Grant no. FP7-232527

[3]The CDT evolution of XT-ADS is called Fast Spectrum Transmutation Experimental Facility.

[4]MYRRHA will have the capability of operating both in critical and in subcritical/ADS mode.

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An important step on the way to ADS is the GUINEVERE experiment [6] being conducted at SCK•CEN at the zero power VENUS-F test facility. It consists of the coupling of an electrostatic deuteron accelerator (GENEPI-3C), a Tritium target and a solid Pb filled subcritical assembly [22]. The experimental program will investigate the reactivity monitoring techniques to be applied in an operational ADS, typically using the foreseen beam time structure "continuous with 200 μs holes".

US

A common effort of several laboratories has led to the Office of Science White Paper on ADS [23], indicating the feasibility of industrial scale transmutation by ADS, under the condition of demonstration of a number of critical components, and especially of the reliability. Nevertheless, up to now this has not crystallized into a funded ADS initiative, nor into a strong participation in a collaborative effort.

With respect to the accelerator for ADS, however, several US laboratories have very significant expertise in such fields as superconducting RF cavities and their reliability (CEBAF), and of high power proton accelerators with clear ADS relevance (SNS) [7]. In the framework of Fermilab's Project-X [24] there is ongoing prototyping effort on SC Half Wave Resonators and Spoke cavities (with ANL) on one hand, on single cells for 5-cell elliptical cavities on the other hand (with JLab). Furthermore, Argonne National Laboratory has funded research for defining a Spent Nuclear Fuel Disposal scenario, in which ADS plays a key role for near term deployment. Finally, Jefferson Lab shows a clear interest in ADS which is largely based on its pioneering work in large-scale use of superconducting RF for accelerators. Their SNS experience is obviously of great value.

Japan

ADS activities in Japan are primarily dealt with at the J-PARC facility, where JAEA and KEK collaborate. Specific ADS activities, however, are at the level of the conceptual designs of a commercial-size transmuter of 800 MW_{th} and of its associated superconducting linac (1.5 GeV, 20 mA CW). The future experimental plan at J-PARC comprises the Transmutation Experimental Facility (TEF), with TEF-P for transmutation physics experiments on a 10 W beam line, TEF-T for tests on a 200 kW Pb-Bi target.

KEK is contributing to a broad collaborative effort on superconducting RF technology for the International Linear Collider and for the Energy Recovery Linac which may be relevant for ADS. KEK is also putting much effort in in-house fabrication and testing of superconducting cavities.

India

The interest of India in ADS technology is predominantly given by its fundamental interest in the utilization of Thorium for energy production. In this context the main development lies in the Advanced Heavy Water Reactor as a technology demonstation for stage III of the Indian Nuclear Power Programme. However, as indicated earlier, the ADS concept may be of significant interest for Th-based scenarios. Hence there is a strong involvement in the development of ADS-related technology. Furthermore the use of ADS for transmutation of waste is considered as an important argument.

Activities:

- RRCAT is collaborating with Fermilab for the development of elliptical superconducting RF cavities and cryomodules. A full size infrastructure for cavity fabrication, processing and testing is being installed, including vertical and horizontal test stands. Furthermore there are R&D activities on Nb material and on Solid State RF amplifiers.
- at BARC, the long term goal is a 1 GeV, 30 mA linac. In this frame a 20 MeV, 30 mA injector is being developed, with a possible application for ADS experiments in a HWR critical facility.

China

The C-ADS project has been initiated by the Chinese Academy of Science (CAS), and it involves 4 institutes:

1. IHEP (Beijing) leading institute for the accelerator
2. IMP (Lanzhou) leading institute for the target, collaborator for the accelerator
3. IPP (Hefei) leading institute for the reactor
4. USTC (Beijing) collaborator for the reactor.

Keywords of this ADS project are: proton linac, liquid metal target, Pb-Bi cooled reactor. The full project is defined as a phased sequence with 3 main milestones: (i) R&D and test facility; (ii) experimental facility (100 MW_{th}, 2022); (iii) industrial demo facility (1 GW_{th}, 2032).

The project is an integral part of an extremely ambitious long term nuclear power development program which has been laid out till 2050. Today decisions have been taken about CAS supporting the R&D on ADS for transmutation, and on the Thorium-based Molten Salt Reactor. Budgets for phase 1 have been allocated. A candidate site for the C-ADS facility has been identified in Inner Mongolia.

Phase 1 will be executed in the leading institutes, and during this phase test platforms will be set up for all the relevant ADS subsystems.

The accelerator [25] will be a superconducting proton linac, base frequency 325 MHz. Only the RFQ will be normal conducting. In its final declination it will deliver 1.5 GeV, 10 mA CW, and its development will follow the phased approach. Its design has strong fault tolerance features (double injector, independently controlled cavities, tolerant beam dynamics), but the accepted beam trip spectrum matches the "White Paper" one, less stringent than MYRRHA. Phase 1 should produce a 50 MeV beam, with intermediate milestones at 5 MeV (2013) and 25 MeV (2015). Two different injectors (10 MeV) will be built and tested: one at 325 MHz with spoke cavities, one at 162.5 MHz with half-wave resonators.

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CONCLUSION

ADS is taken up by the accelerator community as a promising and challenging application. Linacs, and more specifically superconducting proton linacs, are almost generally considered as the right answer to the challanges that are, in short, very high availability multi-MW CW proton beams, energy around 1 GeV. The high modularity of these linacs is a key issue, and the positive experience feedback from SNS is convincing. Several laboratories around the world are developing low-β superconducting cavities with the aim of pushing the normal conducting to superconducting section transition energy as low as possible. At the same time the research on cryomodule technology and on Nb technology goes on as well, and highly modular solid state RF amplifiers make significant progress. Most of these developments serve both the ADS and the neutron spallation source communities.

The potential of ADS for safe and efficient transmutation of long living minor actinides is globally acknowledged, and a fair amount of conceptual design studies have been conducted. Nevertheless, the number of identified integrated ADS experiments at significant power level is small indeed. A sense of urgency is lacking. It is fair to say that today the list is restricted to the Chinese C-ADS and the European MYRRHA proposals, both expected to become operational in the years 2022-2023. Meanwhile the associated R&D, on low power integrated systems or on specific components, should be defined in a strategic way for maximum efficiency.

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