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This document is intended to design the XADS accelerator reference scheme, to describe as precisely as possible the various elements to be used, and to point out the needed R&D to be done before starting the construction phase of the machine.

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DEFINITION OF THE XADS-CLASS REFERENCE ACCELERATOR CONCEPT & NEEDED R&D

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1 INTRODUCTION

The present deliverable D63 is the synthesis document of the studies performed by Working Package WP3, "The Accelerator", of the FP5 project PDS-XADS.

At the beginning of the project, the main initial specifications for the accelerator system (e.g. beam energy, beam intensity, beam profile, their stability and the accelerator availability and reliability) have been defined by WP1, "Global Coherence", in connection with the other WP of the project (see the first PDS-XADS deliverable D1 **[1])**. We recall these specifications in section 2 of the present document.

Then, in its deliverable D9, WP3 has assessed the main requirements and the corresponding technical answers for the accelerator **[2]**. A reference solution, based on a linear superconducting accelerator with its associated doubly achromatic beam line has been worked out up to some detail. The main arguments for this reference solution are summarized in section 3 of the present document. For high reliability, the proposed design is intrinsically fault tolerant, relying on highly modular “de-rated” components associated to a fast digital feedback system. The corresponding studies have been presented in deliverables D57 **[3]** and D47 **[4]**. They will be synthesized in section 4. The proposed solution also appears to be robust concerning operational aspects like radioprotection and maintenance that were investigated in D48 **[5]**. Sections 3 and 4 will contain the relevant facts, respectively.

The proposed reference solution relies on the accomplishment of an R&D programme, focused on reliability aspects. This programme has been gradually elaborated during the PDS-XADS project **[6]**. It is summarized in section 5. Much of it has been included in a new and specific WP that is part of the FP6 project EUROTRANS. The infrastructure requirements, the construction schedule and costing of the XADS accelerator are also addressed in section 3, whereas section 4 gives some details about commissioning, routine operation and safety grade shutdown.

The following institutions have collaborated on these studies: ANSALDO (Italy), CEA (France), CNRS-IN2P3 (France), ENEA (Italy), Framatome ANP (France), Framatome GmbH (Germany), IBA (Belgium), INFN (Italy), ITN (Portugal), University of Frankfurt (Germany). The coordination of WP3 has been assured by CNRS-IN2P3. The important help from Paul Berkvens related to radioprotection aspects is acknowledged.

2 XADS ACCELERATOR SPECIFICATIONS

The subsequent chapters will describe the proton beam specifications for the XADS accelerator. But in fact, different parameter sets were to be analysed: both the Pb-Bi and gas-cooled XADS require a proton energy of 600 MeV, whereas the smaller scale MYRRHA-XADS requests 350 MeV. The beam line connecting the high-energy outlet of the accelerator to the spallation target within the reactor vessel also has the important function to provide the demanded beam profile at the target. This profile is rather different for the three XADS versions under study.

The present deliverable D63 will essentially describe and discuss the accelerator and associated beam line for these three XADS. A subsequent deliverable D80 will present, in a concise form, pertinent considerations for an extrapolation to the requirements of an industrial transmuter that may require 1 GeV or so.

2.1 PROTON BEAM SPECIFICATIONS

The main technical specifications for the XADS accelerator are summarized in Table 2-1. These characteristics clearly show that this machine belongs to the category of the so-called HPPA (High-Power Proton Accelerators), presently very actively studied or even under construction for a rather broad use in fundamental or applied science. The overall performance of the sub-critical system will be critically determined by a strict adherence of the XADS accelerator to these 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. Therefore, the WP3 studies had to integrate this stringent requirement from the very beginning, since this issue could be a potential "show-stopper" for ADS technology in general.

Table 2-1 – XADS proton beam specifications **[1]**

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 **[7]**
Beam trip number	Less than 5 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

***Proton beam energy and intensity* ---**

The European Technical Working Group (ETWG) on Accelerator Driven Systems (ADS) considered, in its final report **[8]**, that the physics of spallation and of energy deposition favours the choice of a proton beam energy of the order of 1 GeV or more. Moreover, "*an energy of the order of several hundred of MeV (600 MeV – 1000 MeV) is well within the state of the art and extrapolation to energy higher than 1 GeV seems feasible. However, as the mission of the XADS plant is a global demonstration of the operation and safety and not the industrial operation for waste transmutation, cost considerations could favour the choice of a lower energy. In any case, a lower limit of about 600 MeV can be set in order to have a reasonable efficiency in neutron production and an affordable beam load on the target window*". Therefore, for the demonstration purpose, the proton final energy has been set to 600 MeV. The accelerator itself will be designed for that final energy, keeping in mind that an eventual extrapolation up to 800 MeV or 1 GeV should remain easily implementable. Another accelerator (and associated beam-line) to be considered is the one of the smaller-scale MYRRHA XADS **[9]** studied by WP 5.3, "Small-Scale XADS: System Integration". The requested proton beam energy of 350 MeV goes with a target design that is not critical to lower beam energies and correspondingly higher beam intensities (the window-less design).

The beam intensity can be deduced from the multiplication factor of the sub-critical assembly and the thermal power of the ADS reactor. WP1 assessed in its Deliverable 1 that for a power level of P_{max} = 100 MW, and a core load with MOX type fuel and with a multiplication factor k_0=k_{max}=0.98, the proton beam current needed at 600 MeV is about 2 mA average. With a core multiplication factor as low as k_0=0.90, the current would rise up to about 10 mA. Beam currents higher than 10 mA should in principle also be considered for the XADS accelerator in order, for instance, to demonstrate not only the basic principles of an ADS for waste transmutation, but also the feasibility of industrial operation of this kind of plant. Conversely, the effective level of beam intensity shall be also dependent on the actual XADS fuel core design and specific fuel cycle, as well as on the practical feasibility, operability and relevant safety issues which are linked to the target-core coupling. Based on theses considerations, it was proposed to design the accelerator for a maximum (average) current of 10 mA, and to design the operation of the XADS target and core for a value up to 6 mA. It is also very important to point out that, from a safety point of view, design provisions must be taken in order to limit the current intensity value in the core zone to 6 mA.

Beam time structure ---

In principle, to avoid thermal stresses on the beam window, target and sub-critical assembly, a continuous wave (CW) beam would be the best solution. However, a pulsed operation of the accelerator is also feasible, since the time scales of thermal inertia of the different components of the target and the reactor are much longer than that of the beam period. Moreover, the use of a pulsed mode of the accelerator would enable the in-line measurement of the sub-criticality level through dynamic measurements; this point is considered as a major concern in order to ensure a safe operation of the XADS.

From the accelerator point of view, it is an important design issue to decide between a continuous wave (CW) and a pulsed machine, no matter what the beam time structure*. Operation in CW (RF) mode is generally preferred to a pulsed one in this kind of machine. A thorough and quantitative analysis has for example been made for the EURISOL driver machine **[10]**, leading to the conclusion that CW machine solution is recommended: reliability is maximum (lower peak power), the Lorentz forces problem vanishes in the superconducting accelerating cavities, the R&D effort is significantly lower, and the machine is simpler and more flexible. Therefore, Deliverable 9 highly recommended to choose a CW operation mode for the XADS accelerator, the RF remaining continuously applied on the RF structures, while the beam intensity could be arbitrary shaped.

* One has to distinguish between a pulsed beam current and a Radio-Frequency (RF) pulsing of the accelerating structures. It will be considered here that a machine is pulsed whenever the RF power is applied in repeated pulses, the duty factor being the percentage of time the power is on. On the other hand, when the RF field is continuously maintained in the accelerating structures, the machine will be considered as a CW accelerator, no matter what the beam time structure. As a matter of fact, the beam current may be pulsed (for example at the source) in either a CW or a pulsed machine. On the contrary, a CW beam can only be implemented in a CW machine, not in a pulsed machine; this is because in a pulsed machine, the beam duty factor must always be lower than the RF one.

Given these considerations, WP3 proposed, in agreement with WP1, the following recommendations concerning the XADS proton beam structure **[11]**:

- A CW-based time structure appears to be a natural and simpler choice for the XADS beam.
- Additional short and well-defined (sharp edge) beam interruptions of 200 µs* can be easily implemented with a repetition frequency in the order of 1 Hz. These beam holes, shutting down the neutron power source from time to time, should enable continuous and very accurate on-line measurements and monitoring of the reactor sub-criticality.

These specifications are shown on Figure 2-1, where I_0 is the mean beam current between two holes. Its value should be adjusted from zero to maximum (full beam) to produce the desired number of spallation neutrons in the sub-critical core. This can be done at the source output and checked all along the linac up to the beam line delivery to the target.

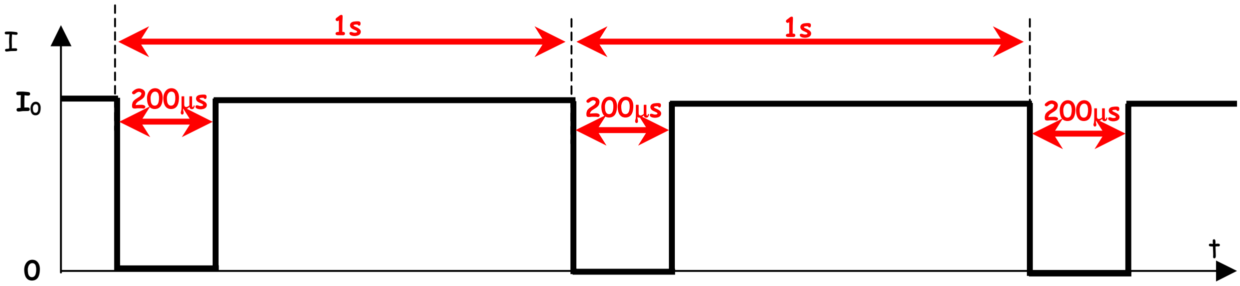


Figure 2-1 – Recommended XADS beam time structure during normal operation.

Beam power stability ---

The total power of the beam is given by the product of the beam energy and the beam intensity. The total power defines the source term of the ADS since it is, for not too large excursions around the nominal energy, strictly proportional to the number of produced spallation neutrons. Therefore, one could, at least in principle, control the XADS by either the beam energy, or the beam intensity, or a combination of both. However, for practical reasons, it is most convenient to operate at fixed beam energy, and hence use the modification of the beam intensity for the control of the total beam power. We have thus opted for a design in which the overall acceleration is kept constant at a level of precision better than 1%, which should a priori be quite easy to achieve. Therefore, as the beam power is uniquely controlled by the beam intensity, the feedback system monitoring the intensity and readjusting it must ensure that the beam current stays precise at the level of about 2% absolute value. This is a rather stringent requirement considering the actual fluctuations of nowadays ion sources.

* This value is a good compromise between, on the one hand, long enough holes to allow a good measurement of the reactor sub-criticality, and, on the other hand, short enough holes to avoid any trouble concerning the RF operation of the accelerating cavities. The length of this beam hole could eventually be increased from 200 up to 250 or 300 µs if needed.

A fluctuation of the total power, i.e. of the intensity, for a time period smaller than one second has been assessed by WP1 as being of no consequence for the overall operation of the XADS and all its components, as specified in Table 2-1. However, recent input from WP 4.3 **[12]** pointed out that, concerning the target, a maximum allowed time of 300 ms for a 100 % fluctuation (i.e. the complete disappearance of the proton beam) might be more appropriate. Using for a preliminary assessment of the specifications for the intensity still the 1 sec maximum disappearance time, we therefore propose the following definition for allowed intensity fluctuations: $\mathbf{98\%\ I_{nominal}} < \frac{1}{\Delta t}\int_{\Delta t} I(t).dt < \mathbf{102\%\ I_{nominal}}$ **,** where Δt = 50 sec, and $I_{nominal}$ is the required mean beam current. In other words, we propose a definition of the intensity fluctuations that uses an integration time of 50 sec, which would permit the same definition for the intensity stability during normal operation and the (wanted or unwanted) interruptions of the beam for a 1 sec maximum**.** The intensity control system has to be designed to measure and to stabilize for this value. If not, the emergency shutdown procedure has to be started.

The above definition always ensures that the beam power stability, integrated over a 50 sec time period, is better than ± 2%. Concerning beam interruptions, it allows for example the occurrence of a 1 sec beam complete disappearance every 50 s, but prohibits a longer interruption. At the opposite, this definition also allows in principle an overpower condition of 200 % nominal beam power for 1 sec every 50 sec. However, this will not occur in practice. First of all, it would mean, that the ion-source suddenly provides such an intensity increase, e.g. because of a fluctuation in gas pressure. It would further mean, that all accelerating elements simultaneously run at about twice their nominal power, which also has to be provided by the electrical power grid. In fact, we propose in spite of everything to specify for an additional absolute limitation of 120 % of the total electrical power delivered to the accelerator RF system regardless of any time aspect. This can be guaranteed by a "mains fuse" limited to the required value.

***Specifications towards a reliable operation* ---**

The ADS plant is optimised for operating at nominal power (3.6 MW beam). But it has also to be capable to operate for long periods at partial load (from around 20 % to 100 % of the nominal power) without significant penalties. Moreover, during the plant commissioning and after a refuelling shutdown state, operations at very low power (< 3 %) may be requested. For that purpose, it should be envisaged to run the XADS CW machine with short beam pulses at low beam duty factor. Such an operation mode should a priori be easily implementable under the condition sufficiently short beam pulses are used (in the order of a few tens of μs, some 100 μs at maximum).

The reliability requirements are essentially related to the number of allowable beam trips. Frequently repeated beam trips can significantly damage the reactor structures, the spallation target or the fuel of the sub-critical core and, also, decrease the ADS plant availability. On the basis of current results, the order of magnitude of the allowable duration of the beam trips is 1 second. For an ADS burner of which the primary goal is not electricity production, the number of unexpected shutdown for the accelerator should not exceed 5 per year. For the successful demonstration of the ADS coupling, the XADS accelerator will therefore have to be designed to match this objective of a few beam stops per year. Given the state-of-the-art in the field of accelerator reliability **[13]**, this requirement appears to be highly challenging, and could reveal itself as being a "show-stopper" for ADS technology. The suitable design strategies developed to cope with this crucial requirement are detailed in the subsequent paragraph.

2.2 THE RELIABILITY REQUIREMENT

The requirements concerning the XADS accelerator reliability have been discussed in the ETWG Report and in several deliverables of the PDS-XADS program (among which the most important are Deliverables D1, D9 and D57). Indeed the accelerator configuration that has been outlined by the WP3 is aimed at implementing the necessary strategies for reaching a very reliable operational goal.

In all previous work, three different time ranges of beam interruptions have been identified, with different aspects concerning the safety of the overall XADS plant.

- Beam trips with extremely short time duration, of the order of a few hundreds of milliseconds or less, do not have a significant impact on the subcritical assembly operation, if their occurrences do not contribute substantially on the average delivered current. As a matter of fact, the proposed methods for subcriticality measurements are aimed to deliberately generate short (200 μs) beam trips from the accelerator, in a controlled way.

- Longer beam trips, up to a value of several hundreds of milliseconds to approximately 1 second, can induce transients on crucial elements as the beam window or the fuel assembly pins. Beam trips falling in this category are the ones that are dealt with automated beam recovery procedures without the need of manual intervention. The order of magnitude on the allowable number of these beam trips of intermediate duration depends on several technological details of the XADS subcritical assembly (whether is used a windowless or windowed spallation target, the choice of the coolant for the primary system, or the precise design of the fuel elements). Assessments are being developed for the several envisaged options in terms of the identification of a more precisely identified temporal threshold and allowed number for this class of trips. For an eXperimental ADS class device, it is felt that the number of these interruptions could fall in the hundreds or thousands per year range.

- However, beam trips with even longer duration, and caused by failures that require human intervention for the necessary fixing or compensating actions and restart procedures will lead to a large thermal excursion in the internal structures of the subcritical system, in the primary coolant system and possibly in the main vessel. Indeed, the restart procedure after such a failure, requiring access and maintenance operations on the accelerator tunnel, will be dominated by the procedures enforced by the safety analysis of the XADS system for this kind of beam losses. Deliverable 1 sets the limit at a maximum of 5 such long beam interruptions – leading to unexpected shutdowns – per year of operation.

The operation records of existing accelerator facilities for nuclear and high-energy physics or condensed matter physics surely show that these accelerators exceed by a great factor these tight requirements. However, the design of these machines takes often into account a beam availability goal, defined as the ratio of the delivered beam to experiments to the scheduled beam operation. Experience at synchrotron light sources has shown a steadily improvement of their availability budget up to levels of more than 99%, and almost all operate above 95%. The estimation of the availability budget, however, often does not include the major yearly shutdowns and the short frequent (weekly) shutdowns planned for preventive maintenance operation of the machine components.

For the XADS, the high beam availability and the small number of allowed failures should be guaranteed on the basis of an operation cycle that is compatible with the fuel cycle of the subcritical system. Again, the choice of the operation and maintenance cycle depends on technological details of the subcritical system, and an assumption of three months of continuous operation, followed by a one-month shutdown has been used as a possible compromise between the different scenarios discussed.

In order to be compatible with the three months of continuous operation and with the requirement of 5 unexpected shutdowns per year, an overall goal of nearly 1400 h can be set for the MTBF of the overall accelerator system, for events that lead to the long beam trips, as described above. Such a high MTBF – which is approximately 30 times longer than the currently experienced MTBF of the ESRF facility – can be reached only if suitable reliability-driven strategies are followed in the design stage of the accelerator.

The three main strategies on the path to reaching the small yearly rate of faults have been outlined in Deliverable 57, and are a standard practice in reliability engineering in many fields and in industrial applications: derating (avoiding stresses on components close to their maximal operational capabilities), redundancy (including more than a single component to provide a function to the system) and fault tolerance (the capability of the system to use the redundancy in order not to fail after the failure of one of its components).

The capability of extensively incorporating these guidelines into the accelerator design has motivated, even more than other technical aspects, the choice of a linear accelerator based on independently phased superconducting resonators as the reference XADS accelerator, which has a clear possibility to be extrapolated to the even tighter requirements of the XADT case. The modular structure of such a machine, described here and in the various WP3 deliverables, and the somewhat relaxed requirements on its component with respect to the state of the art of the underlying technology, allows to easily incorporate the first two reliability oriented design criteria in the proposed layout. The relatively low beam energy in the extremely modular superconducting linear accelerator layout, combined with the beam dynamics driven requirement of limiting the longitudinal phase advances (thus keeping relatively low accelerating fields) is the ideal candidate for providing redundancy and component derating without paying an excessive price in the overall length of the accelerating system.

The fault tolerance capability, explored in Deliverable 47 **[4]** and in a more systematic study in the following chapters, has been assessed by means of beam dynamics simulations. It is clear that a new class of machine control system need to be devised for an XADS system, with respect to the existing accelerator facilities. This control system will, to the maximum extent, handle signals from devices in order to manage the necessary preventive or corrective actions in order to limit the duration of beam trips below the time limit corresponding to the scale of the unexpected shutdown. Failures corresponding to slow cavity degradation or RF couplers arcs could be detected early before the onset of failures, and the component could be gracefully put offline while maintaining the beam operation within the acceptable parameter range. For most of the failures of the main components (as the ones described in section 4.1 “Fault Scenarios”), such a control system needs to store all the necessary set points that will allow implementing the required system fault tolerance. Dedicated R&D activities, aimed at both experimentally characterizing the fault scenario of the most critical components and implementing a control system with the necessary corrective actions, have been identified for the 6^{th} FP, and will be described in section 5.

All the remaining areas where the fault tolerance is more difficult to implement with respect to a number of component failures (e.g. at the source, RFQ or low energy stage, in the beam transfer and matching lines, for the various support and safety systems) need to be explored in more detail, by using reliability prediction methodologies. The lack of a standard and validated component database requires the use of expert judgment and extrapolation from operational data from existing facilities and raises many doubts on the ability to effectively provide this kind of predictions with a reasonable confidence margin. A few cases will be treated in section 4.3.

2.3 SAFETY ASPECTS AND RADIOPROTECTION

There are several high-energy proton accelerators operating in the world and the XADS accelerator facility will largely benefit from the experience gained in these facilities in terms of safety. Although several safety hazards must be dealt with around a high-energy proton accelerator (electrical safety, non-ionising radiation, maintenance hazards, etc.), the primary concern will be ionising radiation.

Ionising radiation produced in accelerator facilities includes prompt radiation and induced radiation. Adequate shielding, together with an appropriately designed personnel safety system, will protect against prompt radiation. The production of induced radioactivity around a high-energy proton accelerator is important and must be dealt with correctly in terms of radiation protection for the workers (example: administrative procedures and optimisation for maintenance) and the protection of the environment (example: activation of earth/water, radioactive waste).

European legislations ---

The European Directive 96/29/Euratom of 13/05/1996, based on the ICRP recommendations no. 60 **[14]**, lays down the basic safety standards for the protection of the health of workers and the general public against the dangers arising from ionising radiation. All member states of the European Union must integrate these basic standards in their national legislation. In particular, the following rules must be respected.

- All practices involving a risk from ionising radiation emanating from an artificial source require reporting to the national authorities or require prior authorization of the national authorities. In particular, the following practices are subject to an authorisation:
  - operation of any facility of the nuclear fuel cycle;
  - use of particle accelerators with energy above 1 MeV.
- The disposal, recycling or re-use of radioactive substances arising from any of the above mentioned practices is subject to prior authorization, unless they comply with clearance levels established by national competent authorities. The European Directive gives the basic criteria for establishing these clearance levels.
- Justification, optimisation and dose limitation for practices:
  - in the context of optimisation all exposures shall be kept as low as reasonably achievable (ALARA principle) for the concerned personnel, economic and social factors being taken into account;
  - the limit for effective dose for members of the public is 1 mSv in a year.

The implementation of the directive 96/29/Euratom has introduced changes in the national legislation of the member states of the European Union. As examples we can cite:

- Belgium: the royal ordinance of the 20th of July 2001, defining the general rules concerning the protection of the general public, the workers and the environment against the dangers arising from ionising radiation;
- France: decree no. 2002-460 of the 4th of April 2002, dealing with the general protection of the health of the general public against ionising radiation hazards and decree no. 2003-296 of 31st of May 2003, dealing with the protection of the health of workers against ionising radiation hazards;
- Germany: German Radiological Protection Ordinance (Strahlenschutzverordnung, revised version applicable since August 2001).

It should be noted that very similar requirements for the XADS accelerator facility result from these national legislations, in particular:

- need for a public enquiry to authorize the facility;
- requirement to include a detailed decommissioning plan in the safety assessment document.

Some differences however exist between the different countries. We can cite the more restrictive definition in the Belgian law of “radiation worker” compared to the European Directive, or the absence of exemption limits for radioactive waste in the French law.

Shielding calculations --

The shielding calculations must be in line with the general radiation protection philosophy. The recommendations from the ICRP publication no. 60 **[14]** have been adopted in the European decree Euratom/96/29; all national legislations of the member states of the European Union must respect this European decree. Independent of the country where the XADS facility will be built we should therefore base the radiation protection policy on the ICRP-60 recommendations. The general principles outlined in the ICRP publication 60 have therefore been taken into account to obtain practical criteria for the shielding design of the XADS accelerator in the following way.

1. The goal of the shielding design is to guarantee that, under normal operational conditions, the added integrated dose to anybody working around the XADS accelerator will be extremely small, i.e. comparable or smaller than the natural background. To obtain this goal, we rely on:

- the use of conservative (= pessimistic) normal beam loss assumptions;
- the use of a conservative shielding model;
- the fact that the real earth profiles will provide systematically more shielding than the calculated minimum thickness, in all areas where “unrestricted” access is possible;

- the assumption of an occupancy factor = 1; this means that for the shielding calculations we assume that a person will be present during 2000 hours per year immediately behind the shield wall where maximum dose rates exist.

For the shielding calculations we have used a design dose rate of 0.5 $\mu Sv.h^{-1}$, corresponding to the ICRP-60 annual limit of 1 mSv for the public, taking into account an annual working time of 2000 hours (= derived limit for non-exposed workers). The natural background being of the order of 1 $mSv.y^{-1}$ the conservatism built into the shielding calculations should therefore guarantee that the effective dose for any person resulting from the operation of XADS accelerator will be smaller than the natural background. This is an important argument because it is not unlikely that future ICRP recommendations will go in the sense of comparing exposure from "man-made" sources to exposure from natural sources.

2. The shielding defined for the normal operational conditions, with the conservative criteria explained above, must guarantee that extra exposure to radiation created from abnormal operational conditions must remain sufficiently low, in order not to jeopardize the main shielding objective, i.e. keep the total integrated dose added by the operation of the XADS accelerator, for any person, below the natural background.

3. The exposure to radiation from activated accelerator components is minimized via a system of administrative measures, and by keeping the normal beam losses in the accelerator small and keeping the integrated power of accidental beam losses as low as possible via a powerful accelerator interlock system.

One of the problems associated with induced radioactivity is the activation of earth surrounding the XADS accelerator tunnel and the risk of having to treat this earth as radioactive waste during the final decommissioning of the facility. The European Directive 96/29/Euratom has defined exemption limits, below which activated material can be treated as standard waste. Preliminary results from calculations concerning the activation of the earth layer around the accelerator tunnel show that one can expect that, even after a cooling down period of 10 years, the first one to two metres of earth surrounding the tunnel should be treated as radioactive waste. A possible solution to avoid this would be to increase the thickness of the concrete tunnel walls.

3 THE XADS ACCELERATOR REFERENCE LAYOUT

The aim of this section is to describe the features of the accelerator needed for an eXperimental Accelerator Driven System (XADS). The accelerator is basically a high-intensity proton machine, delivering beam on a spallation target to provide an external neutron flux source for a sub-critical core.

We will first shortly discuss the technical solutions that can meet the requirements of section 2, and show that the linear accelerator (linac) concept is an unavoidable choice, especially considering a future industrial extrapolation.

We will then detail the layout of the XADS reference linear accelerator, with its front end, its independently phased superconducting linac, its final beam transport line, and their associated diagnostics and feedbacks. The accelerator shielding for radiation protection will also be briefly described, such as the needed infrastructures. Finally, preliminary construction time schedule and cost estimates will be presented.

3.1 CHOICE OF THE BASIC ACCELERATOR CONCEPT

With the present state-of-the-art in accelerator technology, only two basic concepts of accelerators have shown to be able to deliver proton beams with intensities in the mA range. These namely are sector-focused cyclotrons and linear accelerators (linacs). Typical examples, running since a quarter century, are the 590 MeV separated-sector cyclotron of the Paul Scherrer Institute (PSI) at Villigen, Switzerland, and the 800 MeV linear accelerator of the Los Alamos Neutron Science Center (LANSCE) in New Mexico, USA (see Figure 3-1 & Figure 3-2 respectively).

The PSI cyclotron is a CW-type machine of which the maximum average intensity has been continuously improved: starting initially with 100 μA, steady improvements allow at present to extract up to 2 mA from the machine **[15]**.

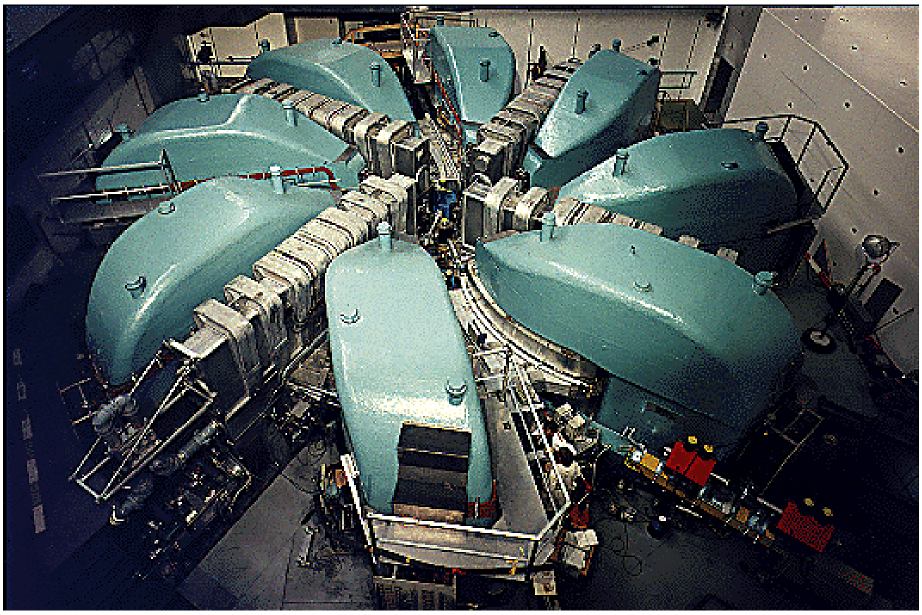


Figure 3-1 – The 590 MeV “Ring” separated-sector cyclotron of PSI.

