THE PDS-XADS REFERENCE ACCELERATOR

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Abstract

Accelerator-driven systems place very stringent availability requirements on the proton beam led into the subcritical reactor core. This paper describes the technical options chosen by a European collaboration supported by the European Commission in the framework of a Preliminary Design Study of an eXperimental ADS (PDS-XADS). These options are considered a sound basis for the development of an ADS-compatible accelerator. It mainly consists of a superconducting linac fed by an ECR ion source and a four-vane RFQ. The modularity of such an accelerator is a strong advantage, and high availability may be obtained by the proper combination of maximum reliability and of a powerful fault tolerance scheme. The methods to obtain fault tolerance are described, and the upcoming R&D programme is presented. The importance of an adapted construction methods is stressed.

Introduction

The Preliminary Design Study of an eXperimental Accelerator-Driven System (PDS-XADS) is a project is supported by the European Commission within its Fifth R&D Framework Programme under contract number FIKW CT-2001-00179. It has 26 participants, and is co-ordinated by FRAMATOME ANP SAS.

The project is subdivided into Work Packages, among which WP3 has the mission to work out the technical answers concerning accelerator requirements. WP3 is a collaboration among Belgium (IBA), France (CEA, CNRS, FRAMATOME ANP SAS), Germany (Universität Frankfurt, FZ Jülich, FRAMATOME ANP GmbH), Italy (INFN, ENEA, Ansaldo) and Portugal (ITN).

The requirements for the particle beam delivered by the accelerator are defined by WP1, which is responsible for the global coherence of the project. The most relevant ones are listed as follows:

Particle	Protons
Energy	350-600 MeV – 1%
Intensity	0-6 mA – 2% (but 10 mA capable)
RF duty cycle	CW
Beam time structure	200 ms holes at 1 Hz
Beam trips < 1 s	Not accounted for
Beam trips > 1 s	5 per year

Clearly, the last of these requirements is particularly challenging: an availability of this level has never been obtained or demanded of any particle accelerator. However, there is no *a priori* reason to believe that this level of availability is unattainable. It is WP3's task to identify the topics needing further R&D and which will allow us to reach the stated goal.

At the start of the project the design of the accelerator, and even its type, was entirely free. Very soon, however, the need for a reference design was obvious; reliability studies, in particular, cannot be conducted without a reasonably concrete representation of the machine. The reference design will be presented here.

Options and choices

When dealing with the reliability challenge, very early analyses have shown that a general principle must be adopted, underlying the set of fundamental choices to be made for the reference design. This principle is:

> The required level of reliability can only be achieved
> if a high degree of *fault tolerance* can be implemented.

Indeed, we consider that present-generation storage rings actually do obtain a remarkably high reliability (certainly the highest in the accelerator world), but that this level is definitely below our requirement. Of course, these machines are built with state-of-the-art components in terms of mean time between failure (MTBF), but this is not sufficient; hence the need for an "added principle". It is lucky that, in theory, our ADS application can well accept the fault tolerance principle because short beam interruptions may be tolerated.

Immediate corollaries of fault tolerance are redundancy and modularity. It is clear that our reference design has to be built along these lines of thought.