The LANSCE’s linac **[16]**, designed for (100 Hz) pulsed-beam operation, delivers an average intensity of 1 mA. That means that the instantaneous intensity in the 625 μs lasting beam bunches amounts to 16.5 mA. The high-current capability of linear accelerators, due to the intrinsic strong focusing, is also demonstrated by the 50 MeV CERN injector LINAC-2, which reaches 170 mA during its 150 μs pulses **[17]**.

In principle, strong focusing is also present in a FFAG-synchrotron, and some R&D is presently underway in Japan. A 150 MeV proof-of-principle machine, pulsed at 120 Hz, is under construction at Kyoto University, and aims at an intensity of 1 μA **[18]**. However, this type of accelerator is not sufficiently advanced for assessing the very large extrapolation to the required machine parameters for an XADS, and also its transmission and cost.

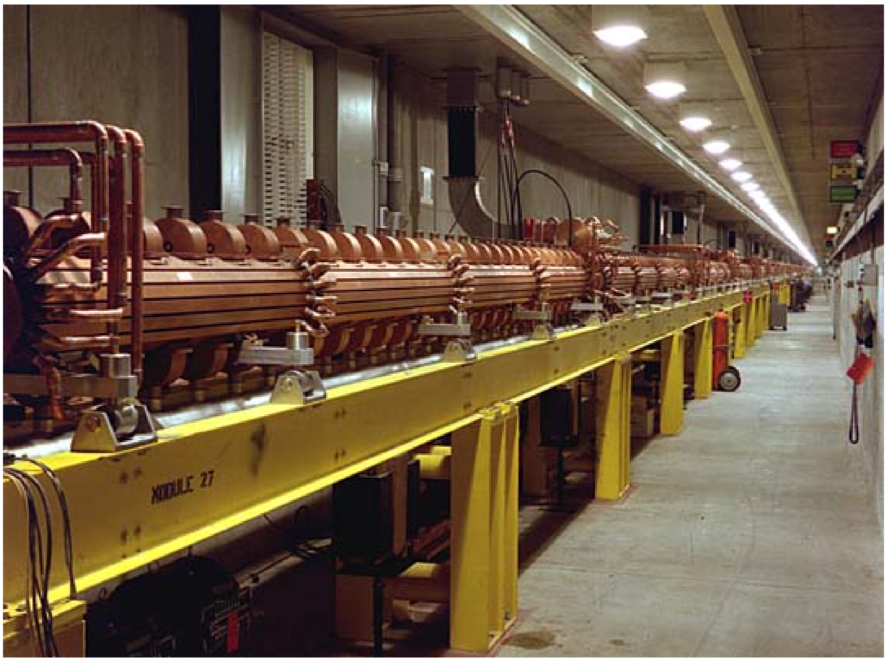


Figure 3-2 – The LANSCE Coupled Cavity Linac (CCL), high-energy section of the 800 MeV Los Alamos proton linac.

Concerning cyclotrons, a final energy of 600 MeV is well established, namely with the experience of the PSI machine, and from this, it is felt in the cyclotron community, that a value of 5 mA should be considered as safely reachable **[19]**. However, extrapolating up to 10 mA is more questionable, and might require a complex of at least two cyclotrons with the two beams being funnelled together. A (given) cyclotron also cannot be expanded in energy, so that boosting the energy from 600 to 800 MeV, as envisaged by WP1, would require the full replacement of the final and main stage, an absolutely not cost effective operation. For energies reaching the 1 GeV range (industrial transmuter), the intrinsic limits of the very principle of cyclotrons are reached because the proton is becoming too relativistic. In addition, a cyclotron is basically a CW machine and the requirement to provide pulses for neutronic measurements is a major difficulty for a cyclotron of such power. None of all these limitations are present in a linac where intensities can reach more than 100 mA without any intrinsic energy limit.

As discussed in section 2, the minimisation of the number of beam trips in order to match the XADS specifications is a very specific requirement for the accelerator. In fact, the potential disability of accelerators to reach the goal of a few beam-trips per year could reveal itself as being a "show-stopper" for ADS-technology. WP3 has concentrated major resources in order to elaborate the most promising way of tackling this issue (see in particular deliverables D57 and D47, and section 4 of the present document). It was clearly established that reliability can be implemented into an accelerator by adopting, in a very dedicated manner, the triple-concept of over-design, redundancy and fault tolerance.

This strategy requires a highly modular system where the individual components are operated substantially below their performance limit. In contrast to circular machines like cyclotrons (and FFAG), a superconducting linac, with its many repetitive accelerating sections grouped in "cryomodules", conceptually meets this reliability strategy. It further allows keeping the activation of the structures rather low, which is important for radioprotection and maintenance issues, whereas the extraction channel of high power circular accelerators is in this respect a considerable concern. Finally, a superconducting linac permits CW operation at the highest power levels, including aspects like economy of operation, and has also the capability of running in pulsed mode.

For all these reasons, WP3 concluded that the cyclotron solution for an XADS presents a number of difficulties if not impossibilities: funnelling, pulsing, beam trips, double-machine scheme, intrinsic current limitation, energy upgrading that precludes this solution despite its advantages such as lower unit price, proven technology at the MW level as demonstrated by PSI, and compactness. Therefore, the reference solution discussed in the following is a superconducting linac.

Finally, it should be noted this assessment is corroborated by the one of OECD/NEA **[13]**:

"*Cyclotrons of the PSI type should be considered as the natural and cost-effective choice for preliminary low power experiments, where availability and reliability requirements are less stringent. CW linear accelerators must be chosen for demonstrators and full-scale plants, because of their potentiality, once properly designed, in term of availability, reliability and power upgrading capability*".

3.2 THE XADS LINEAR ACCELERATOR LAYOUT

A high power proton linac is classically divided into three main sections.

- The first one is the injector ("low-energy section") that includes the source, usually delivering a continuous current, followed by an accelerating structure that bunches the beam at the operating frequency, like a RFQ (Radio-Frequency Quadrupole). The beam usually comes out from the injector at energies between 2 and 10 MeV.
- The second part, often called "intermediate section", brings up the beam to energies in the vicinity of 100 MeV.
- At 100 MeV, although the proton is not yet fully relativistic ($\beta = v/c = 0.428$), its speed is already high enough to use "low-beta" elliptical cavities. The final (and most efficient) section of the linac using these elliptical cavities is often called "high-energy section". It starts from 100 MeV up to any desired final energy.

The injector section is quite straightforward because of the relatively low proton beam current. The source is an Electron Cyclotron Resonance (ECR) ion source (but microwave or volume sources are also possible), based on the experience accumulated in many laboratories around the world **[20,21]**. ECR sources have demonstrated delivering reliable proton beams exceeding 100 mA, an order of magnitude higher than the requirements needed for the XADS. The source is followed by an RFQ that has two main functions: it prepares the particles in bunches separated by the RF period (the beam is now microscopically pulsed in burst of particles flowing at the rate of the RFQ frequency) and it accelerates the beam to an energy of a few MeV while maintaining a strong confinement. The RFQ should have low Kilpatrick values (≤ 1.7) due to the CW mode. It operates at a frequency of 352.2 MHz, which is a good compromise between lower sensibility to space charge effects and relaxed fabrication tolerances at lower frequencies, and higher shunt impedance and smaller dimensions at higher frequency. This frequency choice also relies on the existing RF technology at this rather common frequency, traditionally used e.g. at CERN **[22]**.

In a similar manner, there is a general agreement that the high-energy section should be made of superconducting elliptical cavities. These have been demonstrated to be extremely effective and a lot of experience and knowledge has been accumulated. Moreover, large size machines using Superconducting RF Cavities (SCRF) have been constructed or are currently under construction (like the Spallation Neutron Source **[23]** at Oak Ridge, USA), giving confidence in the achievable performance for a XADS type accelerator. Concerning the operating conditions of these elliptical cavities, a good compromise **[24]** is an operation at a temperature of 2 K and at a frequency of 704.4 MHz, twice the frequency of the RFQ. These superconducting cavities are subject of important R&D programmes presently underway, e.g. at the laboratories of the collaborating institutions of WP3. The performance of the prototypes has been measured to exceed the operational characteristics for the XADS by a very comfortable safety margin (see section 3.2.2) that ensures the "over-design" criteria imposed by the reliability strategy.

For the transitional region, between the injector and the high-energy section (from 5 MeV to 100 MeV), however, there is at present no decisive argument in the linac community for a single best RF structure to be used. Two basic concepts have been retained in the PDS-XADS context in order to elaborate a final solution in the future. They will be discussed in the following with the vista that an R&D program will allow to choose either one or, possibly, a combination of both.

The first concept consists in extending the low-energy accelerating philosophy towards high energies by using DTL (Drift Tube Linac) type structures. These structures are classically room temperature normal conducting devices, and are generally considered as the base solution in most of the existing (and under design) proton linacs developed in the last years. Superconducting versions of such devices have been also recently developed, like the superconducting CH-DTL structure that can be a very good candidate. The second concept is to extend the high-energy superconducting linac philosophy towards low energies by using independently-phased superconducting “low-beta” resonators like spoke cavities, and benefiting from all the advantages of SCRF cavities towards “warm” devices (large beam apertures, negligible RF losses, modularity).

Advantages and disadvantages of these different structure types can be compared, especially regarding the XADS specific requirements focused on reliability and tuning. First of all, it has to be underlined that a superconducting solution is very promising, especially because it leads in a strongly reduced AC power consumption, which makes big savings in the operating cost. This has been shown for example in the frame of the EURISOL study **[10]**. Moreover, the spoke cavities solution, with its independently phased modular structures, has the capability to guarantee stable and reliable operation, even in the case of a failure of one cavity (fault-tolerance concept, see section 4.1). This is a crucial advantage in order to achieve the XADS reliability requirement. Nevertheless, in the very low energy region ($\beta < 0.2$), the beam dynamics in such a spoke linac becomes quite inefficient, leading to very low real-estate accelerating gradients. In this low velocity region, DTL-like structures are far more efficient in terms of accelerating gradients. But on the other hand, they have the disadvantage of not exhibiting any fault-tolerance capability, which means that a fault in such a structure would lead to a complete beam shutdown.

Anyway, Figure 3-3 presents a possible reference layout for the XADS accelerator, as defined in Deliverable 57 **[3]**. This reference design is optimized for reliability, and all selected components have the capability to accelerate higher beam currents (~ 40 mA) without major changes. It uses a "classical" proton injector (ECR source + normal conducting RFQ), followed by additional warm IH-DTL or/and superconducting CH-DTL structures up to a transition energy still to be defined between 5 and 50 MeV. At this point, a fully modular superconducting linac accelerates the beam up to the final energy. At the high-energy end, a beam dump is needed for taking the beam during the commissioning phase of the accelerator or in case of emergency during normal operation of the reactor. A beam switchyard will direct towards the reactor or the beam dump.

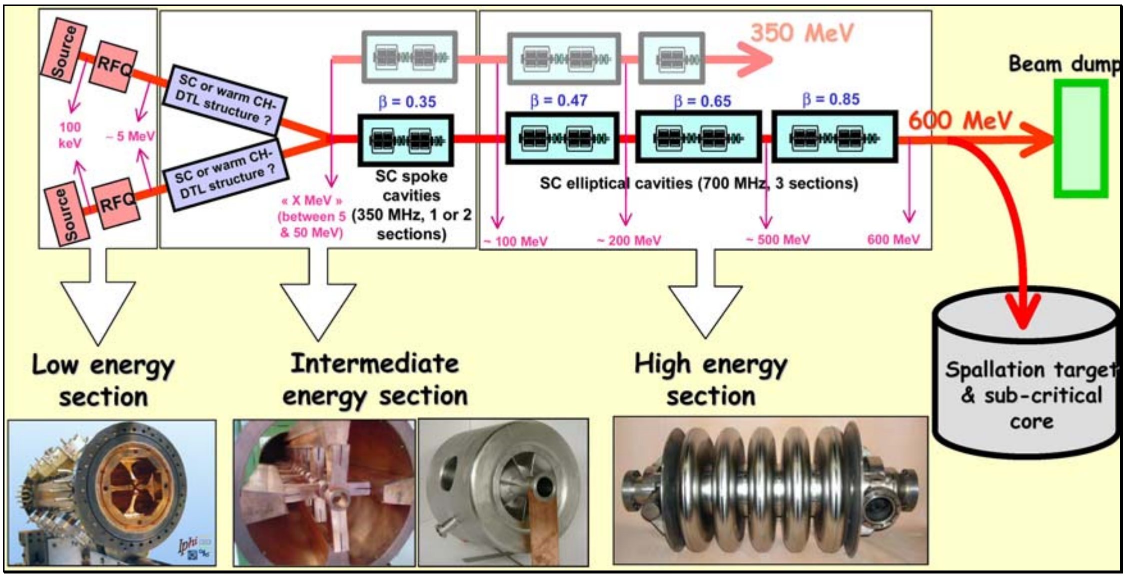


Figure 3-3– The XADS linear accelerator reference scheme; photos, from left to right: IPHI RFQ (CEA/CNRS), CH-DTL prototype (Univ. Frankfurt), β=0.35 spoke cavity (CNRS), β=0.47 elliptical cavity (INFN).

Up to the transition energy, fault-tolerance is guaranteed by means of a "hot stand-by" spare, keeping the possibility to switch the second injector on if the first one fails or have any long beam trip. Above this energy, "spoke" and, from 100 MeV on, "elliptical" cavities are used. An individual cavity failure in this part can be handled at all stages without loss of the beam. Besides this fault-tolerance, another remarkable feature of the concept is its validity for a very different output energy range: 350 MeV for the smaller-scale XADS require for example nine β=0.65 elliptical cavities cryomodules; in order to obtain 600 MeV, simply ten more cryomodules have to be added (7 with β=0.65 and 3 with β=0.85) and 12 additional (β=0.85) boost the energy to 1 GeV. Therefore, already the small-scale XADS accelerator is fully demonstrative not only of the 600 MeV XADS (and could be converted to it), but even for an industrial machine.

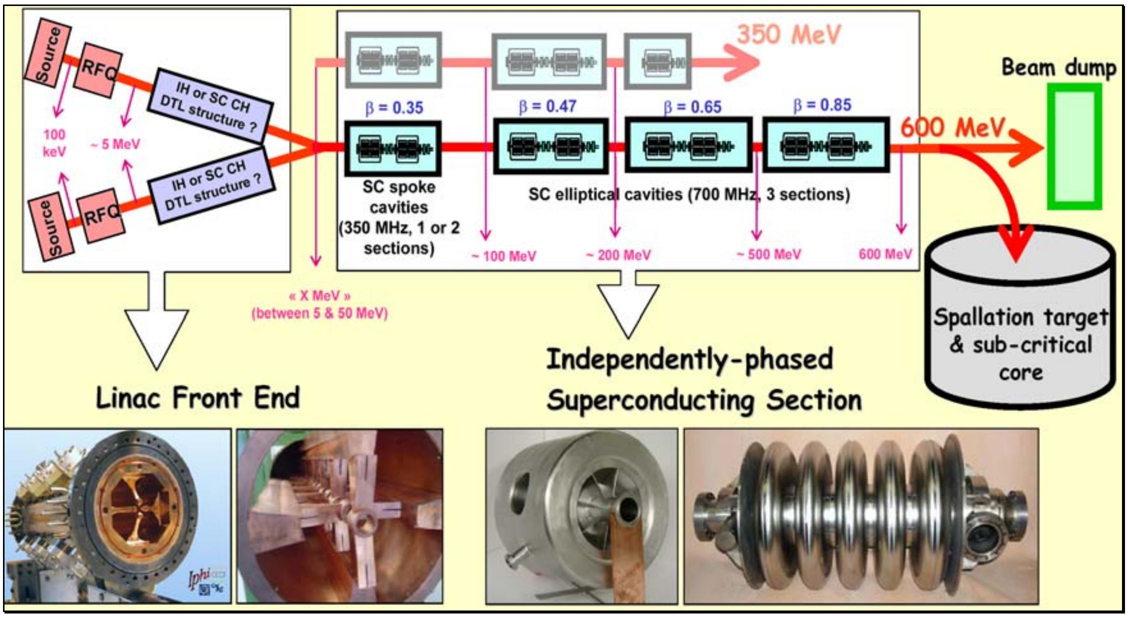


Figure 3-4– The XADS linear accelerator reference scheme (new & alternate version).

In the following, a detailed description of each accelerating structure used in this reference design will be made. We will first review the “linac front end”, up to the transition energy, and then review the “independently phased superconducting section”. An alternative scheme of the XADS accelerator reference layout, including these new denominations, is presented in Figure 3-4.

3.2.1 Linac front-end

3.2.1.1 The ECR ion source

An ECR source should be the best choice to fit in with the high reliability/availability request of the XADS. This type of source does not need any filament or antenna inside the plasma chamber. The proton beam produced by the source can be injected in an RFQ cavity to be accelerated up to few MeV. Also other types of ion sources would fulfil the ADS requirements (as microwave sources or volume sources), but may suffer from its lifetime.

***Source description* --**

The ion source operates at 2.45 or 3 GHz with an axial magnetic field providing two ECR resonance zones at both plasma chamber extremities simultaneously. The source and its ancillaries are installed on a 100 kV insulated platform to fit in with the RFQ entrance energy. The RF power is produced either by a 1.2 kW magnetron source or a klystron and fed to the source via standard rectangular waveguides. An automatic tuning system help to accommodate and adapt the RF load. The magnetic field is provided either by coils or permanent magnets. The small copper plasma chamber (0.5 litre) located at the centre of the magnetic structure has to be water-cooled.

A single aperture extraction system has been designed. An intermediate electrode located in the accelerating gap can be tuned to minimize the distortions in the phase-space distribution. An electrode at ~ -2 or -3 kV is inserted between two water-cooled grounded electrodes to avoid the acceleration of electrons produced by ionization of the residual gas in the beam line. The electrode construction takes into account possible beam losses leading to damage. Figure 3-5 shows a scheme of the French source SILHI **[25]** and accelerator column developed in the framework of the IPHI (High Intensity Proton Injector) project.

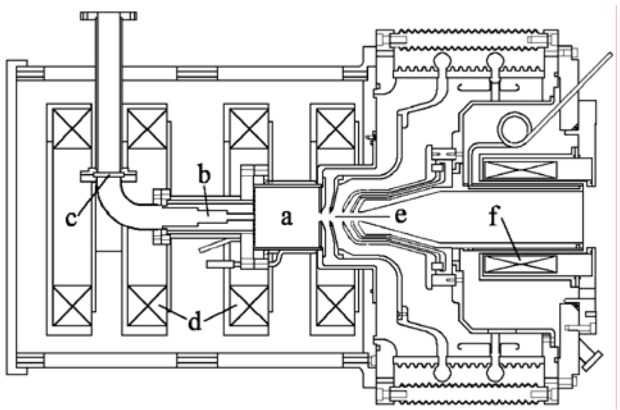


Figure 3-5 – Source and 95 kV extraction column: a) plasma chamber; b) RF ridged transition; c) quartz window; d) coils; e) 5-electrode extraction system; f) DCCT.

***Optimisation of performance* --**

To minimize possible breakdown and to optimize the reliability, different developments and technical choices can been adopted. The following non-exhaustive list presents several topics able to improve the reliability, as already successfully tested with SILHI at Saclay:

- quartz window protected behind a water cooled bend,
- electrode shape optimization to minimize the electric field and the spark rate,
- large safety margins on every power supply (high voltage and others),
- optimization of power supply air or water cooling,
- separate cable path and shielding for signals and power,
- galvanic insulation of analogue and digital signals,
- use of EMI hardened devices especially for all sensitive electronics and PLC,
- development of beam current feedback,
- development of automatic start/restart procedures,
- development of specific beam diagnostics.

Beam availability as high as 99.8 % (see Figure 3-6) has already been achieved with SILHI, for a 90 mA proton beam (total extracted beam = 114 mA) during a 162 hours long run. The source was operating in a continuous mode, a feedback loop maintaining a beam stability of ± 0.2 mA. This loop would authorize a very precise adjustment of the extracted beam in case of the XADS commissioning for example. Figure 3-7 shows the SILHI extracted beam current as a function of the RF power. This source has been designed to inject a 100 mA proton beam in the IPHI RFQ. Developments are still in progress to minimize the number of beam trips and to reduce their duration. Specific run tests for XADS (with lower current) will be performed to quantify the overdesign method efficiency in term of reliability. Finally note that a similar ECR source (TRIPS, 30 mA CW beam current, 80 kV) has been developed for the Italian TRASCO project, and is now operational at INFN-LNS in Catania **[26]**.

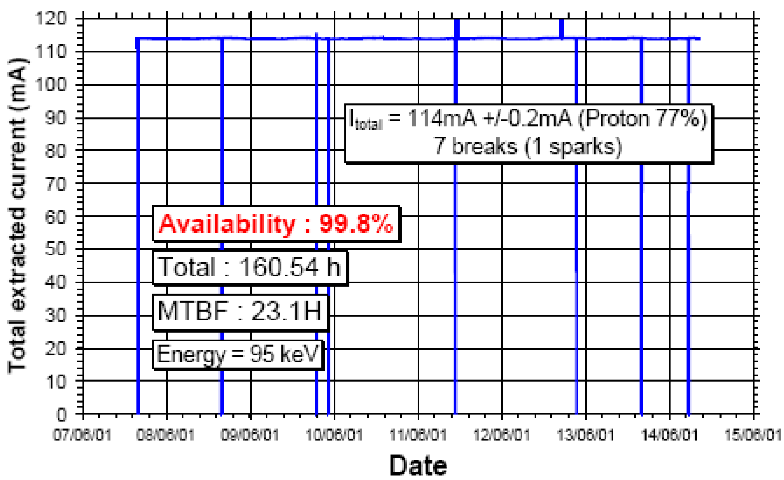


Figure 3-6 – A 162-hour long run reliability test performed with the SILHI source at CEA Saclay.

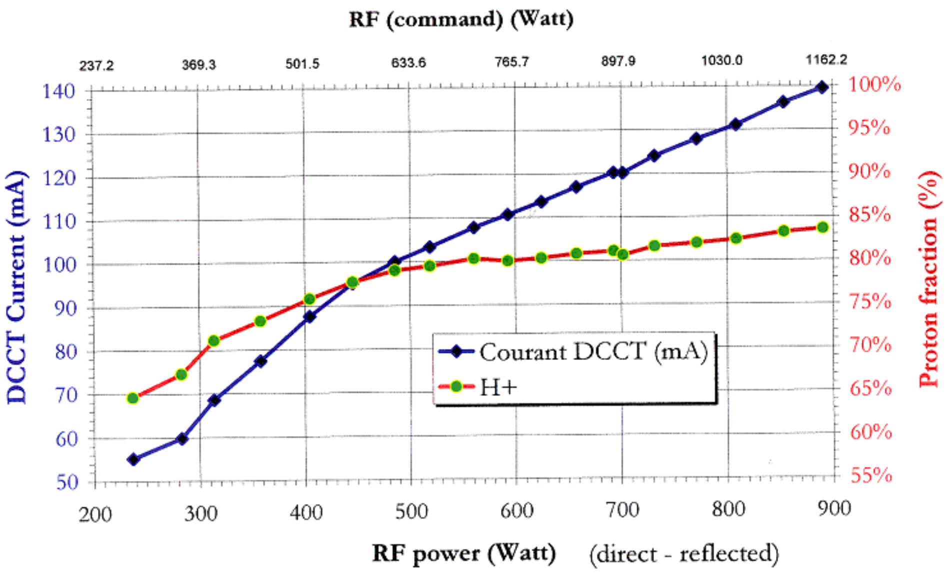


Figure 3-7 – Extracted beam current and proton fraction vs. RF power (SILHI source).

3.2.1.2 The Low Energy Beam Transport

The low energy beam transport (LEBT) line is designed to guide the beam into the RFQ acceptance, taking into account the variable space charge compensation (SCC). It consists of 2 solenoids that match the proton beam into the acceptance of the following RFQ, whereas the unwanted ions from the source (H_2^+, H_3^+,etc.) will be separated from the main beam. The SCC depends on the amount of free electrons due to beam losses on the walls or beam interaction with the residual gas. A small amount of heavy gas (Ar or Kr) in the LEBT allows better space charge compensation. Interceptive diagnostics also lead to secondary electron production and locally modify the beam compensation.

Figure 3-8 – The SILHI LEBT installed at CEA Saclay.

To allow an accurate beam matching to the RFQ, a precise knowledge of the beam characteristics is required at the cavity entrance. Presently the beam position and size could be obtained from CCD cameras. Faraday cup, beam stopper and toroids (DC and AC current toroids) allow the measurement of the beam current and of its high-frequency fluctuations. Insulated screens give information on beam losses and beam axis. Emittance at the RFQ entrance has also to be well known to minimize RFQ transmission limitation. Figure 3-8 shows as an example the magnetic SILHI LEBT, installed in CEA Saclay. A similar LEBT is in operation at the Institut für Angewandte Physik (IAP) in Frankfurt.

3.2.1.3 The RFQ section

The ECR source, chosen for its well-known advantages, should deliver up to 10 mA at 95 keV to the RFQ (Radio-Frequency Quadrupole). As mentioned earlier, the existing test stand SILHI has already produced a 130 mA, 95 keV proton beam with an emittance better than 0.15 π.mm.mrad (r-r’, rms normalized), and with a very promising reliability. The following accelerating stage of the injector shall be a four-vane type RFQ **[27]**. Although this RFQ assembly could look somewhat delicate, recent progresses were made in the field of long duty cycle (up to CW) 350 MHz four-vane RFQs. At Los Alamos National Laboratory, the construction of the 110 mA, 6.7 MeV, CW RFQ for the Low Energy Demonstration Accelerator (LEDA) has been commissioned at the design performance **[28,29,30]**. The IPHI RFQ with a final energy of 3 MeV is under construction in France at CEA Saclay **[31,32]**. It already integrates some improvements, thanks to a close collaboration with the LEDA team. In Italy at INFN-Legnaro, a third RFQ of this kind is under development for the TRASCO project **[33]**. In this context, given the experience of the teams, a large number of the technical difficulties such as the cooling system or manufacturing tolerances are more easily addressed.

RFQ design ---

The input energy of 95 keV is the results of a compromise between RFQ length, source reliability and space-charge control. The 5 MeV output energy results of a compromise between cavity length, feasibility of the next accelerating structure (DTL using EM or PM quadrupoles, superconducting CH-DTL or spoke-type cavities), and high beam transmission. The design current of 100 mA is selected to reach a high reliability at the lower currents needed by the application. The expected normalized rms emittance from the source is 0.2 π.mm.mrad. Nevertheless, a safety margin is taken using 0.25 π.mm.mrad in beam dynamics calculations. The maximum field inside the RFQ, commonly measured in Kilpatrick units, is a parameter that strongly influences the length of the structure, its transmission and its robustness with regards to RF breakdowns. The maximum electric field has been limited to 1.7 Kp (31.34 MV/m) taking into account experience with the CRITS Experiment at Los Alamos, the LEDA test stand in Los Alamos and RFQs operated at Saclay in the past.

At this stage, a longer RFQ designed with the view to guaranty the longitudinal field stability is preferred despite of the small price increase of the overall project. With this choice of 1 or 2 additional meters of RFQ structure, the overall performance (lifetime and availability) will be improved. Great care has to be taken on lost particles in the RFQ cavity. The final design has to be selected to avoid localized and high-energy losses (activation problems), and to provide the highest transmission avoiding any bottleneck **[27]**. Good availability might therefore be achieved on the short term (spark down avoided by excellent transmission and low surface field) and long-term range (sputtering in the cavity, activation). Many beam dynamics computations including error studies will have to be done as for the French IPHI project, using several complementary existing codes like PARMTEQM, TOUTATIS **[34,35]**, or LIDOS.RFQ **[36]**.

The RFQ structure and associated ancillary systems ---

To overcome the difficult problem of cooling the normal conducting RFQ, the cavity type will be a 4-vane RFQ, which is much easier to cool than a 4-rod RFQ. The structure is made up of 8 one-meter long sections accurately machined, brazed, and then assembled with resonant coupling every 2 meters, like for the LEDA and the IPHI designs (see Figure 3-9 an Figure 3-10). The coupling plates allow a damping of the RF longitudinal parasitic modes and the introduction of fingers to push away the dipolar modes.

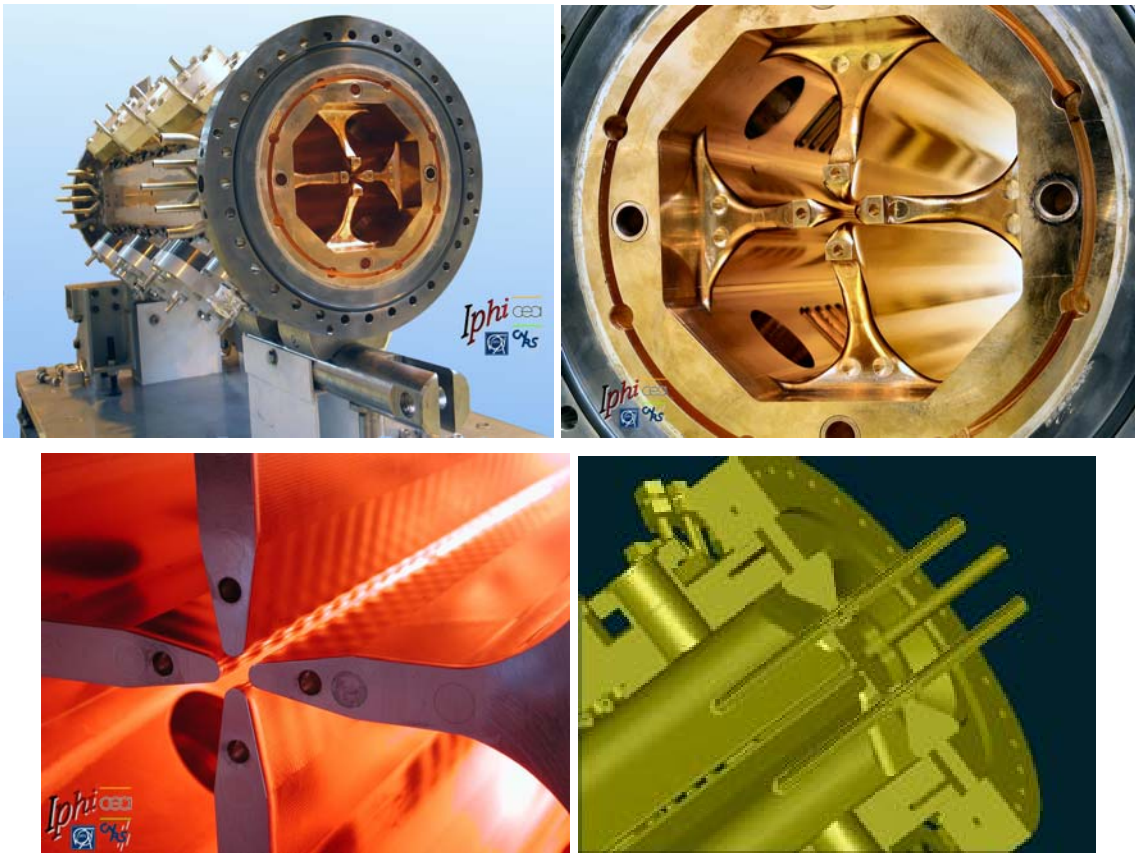


Figure 3-9 – (Up-Left) First meter of the IPHI RFQ after brazing at CERN. (Up-Right) Radial section of the IPHI RFQ. (Down-Left) View of the RFQ vanes machining. (Down-Right) Drawing of the coupling plate.

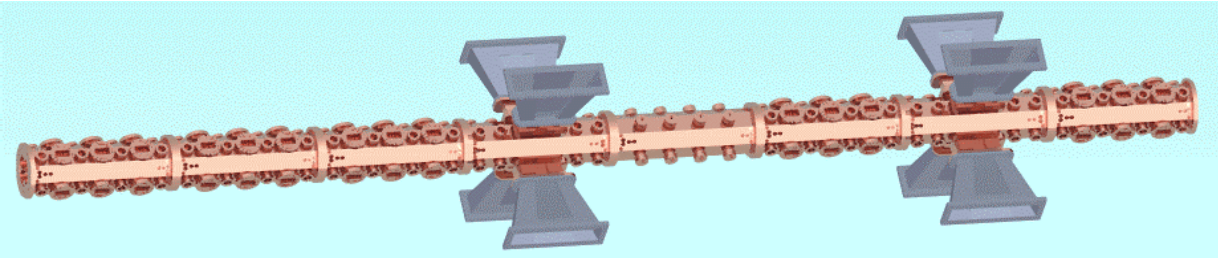


Figure 3-10 – Sketch of a 5 MeV, 8 metres RFQ for the XADS linac (originally designed for the IPHI project).

The RF design of the cavity requires intensive 3D simulations and developments **[37]** with crosschecking on cold model. The field will be tuned using 128 tuners equally distributed along the RFQ. Since the electrode voltage all along the RFQ has to be tuned with a high accuracy, it has been decided, in the case of the IPHI RFQ, to use automatic tuning procedures **[38]** based on the bead pulling principle associated with a powerful mathematical formalism **[39,40]**. A six-meter long cold model was built to develop and validate these procedures **[41]**, which were already successfully tested on two sections equipped with a coupling plate **[42]**. A procedure was also developed in order to check possible vane displacements during the brazing process **[43]**, and allows the detection of a 20 µm vane displacement.

The RFQ will be fed by 1.3 MW of RF power (see Table 3-1) that might be provided by two 352.2 MHz, 1.3 MW klystrons (LEP type) through highly reliable windows and RF couplers (> 250 kW). Similar RF windows to those needed have been already successfully tested up to 700 kW at LANL for LEDA.

Table 3-1 – RF power needed for the 5 MeV XADS RFQ.

	10 mA operation (XADS)	***100 mA operation (IPHI)***
Dissipated power on copper	1200 kW	*1200 kW*
Beam loading power	50 kW	*500 kW*
Total RFQ power	1250 kW	*1700 kW*

The cooling system of the RFQ must fulfil two essential functions: first to evacuate the 1.2 MW of dissipated power in the copper (independently of the current beam value) and then to maintain, by adjustment of the temperature, the resonance frequency of the cavity at the right value. The slow frequency tuning will be done using the cooling system of the cavity based on the LEDA design. The inlet water temperature is 10°C with a tuneable water flow up to 6 m/s. An erosion/corrosion analysis is presently done to check the long-term effect.

Great care has also to be taken in the optimization of the pumping system. In the IPHI design, two of the 1-m long sections are dedicated to the RF feed while all the remaining sections are equipped with a total of 72 pumping ports carefully designed to maximize the pumping speed (see Figure 3-11). Eight cryogenic pumps will provide through those 72 ports a vacuum lower than 2.10^{-5} Pa in the RFQ **[44]**. The port and manifold conductance have been optimized to obtain a pumping speed of 5700 l/s at the cavity level for 12000 l/s at the pump level.

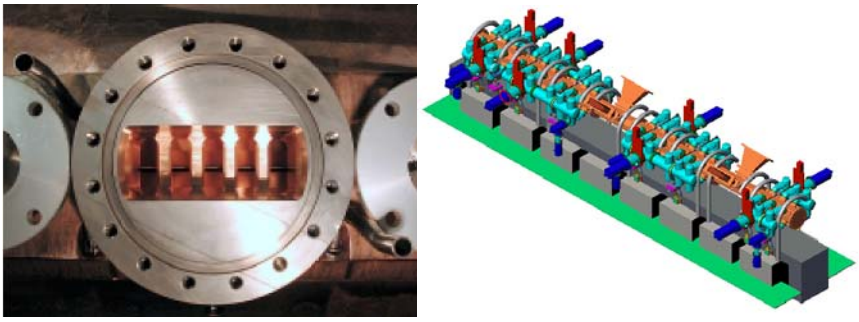


Figure 3-11 – (Left) IPHI RFQ pumping port. (Right) Sketch of the vacuum system surrounding the RFQ.

Finally, a Medium Energy Beam Transport (MEBT) is necessary to transport the proton beam from the RFQ exit to the entrance of the following accelerating structure (here a DTL-like structure or a spoke linac). At this energy (5 MeV), such a MEBT is usually composed of at least 4 quadrupoles for the transverse focusing, of 2 bunching cavities for longitudinal focusing, and of adequate diagnostics. A second MEBT will also have to be used at the transition between the DTL section and the spoke linac if the DTL option is chosen. Finally note that in the MEBT located before the spoke section, a fast switching bending magnet will have to be included in order to ensure the possibility, in the case of a failure in the front end linac, to quickly switch on the beam coming from the "spare" front end linac.

3.2.1.4 The DTL-like section – normal conducting option

The section following the RFQ may be constructed using normal conducting copper structures. As a matter of fact, every high-intensity proton accelerator design known today uses copper RF structures in this energy range. These structures are usually based on Drift-Tube Linac (DTL) with sometimes some variation or improvement, trying to optimize either RF fields, efficiency or reliability. As an example, the SCDTL (Side Coupled Drift-Tube Linac), IH-DTL (Interdigital H-structure) or CCDTL (Coupled-Cavity Drift-Tube Linac) and the well known Alvarez accelerator fall in that category. Some detailed typical layouts maybe found in many accelerator designs (ESS, SNS, APT, TRISPAL, etc.). In the intermediate section of the Spallation Neutron Source (SNS) under construction at Oak Ridge (Tn, USA), an Alvarez-DTL is foreseen just after the RFQ output at 2.5 MeV up to an energy of 20 MeV. Then, a short section with several tanks based on CCDTL structures will bring the beam up to 86.8 MeV. Finally, CCL (Coupled Cavity Linac) structures will follow up to 185 MeV prior injection in the superconducting high-energy cavities. In the APT project, only two types of structures (CCDTL and CCL) were planned to be used from 6.7 MeV (RFQ output) up to an energy of 217 MeV.

Classical DTL-like structures ---

A DTL structure is convenient because it allows the use of focusing quadrupoles (using EM – Electro-Magnets, or PM – Permanent Magnets) embedded inside, which is a good way for providing compact and strong focusing for low energy protons. In the energy range in question for the XADS DTL-like section (5 to 50 MeV), this structure also shows a high shunt impedance, thus minimizing the RF power dissipated in the copper structures. The CCDTL is also a well-known solution in this energy range. It is a hybrid RF structure composed with short DTL sections contained in a cavity, alternated with quadrupole magnets. Then, two adjacent cavities are linked together by side-coupling cells. That structure has been designed in order to combine the advantages of both the DTL and the CCL, which advantage is its capability to be used as short individual accelerating cavities (just like SCRF cavities), but which is classically used at higher energies (> 50 MeV).

But on the overall, the main disadvantage of the warm option is the need for a rather high RF power only to maintain the electromagnetic fields inside the structures. The RF to beam efficiency is therefore quite poor, especially for low intensity CW beams. On the other hand, there is a lot of experience for pulsed DTL (but not for the CW case) on these structures since they have been (and will most probably continue to be) used for a long time. The associated risk in the choice of this option is low. Also, some development is required to demonstrate its performance adapted to the XADS case and to solve the severe cooling problems for a CW application like XADS.

Design of an IH-DTL structure for the XADS linac --

H-type cavities were successfully developed during the last 30 years to serve for a large variety of applications in the field of ion acceleration **[45,46,47,48]**. RFQ and DTL versions were designed in the H11-mode (IH-DTL, like at GSI, CERN, TRIUMPF…) as well as in the H21-mode (4-Vane RFQ, standard structure at RF frequencies above 200 MHz). The Inter-digital H-type (IH) drift tube structure (H11(0)-mode) is efficient for an energy range from 100 keV/u up to 30 MeV/u, especially when combined with the KONUS beam dynamics **[47]**. Effective voltage gains as high as 10.7 MV/m were demonstrated in pulsed room-temperature operation.

In view of its well-proven low energy efficiency, it is appealing to consider an H-type structure that is able to accept a significantly lower initial energy than the presently foreseen 5 MeV RFQ output energy. Indeed, the acceleration efficiency of the RFQ is poor in comparison with that of a dedicated H-type accelerating structure. On the other hand, this low energy domain is presently not accessible to superconducting structures. So, IBA launched the study of a normal conducting structure satisfying all the standard XADS conditions and requirements, but adding that of the lowest possible initial energy. Such a development shall simultaneously serve IBA’s proper industrial development program. In that context the design beam current will be 20 mA.

In the framework of a preliminary feasibility study, the following conditions are envisaged (see Table 3-2). The choice of maximum electric field is the same as in the RFQ. It should allow for an average axial field around 4.5 MV/m in the accelerating section.

Table 3-2 – Characteristics of the IH-type accelerating structure studied for ADS application

Operation temperature	Room Temperature
Initial energy	< 2 MeV
H-type	Interdigital, H11 mode
Transverse focusing scheme	DFD – FDF (“Konus”)
RMS normalized emittance	0.25 π·mm·mrad
Frequency	176 MHz
Max. electric field	1.7 Kp (23.8 MV/m at 176 MHz)

The most striking parameter in this list is certainly the choice of the frequency at 176 MHz, i.e. half the normal XADS frequency. This choice is based on several arguments.

1. As a rule of thumb we adopt the following conventions: (i) the minimum length of a quadrupole is taken equal to its bore diameter; (ii) the minimum length of a drift tube is taken as 2 times the diameter of its opening. Furthermore, for the length of a drift tube we use 70% of the cell length. Using the “Konus” scheme triplet optics and a conventional normalized r.m.s. emittance of 0.25 π·mm·mrad, we obtain the following diameter requirements: Ø quadrupole = 23.2 mm, Ø drift tube = 17.5 mm. This focusing scheme assumes a triplet length of 4 cells and a 12-cell acceleration section. After compiling the corresponding data sheet it is shown that the quadrupole limitation is satisfied above 1.3 MeV, but that the drift tube limitation can only be satisfied above 1.6 MeV. Hence at this stage the input energy of the structure is fixed to 1.6 MeV, $\beta = 0.0583$. Note that applying the same criteria to a 352 MHz structure brings the lowest initial energy in the 4 – 5 MeV range.

2. For a normal conducting structure, and especially for CW operation, appropriate cooling is a severe challenge. In this context the choice of a lower frequency is an asset. The scaling law with frequency (at a constant gradient!) says that the power density scales as $\sqrt{f}$.

3. At 176 MHz one may use tetrode tube RF power amplifiers. In this frequency range these are nowadays available up to a CW power level of 1 MW (TH628 Diacrode® from Thales). Especially for a development in IBA’s industrial context this aspect is seen as a considerable advantage with respect to the use of klystrons and/or IOT’s, because it builds on a long-lasting experience in the application field of the tetrode tube amplifiers on several types of particle accelerators. Both cost and reliability will significantly profit from this.

It is an undeniable drawback of the 176 MHz solution that a new, dedicated RFQ has to be developed. On the other hand, also this RFQ will benefit from the frequency scaling and from the tetrode RF amplifier, and of course its limited output energy will greatly shorten the structure.

The study of the first 16-cell long IH structure has been initiated. It consists of 2 cell lengths for the first half-triplet, 12 cell lengths of accelerating structure with drift tubes of increasing length, and again 2 cell lengths for the second half-triplet. As an initial guess the electric field between drift tubes is taken as 15 MV/m. This section has a total length of 1.13 m and it would accelerate from 1.6 MeV to around 5 MeV. The diameter of the cavity varies between 328 (low energy end) and 406 mm (high energy end). Figure 3-12 shows this initial geometry.

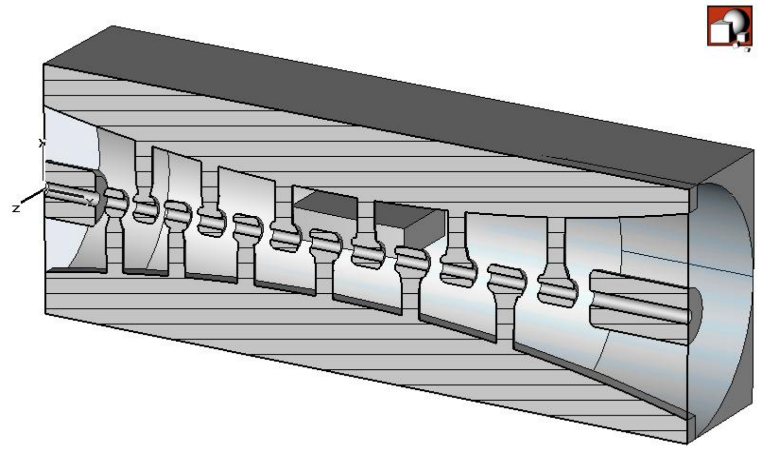


Figure 3-12 – Geometry of a IH-DTL structure for XADS.

This geometry has been introduced into an eigenmode analysis using CST's Microwave Studio®. The resulting electric field distribution in the stem plane is shown in Figure 3-13. The same analysis also obtains approximate figures for the power budget. For an acceleration voltage of 3.4 MV the structure needs around 95 kW rms RF power. The calculated Q-factor is around 12500, and the shunt impedance $Z \approx 54$ MΩ/m. For 20 mA of beam the structure should typically be fed by a 200 kW tetrode tube (e.g. TH781 from Thales).

The distribution of the surface currents clearly shows that the highest power densities will be found on the stems and on the drift tubes. With a surface resistance of 3.4 mΩ for copper, small regions with 150 W/cm² tend to occur. Typical power densities on the stems are around 40 W/cm². However, the IH structure allows for quite massive stems (Ø 30 mm in this model) and in the "Konus" focusing scheme the drift tubes have no secondary constraints (like e.g. the housing of quadrupoles). These characteristics will significantly help to successfully solve the cooling problem (and, by the way, also the alignment problem).

In summary it is felt that this room temperature IH accelerating structure at 176 MHz with low injection energy is a realistic option for the intermediate energy section of XADS, and that its detailed design and analysis should be pursued. The construction of a 1 m long cavity as described here will yield adequate experimental evidence of its feasibility and of the possibilities of extrapolation.

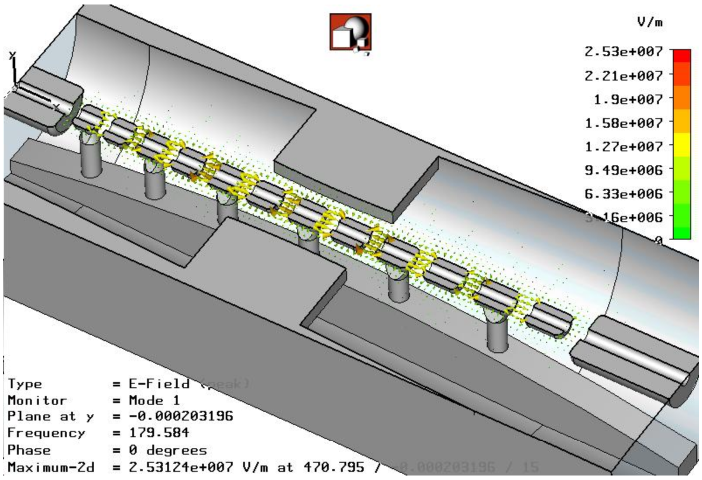


Figure 3-13 – Vector plot of the electrical field distribution in the lowest eigenmode of the IH structure.

3.2.1.5 The DTL-like section – superconducting option

Another H-type cavity is the Cross Bar H-type (CH) drift tube structure (H21(0)-mode), which shows a large potential at beam energies between 5 MeV/u and 150 MeV/u. Whereas the IH structure is not very well suited to realize superconducting versions because of its mechanical properties, the CH structure can be envisaged as well for room temperature as for superconducting designs [**49**]. This is because the CH-structure has an enormous advantage: its mechanical robustness, which is provided by the crossed stems. Moreover, as all H-type structures, the CH-structure has rather small transverse dimensions when compared to competing SC structures like 2-gap quarter wave, spoke-type or elliptical cavities at the same RF frequency **[50]**. Finally, while the acceleration mode is identical to the one used to operate the 4-vane RFQ, the dipole modes are shorted by the drift tube stems. Consequently mode separation is guaranteed in case of the CH-DTL, while in case of the 4-vane-RFQ special concepts had to be developed to push the dipole modes apart.

This new CH structure is therefore a promising candidate for the 5 to 50 MeV XADS linac section. Investigations and extended particle dynamics studies for a Superconducting Cross-bar (SCCH) cavity have already shown the general capability of this resonator type for the acceleration and focusing of intense beams **[51]**. A superconducting CH layout for the medium energy XADS linac part is presented together with the corresponding beam dynamics calculations performed with the KONUS dynamics program LORASR **[52]**. A preliminary resonator layout made with MICROWAVE STUDIO **[53]** for the second tank of the proposed SCCH DTL linac has been done and the results are outlined. A β=0.1 19-cell prototype cavity has been designed and is being fabricated and chemically treated; it is planned to be delivered from industry to IAP Frankfurt in July 2004. The CH-cavity development can profit a lot from the experience gained on IH structures but needs some additional design effort.

Design of a SCCH-DTL section for XADS ---

The preferred CW operation favours a superconducting approach with shorter length, high efficiency and larger aperture, which gives a higher safety margin against possible particle losses and resulting structure activation. But the most important point is that the cavity RF power losses are reduced by about 5 orders of magnitude compared to a normal conducting device. The multi-gap SCCH structure combines this crucial advantage with high acceleration efficiency, small geometrical dimensions and high mechanical robustness.

In a first attempt, a beam dynamics design has been studied: a chain of superconducting 350 MHz CH-sections up to an energy over 55 MeV was designed, then a frequency change to 700 MHz was made to increase the acceleration efficiency at higher energy (up to 100 MeV) and to prepare the beam for a possible transition into the 700 MHz high-energy SC linac. Table 3-3 shows the structure parameters of such a 5 – 100 MeV SCCH-DTL linac generated with the multi particle program LORASR. In the next design phase, this layout will be easily changed to a design closer to the XADS actual reference design, i.e. with a lower current, a lower energy end (up to 50 MeV) and without a frequency doubling.

Table 3-3 – Structure parameters of the SCCH-DTL design study for an ADS application.

First design parameter	**SC CH-DTL**	Units
Mass to Charge Ratio (A/q)	1	
Design current I	40.0	mA
Frequency f_{RF}	350 / 700	MHz
Focusing structure	FDF - DFD	
Number of tanks	6 + 4	
Average tank length L_T	1.64	m
Average total RF power per tank $P_{tot/T}$	380.0	kW
Injection energy W_{in}	5.0	MeV
Extraction energy W_{out}	100.0	MeV
Total energy gain $(W_{out} - W_{in})$	95.0	MeV
Effective energy gain per meter W_{tot}/L	4.15	MeV/m
Number of cells N_c	202	
Total linac length L_{tot}	22.85	m
Effective electric field amplitude E_oT	4.10 – 4.92	MV/m
Bore radius r_o	1.5 / 2.0	cm
Max quad gradient G_{max}	6.15	kG/cm
Max quad field B_{max}	1.23	T
Max Kilpatrick factor b	0.80	
Input / Output rms ε^n_{trans}	0.3 / 0.385	mm.mrad
Input / Output rms ε^n_{long}	0.53 / 0.97	keV/u.ns

The next figures show the results of a multi particle simulation calculated with the program LORASR and applying the KONUS beam dynamics concept. Space charge forces are calculated by the particle in-cell technique PIC. Each calculation was performed with 10 000 macro-particles. As a starting distribution, we used a six-dimension ellipsoid with a constant charge density in 3D space. Figure 3-14 shows the 100% beam size of the linac in the horizontal, vertical and longitudinal plane along the linac. No particle hits the structure, and due to a large aperture factor, the safety margins in the high beta region of the accelerator are sufficiently large.

The phase space distributions at 100 MeV are plotted in Figure 3-15. One can notice that it is well suited for an injection into the high-energy part of the linac since $\Delta E/E < 3.10^{-3}$ and $\Delta\phi < \pm 8°$. Finally, Figure 3-16 displays the relative transverse and longitudinal rms normalized emittance growth along the linac. In addition, some errors studies, including beam mismatching, quadrupole errors or RF errors, were performed with the multi-particle program LORASR, and they all showed the capability of the SCCH-DTL to handle the beam without particle loss **[54]**. But simulations with a complete failure of one SCCH-cavity, either in the low energy area or in the higher one, showed that the linac is then not retunable anymore, confirming that this type of cavity can not exhibit any fault tolerance capability.

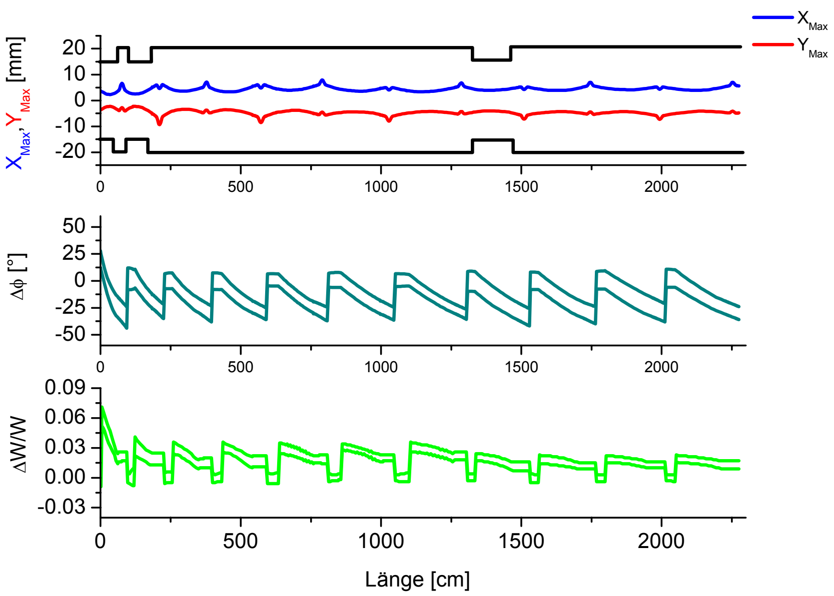


Figure 3-14 – Full transverse phase space beam envelope of the SCCH linac of Table 3-3 (Black lines: aperture of the drift tubes).