The type of accelerator

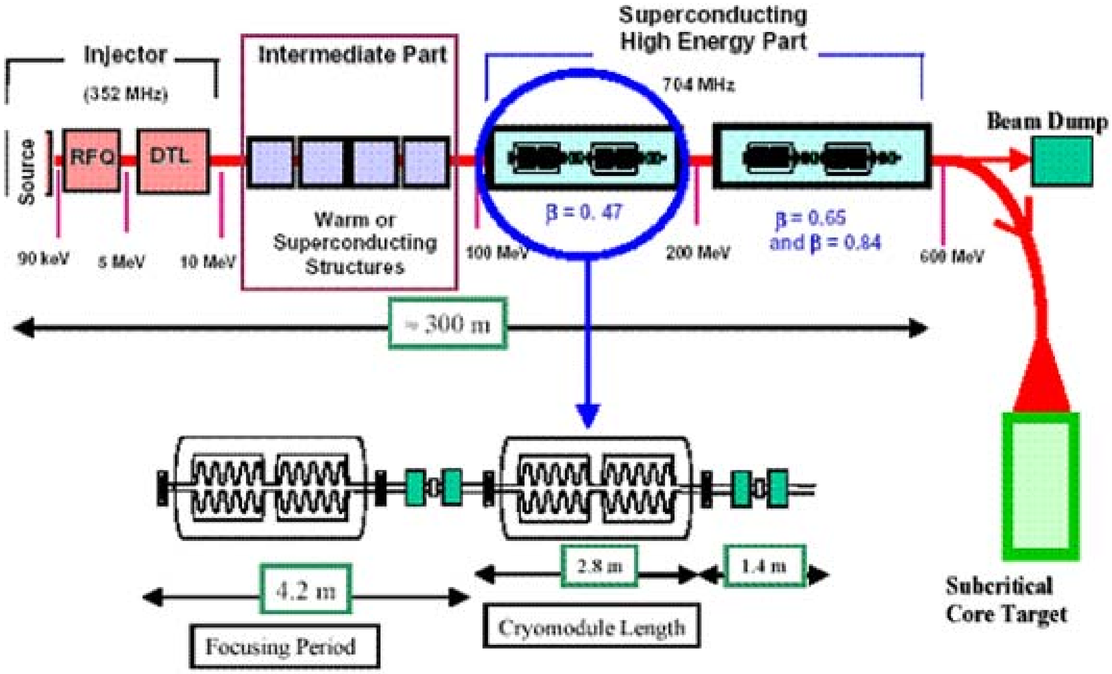
At the start of the project, cyclotron and linac accelerators were considered in parallel. It was soon concluded, though, that the cyclotron's potential for reliability increase is very limited, and that the possibilities of implementing fault tolerance are practically inexistent. Also, extrapolation towards higher performances is hardly conceivable. Hence, the cyclotron is ruled out, and the PDS-XADS reference accelerator will be of the linac type.

Global structure

The first point to be addressed: the design should be based on proven principles and on average performances. The second point: for a CW linear accelerator, it is very appealing to apply RF superconductivity wherever possible. At the same time, superconducting RF cavities naturally appear as the ideal candidates in a scheme where modularity is wanted. They are in agreement with the first point, but the low b application makes a rather new domain for them.

So, globally the linac will have a classical layout in which the main high-energy section is preceded by an intermediate-energy section, itself being fed by an RFQ and, of course, an ion source. The high-energy section will consist of *elliptical* superconducting cavities, the frequency being set to 704 MHz. Fault tolerance will obviously be translated into "missing cavity tolerance", and this property will have to be demonstrated. For the intermediate-energy section, a number of options are open, and they will have to be evaluated individually against our criteria. The low-energy section relies on existing designs, but their reliability will have to be established.

Figure 1. Schematical layout of the XADS linear accelerator



Low-energy section

The low-energy section or injector section consists of an ECR-type ion source feeding into a room temperature RFQ.

The French source SILHI [1] has been designed and built for a proton current of 100 mA in the framework of the IPHI project [2]. Its long-term availability has been shown and improved in several test runs. Its performance in terms of reliability will have to be established in the down-rated situation of XADS during a dedicated test run.

The RFQ is of the four-vane-type at a frequency of 352 MHz. Fully relevant designs, compatible with CW operation, have been made at several laboratories [3-5]. They are typically capable of beam currents around 100 mA and output energies of $\geq$ 5 MeV. For our XADS application, some design parameters are optimised for reliability and availability, possibly at the cost of an increase in length. On the other hand, it is definitely our goal to limit the output energy of the RFQ as much as possible by an adequate choice of the subsequent accelerating structure.

It should be mentioned that these designs will be optimised to achieve the highest reliability, but that the fault tolerance principle cannot be realised at the level of the beam by a single one of these sections: the failure of any element will cause the beam to disappear. Hence, it appears that explicit redundancy by doubling the low-energy section will be required.