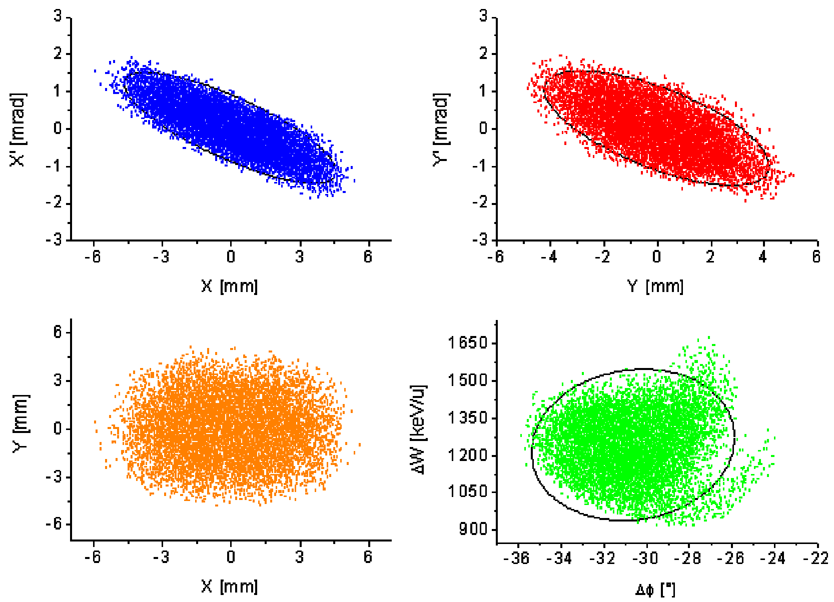


Figure 3-15 – Output beam distribution of the SCCH-DTL linac in the phase space at 100 MeV, with 95 % emittance ellipse drawn for a beam current of 40 mA.

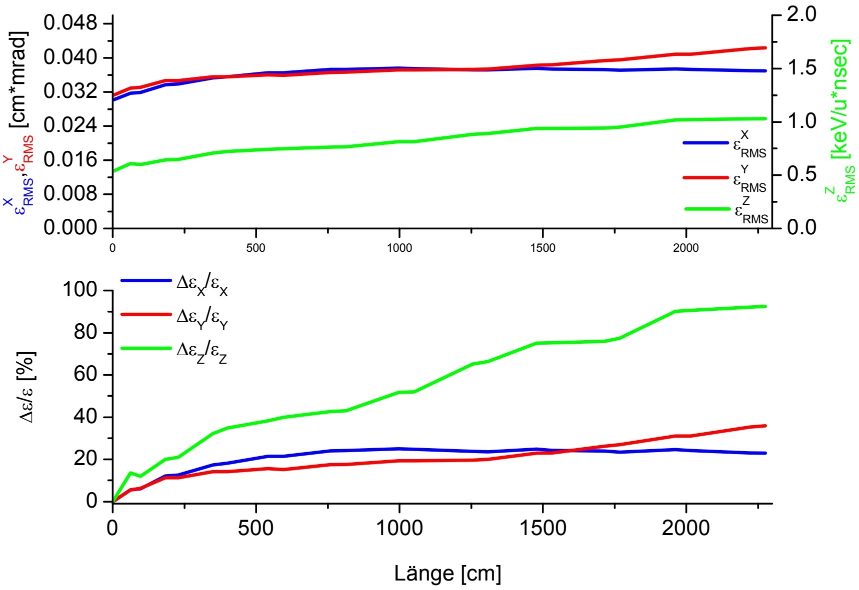


Figure 3-16 – Absolute and relative RMS normalized emittance growth along the SCCH-DTL linac.

SCCH-DTL "state-of-the-art" ---

A design of a chain of SCCH resonators with inter-tank focusing has been found which fulfils the requirements for a high intensity, low-loss medium energy DTL for XADS. The multi-cell superconducting CH resonators provide in this range very high RF and acceleration efficiency and, due to its special cell geometry, high mechanical robustness. The drift tube linac has a total length of only L_{tot} = 23 m for a total energy gain of 95 MeV. The shortness of the structure is a big advantage in comparison to 2-cell resonators, and may reduce drastically building and equipment costs; on the other hand, such a solution will not exhibit any fault tolerance capability. The multi-particle simulation results showed a smooth beam behaviour with moderate emittance growth and no particle loss. In addition, a comfortable aperture factor between beam and inner tank structure wall guarantees maintenance, reliability and availability of the facility. Therefore the results of particle dynamics calculations demonstrate the capability of the CH structure to handle high-current and high-intensity beams without particle losses.

At present, the Institute für Angewandte Physik (IAP, J. W. Goethe-Universität Frankfurt) is equipping a cryogenic laboratory especially for the development of SCCH cavities. A design study of a 19-cell, 350 MHz prototype cavity with β = 0.1 has been completed (see Figure 3-17). This cavity, which corresponds to the second XADS SCCH module, was simulated with Microwave Studio to check the peak surface fields and the RF characteristics. The results are quite good, since the maximum magnetic surface field (44.6 mT) and the maximum peak electric surface field (25.1 MV/m) are far below the theoretical niobium limits.

A technical design study was successfully done in collaboration with industry, which points out technological solutions for all components **[55]**. A 350 MHz RF "cold model" for extended higher order mode and field flatness measurements is already available at IAP, and the fabrication of the 19-cell, β=0.1 CH-cavity prototype is underway at ACCEL in Bergisch Gladbach. Besides the demonstration of attractive accelerating field levels, adequate RF couplers have to be developed for this structure; the RF tuning will be accomplished by a mechanical tuning of the cavity end walls, which means a variation of the end cell capacities. In a next step, new prototypes will be developed to investigate a SC larger aperture cavity at 350 MHz and, later on, at 700 MHz if SCCH cavities are needed at higher energies.

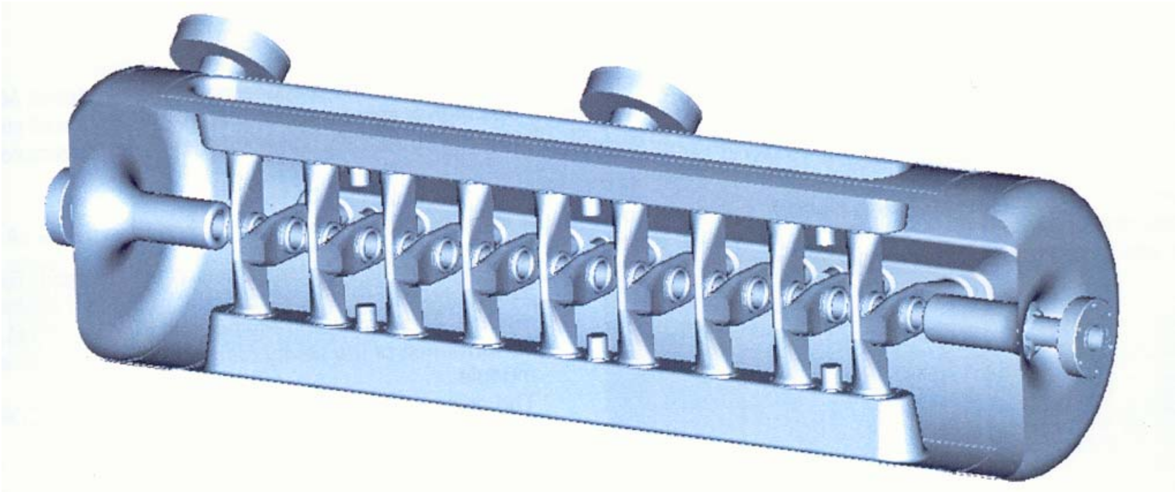


Figure 3-17 – Sectional view of a superconducting CH cavity prototype for XADS.

3.2.2 Independently-phased superconducting section

Above the "X MeV" transition energy (X to be defined between 5 & 50 MeV) up to the final energy, independently phased superconducting structures are used. Two-gap spoke cavities first bring the beam up to around 100 MeV, and multi-cell elliptical cavities are then used up to the high-energy end.

Such a solution first allows to benefit from the inherent advantages of superconductivity: optimal efficiency, with almost 100% of the RF power transmitted to the beam; reduced overall length, thanks to the negligible losses in the accelerating structures that can allow to use high gradients to accelerate such a CW high intensity beam; reduced activation of the accelerating structures from beam halo thanks to the large apertures of the cavities; high flexibility provided by the ease of changing beam energy and current. Moreover, as already mentioned, this solution should maximise the accelerator reliability, especially because it allows to implement the "fault-tolerance" strategy (see section 4.1.2): by using highly "de-rated" and independently powered accelerating components, an individual cavity failure in this section should be handled at all stages without loss of the beam.

3.2.2.1 Spoke cavities section

Superconducting cavities have been recently considered as a very promising technical solution for a use as accelerating devices in the intermediate section of high-intensity proton linear accelerators **[56,57,58,59]**. As a matter of fact, comparative studies show that the use of superconducting cavities in the energy range 5–100 MeV should provide many advantages compared with classical room-temperature structures: while the investment cost and the overall length for both solutions seem to be of the same order, the AC power consumption is much lower using SC cavities, that makes a huge difference in the operating cost; the savings have been estimated to be in the order of 2 M€/year for the EURISOL 5 mA CW proton beam **[10]**, and should be around 3 M€/year for the XADS 10 mA beam. Moreover, as previously mentioned, the superconducting solution gives higher safety (larger beam tubes), and has great potential in terms of reliability and flexibility thanks to its independently powered structures.

Considering the great potential of such a solution, R&D programs on low-β SCRF resonators, and in particular on spoke-type cavities, have been developed in various laboratories within the framework of several accelerators projects (e.g. AAA, ESS, RIA, EURISOL). Spoke-type cavities appear to be one of the most promising structures in this field (high shunt impedance, good mechanical stability, negligible steering effect). The first test of a spoke prototype was achieved successfully in 1992 **[60]**, and very encouraging RF performances have been achieved in the last years at Argonne **[61]** and Los Alamos **[62]**. Since 2001, a R&D program has also started at IPN Orsay on this type of cavities. A major part of this program has been done within the frame of the XADS project.

Spoke cavities design for XADS ---

In principle, from considerations on the transit time factor of the 2-gap spoke cavities, only two different structure types are needed in order to cover the energy range up to the elliptical cavity transition: β=0.15 spoke cavities are used from 5 MeV up to 17 MeV, and β=0.35 cavities from 17 MeV up to 80 or 100 MeV. These cavities operate at 352.2 MHz (RFQ frequency) to keep sufficiently large beam apertures, and at a temperature of 4K (or possibly 2K). The use of 2-gap cavities was first motivated by the fact that they have large energy acceptance, and that they remain quite easy to fabricate as compared with multi-gap structures. An alternative design could consist in using 3-gap or 4-gap cavities; but one can show that this configuration is not very attractive because first, 3 different β-values are needed in this case, second, the gain in terms of overall length and cavity number is not significant, due to the very strong longitudinal phase advance in this energy range and the subsequent limitations on the accelerating field, and third, more gaps per cavity directly means less fault-tolerance capability, i.e. less reliability.

The 2-gap spoke cavity design optimisation has been done for each β-value **[63,64,65,66]** so as to minimise the peak surface fields in the cavities during operation (usual limitation: E_{pk}<25 MV/m), while reaching good RF and mechanical properties, and keeping large beam apertures. In both cases, the optimisation study led to a final shape exhibiting a cylindrical spoke base (minimum B_{pk}/E_{acc} value), a racetrack spoke centre (maximum transit time factor), and a spoke centre thickness of 1/3 the iris-to-iris length (see Figure 3-18). The main characteristics of these two 352.2 MHz, 2-gap cavities are summarized in Table 3-4.

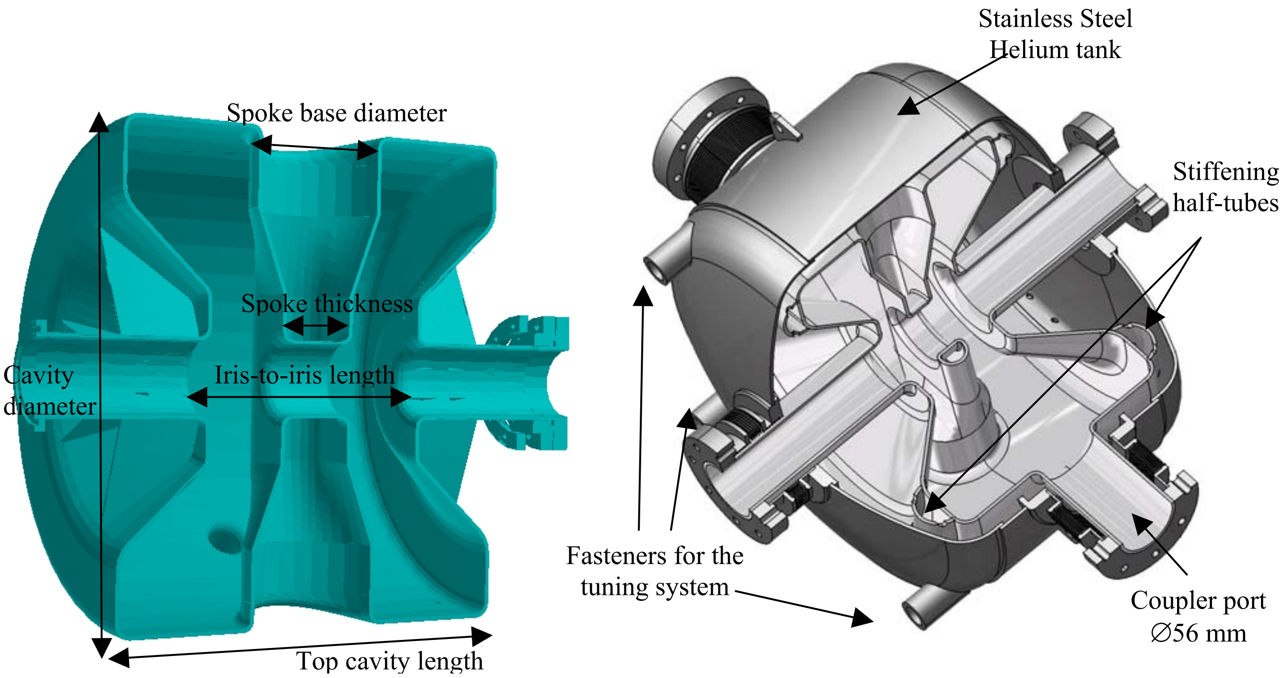


Figure 3-18 – (Left) Cross section of the β=0.35 2-gap spoke cavity. (Right) β=0.15 spoke cavity 3D drawing, equipped with its Helium tank and coupler port.

Table 3-4 – Main parameters of the 2-gap spoke cavities to be used in the XADS reference accelerator.

	“β=0.15” cavity	**“β=0.35” cavity**
Geometrical beta β_g*	0.135	0.314
Optimum beta	0.194	0.363
Cavity diameter	354 mm	408 mm
Top cavity length	217.5 mm	354 mm
Spoke base diameter	72.5 mm	118 mm
Spoke thickness	28 mm	67 mm
Iris-to-iris length	85 mm	200 mm
Beam tube aperture	50 mm	60 mm
Shunt impedance (linac definition) R/Q**	101 Ω	220 Ω
Geometrical factor G	72 Ω	101 Ω
Epk/Eacc**	3.56	3.06
Bpk/Eacc**	7.59 mT/(MV/m)	8.28 mT/(MV/m)
Eacc @ Epk = 25 MV/m**	7.02 MV/m	8.18 MV/m
Maximum voltage**	0.60 MV	1.64 MV
Quality factor @ 4K *(and @2K)*	$1.4\ 10^9$ *($6.5\ 10^9$)*	$1.9\ 10^9$ *($8.8\ 10^9$)*

* Defined here as $\beta_g\lambda/2$=gap-centre-to-gap-centre length

** Given for β=0.15 & β=0.35 protons respectively; Eacc is normalised to the iris-to-iris length.

Spoke cavities prototyping --

Recently, a β=0.35, 2-gap spoke prototype has been successfully built and tested at IPN Orsay. A series of mechanical and RF tests at warm and cold temperature has been performed **[63,65,67]**. These tests have demonstrated, on the one hand, the good feasibility, stiffness and tunability of the spoke cavity and, on the other hand, its excellent RF performances at cryogenic temperatures (see Figure 3-19): a maximum accelerating field of 12.5 MV/m was measured at 4K, and 16.2 MV/m was even reached at 2K, exceeding by almost a factor of 2 the XADS nominal operating point. The quality factor was measured to be around 2.10^9 at 4K, as expected (coupling of the RF power by the beam tube). At 2K, the Q_0 was lower than expected because of the extra-losses on the coupling antenna due to remaining magnetic field in the area (coupling by the coupler port); changing the coupler port position (90° with respect to the spoke bar) should avoid this phenomenon.

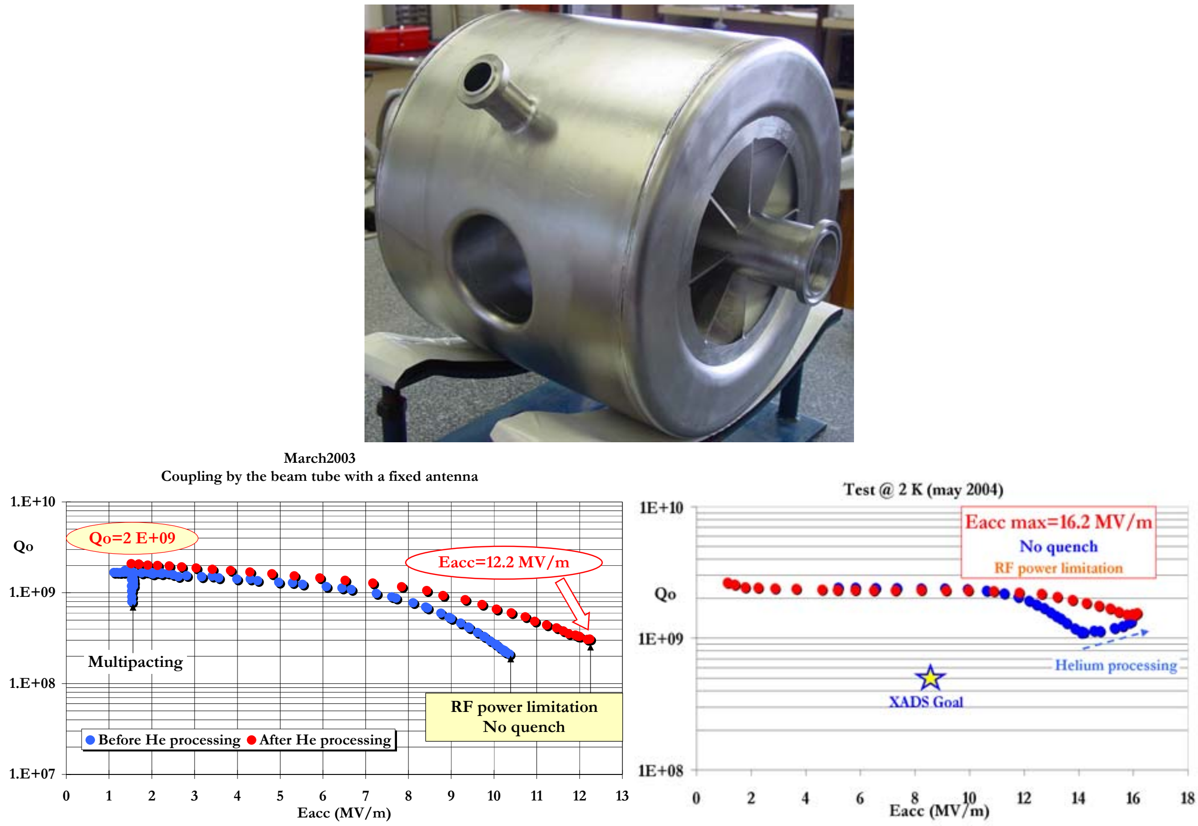


Figure 3-19 – (Up) The β=0.35 spoke cavity prototype. (Down) Test results @ 4K (left) & 2K (right) at Orsay.

A new spoke cavity (2-gap, 352 MHz, β=0.15) is currently under fabrication at CERCA (Romans sur Isère), and should be delivered and tested at the beginning of 2005. As shown on Figure 3-18, this cavity will be equipped with a stainless steel helium tank, a more adapted stiffening system, and a new coupler port location to avoid the extra-losses measured on the β=0.35 prototype. The study of a power coupler for both β=0.15 and β=0.35 spoke cavities has also started. This electric coupler will be designed to reach at least 20 kW CW power. Comparative study between different vacuum window technologies (disc or cylindrical) is under way; a choice will be made soon in order to launch the fabrication of a prototype at the end of 2004. Finally, the design study of a modular spoke-type cryomodule has also begun (see Figure 3-20), based on the “short” cryomodule concept developed for the SPIRAL-2 linac **[68]**.

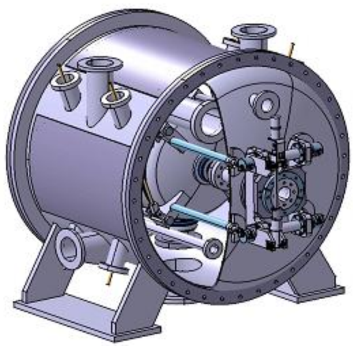


Figure 3-20 – Preliminary 3D drawing of a modular cryomodule for spoke cavities.

3.2.2.2 Elliptical cavities section

Starting from beam energies in the range of 80-100 MeV, the use of superconducting multi-cell elliptical cavities appears as the most efficient and cost-effective solution. As a matter of fact, a worldwide R&D effort for high power proton linacs is in progress since a few years within different programs like tritium production (APT), spallation sources (SNS, ESS) or ADS (AAA, TRASCO, ASH), and the well-developed superconducting radiofrequency technology, that has been greatly improved during the last ten years by the TESLA/TTF International Collaboration **[69]**, has been chosen in all designs above beam energies of 100-200 MeV. In this type of accelerators, the cost per MeV is decreasing with energy up to 1 GeV, and after, this value stays practically constant, with only a marginal decrease. Moreover, a superconducting linac has an intrinsic high modularity, which increases with energy and favors the implementation of redundancy schemes.

Elliptical cavities design --

Due to the varying velocity of the moderately relativistic protons, the superconducting multi-cell cavities need to operate over a given range of beam velocities. Thus, the high-energy part of the PDS-XADS linac is divided in three sections, each covering an energy range with a single type of structure. The geometrical β values of these structures are 0.47, 0.65 and 0.85, respectively. The transition energies between the sections are set to approximately 200 and 500 MeV, and the last family of cavities, bringing the beam to the nominal energy of 600 MeV, could operate to approximately 2 GeV without great losses of efficiency. In the present design, the highest beta section is marginally used (only two beta sections could have been used), but gives a large margin for further upgrades, eventually required for a final industrial plant. The proposed scheme is also consistent with the R&D work ongoing on the lowest beta cavities, and the fine-tuning of the three betas does not affect the technology achievements. Moreover, the TTF Collaboration has fully demonstrated that this technology is mature, and the fabrication, processing, cleaning and handling procedures in order to achieve high accelerating fields have been set.

The SC cavity design itself was performed in close collaboration in the context of the Italian TRASCO program **[70]** and the French ASH program **[71]**, sharing the R&D and prototyping efforts. In particular, while most of the effort of the French group has been concentrated on the work on β=0.65 cavity prototypes, the Italian group was dedicated to the development of β=0.5 cavities. The groups decided to focus the R&D and prototypical efforts on the two shortest beta sections, due to the fact that the technological challenges increase lowering the geometrical beta of the structure.

The baseline cavity design geometries have been chosen using a procedure that takes into account all the electromagnetic and mechanical performances of the cavities, and choosing the most suitable compromise for the required application **[72,73,74]**. The operating cavity parameters in the linac design have been set to conservative values in terms of peak surface field, in according with the derating/overdesign criteria needed for the linac reliability. In particular peak surface magnetic fields of 50 mT and surface electric field of 30 MV/m has been used as upper limits on the cavity operation, while the TTF cavities have been successfully operated up to more than 100 mT and 50 MV/m on the TTF linac. Furthermore, the first three cavity prototypes of the SNS β=0.61 multi-cell cavities have been tested reliably up to 90 mT and 45 MV/m in a test linac cryomodule **[75]**. The vertical tests of the SNS β=0.61 and β=0.81 cavities reached even better performances. The main parameters of the XADS elliptical cavities are shown in Table 3-5.

Table 3-5 – Main parameters of the SC elliptical cavities to be used in the XADS reference accelerator.

Geometrical parameters			
Cavity geometrical beta	0.47	0.65	0.85
Number of cells	5	5	6
Cell geom. length [mm]	100	140	180
Full Cavity Length [mm]	830	1050	1460
Iris diameter [mm]	80	90	100
Tube ∅ at coupler [mm]	130		
Internal wall angle, α [°]	5.5	8.5	8.5
Equator ellipse ratio, R	1.6	1	1
Iris ellipse ratio, r	1.3	1.3	1.4
Full cavity electromagnetic parameters			
Max. E_{peak}/E_{acc}	3.57	2.60	2.37
Max. B_{peak}/E_{acc}	5.88	4.87	4.07
Cell to cell coupling [%]	1.34	1.10	1.28
R/Q (linac definition) [Ohm]	159	315	598
Eacc @ B_{peak} = 50 mT [MV/m]	8.5	10.3	12.3

Elliptical cavities prototyping --

Up to now, several prototypes of the single cell cavities have been built and tested and the results were well above the design specifications **[76,77]**. This R&D programme is being actively pursued by CEA Saclay, IPN Orsay and INFN Milano. Prototypes of full multi-cell cavities have been recently manufactured and tested for both geometries. The performance of the prototypes has been measured to exceed the operational characteristics by a very comfortable safety margin **[78,79]** that ensures the overdesign criteria imposed by the reliability strategy. These excellent cold tests results are summarized on Figure 3-21.

To operate these cavities in a real accelerator, some important associated components are needed, like a RF power coupler (in the range of 100-150 KW) or a cold tuner for the fine adjustment of the resonant frequency of each cavity. Such developments are under way.

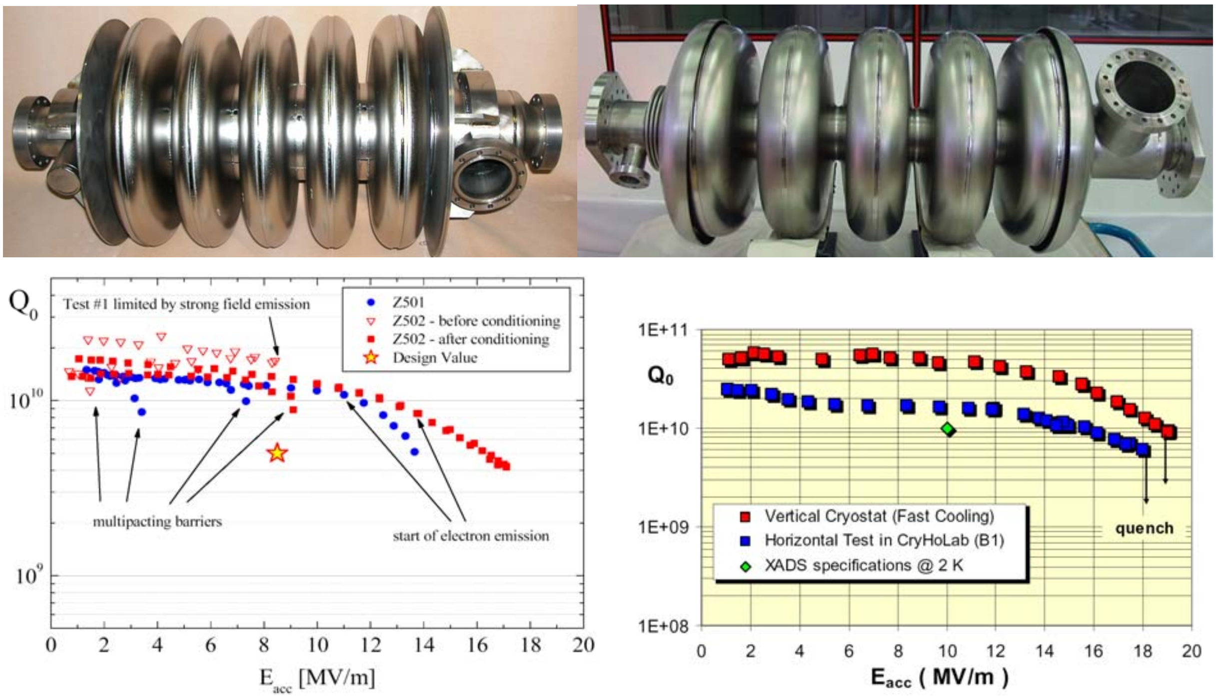


Figure 3-21 – (Up) Prototypes of 5-cell elliptical cavities developed by INFN (β=0.47, left) and CEA/CNRS (β=0.65, right) fabricated by ZANON and CERCA respectively.
(Down) Cold test results at 2K of the β=0.65 (left) and β=0.47 (right) prototypes.