High-energy section

From around 100 MeV onwards the superconducting elliptical cavities at 704 MHz become the most efficient and the most cost-effective choice [6]. In order to span the full range of beam velocities, the high-energy linac is divided into three zones, corresponding to geometrical β values of 0.47, 0.65 and 0.85. Transitions occur around 200 and 490 MeV, and the 0.85 zone could operate up to 2 GeV. A $\beta = 0.47$ realisation is shown in Figure 2. For XADS, multi-cell cavities are foreseen, assembling five or six cells per cavity.

Figure 2. Two of the $\beta = 0.47$ single-cell cavities built for the Italian TRASCO programme, after fabrication (left) and on the test stand before cryogenic measurements (right)

Transverse focusing is obtained by periodic normal-conducting quadrupole doublets with long drift lengths. These drift lengths are filled with cryomodules; a cryomodule typically houses three cavities.

In this section, modularity is strong, both in cavities and in transverse focusing elements. This will allow the implementation of an adequate fault tolerance scheme, which will cope with the loss of a cavity as well as with the loss of a quadrupole.

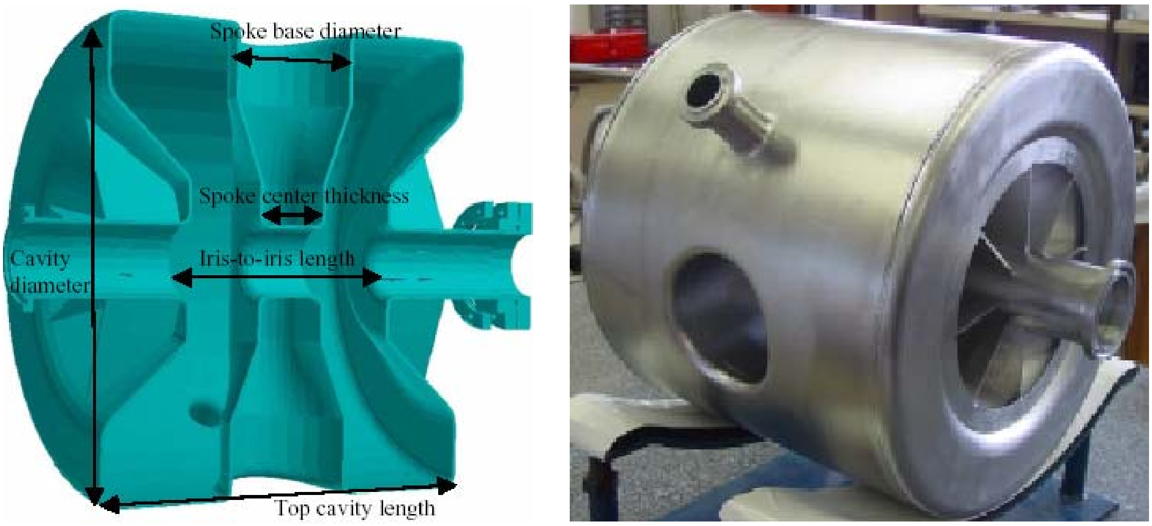
Intermediate-energy section

In this section, going from the exit of the RFQ to around 100 MeV, the optimal choices of the accelerating structures are far less clear, and a number of options remain open. It is most probable that our existing design rules, along with the shortest possible RFQ, will impose the use of at least two different structures to span this energy region.

Coming down from 100 MeV, the superconducting two gap *spoke* cavities at 352 MHz are considered very promising candidates [7]. A “b = 0.35” section would allow to accelerate from ~20 MeV to 100 MeV. As with the high-energy superconducting sections, modularity is high, and it can be made fault tolerant against a cavity loss and against a quadrupole loss. A cross-section and a prototype of a “b = 0.35” spoke cavity are shown in Figure 3.