3.2.2.3 The XADS independently-phased SC linac layout

The main philosophy used for the conception of the linac architecture consists in classically keeping as much as possible the lattice length continuity in the whole linac. The transverse focusing lattice is provided by a periodic array of normal conducting quadrupole doublets, and modular SC cavity cryostats are placed in the long drifts between quads, as illustrated on Figure 3-22 for the elliptical section. Table 3-6 reports the main characteristics of a full 5 to 600 MeV independently phased SC linac for XADS.

Table 3-6 – General layout of the 5 – 600 MeV XADS linac using only independently phased SC cavities.

Section number	1	2	3	4	5
Input Energy [MeV]	5	16.7	90.5	191.7	498.1
Output Energy [MeV]	16.7	90.5	191.7	498.1	614.7
Cavity Technology	Spoke 352.2 MHz		Elliptical 704.4 MHz		
Structure β	0.15	0.35	0.47	0.65	0.85
Number of cavity cells	2	2	5	5	6
Number of cavities	36	60	28	51	12
Focusing type	NC quadrupole doublet				
Cavities/Lattice	2	3	2	3	4
Synch Phase [deg]	-40 to -27	-27 to -20	-25		
Lattice length [m]	1.58	2.42	4.16	5.73	8.37
Section Length [m]	28.5	49.0	58.5	98.5	26
<gradient> [MeV/m]	0.4	1.5	1.7	3.1	4.5

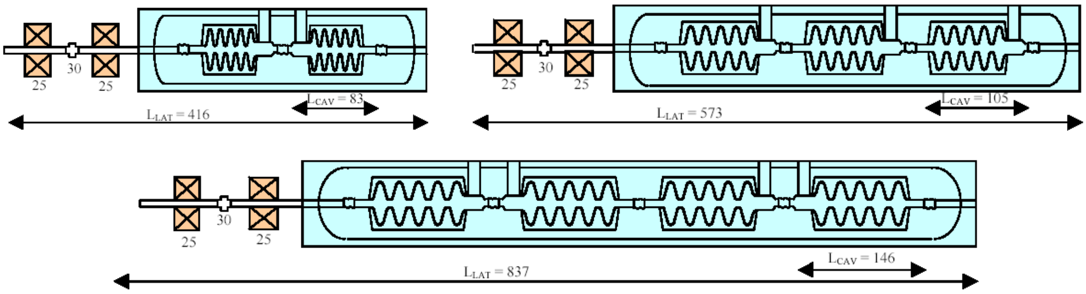


Figure 3-22 – Schematic lay out of the SC elliptical section of the XADS accelerator.

Beam dynamics simulations ---

Beam dynamics simulations of the full beam line showed that no showstoppers for the superconducting linac exist. Indeed a beam line from 5 MeV to the final nominal energy is feasible and looks promising from many points of view (possibility of intrinsically redundant design, modular structure, simplicity, fault tolerance, etc.). Note that comfortable margins on critical values have been chosen in this study to ensure a design as robust as possible. These margins leads especially in limiting, in a reasonable way, the minimum beam apertures, the field in the cavities, the phase advances along the linac, the sensibility to beam mismatch, or the possibility of halo creation. Moreover, the high-current beam physics is well understood. The linac has been designed in order to satisfy the necessary smoothness criteria in order to avoid beam quality degradation and to avoid the possibility of particle losses. The structure and the intensity of the focusing lattice are smooth, and the matching between the sections has been carefully studied. The design stays clear from all types of resonances: structure resonances (by means of phase advance limitations), envelope-particle parametric resonances (by means of limitations of tune depression) and resonances between planes (by avoiding resonances between the different planes).

The following figures show the main characteristics of the linac design and the results of beam dynamics simulations for the whole beam line, from the output of the RFQ, through the spoke cavity beam line and into the high-energy elliptical cavity section. Very safe and smooth envelopes are obtained, with emittance growths below a few %, and no phase space distortion is observed. The calculations have been performed using the TraceWin & Partran codes developed in Saclay **[80]**, and on the basis of the 5 MeV – 600 MeV XADS reference linac layout presented in Table 3-6. In all cases, a 10 mA proton beam is considered, and the normalized rms emittances values at the 5 MeV input are assumed to be 0.27 π.mm.mrad in the transverse planes, and 0.39 π.mm.mrad in the longitudinal plane. Multiparticle calculations have been performed using at 100 000 particles and considering a gaussian (truncated at 4σ) phase-space distribution (see Figure 3-27).

Concerning the extremely low energy section of the linac (from 5 MeV to roughly 25 MeV), it has to be noted that the design is not very efficient in terms of real-estate gradients (defined as the energy gain per lattice, divided by the physical length of the focusing lattice cell). This inefficiency is mainly due to the rather long focusing period of the first spoke section. This characteristics is typical of SC linacs where the packing factor of RF structures is greatly reduced with respect to NC linacs, and at such low beam energies, this long lattice length is not very well suited for a good longitudinal focusing of the beam (ramping the synchronous phase is for example needed). Moreover, the longitudinal phase advance is very strong, that requires to greatly limit the accelerating field in the cavities, operating them well below their nominal specifications. It is therefore advisable to identify alternative solutions in the region from 5 to 20/30 MeV, like a warm DTL section or a different structure (e.g. the Frankfurt proposal), while keeping in mind that such solutions will not exhibit any fault tolerance capability, contrary to the spoke solution. Concerning this item, a systematic study of the 5 MeV – 600 MeV SC linac fault-tolerance capability has been also performed, based on beam dynamics calculations. The conclusion of this study, which is presented in section 4.1.2 (page 85), states that in every cavity failure case, the beam can be recovered without any significant beam losses.

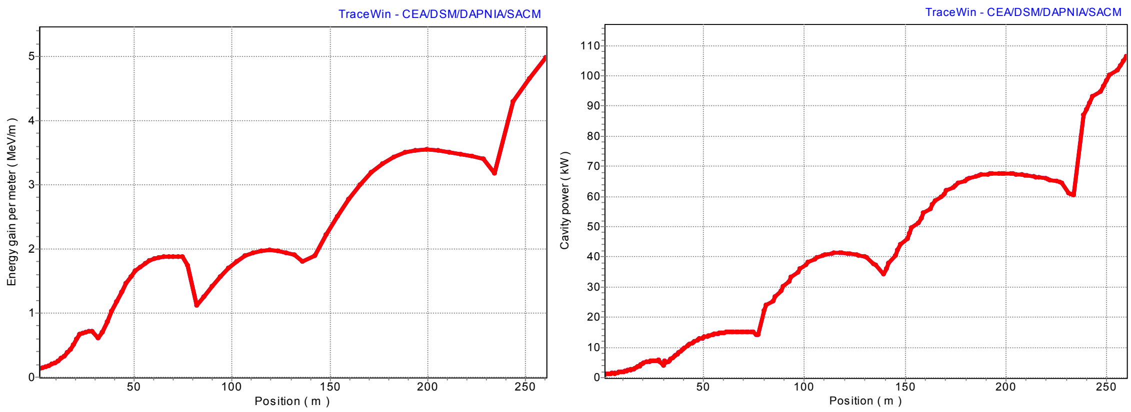


Figure 3-23 – Real estate gradient through the linac (left), and needed RF power per cavity (right).

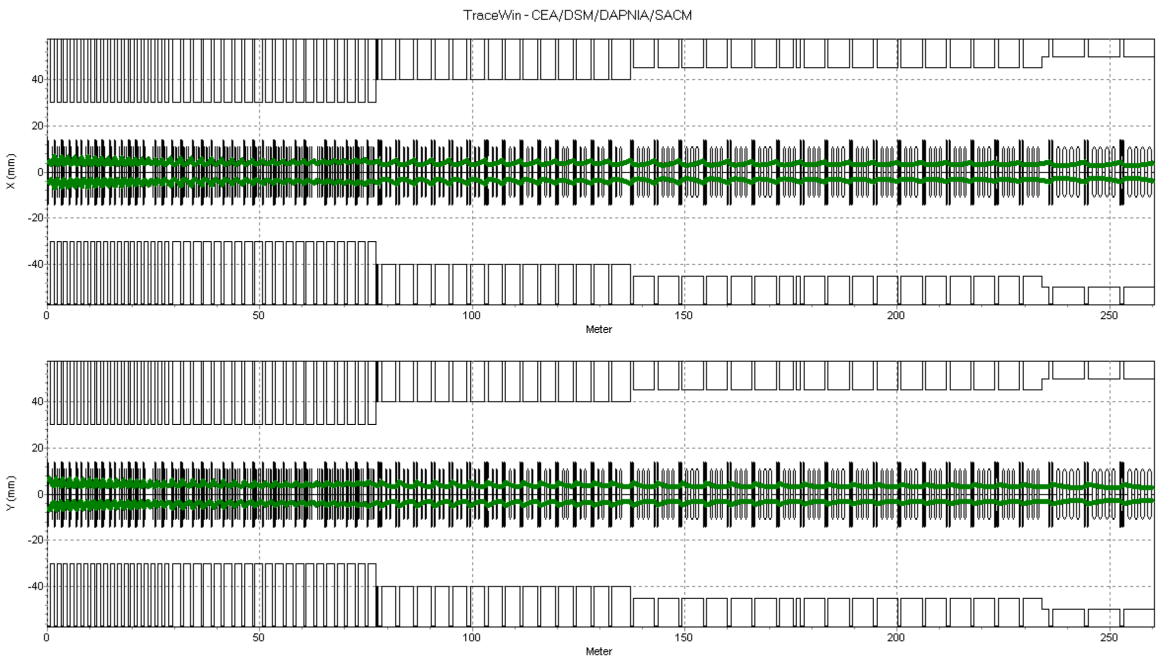


Figure 3-24 – Full beam size ($\sqrt{5}$ times the rms size) through the linac (envelope calculation).

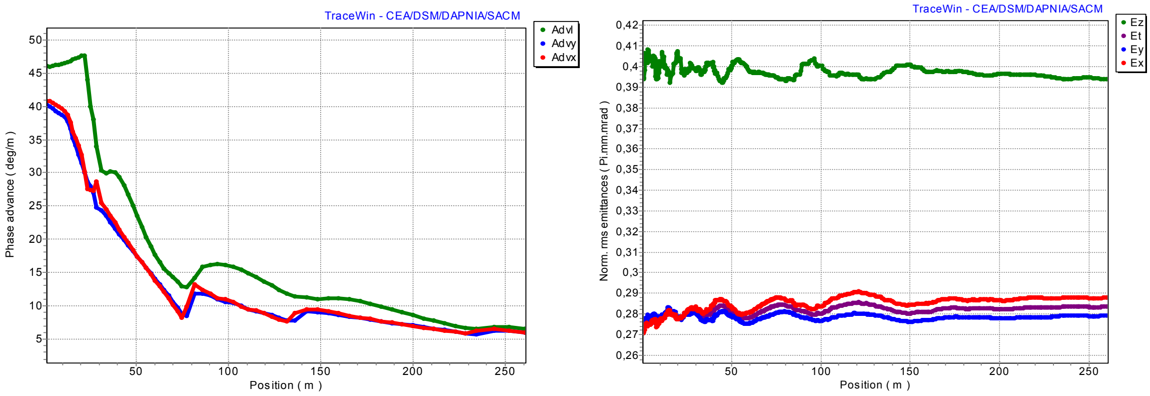


Figure 3-25 – Phase advance per meter (left) and norm. rms emittance evolution (right) through the linac.

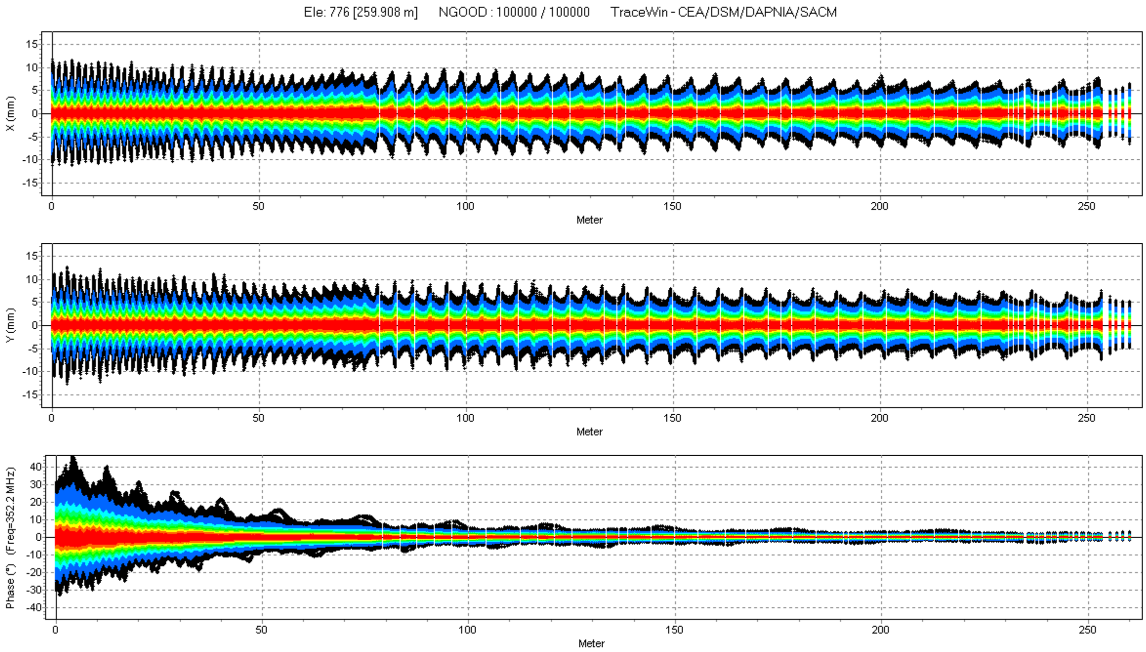


Figure 3-26 – Multiparticle envelopes through the linac (100 000 particles).

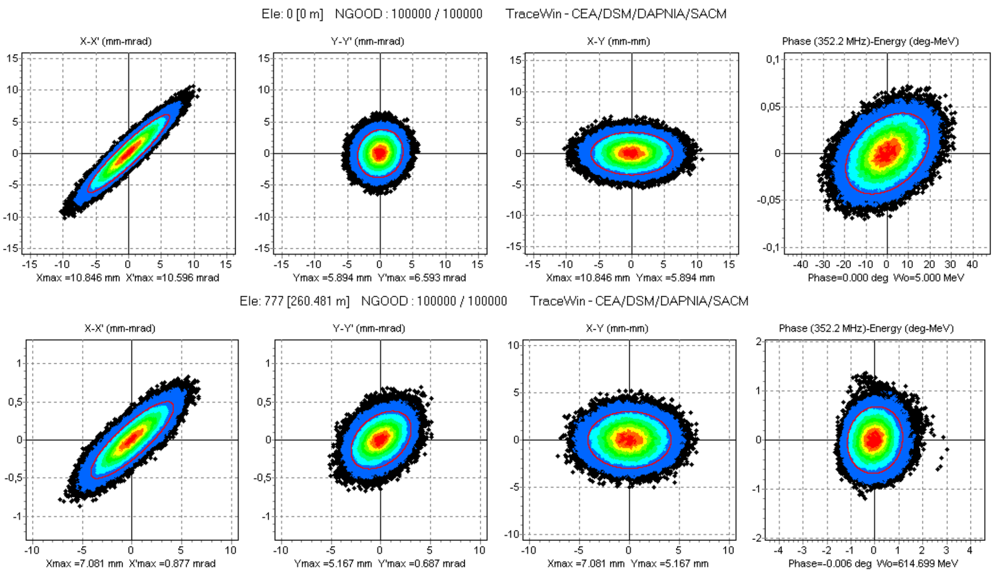


Figure 3-27 – Phase-space distributions of the beam at the input (up) and at the output (down) of the SC linac.

RF system needs ---

The power needed in each superconducting cavity for CW operation at nominal current (10 mA) is reported on Figure 3-23. This leads to a total AC power consumption for the RF needs of roughly 12.7 MW (see Table 3-7).

Table 3-7 – Rough estimation of the RF power consumption in the 5 – 600 MeV superconducting XADS linac.

	RF beam power	RF power consumption*
Spoke b=0.15 section	117 kW	134 kW
Spoke b=0.35 section	738 kW	849 kW
Elliptical b=0.47 section	1012 kW	1164 kW
Elliptical b=0.65 section	3064 kW	3524 kW
Elliptical b=0.85 section	1019 kW	1172 kW
Total RF power	**5950 kW**	**6843 kW**
Total DC power†		11.4 MW
Total AC power‡		**12.7 MW**

Each cavity will be driven with an independent and de-rated RF power source in order to obtain precise control of each cavity's accelerating gradient and phase. This is an important design aspect, necessary for the improvement of the accelerator reliability. The high power sources of the high-energy section, up to powers around 150 kW if a 50 % margin is considered for both the de-rating principle and the RF control needs, should be reached with commercial IOT tubes (EEV, Thomson). Recent tests of a 700 MHz Thomson IOT (Ref. N°790) have exhibited power levels reaching 80 kW with very good efficiency (> 65 %). For the lower power sources, up to around 25 kW, needed in the spoke section, 350 MHz solid-state amplifiers will be a priori used. Figure 3-28 shows a possible scheme of the RF system needed to drive each accelerating SC cavity. Note that the low level RF system is a crucial element of the system, especially for the practical implementation of the fault-tolerance strategy (see section 3.2.4.2).

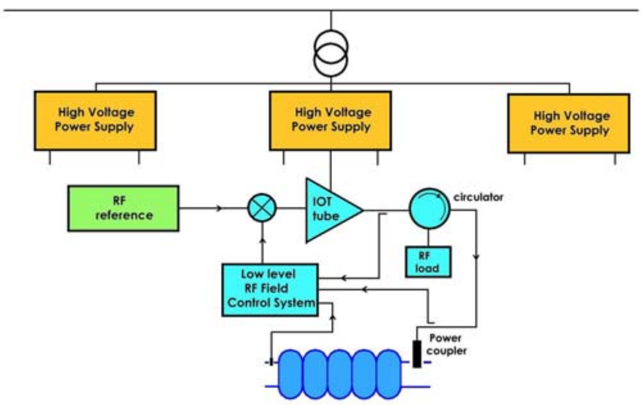


Figure 3-28 – General scheme of the RF system.

* Including an arbitrary 15% excess power consumption for the RF control needs.
† Taking into account an average DC to RF efficiency of 60 %.
‡ Taking into account a AC to DC efficiency of 90 %.

Cryogenic system --

The operation of 700 MHz SC cavities at 2K is a very interesting choice since the dynamic losses, directly proportional to the RF surface resistance, are drastically reduced. In a first approach this resistance is reduced by a factor greater than 10 compared with a 4.2K operation temperature. The gain obtained in thermal stability by increasing both the quench margin and the high heat transfer capability of superfluid helium is also a favourable condition. On the other hand, at 350 MHz, the RF surface resistance is already low enough at 4.2K to ensure efficient operation of the spoke cavities; but going down to 2K can also be envisaged, benefiting from the existing 2K cryogenic facility needed for the 700 MHz cavities.

A 2K cryogenic system is more complicated than a "simple" 4K helium liquefier, needing the introduction of low temperature compressors operating at low pressures, reducing the overall thermo-dynamical efficiency. Nevertheless, several large facilities, i.e. CEBAF, are now in routine operation with very good reliability.

Table 3-8 – Rough estimation of the main heat loads in the XADS linac (static + dynamic contributions)

	2 K, 0.04 bar	**4.2 K, 1 bar**	**Thermal shields**[*]
Spoke b=0.15 section	-	10+8 = 18 W/module	60 W/module
Spoke b=0.35 section	-	13+39 = 52 W/module	90 W/module
Elliptical b=0.47 section	10+26 =36 W/module	0.04 g/s per module[†]	100 W/module
Elliptical b=0.65 section	13+54 = 67 W/module	0.08 g/s per module[†]	120 W/module
Elliptical b=0.85 section	16+124 = 140 W/module	0.1 g/s per module[†]	150 W/module
Transfer lines & distribution	2 W/meter	2 W/meter	10 W/meter
Total load	769+1654 = **2423 W**	600+924 = **1524 W** + **2.2 g/s**[†]	**9370 W**
Refrigerator capacity (+ 50%)	**3600 W**	**2300 W + 4 g/s**[†]	**14000W**

Table 3-8 roughly summarises the heat loads for the 34 elliptical cryomodules and the 38 spoke cryomodules needed in the XADS independently phased SC linac, from 5 to 600 MeV (see Table 3-6). Note that the power couplers for the elliptical cavities need also an extra cooling capacity (4.5 K helium flow rate in g/s) in order to remove the heat dissipated into the coupler walls and minimize the heat transfer towards the superfluid helium bath. Assuming a safety margin of 50%, the XADS superconducting linac requires a cryogenic refrigeration system having the following capacities: 3.6 kW @ 2K, 2.3 kW @ 4.2K + 4 g/s @ 4.5K, and 14 kW @ 50 K.

[*] The temperature can range between 50 K and 70 K (to be optimised); P = 3 bar.
[†] Contributions from the power couplers' cooling loops, directly fed with 4.5 K, 3 bar, supercritical helium.

If we assume an efficiency of 1.5×10^{-3} (thermodynamics and technical efficiency) for the 2 K temperature level, 4×10^{-3} for the 4.2 K level, and 5×10^{-2} for the 50 K level, the total AC power consumption of the refrigerator operating at nominal beam conditions is about 2.25 MW (and about 3.4 MW for the maximum installed refrigeration capacity).

The size of this refrigerator is close to that of the CEBAF facility. This system, after several years of reliable operation, is now running very stably, delivering more than 5000 hours of beam to the experimental areas each year. The SNS refrigerator, presently under construction, has also very close capacities: 2850 W @ 2 K, 15 g/s @ 5K, and 8300 W @ 35-55 K **[81]**. Figure 3-29 presents a possible refrigerator block diagram, inspired from the SNS system. This concept allows to distribute supercritical helium (4.5 K, 3 bar) along the transfer lines, and the subatmospheric subcoolers (heat exchangers and JT valves) are installed in the cryomodules.

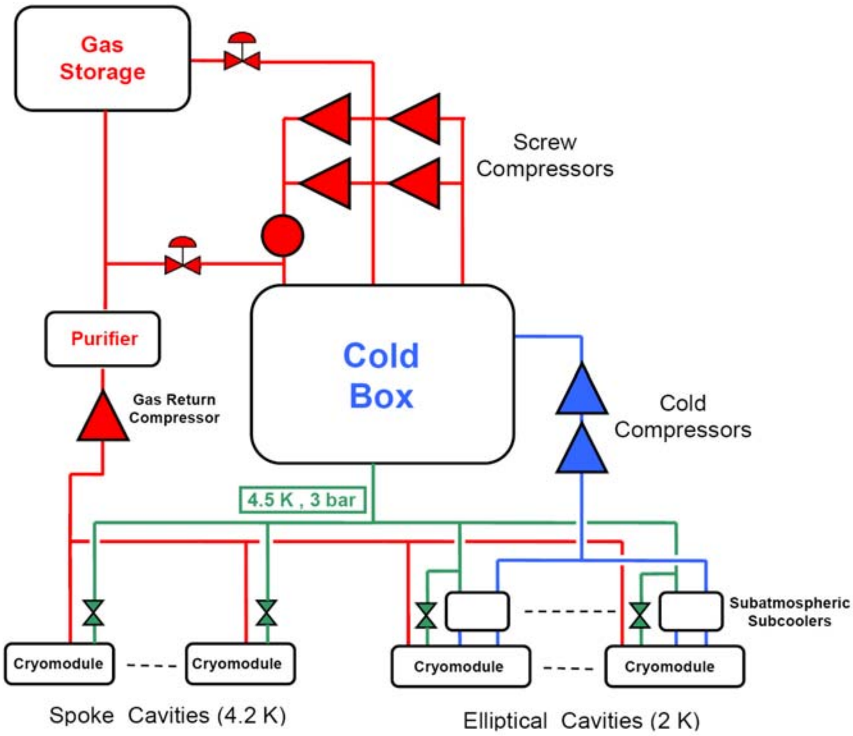


Figure 3-29 – General scheme of the cryogenic system.

3.2.3 Beam transport line

The objective of the final transport line is to safely inject the 600 MeV, 6 mA (10 mA rated) proton beam delivered by the accelerator into the subcritical reactor assembly and to provide a stable beam footprint at the target satisfying the following specifications:

- beam footprint shape and dimensions:
  - rectangle of 10x80 mm^2 for the Lead-Bismuth Eutectic (LBE) XADS concept;
  - disk with a diameter of 160 mm for the gas-cooled XADS concept;
  - disk with a diameter of 72 mm for MYRRHA;
- beam focalisation stability: ± 10%.

Beam transport system overview **---**

Deliverables D4 **[7]** and D9 **[2]** have evaluated the technical answers able to provide these characteristics. Although large bending magnets have to be placed in the upper region of the reactor building, a doubly achromatic optical module penetrating the reactor vertically from above has been assessed to be the most suitable concept and has been adopted for both the gas-cooled and LBE cooled reference XADS concepts which have been selected by ANSALDO and FRAMATOME ANP. This generic solution also fulfils the specifications required for the smaller scale XADS MYRRHA using only 350 MeV protons.

Such a doubly achromatic optical system is non-dispersive. Therefore the beam position at the target does not depend to first order on the central energy variations and in addition, the beam size is independent of the internal beam energy spread. In practice, this means that possible energy spread and central energy fluctuations induced by the accelerator RF system will have no effect on the beam stability at the target if they do not exceed a few percents. It has to be noticed that though the system is non-dispersive at both extremities it is dispersive in the region situated between the two dipoles. As a consequence, beam position and beam size monitors located in this region will be able to provide information on proton energy variations and to trigger a feedback system if the beam instability is too large.

Figure 3-30 illustrates the beam line arrangement, which has been studied for the FRAMATOME ANP reactor concept **[82]**. To limit the size and the weight of the last magnet, a deflection angle of only 45 degrees has been chosen. A second magnet is placed at a distance of 10 m from the last dipole and restores the beam in the horizontal direction. Three focusing quadrupoles are inserted between the two magnets to control the beam envelopes and to cancel the dispersion function at both extremities of this 90 degrees deflection module.

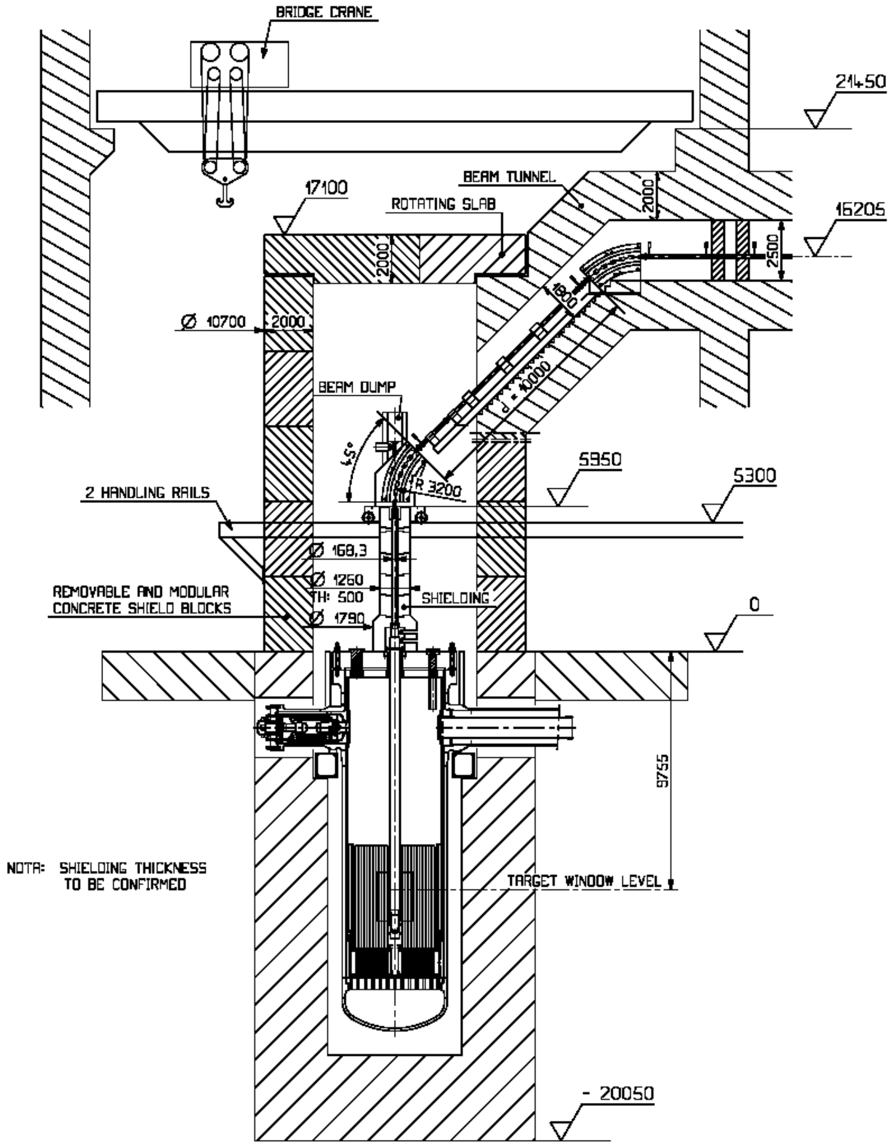


Figure 3-30 – Beam line arrangement for the FRAMATOME ANP gas-cooled reactor concept.

The design of the line connecting the linac to the entrance of the final beam line discussed here above could be composed of a simple FODO beam line located between two matching sections, the first one at the linac exit, and the second one before the 90° deflecting module of the final beam line. The final design of this connection line will strongly depend on the relative positions of the reactor and the accelerator with respect to the ground level; this will especially dictate the beam dump location, and indicate if the connection line has to include an additional vertical deviation or not.

Beam footprint on the target ---

To expand the beam onto the target, two approaches are available in principle. One technique involves defocusing the beam by means of additional quadrupoles, another is to apply the so-called raster scanning method which consists in deflecting a pencil-like beam with fast steering magnets operated at frequencies of 50 to a few hundreds Hertz and acting in the two transverse directions in order to paint the target area. Various shapes (rectangular, circular) and various particle distributions (uniform, parabolic…) are achievable by simply adjusting the rastering frequencies of the steerers. To give an example, Figure 3-31 shows the beam pattern and the resultant uniform distribution obtained for a circular footprint. In this example, the scanning magnets are operated at frequencies close to 500 Hz **[83]**.

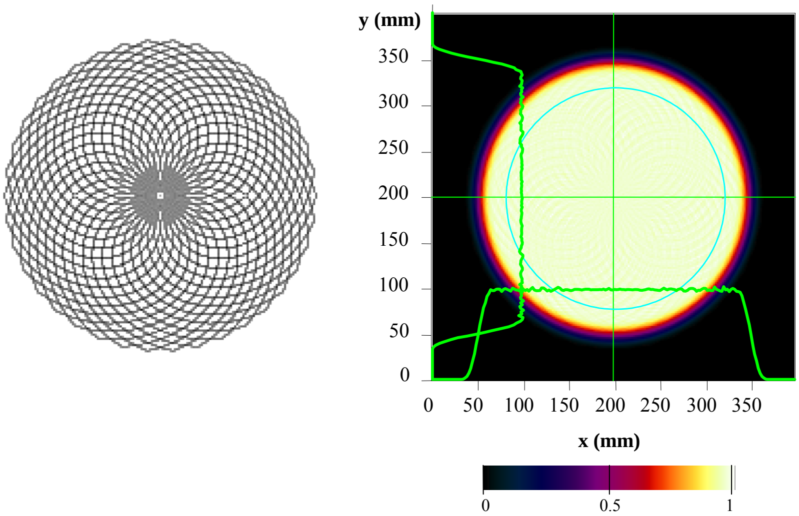


Figure 3-31 – Example of a circular beam scanning: (left) pattern of the beam displacement and (right) power density deposited in the target.

The first technique is foreseen for spallation neutron source like ESS and SNS. In that case, the beam expansion does not require too strong defocusing quadrupoles because the emittance of the beam extracted from the accumular ring is very large. In our case, the accelerator beam emittance is about one hundred times smaller, the defocusing method would therefore imply the use of strong gradient quadrupoles carefully aligned and regulated. As a consequence, we have selected the second method that is based on existing techniques successfully applied at GSI in Germany for cancer therapy with ion beams **[84]** and validated by the R&D programs undertaken in the U.S. for the APT and ATW projects **[85,86,87]**.

This scanning system has proven to be extremely reliable. Reliable steering magnets and control systems are indispensable for medical practice in order to respect stringent requirements in terms of reliability, safety, maintainability and legal aspects. Currently, such a sophisticated system is under development for the Heidelberg cancer therapy facility HICAT **[88]**. In our case, the scanning system could be very similar (but less demanding) to the one studied for the APT and ATW projects.

Four raster magnets will be operated synchronously and independently so that the beam will be always moved at the target if one magnet fails. Redundant fault detection circuits will monitor the magnet current and the magnetic field to ensure proper operation and to shut down the beam in case of necessity.

Reliability aspects --

Most of the reliability issues concerning the final part of the beam delivery system to the target in the reactor are very similar to those of the other beam transport systems (LEBT, MEBT, HEBT) which have to connect the injector to the main linac and the accelerator complex to the reactor. For instance, the failure of major components like main bending dipoles certainly implies the necessity of switching-off the linac proton source as soon as first beam losses are detected by loss monitors. Fortunately, MTBF for beam transport lines is generally rather long because all major components (dipoles, quadrupoles, steerers) are very robust and reliable. This fact has been confirmed by numerous recent reliability analyses. In the case of the LANSCE facility where a total of about 800 DC magnets are used, the MTBF estimate for a single magnet exceeds 230 000 hours (~26 years) and individual magnet power supplies show an MTBF of approximately 8 500 hours (~1 year) **[89]**.

Experience at various large accelerator facilities shows that the principal causes of faults in electromagnets are due to water-cooling problems (failures at water pipes and connections) and power supply malfunctions. It is probably possible to overcome or to prevent most of these problems by using a reliability-based approach for selecting the right components and the appropriate construction technology of cooling systems, and by derating/overdesigning power supplies which should be operated at reduced voltage and current. Preventive maintenance and redundancy concept will also prevent that individual system failures could affect the beam line operation. Matrix switching boards allowing any magnet to be powered by a spare power supply, as a successful practice in the ESRF experience, can be envisaged to avoid beam interruptions on the order of one second.

The main components of the beam line hardware will not differ appreciably from those that will be installed in other parts of the accelerator facility. This beam line hardware consists of electromagnets with their associated power supplies, vacuum pipes and devices such as valves, gauges or pumps and beam diagnostics instruments such as position or current monitors. From the point of view of the maintenance management and policy, to each class of equipment the same maintenance procedure applies wherever it is installed along the facility. Many examples of preventive or curative maintenance needs and procedures for these equipments are described in many papers presented at workshops dedicated to accelerator operation **[90]**. Most important actions to be performed are presented in section 4.4 and in the Deliverable 48 **[5]**.

3.2.4 Diagnostics and feedbacks

The control of any accelerator is generally done using powerful feedback systems relying on specific diagnostics. It is more and more acknowledged that these systems are of prime importance because they ensure the future operability and stability of these large machines. Feedbacks and associated diagnostics are even more important in the case of the XADS linear accelerator. These subsystems will have a considerable and direct impact on whether this accelerator could achieve the required fault tolerance capability. In particular, a new class of radiofrequency (RF) control and feedback system for the superconducting linac will be needed. In addition to the usual control of the superconducting cavity frequency, amplitude and phase, this system should also be able to cope with some given failures without inducing a beam interlock. Consequently, the design of the XADS diagnostics and feedbacks will be based on new and innovative techniques either already tested or currently under development. Some of these techniques will have to be pushed even to higher limits in order to obtain the unprecedented required reliability. A preliminary full study of the diagnostics and feedback systems needed for the XADS accelerator can be found in Deliverable 47 **[4]**.

Obviously, control of the operation of those accelerators, beam breakdown prevention, beam monitoring under daily operation and beam losses prevention along the accelerating structures must be taken into account at the beginning of the design of the accelerator. Studies associated with high intensity beams have shown that phenomena associated with space charge, instabilities and beam loss have significant impact on the design of such projects. It is well established that accelerators involving a beam power of the order of several Megawatts need improved control of beam loss beyond present experience. For linear protons accelerators under consideration, less than 1 W of beam loss per meter of structure should be aimed at. This requires a reduction of the beam loss to as low as 10^{-6} in linacs, which is far beyond the state-of-the-art of experiments as well as conventional approaches of computer modelling. Same considerations must be kept in mind for beam transport from the accelerator output to the target inside the reactor.

3.2.4.1 Diagnostics

A large number of different beam instrumentation is required all along the accelerator and the beam transport line for a safe and proper machine operation as well as for the interlock system in case of failure. Due to the high beam power in the XADS linac (up to 3.6 MW), a special care should be given to operate with the lowest possible beam loss inducing low enough activity to allow maintenance. Even if some intrusive sensors may be used for specific measurements, the large amount of beam energy deposited in any material, especially in the low energy sections of the accelerator, forces to use non-interceptive beam sensors. In addition to destroying the sensor, the interception of some fraction of the beam will lead to a high activation level in the structure of the accelerator and its surroundings.

Specific beam instrumentation will be required for machine commissioning, taking advantage of that period to verify and understand all the beam behaviour under any operating condition. In particular, after checking experimentally the beam dynamics calculation under normal operation, all abnormal events (like for example a cavity loss) should be tested and the beam characteristics measured using appropriate diagnostics, including the transient beam loss monitoring after mitigation of the event. That also includes the validation of the raster scanning system performing the power distribution of the beam onto the spallation target.

This commissioning step is essential to record as much as possible all different processes and ways of operation that may lead to beam quality deterioration. At the end of this experimental study, one should be able to give the set points for normal and some off-normal conditions of operation for both the machine and the high-energy beam transport line.

Beam current measurements ---

DC and average-beam current measurements are required during facility operation. The DC component of the beam current can be measured using DCCT (Direct Current - Current Transformer). The DCCT is based on the amplification of the magnetic field induced by the passage of the beam current through a coil. While the present industrial state of the art typically gives a 100 μA absolute accuracy, it is quite important for the XADS requirements on beam loss to provide the highest possible quality sensors able to achieve a much better resolution (about a 100 times lower).

After the RFQ, the beam is bunched. Therefore, ACCT (Alternative Current - Current Transformer) may be used to monitor the accelerated particle bunches even under CW operation. Commercial devices are available with a cut off frequency as high as 1.5 GHz but careful attention should be paid to the response drop of ACCT under low duty factor pulse mode operation. An ACCT in the LEBT (Low Energy Beam Transport) line could be also used as a feedback for the control of the current source.

Destructive current measurements of the beam can also be achieved in some special cases like a water-cooled Faraday cup (for beam power lower than 10 kW).

Transverse beam centroid measurements --

Beam position diagnostics are required for both transverse planes along the accelerating structures, essentially in the high-energy part and the beam transport line with the raster scanning system. These diagnostics will be directly connected to the command-control system using automatic beam alignment procedures. Half a mm absolute beam position is expected to be measured with a resolution of a tenth of mm. In the LEBT, beam position can be given either by grid profilers or alternatively using a new non-destructive technique sensing the light emitted by the collision of the proton beam with the residual gas. When the beam is bunched, any capacitive or electromagnetic sensor such as strip-line pickup or Beam Position Monitors (BPM) may be used with a 0.1mm resolution.

Transverse beam profile measurements ---

Beam profile measurements are important for the control of the beam characteristics all along the linac, essentially during the commissioning period to check the proper values of the magnetic elements (focusing, steering, etc…). Although transverse profile monitors could not presently sustain the very high beam power of the XADS linac, traditional interceptive techniques like harps, wire scanners or view screens should be used to measure the beam profile in low duty cycle pulse mode. Some non destructive diagnostics such as residual gas ionisation monitors or fluorescence devices could also be applied, but these techniques are still under development and a validation test phase will be required prior to assess their use for high power proton accelerators.

Energy and phase diagnostics --

Other beam measurements include the bunch shape, its phase with respect to the accelerating RF voltage, the longitudinal emittance or the beam energy at some given location. Although some of these parameters could be deduced from previous beam current or profile measurements, it is quite helpful, especially during the commissioning time, to install dedicated sensors measuring directly the desired characteristics.

Beam losses measurements ---

This is one of the utmost important signals for the interlock system. Should any excessive beam loss be detected along the machine, the proton source will be immediately shut down because the corresponding loss can induce very high radiation or even irreversible damage. In some cases, beam loss measurement may also indicate an abnormal accelerator condition such as a mismatch without necessarily inducing a beam trip.

Fault diagnostics ---

In connection with beam loss monitors, a variety of diagnostics is needed to prevent any damage of accelerators components or subsystems. A robust beam instrumentation system requires fast processing circuits in order to deliver to the machine interlock system information for a fast sensing of abort conditions. This processing delay must be short enough to allow beam interception in the low energy section of the accelerator, stop the RF or kick the beam into a dump. It must be completed by a fault history report based on the data delivered by beam diagnostics for an easy retrieval of faults. The machine protection system related to beam loss monitors must have a response time short enough to stop the beam well before any damage on accelerator hardware and allow the operation of the machine minimizing the induced activation of components. Instrumentation of the accelerator must be designed in such a way that it is able to produce a comprehensive situation of the running of the accelerator as well as a specific situation of a particular part of the accelerator. It must also contribute to establish a fault order of severity in failures.

3.2.4.2 Feedbacks

Feedback will be required to ensure the stability of any given parameter of the machine, whenever the natural fluctuations of this parameter will be exceeding the acceptable limits for safe operation. For example, the fluctuations of a superconducting cavity frequency simply due to ground vibrations (microphonics) are large enough (compared to its very narrow bandwidth) to inhibit any operation without a frequency locking using a feedback loop. Also, the precise tuning of the beam current to within 1% will require a feedback system using for example a beam current monitor located at the output of the LEBT (Low Energy Beam Transport) line.

Beam current ---

If the source is correctly tuned, the extracted beam noise should be less than 1%. Then, the extracted beam can be easily tuned using the input RF power (for a current ranging from 70% to 100% of the maximum design value). If a larger current range is needed, two options are suggested to provide the coarse tuning: either a water-cooled iris (Figure 3-39) or a collimator. The iris device works like a camera iris, stopping the beam on its multiple water-cooled elements. The circular aperture diameter can be tuned continuously from zero to the full aperture with a steeping motor, allowing a current tuning from zero to full current. One should remember that copper sputtering occurs, and questions may arise for the long-term reliability. Because of the beam power deposition on the iris blades, this device has to be located at the lowest beam energy location. The other option could be the use of a collimator located at the defocusing plane of magnetic lenses. Depending on the defocusing strength, the collimator can intercept a fraction of the beam, letting only the on-axis beam going through. Devices using that technique have been designed to work even for beam transmission as low as 0.1% **[91]**.

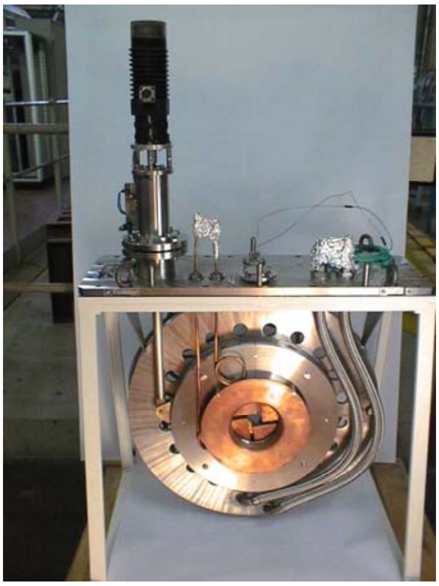


Figure 3-32 – Example of a water-cooled iris.

Superconducting cavities **---**

By construction, a SCRF (Superconducting Radiofrequency) cavity is much more sensitive to perturbations since the superconducting material like niobium exhibits a low tensile strength and the cavity wall has to be thin enough in order to facilitate the thermal transfer. As a result, the electromagnetic pressure, the environmental vibrations (microphonics) and the residual liquid helium bath instabilities may produce a significant detuning of the cavity, which would have a severe impact on the amplitude and phase stability because of the narrow bandwidth of the cavity usually operated with a high loaded Q (10^5 to 10^6). The microphonics perturbation covers a spectrum of a few hundreds of Hertz while the mechanical resonances of the cavity structure (including its tuner inside the cryomodule) are in the range of few tens of Hertz. The dynamic of these perturbations imposes a careful design of a fast RF feedback system, which should perform a proper compensation. In addition, different important aspects specific to XADS have to be taken into account. First, the non-relativistic proton beam will induce a phase slippage inside a multigap resonator. In addition, beam current gaps have to be added in the beam time structure to allow for target criticality measurements. And whenever the beam current is modified, transient beam loading and set point tracking are necessary to maintain beam power on the target.

Here, two approaches can be envisaged for the Low Level RF system: the frequency domain and the time domain approach. In the frequency domain analysis, both amplitude and phase of the cavity voltage have to be regulated and loop parameters such as maximum gain and delay can be derived from basic feedback algebraic methods. A digital system offers a higher flexibility required by XADS to switch on different failure recovery scenarios, but will also imply a longer delay. The accuracy of a feedback system is all the more better as the gain is higher. For loop stability, the longer the delay, the lower the gain. As an example, the maximum loop gain as a function of the delay time is drawn in Figure 3-33 for 350 MHz and 700 MHz cavities having both a loaded $Q_L = 5\ 10^5$.

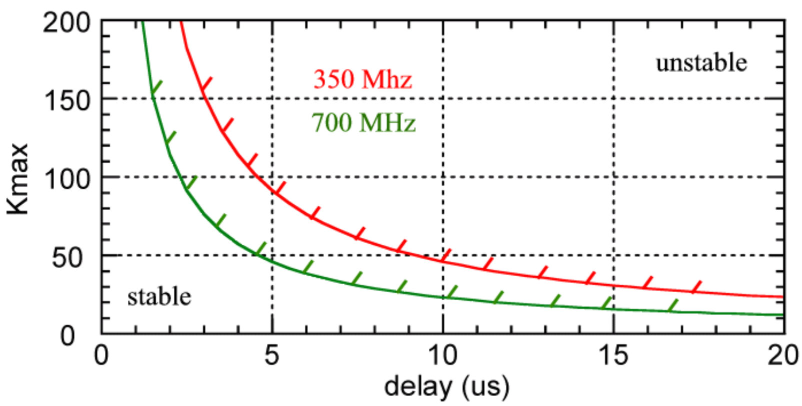


Figure 3-33 – Maximum gain estimation versus loop delay for SC cavities.

The time domain approach proves to be much more efficient in the case of a SCRF proton cavity. The synchronous phase (angle between the beam and cavity voltage phasor) in a proton accelerator ensures the longitudinal stability. As a result, the cavity has to be detuned to minimize the reflected power (reactive compensation). In such a case, I and Q loops (or amplitude and phase loops) should be mutually coupled. Also, one should take into account the holes in the beam current time shape (of the order of 200 µs) to allow for measurements of the core sub-criticality. In the following, it was chosen for example to simulate what would be the feedback control loop response if the beam current were to be decreased to 70% of its nominal value for 1 ms.

The goal of the feedback system consists in reducing the effects of all perturbations on the signal amplitude to less than 0.5%, and to less than 1° for its phase (typically 0.1% and 0.5° could be achieved). Here, a digital feedback system is considered for the simulation. The choice of a 14 bits resolution, a 1 MS/s sampling rate with a signal processing delay of 5 µs appears as reasonable with the currently available technology. The feedback gain of 150 for the in-phase loop and quadrature loop, well below the critical gain limit insures an excellent stability margin and good enough feedback performances (Figure 3-34). About 30% of additional RF power is required from the amplifier (klystron, IOT or solid state amplifier) as compared to the nominal power needed (14.2 kW). The amplifier saturation is modelled by a sine function. Simulation results show that excellent amplitude stabilization can be obtained. Relative error values amount to less than 2 10^{-4} far form the beam hole, without exceeding 2 10^{-3} during the beam transient, which should be quite satisfactory for XADS operation.

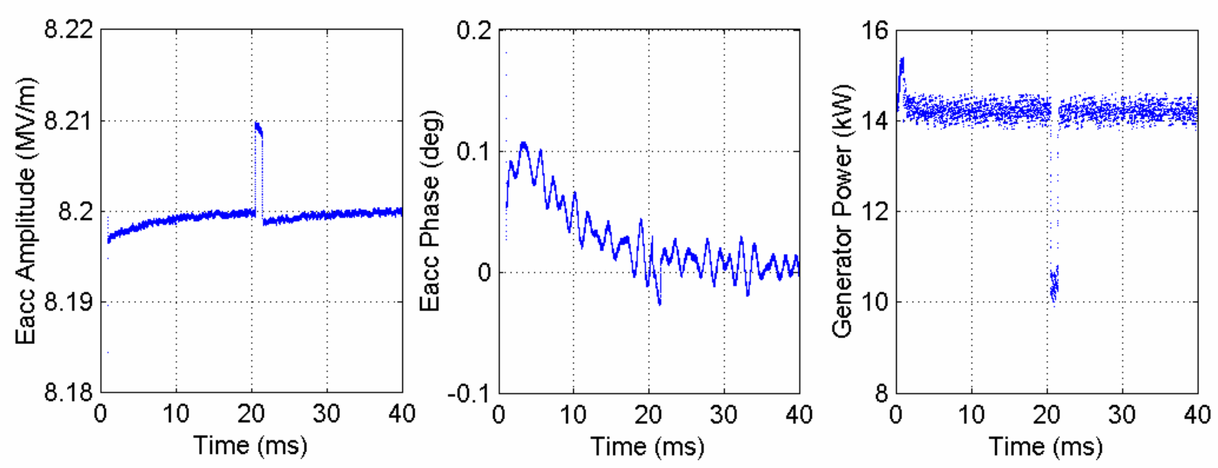


Figure 3-34 – Feedback performances with constant set points in the presence of perturbations.

The most stringent constraint on XADS concerns the reliability, as the number of trips longer than one second should be limited to a few per year. This implies some fast failure recovery scenarios (see section 4.1.2), which may necessitate a fast update of the phase set point. In order to check the capability of the proportional-integral corrector in tracking a phase set-point variation, a sine modulation (of 5 degrees in amplitude at a frequency of 50 Hz) is superposed to the nominal phase. Figure 3-35 shows the very satisfactory result. Not only the phase tracking was performed with an excellent accuracy (0.05°), but also the amplitude error is still maintained below the transient beam loading error due to the hole. On top of all, these simulations were carried out from the transient regime to the steady regime. The beam injection time was set to 1.1 ms. This shows that, even if the XADS accelerator operates in a

CW nominal mode, the RF feedback system should cope with transients due to failure recovery scenarios.

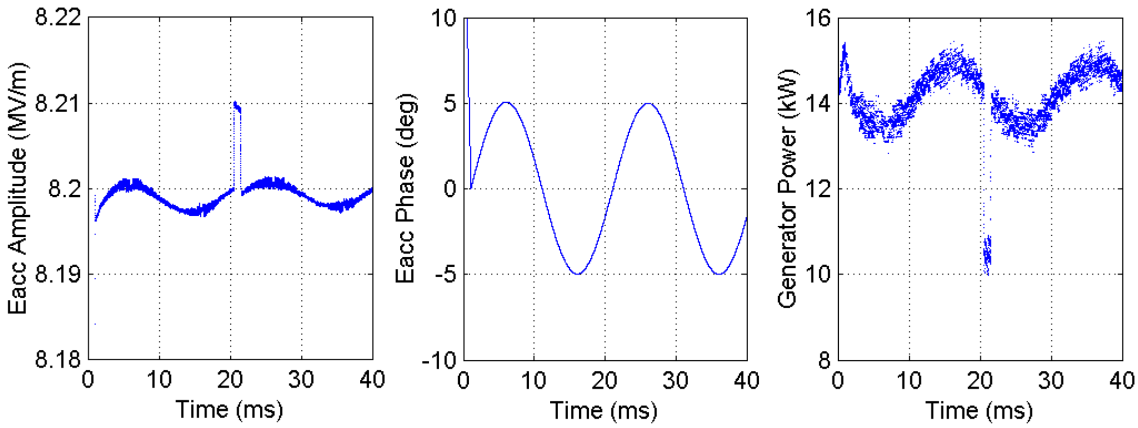


Figure 3-35 – Phase tracking (sinusoidal modulation, 50 Hz, amplitude 5 degrees).

The transient behaviour during beam interruptions is anyway quite difficult to simulate exactly. However, in order to give some insight of what could happen during the transients, the feedback response have been simulated assuming a beam interruption during a very short time from few hundreds of microseconds to a few milliseconds at regular intervals and changing the feedback system set points in the other cavities, while still operating in closed loop. Then, a new value to the amplitude or phase, or both set points at the beginning of the gap is given. A change of the amplitude set point impacts on the phase of the cavity and vice versa. When the beam is switched on at the end of the gap, transient beam loading is induced. Simulations have been carried out to estimate these effects. Figure 3-36 shows a 10% increase of the field amplitude set point (at time = 20.6 ms for a 1 ms gap) and the transient effect both on the cavity amplitude and phase. A phase step about 1.2 degree is observed immediately. Since the beam is switched off during the gap, this step does not have any effect on the linac operation. The real transient effect is observed when the beam is switched on after the gap. The deviation about only 0.1 degree shows the good performance of the fast feedback system. The influence of a phase set point change is also shown on Figure 3-37. These perturbations should be perfectly under control.

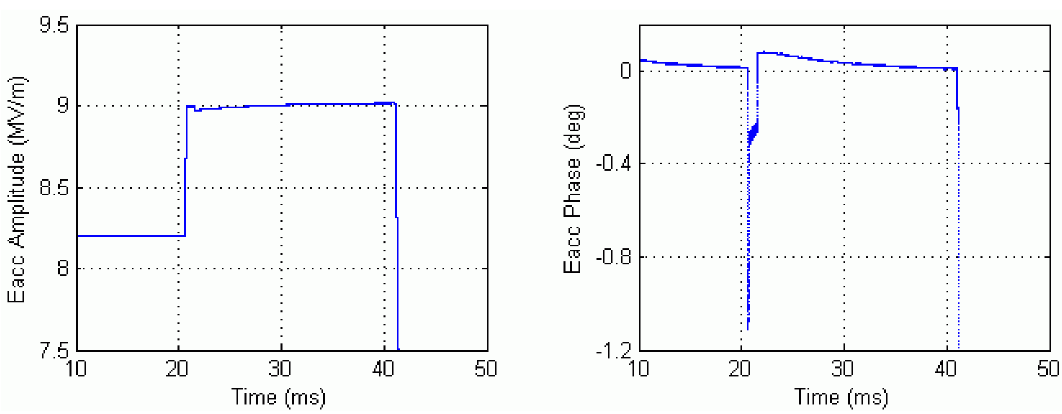


Figure 3-36 – Transient effect due to a 10 % amplitude set point increase.