Figure 3. “b = 0.35”spoke cavity

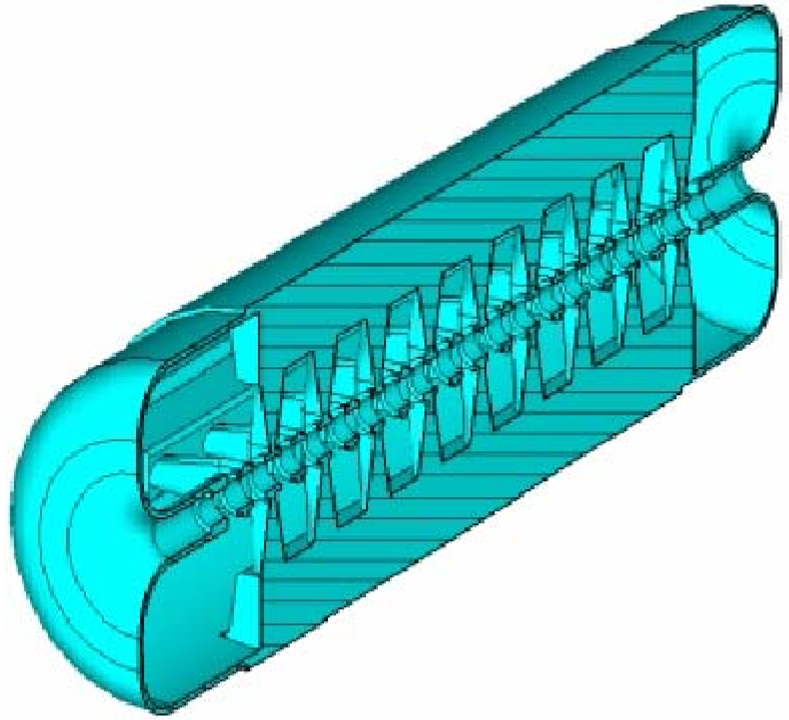
Left – cross-section, right – prototype (IPN Orsay – CERCA)



At the low-energy side, exit of the RFQ, the lowest possible injection energy is looked for. Here, the H-type drift tube structures are considered as the most effective. They are combined in multi-cell cavities, and taking advantage of the KONUS focusing scheme [8], which allows for long drift spaces between the quadrupole triplets, the drift tubes can be free of focusing elements.

For room temperature structures, either the IH or the CH configuration may be used, depending on frequency and on beam velocity. They have appealing properties concerning their radial size and their shunt impedance, and their CW capabilities are significantly superior to those of the classical DTL. Nevertheless, they will have to be studied and proven. A promising candidate would be a RT IH structure with a very low b capability (e.g. b = 0.065, 2 MeV injection energy) accelerating up to, say, 20 MeV. Such a structure would very effectively limit the RFQ requirements.

Figure 4. Sectional view of a 350-MHz CH-type DTL cavity



The CH structure may also be considered in a superconducting version [9]. Its mechanical robustness and its very good voltage breakdown properties allow for this. This option is really attractive for XADS, but its very low b capabilities may be limited. A 350-MHz 19-cell prototype for b = 0.1 is being designed (University of Frankfurt) and will be constructed.

The situation of these multi-cell cavities with respect to our fault tolerance philosophy is equal to that of the low-energy section. Therefore, here again, explicit redundancy by doubling the structures will be required.

Fault tolerant schemes

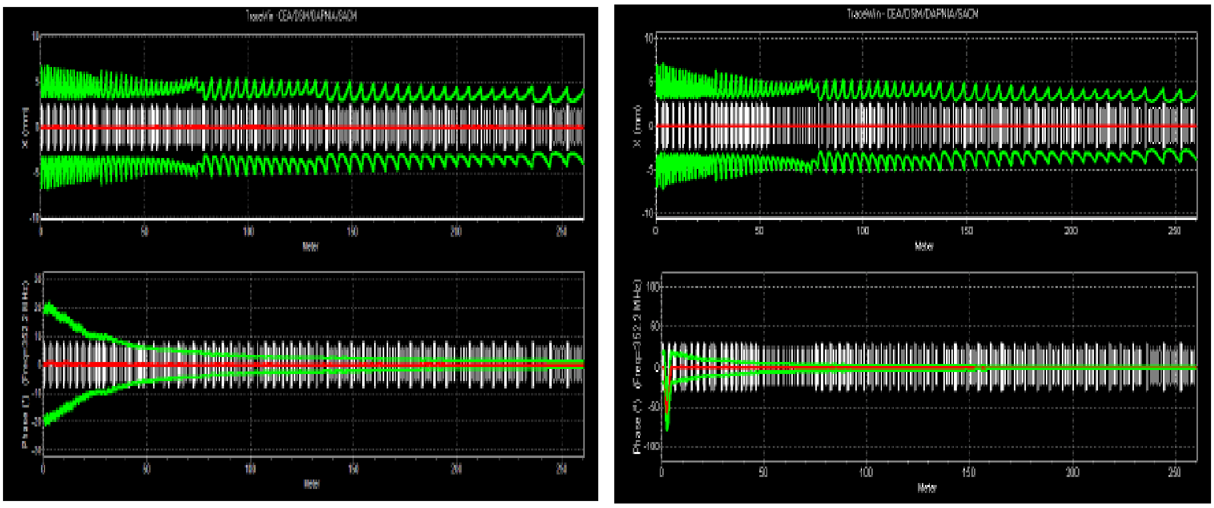
The capacity of recovering a good quality beam with a failing cavity or with a failing quadrupole is fundamental for the fault tolerance principle to be valid. This capacity has been studied in a spoke cavity section. At present this study is limited to a “before – after” situation, and the actual possibilities of a smooth transition are still unknown. However, certain rules may already be established:

- If a cavity fails and nothing is done, the beam is always completely lost.
- If a cavity fails and an appropriate local compensation is applied, the nominal beam parameters at the target may be restored.
- If a quadrupole fails, the whole doublet is to be switched off. Nominal beam parameters at the target can be restored by readjusting a few surrounding quadrupoles.

The local compensation for a failing cavity typically concerns the four surrounding cavities, which are retuned in amplitude and in phase. When also retuning the quadrupole gradients, an almost perfect re-matching of the beam may be obtained (see Figure 5).

Figure 5. Beam envelopes in the 5-600 MeV XADS reference linac

Left – Nominal case. right – case with failure of spoke cavity #4, after retuning of the field amplitudes and phases of spoke cavities #2, #3, #5 and #6, and adjusting the four nearest quadrupoles. Note the different scales on the phase (bottom) plots.



In order to implement such a correction scheme, it is of course required to have adequate margins on the accelerating fields and on the available RF power. Moreover, the low-level RF control system has to cope with these correction schemes, and it will require the development of novel fast digital feedback circuits.

Global overview

In view of the above discussion on reliability and fault tolerance, the XADS reference linac becomes different from the schematic in Figure 1. Let us assume that the spoke cavity section starts at energy X (X will most probably lie in the range 20-40 MeV). The part of the linac below X will not benefit from the “missing cavity correction scheme”. Therefore, it is now foreseen to double this part entirely, thereby introducing a permanent hot spare. For recall, it will consist of an ECR ion source, an RFQ and some kind of H-type structure. Figure 6 shows the corresponding schematic.