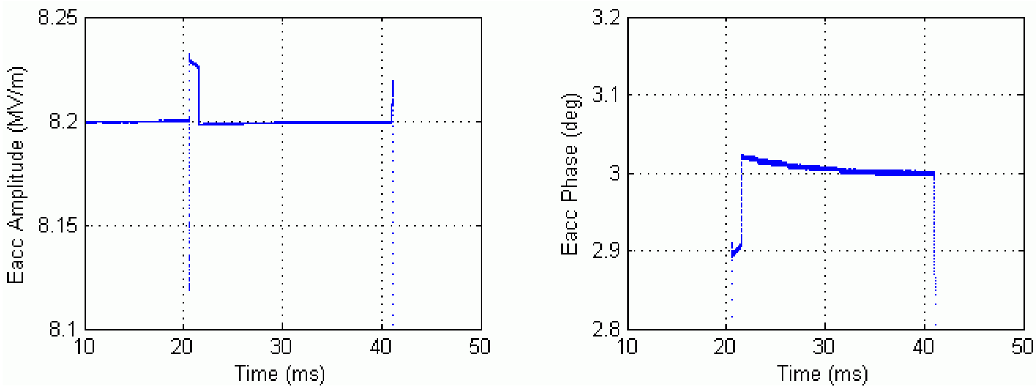


Figure 3-37 – Transient effect due to a 3 degrees set point change.

In the field of feedback systems for accelerators, analog techniques have been successfully implemented for even very demanding specifications, i.e. high gradient and pulsed beam **[92]**. Their main advantage consists in the very short propagation time in the analog components, particularly in the corrector. An Amplitude-Phase (A-P) loop delay lower than one microsecond is easily achievable, allowing consequently a high gain to accommodate a fast response and a better accuracy. Furthermore, the accuracy is not limited by the resolution of the digitized signals. Basically, a digital system would not differ too much from its analog counterpart, except that the I-Q loop has been substituted to the A-P loops (Figure 3-38). The reasons lie on the easy way to implement I-Q demodulation using Digital Signal Processing (DSP). The digital signal processing limits the loop delay to a few microseconds with the current semiconductor technology. Nevertheless, this delay is compatible with most feedback systems used for accelerators. In return, a digital implementation offers a high flexibility impossible to obtain otherwise. Filtering, correction and feed forward parameters can be changed or updated by a simple software configuration. A unique hardware is developed for all type of superconducting cavities feedback. In comparison with the analog system, the digital system presents also a higher level of integration. All key components can be integrated on a single chip, a field programmable gate array (FPGA) or a digital signal processor (DSP), with ADC (Analog to Digital Converter) and DAC (Digital to Analog Converter) front-ends. This integration offers a higher reliability, which is more difficult to achieve with analog assemblies. Flexibility and reliability make the digital scheme the best candidate for XADS. Furthermore, the integration of functionality offers at the same time a lower overall cost (less than 50% of the analog cost).

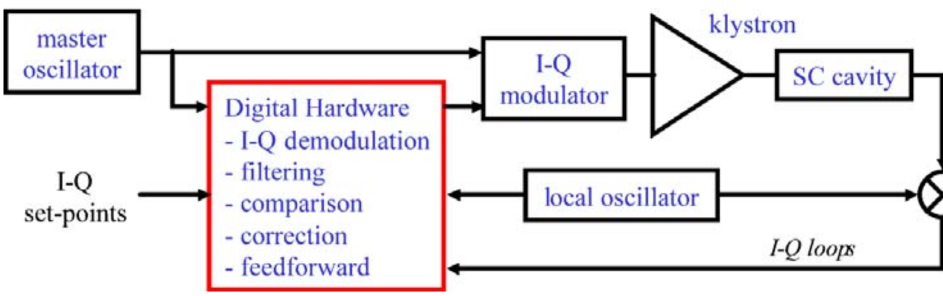


Figure 3-38 – Generic scheme for digital feedback systems.

3.2.4.3 Beam monitoring and hardware protection in the final beam transport line

The purpose of diagnostics and control systems of the final beam transport line is to monitor the beam in order to maintain a normal operation according to specifications and to protect the beam line equipments in case of malfunctioning. Beam protection is one of the main concerns for the XADS because very stringent requirements are imposed on beam stability and availability. Hardware protection is a new issue for all future high intensity facilities like neutron spallation sources, large circular or linear colliders. In these machines, unprecedented high power beams can cause considerable damages in case of uncontrolled beam losses. That is the reason why numerous studies concerning this problem are now in progress for projects like SNS, ESS, LHC, NLC and TESLA **[93,94]**.

Diagnostic devices are required to characterize beam properties (size, position, intensity) in the beam line and to determine the beam profile as close as possible to the target.

Central orbit distortions are induced by bending dipole and quadrupole misalignments or field variations. Maximum errors to be expected from a standard alignment are typically on the order of 0.2 to 0.3 mm for quadrupoles which are the most critical elements and of less than 0.5 mm for bending magnets which are much more tolerant. Although such combined mispositionings will result in maximum beam displacements of less than 5 mm at the target, a permanent central trajectory correction system will be implemented in order to maintain the beam on the reference axis. To this end, beam position monitors (BPMs) located close to quadrupoles will be used to detect beam deviations and to feed correction dipoles that will restore the beam on the axis. Periodic corrections will ensure that beam motion due to dynamic errors will not exceed specifications. It has to be noticed that correlated dipole field errors due to power supply ripple, remanent field or current setting precision will not induce beam drifts at the target if the two magnets are powered in series simply because the system is achromatic.

As mentioned above, a central energy change and an energy spread blow-up will induce a beam drift and a beam size enlargement in the dispersive region between the two bending dipoles. That is why water-cooled halo scrapers will be installed close to quadrupoles in order to probe the edges of the beam and to provide signals that will be used to trigger feedback systems so as to avoid off-normal conditions.

On-line measurement of the beam intensity will be performed with beam current monitors located at the entrance and at the exit of the beam line. They can provide a better than 1% accuracy and therefore will be used to stabilize current variations.

In a high intensity beam transport line, beam losses have to be minimized to keep activation at an acceptable level for hands-on maintenance and to protect equipments. Beam loss monitors are much more sensitive than current monitors. They can detect losses much below the acceptable level of 1 nA/GeV/m and can be used to identify the beam loss locations and timing. In case of unacceptable losses, they will be used to supply a trigger of an interlock that will switch off the accelerator beam.

Beam profile monitors are required to adjust and control the beam size and the proton distribution at the target. As foreseen for SNS and ESS **[95,96]**, secondary electron emission wire monitors also called Harps can be envisaged if they are located a few meters downstream of the last dipole, that is in a place where the beam density is not too high and do not limit drastically their lifetime. Harps will be able to monitor the beam size and the particle distribution continuously and to provide a beam-enable signal to the target protection system if the beam profile is not within specifications.

3.3 ACCELERATOR SHIELDING DESIGN AND ACTIVATION

Accelerator shielding design ---

The shielding calculations for the XADS accelerator facility have been done within Deliverable D48 **[5]**, using the analytical Moyer model **[97]**, extended to include an energy dependence for both the source term and the attenuation lengths for neutron energies below 1 GeV, based on data presented in reference **[98]**. This model has proven to give very reliable results (see different examples given in reference **[97]**) and has e.g. recently been used for the shielding design of the SPL project at CERN **[22]**. Recently, shielding designs were done using Monte-Carlo techniques, e.g. for ESS **[99]** and SNS **[100]**. A comparison between these results and the results obtained with the Moyer model showed that the Moyer model gives conservative, though realistic, results for the shielding requirements **[95]**.

The shielding calculations for the accelerator were assuming the following two normal beam contributions.

1. A constant linear beam loss rate under normal operation. The following conservative loss rates are obtained from the beam dynamics studies (see Figure 3-39): 3% beam loss in the RFQ, 10 nA.m^{-1} in the intermediate energy part of the linac and 1 nA.m^{-1} along the high energy part of the linac.
2. Failures of certain accelerator subsystems (e.g. RF, power supplies, etc.) may cause unwanted beam trips. The probability that a single person will be exposed to radiation from a number of such beam trips per year has been estimated. Events with a probability of > 10^{-2} per year have been included in the normal beam losses used to calculate the shielding requirements. Events with a probability of < 10^{-2} per year were considered as accidental losses (see hereafter). Using very conservative assumptions, the 10^{-2} per year probability corresponds to 8 full beam losses per year, seen by a single person. These 8 beam losses are therefore included in the normal beam losses. It was furthermore assumed that each full power (6 mA) beam loss lasts for 50 ms, a very conservative assumption in view of the reaction time of the accelerator and radiation monitoring interlock systems.

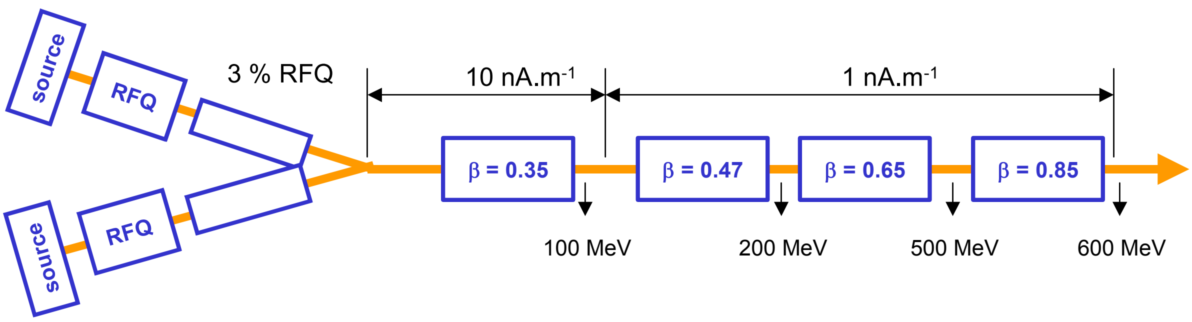


Figure 3-39 – Reference scheme for the XADS accelerator, showing the normal beam losses used for the shielding calculations.

The shielding for the XADS linac is provided by the concrete tunnel walls and the earth covering the tunnel. Figure 3-40 shows the combined concrete/earth thickness required at the maximum proton energy of 600 MeV for a distance between the beam axis and the inner shield wall of 200 cm, for three different values of the linac beam power losses (1, 2 and 5 nA.m^{-1}). Less than 1 m of earth, or 70 cm of concrete are required to reduce dose rates by a factor of 5.

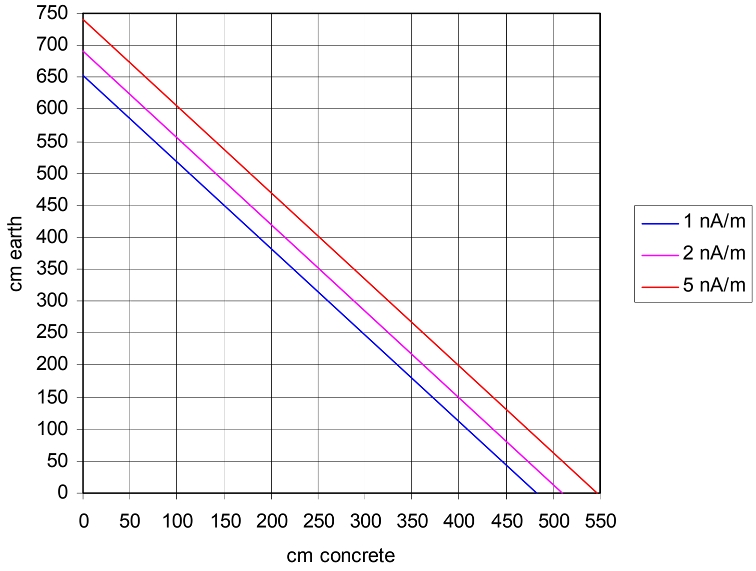


Figure 3-40 – Required concrete/earth combined thickness at 600 MeV, for a distance between the beam axis and the inner shield wall of 200 cm, for 3 values of the linear beam power loss: 1 nA.m^{-1}, 2 nA.m^{-1} and 5 nA.m^{-1}.

Figure 3-41 shows the required earth thickness along the high-energy part of the linac, for 4 different values for the concrete shield wall, for a linear beam loss power of 1 nA.m^{-1} (taking into account the 8 beam trips per year).

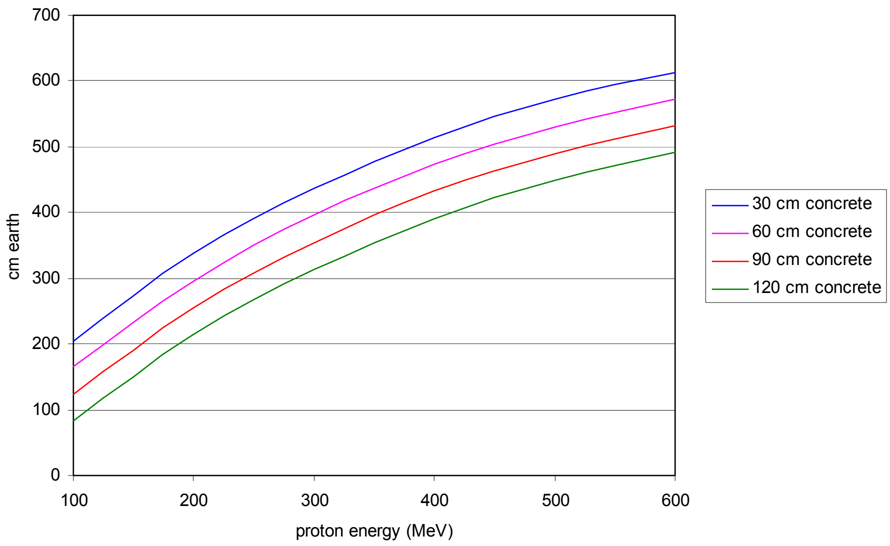


Figure 3-41 – Required earth thickness along the high-energy part of the linac for four different values of the concrete shield wall thickness, for a linear beam power loss of 1 nA.m^{-1}.

As an example, Figure 3-42 shows the required earth profile for a proton energy of 600 MeV, in the case of a 60 cm thick concrete tunnel. In reality the earth profiles will have a less steep slope, especially near the bottom. This implies that, especially in the areas where people can be present, the shielding provided will be more than the minimum shielding required.

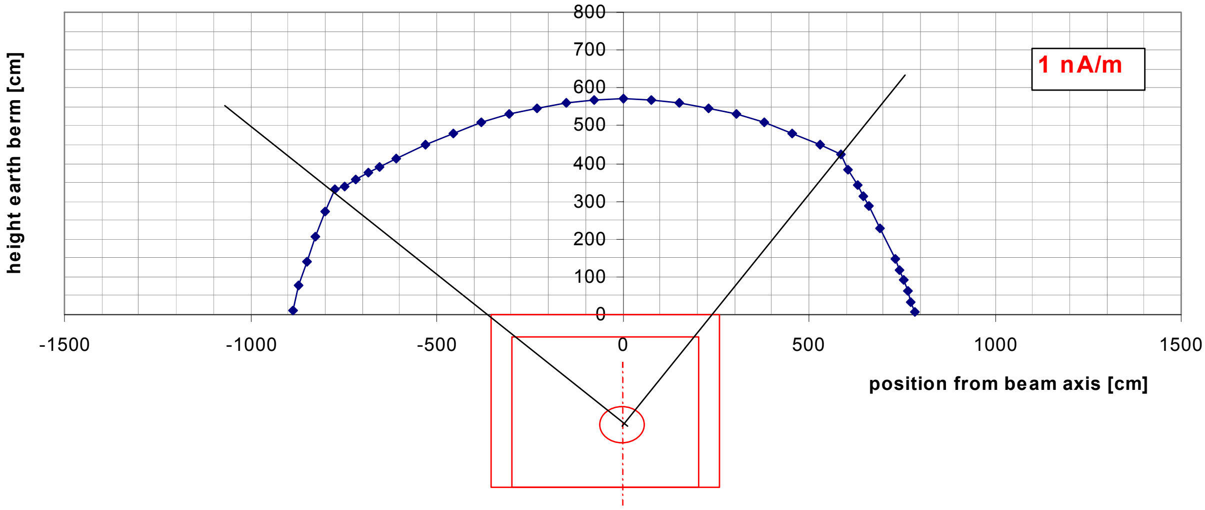


Figure 3-42 – Required earth profile above 60 cm concrete linac tunnel; proton energy: 600 MeV; linear beam loss power: 1 nA.m^{-1}.

The beam dynamics studies show that the linear beam losses in the intermediate energy part of the linac should not exceed 10 nA.m^{-1}. These losses will be located near the scraper after the DTL structures. As a conservative assumption we assumed that the beam losses take place at a proton energy of 100 MeV. Figure 3-43 shows the concrete / earth thickness necessary to reduce the residual dose value outside the shield wall to 0.5 µSv.h^{-1}.

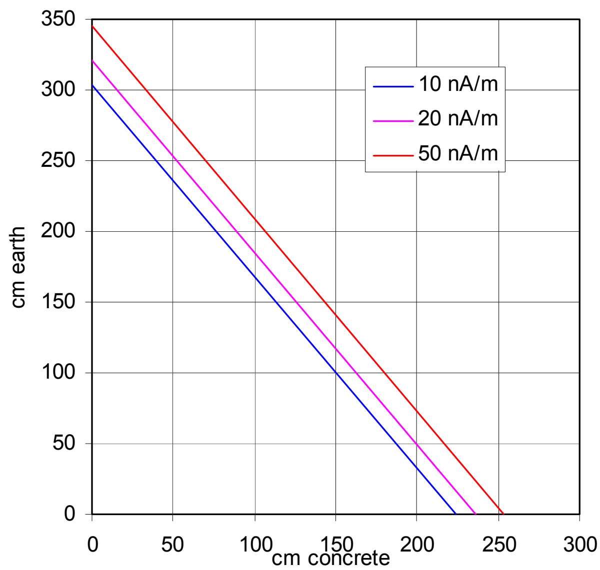


Figure 3-43 - Required concrete / earth combined thickness at a proton energy of 100 MeV, for three values of the linear beam power loss: 10 nA.m^{-1}, 20 nA.m^{-1} and 50 nA.m^{-1}.

The beam dynamics studies show that the beam losses in the RFQ should not exceed 3 % of the beam. The following conservative beam loss assumptions were used for the shielding calculations of the low energy part of the accelerator. A maximum value of 6 mA for the beam current was used. We assumed that the beam is lost in a single point, at a proton energy of 5 MeV. As before, we included 8 (6 mA, 50 ms) beam trips per year. Figure 3-44 shows the concrete / earth thickness necessary to reduce the residual dose value outside the shield wall to 0.5 μSv.h^{-1}.

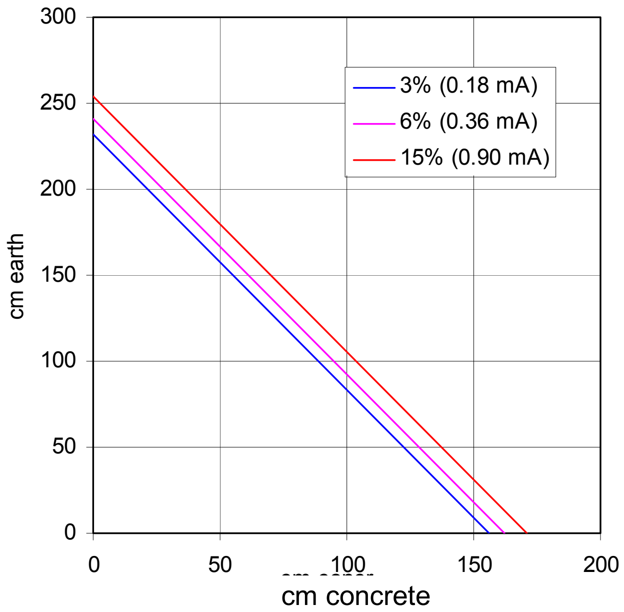


Figure 3-44 - Required concrete / earth combined thickness for the low energy part of the linac, for three values of the local beam power at 5 MeV: 300 nA, 600 nA and 1.5 mA.

The shielding calculated for the normal beam losses was afterwards evaluated for accidental beam loss scenarios. A probabilistic evaluation was made to calculate the risk R for a single person for the following two accident conditions.

1. As explained before, the probability that a single person will be exposed to more than 8 unwanted full beam losses per year is smaller than 1.10^{-2} per year. Exposure of a single person to more than 8 full beam losses per year will therefore be treated as an accident condition.
2. We have assumed that a full beam loss will not last more than 50 ms. The second accident condition we consider is a full beam loss which lasts longer than 50 ms, because of a failure of the accelerator interlock system and the radiation monitoring interlock system.

It was shown that for both scenarios the risk R is smaller than 1.10^{-6} per year (= trivial risk, in line with latest ICRP recommendations) and we can therefore conclude that the shielding defined for normal losses is also safe for accidental beam loss conditions.

Finally, it was also shown that the shielding profiles derived from the requirements for normal operation will provide sufficient shielding for the planned commissioning period as well as for planned periods of beam tuning and setup. Indeed the proposed shielding will allow beam loss rates 100 times higher than during normal operation during significant periods of time.

As we have shown in the Deliverable D48 **[5]**, the considerations are also valid – and the values available – for the 350 MeV as well as for the 1 GeV XADS linac.

Activation inside the XADS tunnel ---

A rough estimation of the dose rate at 50 cm near a E GeV proton accelerator or beam line where beam losses of 1 W per meter occur, taking into account self-shielding from the magnets, can be obtained from **[98]**:

$$D = 30 \times E^{-0.08} \times \ln\left(\frac{T_{irr} + T_{cool}}{T_{cool}}\right) \quad \mu Sv.h^{-1} \text{ at 50 cm}$$

T_{irr} is the time the linac has been running (with losses = 1 $W.m^{-1}$) and T_{cool} is the time since the shutdown of the linac. In the case of 600 MeV protons and 1 $nA.m^{-1}$ beam losses, we obtain dose rates of the order of 100 $\mu Sv.h^{-1}$ after several days of decay. These estimated dose rates show that interventions inside the linac tunnel, in case of a linear beam loss of 1 $nA.m^{-1}$, will require special safety measures (local shielding, planning, design of components for fast dismounting and mounting…).

Activation of earth around the XADS accelerator ---

The problem associated with the activation of earth surrounding the XADS accelerator tunnel is the risk of having to treat this earth as radioactive waste during the final decommissioning of the facility. From the experience of the decommissioning of other large scale accelerator facilities we know that it takes typically at least 5 to 10 years from the last beam to the final decommissioning (removing the earth layers around the tunnels will take place in the final phase of the decommissioning). We have therefore estimated the specific activities after 5 years and after 10 years cooling down to characterize the problem. The European Directive 96/29/Euratom has defined exemption limits, below which activated material can be treated as standard waste. These limits have not been adopted in the French legislation, which means that the earth layer surrounding the XADS tunnel must ultimately be treated as radioactive waste. Belgium, as an example, has adopted these exemption limits. The results from the calculations show that, even after a cooling down period of 10 years the first one to two metres of earth surrounding the tunnel should be treated as radioactive waste.

3.4 INFRASTRUCTURES

The very particular characteristics of the accelerator also mean very particular support infrastructures. Namely, this support infrastructure will play an important role in maintaining the required goals of reliability and availability. In particular, the redundancy required to achieve those goals will mean, for example, more complex circuits and networks.

The infrastructures referred here include the accelerator buildings (front end building, linac tunnel, klystron hall, central workshop, offices building, etc.) and the main services (electrical power distribution network, cryogenic plant with 4.2 K and 2 K transfer lines, demineralised cooling water circuit, compressed air circuit, air conditioning closed circuit, etc.). The exact figures will depend much on the final design parameters (beam energy, etc.) and configuration. It has to be noted that the required large cryoplant is a non standard infrastructure; it is described in section 3.2.2.3.

The accelerator complex infrastructures will also be very much related to the reactor, and this has important implications, for example for the cost estimates, which can only be meaningful if one studies the accelerator and the reactor as a combined system. However, this text restricts itself to the accelerator complex.

Other general site-wide required infrastructures, not clearly identified here, include access roads, good external communication links, industrial water, gas connections, and main sewer connections. Also, the accelerator infrastructures need large buildings and areas physically separated from the linac building (for example, the power network stations or the cryogenic plant).

Main buildings --

In order to establish an initial planning for the infrastructures buildings, one can extrapolate from the experience of the ESS study **[95]**, given the similarities of the two machines.

A possible solution for the front-end building, with a single building including the main services, is sketched in Figure 3-45. This could accommodate the two sources and injection lines (eventually with extra shielding separating them), the klystrons, power supplies, cooling system, etc..

Concerning the linac tunnel, a possible solution is shown in Figure 3-46, detailed for the ESS superconducting high-energy section. Similar cross-sections can be drawn for the other sectors. The main tunnel, which is below the ground level, includes all the main circuits (HVAC, water, air, etc.); it is accessible by several chicane accesses regularly located all along the linac. The klystron hall is external and easily accessible.

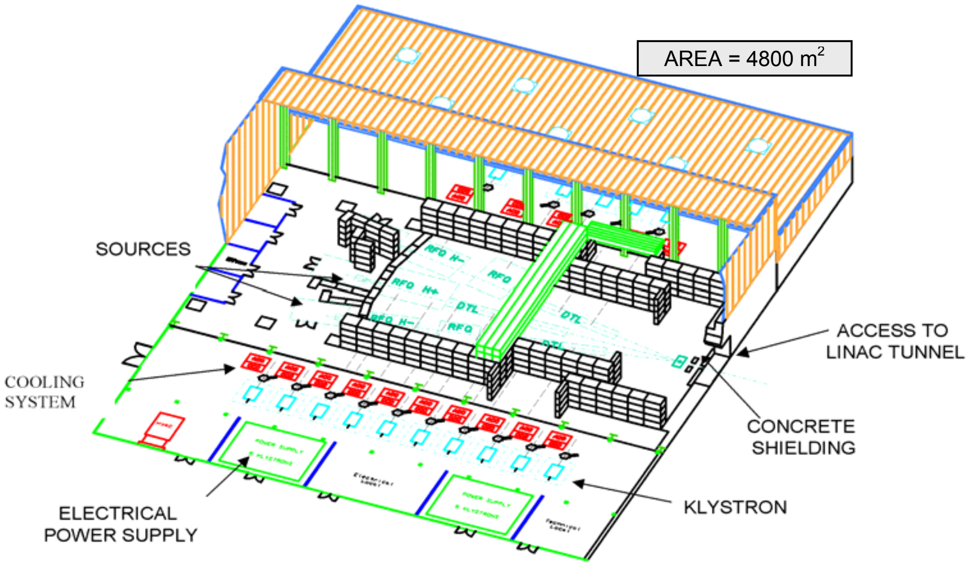


Figure 3-45 – ESS linac front-end 3D view **[95]**.