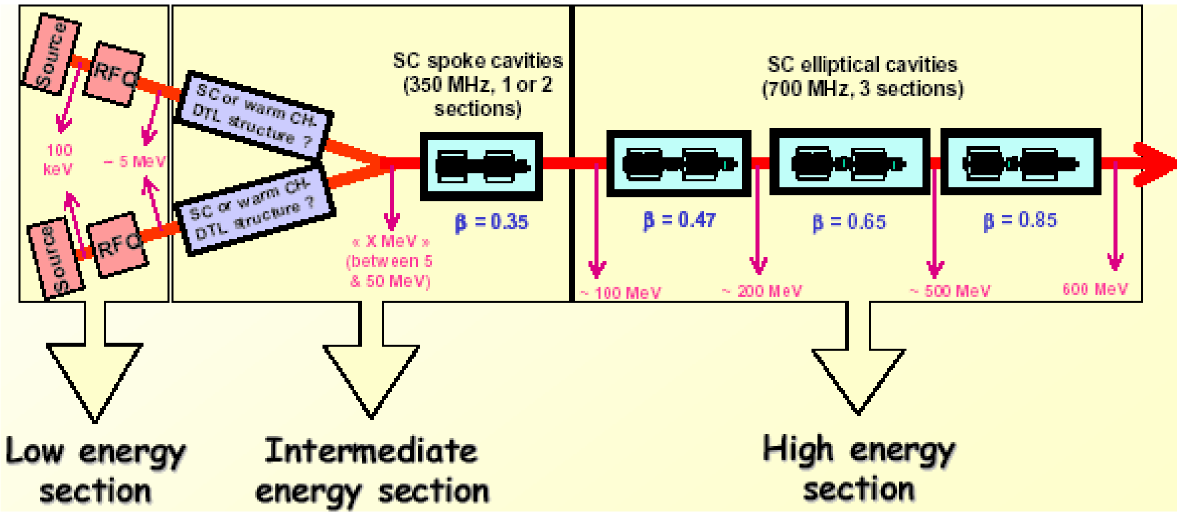
The layout of the beam line will depend on the relative positioning of the accelerator and the subcritical reactor. In any layout, however, a few properties are recurring:

- The beam line, and especially the 90 vertical bend on top of the reactor, will be achromatic. Transverse beam emittances are small, and therefore it will be possible to use light magnets.

- The small transverse beam emittances allow the distance between the last magnet and the target to be ~16 m.

- A raster scanning system will allow determining the beam footprint on the target according to the needs.

Figure 6. Schematic view of the redundant and fault tolerant XADS linac



R&D

The upcoming R&D programme has three major goals, and all of them are in view of obtaining the requested overall availability. The R&D items have been distributed among the WP3 partners, and they have been introduced into the European Commission's 6th R&D Framework Programme proposal called EUROTRANS.

1) It must be proven that the required level of reliability of the individual components can be achieved. This needs prototypical elements to be built and tested. In the low-energy section, a long test run is planned with the existing IPHI injector, i.e. the source and the RFQ (3 MeV) (CEA). In the intermediate-energy section, it is foreseen to build a complete spoke resonator, possibly embedded in its cryomodule (CNRS). Finally, in the high-energy section, a complete b = 0.5 cryomodule with N cavities and their RF-couplers will be built and tested (INFN).

2) The open questions regarding the bridge between the RFQ and the spoke section must be resolved. To that end, it is planned to build a complete superconducting CH accelerating structure on one hand (U. Frankfurt), and a room temperature IH accelerating structure on the other hand (IBA).

3) As the RF low-level control is so vital for the reliability scheme, its development (and mainly of the new fast digital circuits) must be considered as a separate R&D item (CEA). Some remaining questions on the RF power amplifiers have to be resolved (e.g. klystrons vs. IOTs). Finally, a full beam dynamics analysis including transients and fault recovery will be performed.

Design choices and construction methods

The availability of the XADS proton beam can only be brought to a very high level if the fault tolerance scheme, which has been discussed so far only at the level of the global object "accelerator", is generalised to all the lower-lying implementation levels. Therefore, the principles of modularity and/or of redundancy have to be applied as much as possible at all stages of design and development.

This should be considered as a general design guideline that will efficiently lead to the highest main time between failures (MTBF) values. Another guideline for maximising MTBF is the use of down-rated components – note, however, that fault tolerant modularity will usually impose this anyway.

Along with increasing the MTBF, it is equally important to minimise the main time to repair (MTTR), because this is essential for the fault tolerance to express itself in the long run. The lowest MTTR means a very high level of maintainability, which is largely obtained by adequate construction methods. From the largest items (in our case full cryomodules or complete power RF amplifiers) to the smallest power converters, things have to be built for optimal accessibility and easy (= quick) exchange. In the context of an accelerator facility, radioprotection is an important issue, and a two-parallel tunnel building layout seems inevitable. Finally, a maximally pushed application of modularity and of uniformity and standardisation is a good guarantee for fast interventions, but on the strict condition that it is supported by both a performing alarm system and a ditto documentation.

As a final remark, it is of course necessary to safeguard the facility over time through an adequate maintenance plan. The XADS cycle is presently foreseen as a one-month shutdown period after a three-months run. From the accelerator point of view, it is felt that this cycle leaves ample time for a normal four-month maintenance, but that a longer period should be available at a yearly basis.

Extrapolations

The question about the possibilities to extrapolate the given XADS design towards an industrial transmutation application was raised at the outset of the PDS-XADS project, and it is the object of a future deliverable. The feeling with respect to the present linac layout is the following:

- The extension of the energy range is straightforward. The b = 0.85 section will accelerate up to 2 GeV, whereas transmuter systems would typically only require 1 GeV.

- A significant increase in the beam current is well within the possibilities of the present linac design. We are not touching any fundamental space charge limitation: the ion source is designed to inject 100 mA into the RFQ. After some preliminary discussions, the general feeling is that a 1-GeV, 20-mA beam is within the possibilities of our existing design philosophy. Such a beam would be sufficient to drive a 1-GW thermal power subcritical reactor.

Note that, for safety reasons, it is intended to strictly limit the electrical grid power available to the XADS accelerator, so as to create a physical impossibility to exceed a given beam power.

Conclusion

Accelerator reliability levels that are well beyond the present standards are of vital importance for any ADS project. It is clear, however, that this high reliability will not be achieved at the first go. This is why experimental systems (XADS), i.e. relatively small-scale systems but with all the features of a full-size system, are so important: they allow for the mandatory learning process to take place.

We believe that the reliability goal is achievable if, in the first place, the correct rules and principles are applied at all stages of development. At the design stage, these principles aim at reaching optimal modularity and fault tolerance, and at defining correct specifications. At the manufacturing stage, these principles aim at realising the specifications by a strict quality control, thus assuring the highest MTBF figures. At the commissioning stage, the rules must guarantee that the operational parameters are brought in agreement with the design values, possibly by adjusting the design models.

At this point operation starts, and this is where reliability can gradually be set up, by building on the preceding achievements. Reliability can only be “grown” from high-quality technical building blocks by adding the correct mental attitude. Operation needs a “reliability-minded” crew, who will be able to continuously improve the system and bring it ever closer to the reliability goal. The development of an ADS-compatible accelerator will need to go through this learning process. Placing it in the framework of an XADS project is the most efficient way to go.

REFERENCES

[1] Gobin, R., *et al.*, *Proc. EPAC2002*, Paris, France, 1712 (2002).

[2] Beauvais, P-Y., *et al.*, *Proc. EPAC2002*, Paris, France, 539 (2002).

[3] Schrage, D., *et al.*, *Proc. Linac’98*, Chicago, USA, 679 (1998).

[4] Pisent, A., *et al.*, *Proc. Linac2000*, Monterey, USA, 902 (2000).

[5] Ferdinand, R., *et al.*, *Proc. Linac2000*, Monterey, USA, 551 (2000).

[6] Biarrotte, J-L., *et al.*, *Proc. 9th Workshop on RF Superconductivity*, Santa Fe, USA (1999).

[7] Olry, G., *et al.*, *Proc. EPAC2002*, Paris, France, 2271 (2002).

[8] Ratzinger, U., *Habilitationsschrift*, Johann Wolfgang Goethe Univ., Frankfurt, Germany (1998).

[9] Eichhorn, R., U. Ratzinger, *Proc. Linac2000*, Monterey, USA, 926 (2000).

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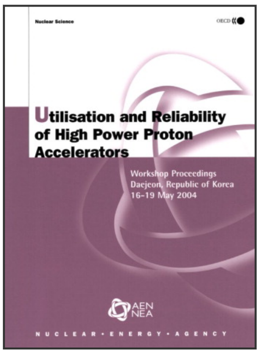

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