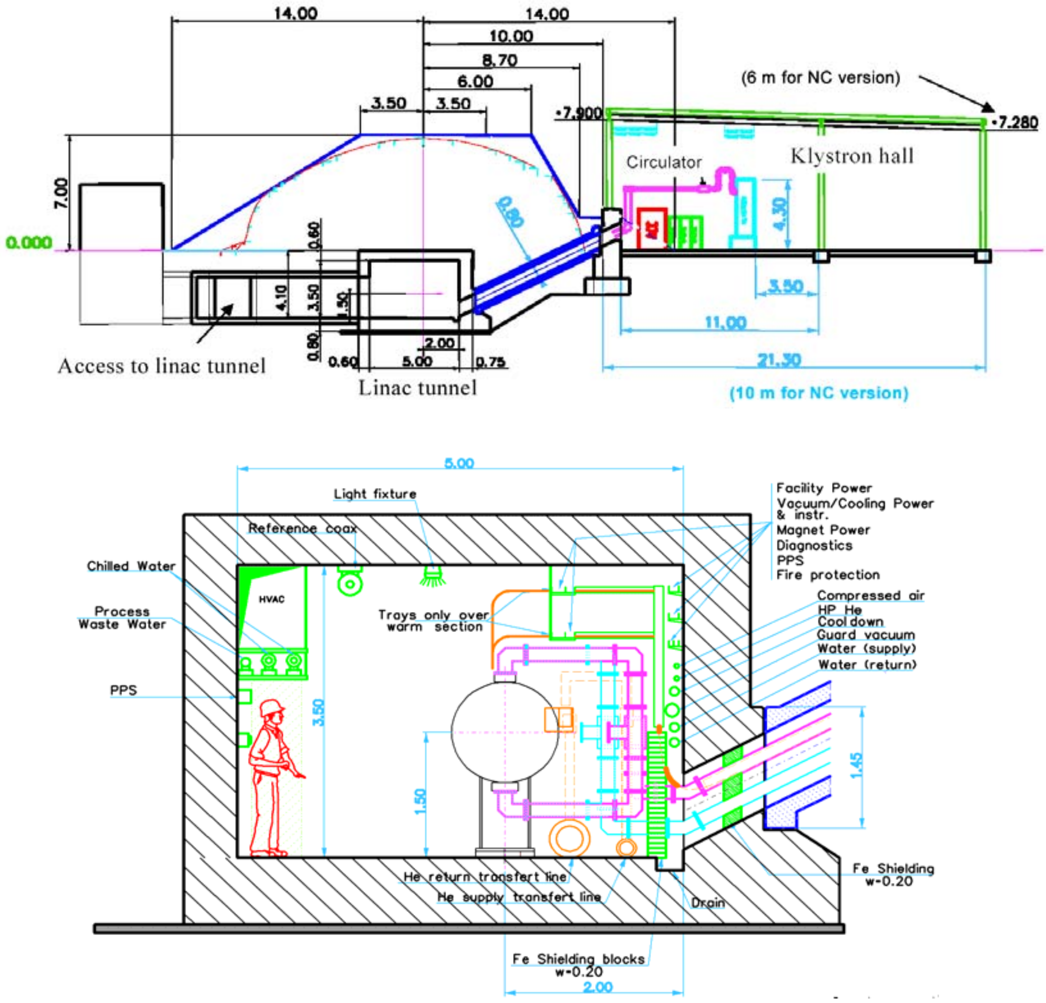


Figure 3-46 – (Up) Cross-section of the ESS linac tunnel and klystron hall. (Down) Detailed view of the ESS linac tunnel (superconducting section) **[95]**.

Electrical power ---

One major infrastructure will be the electrical power distribution network. Although the final linac layout is not yet completely frozen, three scenarios have been identified in order to roughly estimate the electrical needs of such an accelerator:

- scenario n°1: a doubled room-temperature front-end linac is used up to 5 MeV, followed by a superconducting modular linac up to 600 MeV,
- scenario n°2: a doubled room-temperature front-end linac is used up to 50 MeV, followed by a superconducting modular linac up to 600 MeV,
- scenario n°3: a doubled room-temperature front-end linac is used up to 20 MeV, followed by a superconducting modular linac up to 600 MeV.

In scenario n°1, the linac power requirements will come mainly from the RF needs of the two RFQs (one on operation + one on standby) and of the superconducting sections (see Table 3-9). This leads to a total AC power for RF needs of 17.2 MW and to a total AC power for the whole accelerator of about 24.4 MW. This is the "lowest AC power" scenario, thanks to the use of superconductivity from 5 MeV.

The "highest AC power" scenario is of course scenario n°2, where a doubled room-temperature front end is used up to 50 MeV. This scenario, that is actually not very realistic, leads to a total AC power of 33.9 MW. The third scenario should represent a more realistic "upper limit scenario", with a doubled room-temperature front-end going up to 20 MeV. In this case, the total AC power is around 27.6 MW.

Table 3-9 – Rough estimation of the electrical AC power needs of the XADS linac.

AC power for:	**Scenario n°1**	**Scenario n°2**	**Scenario n°3**
Doubled linac front end RF needs*	4.5 MW	15.3 MW	8.1 MW
Superconducting linac RF needs	12.7 MW	11.7 MW	12.4 MW
Cryogenic system	2.2 MW	1.9 MW	2.1 MW
Others: cooling, ventilation, general services…†	5 MW	5 MW	5 MW
Total AC power needs	**24.4 MW**	**33.9 MW**	**27.6 MW**

The electrical power must be provided at 20 kV from 2 feeders. Power stability should be better than ± 7 % in voltage and ± 1 % in frequency, with one maximum power cut off of less than 600 ms per year, a maximum of 3 voltage drops per year (exceeding 400 ms or 12% amplitude, over 2 phases, or exceeding 8% amplitude, over 3 phases), and a short circuit power between 200 and 400 MVA. Moreover, for improved reliability/availability, there must be loops and separate electrical sources for building use, accelerator and target.

* Estimation based on the power consumption of a RFQ followed by a classical copper DTL structure (twice).
† An arbitrary value of 5 MW has been taken here.

Chilled water system---

An idea of the chilled water system, needed for the cooling of room-temperature accelerating structures (1.2 MW RF power is dissipated in a 5 MeV RFQ), is suggested in Figure 3-47. It proposes two separated central utility buildings in order to make possible the use of standard and smaller equipments, given the power and reliability requirements.

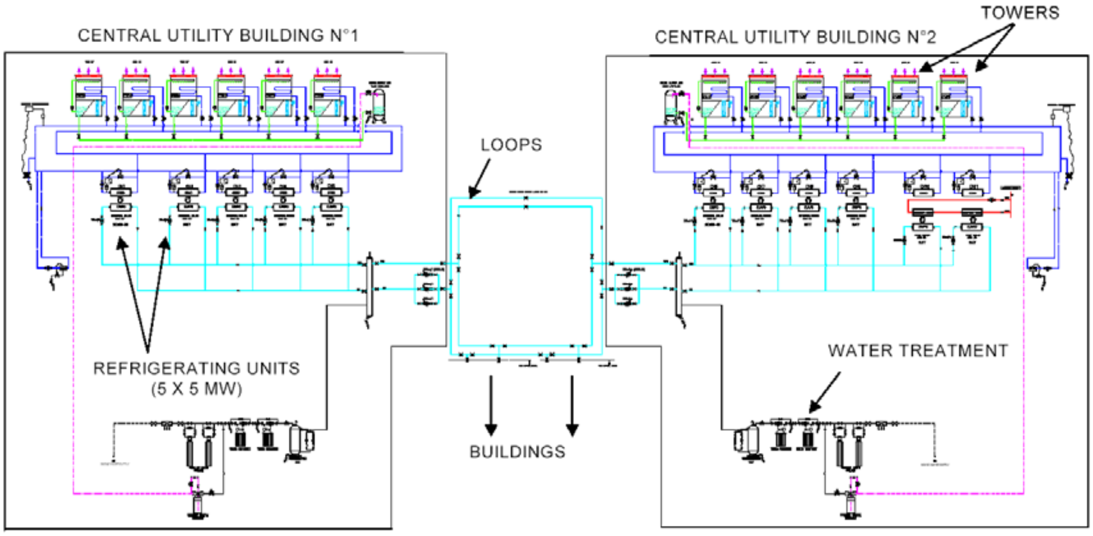


Figure 3-47 – Typical layout of a redundant chilled water distribution (from ESS study) **[95]**.

3.5 ACCELERATOR TIME SCHEDULE AND COST ESTIMATES

3.5.1 Accelerator time schedule

Consecutive to an advanced technology programme which may be completed in a 4-year R&D phase, the construction of the accelerator of the XADS facility typically may take 7 years, as shown in Figure 3-48. We discuss in section 5 this technology programme, focused on the required reliability of the accelerator, and we may note, in passing, that an important part of it will be accomplished within the 6th FP Integrated Project EUROTRANS that has been approved for funding and has entered, at the time of writing, the phase of contract negotiating with the Commission.

The estimated duration for construction is based on industrial studies and experience gained from the construction of similar facilities like ESRF, SOLEIL and SNS. The conventional facilities programme, including the associated infrastructures, is one of the most critical from the standpoints of technical risks, schedule and costs. Machine parts can generally be ready for installation well before the buildings are completed. Therefore, the conventional facilities dictate the overall construction schedule. Highest priority is required for starting the conventional facilities programme and for placing the INdustrial Architect (INA) contract as soon as possible, to be ready when the building licence is delivered by the authorities. Note that the infrastructures of the accelerator are part of the XADS nuclear plant and should be studied at the same time by the same organisation.

However, the critical path for obtaining the building licence also depends on the writing delays in parallel with the request of the nuclear plant creation and the request of the effluent discharge authorisation, followed by the safety authority analysis and public enquiry led by the prefecture. The decrees will be published after additional advice received from different inter-ministerial commissions, which can take many years.

Figure 3-48 shows the XADS accelerator time schedule in terms of project years (PY) relative to the year of a decision to build the facility. After a decision to go ahead with baselining and construction planning for the project, it will take about half a year to assemble a project team and further one and half year and about 20 M€ to carry through this construction planning and baselining. Making reference to the time schedule of Figure 3-48, the relevant activities and milestones can be summarised as follows:

- year 2004 (end of FP 5): general conceptual design of accelerator and beam transfer line up to the spallation target;
- years 2005-2008 (FP 6): advanced technology programme focused on the reliability of the injector (IPHI), intermediate energy section, high-energy section (i.e. fully equipped SCRF cryomodule) and RF system.

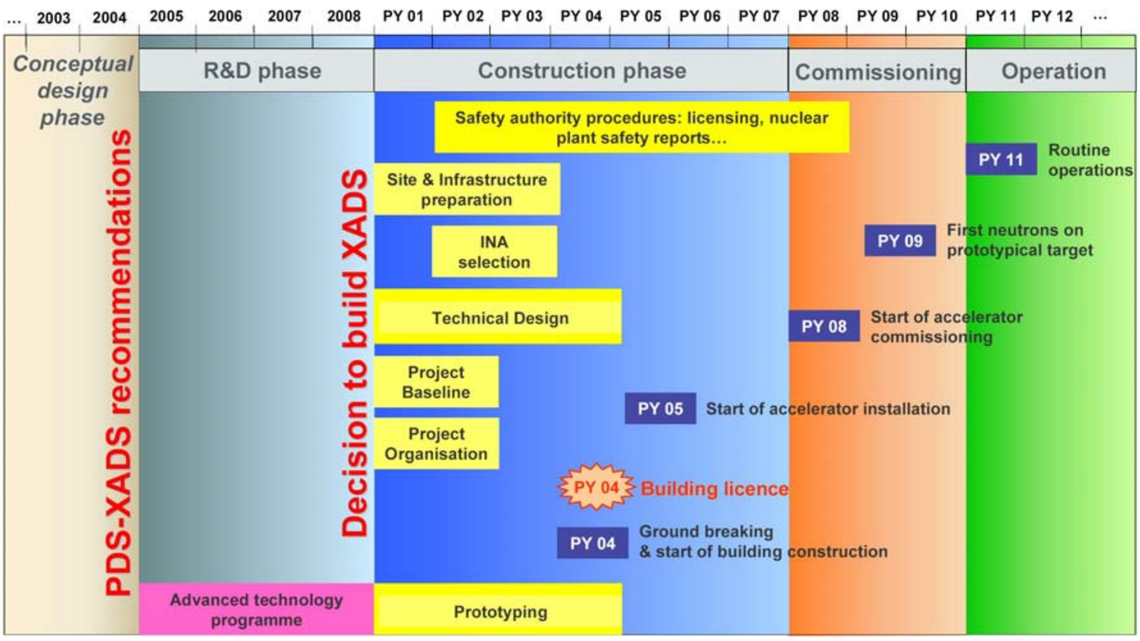


Figure 3-48 – Possible XADS accelerator roadmap with some typical milestones.

And after the decision to go ahead at a selected site:

- years PY 01 and PY 02: are a baselining period corresponding to the:
    - project organisation;
    - project baseline;
    - start of the 4 years technical design period (preliminary & detailed design);
    - start of prototyping
    - selection of the INdustrial Architect (INA);
    - start of infrastructure preparation at the site of construction;
    - this step will also include the start of the licensing procedure of the full XADS plant, which is foreseen to be more troublesome than current procedures for issuing construction and operation permits;

- in the years PY 03 and PY 04 most of these activities continue, the building licence should be obtained and the groundbreaking start;

- this allows to start the accelerator installation in PY 5, which should be finished in typically 3 years.

Assuming that the prototypical spallation target runs on a similar schedule, a commissioning phase of the complete chain of accelerators and the beam transport line up to the spallation target of 3 years is proposed from PY 08 on. This rather conservative number takes into account that

- the power delivered by the accelerator to the target will increase step by step up to full performances at 3.6 MW;

- there is a comfortable margin of time for running in all components so that childhood problems are overcome and maturity for routine operations achieved
- several series of long-term reliability test have been made in order to provide robust statistics on fault-tolerance, preventive maintenance and safety grade shutdown.

With the beginning of year PY 11, the start of routine operation can be envisaged, and in particular the coupling to a subcritical core.

3.5.2 Accelerator cost estimates

The cost estimates are based on the extrapolation to 6 MW of the updated ESS Project studies presented in Bonn Conference (May 2002), taking into account that ESS accelerator has been designed for pulsed operation, whereas the XADS will be operating in continuous mode, with a different RF power distribution scheme. Additionally, the on-going construction of 1.4 MW SNS (to be operational in 2006) is being closely followed and, finally, the experience of other large-scale European facilities (ESRF, PSI, SOLEIL) has been incorporated.

It is assumed that the site is donated free of charge and that no land taxes will have to be paid. Similarly, access roads, telephone and computer links, fire brigades, electricity lines, water mains, etc. should be provided free of charge up to the site boundary by the host country. Construction costs are quoted at 2003 prices, and are exclusive of Value Added Taxes (VAT) and customs duties.

Architecture of the linac ---

Regarding the negligible difference in terms of linac architecture between ESS project and XADS studies, and keeping in mind the potential for the SC version to offer a better solution for XADS, the linac process costing in this chapter will be extracted of ESS, up to 600 MeV. The installed power could give enough safety margins in regard of the full power needed for accelerating the beam (6 MW). Figure 3-49 compares the ESS and the proposed XADS accelerator layouts, with the indications on the relative lengths and transition energies between different acceleration stages. In the same way, Figure 3-49 shows the possible configurations for 350 MeV or 1 GeV.

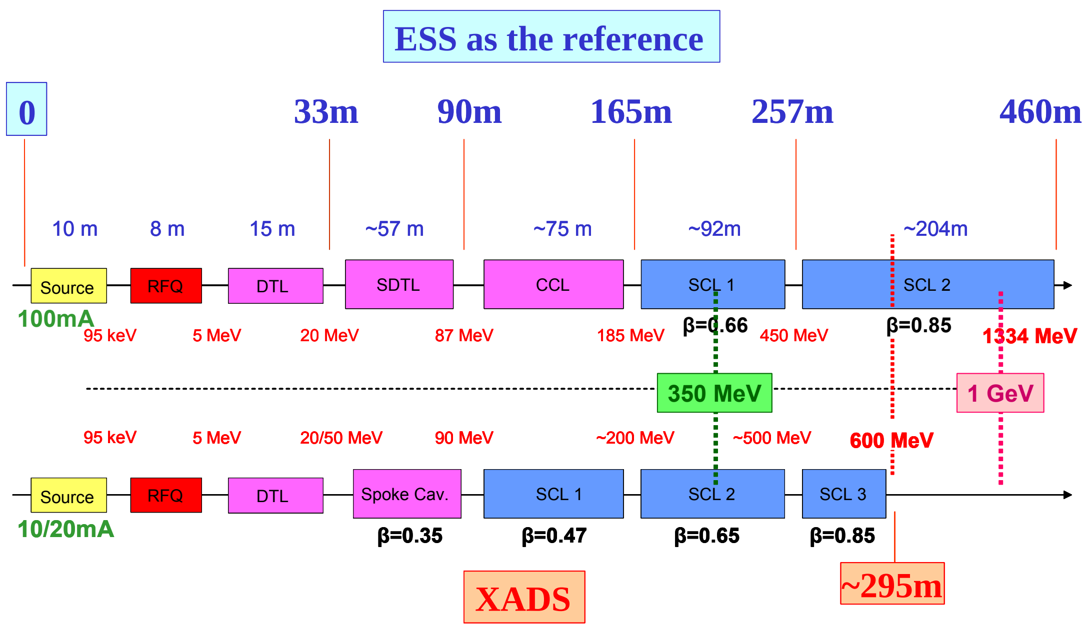


Figure 3-49 – Comparison between the ESS and the XADS accelerator layouts.

Construction costs breakdown **--**

The construction costs of the linac XADS facility amount to **273 Million Euro** at 2003 prices.

This figure includes not only capital investments for all components necessary for the XADS linac baseline as described in section 3.2, but also all the manpower required (in-house and subcontracted staff) at the various stages of the project: detailed design, procurement, construction, testing, installation and commissioning.

A breakdown of construction costs into major subsystems including in-house and external manpower is shown in Table 3-10 here under.

Table 3-10– Breakdown of linac construction costs into major sub-systems.

Major sub-systems	Costs (M€)
Low Energy *	46
Intermediate Energy	18
High Energy	57
RF Power System	45
HEBT + Beam dump (500 kW)	21
Diagnostics + Vacuum + Control System	54
Cryogenic plant	20
Production assembly Hall of cavities	12
Total Estimated Costs (M€)	**273**

* including 2 Injector lines

In order to supply a more complete estimation of the total cost of the linear accelerator several important items should be added to the present estimations:

1. the site engineering and site work;
2. front-end building, linac tunnel, klystron hall;
3. the general service buildings (electrical systems, water systems, chillers and HVAC, ventilation, central workshop, office building, etc.).

The accelerator facility will lay close to the sub-critical system, which will have in turn requirements (and regulations) on electrical power, air and water cooling systems, workshops and office buildings, a meaningful estimate of the costs for these service infrastructures would be provided only by a study of the complete (accelerator + sub-critical vessel) system, answering to the points 1 & 3.

Table 3-11 shows the cost estimates of the linac associated buildings subdivided on one hand in “Civil Engineering”, and on the other hand in “Electricity & Heating, Ventilation and Air Conditioning distribution” (HVAC).

Table 3-11 – Cost estimates of linac associated buildings.

Buildings	Civil Engineering	Electricity & HVAC distrib.	Total
Front - End	7 000	3 000	**10 000**
Linac tunnel	4 500	1 500	**6 000**
Klystron Hall	3 000	7 000	**10 000**
Central Liquifier	600	900	**1 500**
Production assembly Hall	1 250	1 250	**2 500**
Total (k€)	**16 350**	**13 650**	**30 000**

***Dismantling* ---**

The inclusion of the dismantling procedure into the XADS facility during the feasibility studies, may lead to specific technical solutions or specific material choices to facilitate surface decontamination during operation period and reduction of the quantity of waste during dismantling. As a result, a small investment cost-overrun might occur during the construction period. However, this will be compensated by operational ease and a reduction of the eventual dismantling cost.

After a 20 to 30 year period of operation, the dismantling of the facilities will take place according to the safety rules in force at that date in the retained country, to restore the site to a "clean" and grassed condition, similar to the initial one. Dismantling cost will be provided at the end of the baselining period (PY 02) in the final Technical Design report.

However, preliminary cost-estimation can be done. A ratio of 15 to 18 % of the capital cost is commonly used for the provisional dismantling cost-estimate of nuclear plants. Moreover, taking into account the experience of CEA/DAPNIA/SDA during dismantling of ALS and SATURNE, a reasonable ratio should be around 10%. Assuming that the accelerator area (source, linac) as well as the HEBT transfer line up to the spallation target are only activated (not contaminated), the resulting estimate of accelerator dismantling (including waste treatment and evacuation), would be of the order of 30 M€. These dismantling costs will not be provided in the construction phase. However, a dismantling provision should be proposed within the framework of the long-term operational budget.

4 OPERATION OF THE XADS ACCELERATOR

Operating a high power accelerator that, in addition, asks for an extremely low number of beam trips is a very challenging task, which has to be taken into consideration very soon in the design phase of such a machine.

This chapter will try to identify and describe the main stakes related to the XADS accelerator operation. Section 4.1 will first analyse the fault-tolerance capability of the XADS linac, identifying the main fault scenarios which one can expect, their impact on the machine operation, and the consequences concerning the accelerator design. Section 4.2 will describe the main issues dealing with the accelerator's commissioning phase, routine operation, and abnormal operating conditions. In section 4.3, the first results of a completely new reliability analysis of the accelerator are presented. They give confidence in the feasibility of the XADS with regard to beam trip specifications. Finally, preliminary studies on a maintenance strategy in-line with the reliability requirements will be described (section 4.4).

4.1 FAULT SCENARIOS

In current high-power accelerators, specific diagnostics are usually connected to all major accelerator components, continuously sending its status information. When a component fails (this means that the information status suddenly switches from “normal” to “faulty” for any reason), the beam is immediately shut down. Action is then taken to repair the faulty component, eventually necessitating to actually replacing the hardware. After which, when the accelerator operation is ready to resume again, the procedure followed is quite identical to a new re-start, slowly ramping up in beam power. For most accelerators, the number of beam interruptions rapidly decreases with the trip duration time, thus maintaining an overall good level of availability. And in most applications, despite the high number of short time breakdowns, operation is not too much affected as high availability is preserved.

But for an ADS application, any beam trip lasting more than a second will be considered as a major accelerator failure, leading to the reactor core shutdown. Thus, the philosophy prevailing on current machines to cope with component failures should be reconsidered, taking into account that requirement. In particular, for each failure analysis, the design should look at the ability to either maintain the beam under safe conditions, or to recover the beam through, in less than one second. This is a new feature, not required for any other accelerator application, which is quite specific to ADS linacs.

The XADS reliability requirement specifies that a continuous beam operation with only a few (of the order of 5 per year) beam stops longer than approximately one second is considered to be mandatory for the successful demonstration of the ADS coupling. As already mentioned, this requirement appears to be highly challenging given the state-of-the-art in the field of accelerator reliability, but no potential showstopper on the path for achieving an extremely reliable accelerator emerged from the analysis performed so far. It is clear that suitable design strategies had to be followed early in the conception stage of the XADS accelerator. The main guidelines that have been highlighted to drive the design are: a strong design (which makes extensive use of component derating and proper redundancy) and a high degree of fault tolerance (i.e. the capability to maintain beam operation within nominal conditions under a wide variety of accelerator component faults).

4.1.1 Fault tolerance in the linac front-end

The XADS linac front end is composed of a "classical" proton injector (ECR source + normal conducting RFQ structure), followed by additional warm IH-DTL or/and superconducting CH-DTL up to a transition energy still to be defined (between 5 and 50 MeV). Such accelerating structures are obviously not fault-tolerant, that means that a failure of one of them will systematically imply a complete loss of the beam.

To overcome this weakness, the idea is here to double the whole linac front end, adding in parallel a “hot stand-by” spare that can be immediately turned on in case of a failure in the main injector.

Such a "parallel redundancy" improves the overall reliability of the accelerator, under the condition that, in case of failure, a sufficiently rapid switch of the beam can be done from the faulty injector to the spare one. Such fast switching dipole magnets, using a laminated-iron yoke in order to avoid Eddy currents, have proven to be very reliable (e.g. at GANIL, France or for proton-therapy application at Centre de Protonthérapie, Orsay, France).

4.1.2 Fault tolerance in the independently phased SC sections

Above the transition energy*, a fully modular superconducting linac brings the beam up to the final energy, using spoke and elliptical cavities. This section is designed to be intrinsically fault tolerant, which means that an individual cavity failure can be handled at all stages without loss of the beam. This characteristic relies on the use of highly "de-rated" and independently powered accelerating components, associated to a fast digital feedback system and adequate diagnostics. This fault-tolerance capability is a crucial point in the design of the XADS accelerator in order to guarantee the few number of beam stops per year dictated by the target requirements. The state of the art in RF system technology is indeed not reliable enough to envisage an operation of the accelerator during several months without any beam trip. We can actually foresee at least a few tens of failures per year, only due to these RF systems, based on parts count reliability estimates. Therefore, even if a great effort can be surely directed at improving the MTBF of RF systems, it seems difficult to reach the reliability requirements without implementing any fault-tolerance philosophy for the linac design.

Consequences of the failure of a superconducting RF cavity -------------------------------------

Let us assume in this section that the RF system fails to power a cavity somewhere in the linac, and that this cavity is immediately detuned to avoid the beam loading effect. This results in a loss of the energy gain provided by the failed cavity, and then in a beam longitudinal (phase-energy) mismatch at the entrance of the following cavity. Because we deal with a non-relativistic proton beam, this energy loss will imply a phase slip along the linac equal to $\delta\phi = 2\pi\,(\delta z/\lambda)\,(\delta\beta/\beta^2)$, increasing with the distance δz from the faulty cavity; β is the beam velocity (normalized to c), λ the RF wavelength and $\delta\beta$ the velocity loss (compared to the reference beam velocity) at δz **[101]**.

Of course, the consequences of such a failure strongly depend on the position of the cavity in the linac, and on its operating conditions. The problem is more serious when the velocity of the particle is low, but also when the accelerating field and the operating frequency of the cavity are high. Figure 4-1 shows, for each cavity of the XADS reference linac, the phase slip induced at the entrance of the subsequent cavity if a cavity fails. It rapidly appears from this graph that the most critical sections of the accelerator towards the fault-tolerance problem are the first β=0.15 spoke section and the first β=0.47 elliptical section.

Another important parameter to be taken into account in the analysis is the longitudinal acceptance of the linac. The lower is this acceptance (i.e. the higher is the synchronous phase compared with the longitudinal size of the beam), the faster the fault-induced phase slip will off-set the beam towards the phase instability region. One way to avoid the problem could thus be to lower both the synchronous phase (near the -90° bunching value) and the

* We will in this section consider the case of a 5 MeV transition energy.

accelerating gain per cavity along all the linac, but this would lead to an unacceptable increase in linac length and cost.

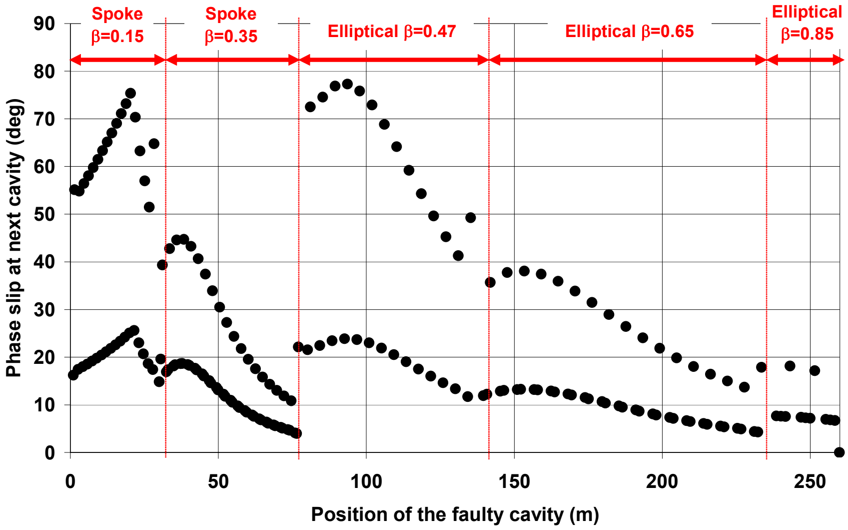


Figure 4-1 – Beam phase slip induced at the subsequent cavity as a function of the position of the faulty cavity in the linac. This phase slip is of course larger for a faulty cavity located at the end of a lattice.

In the XADS reference linac, where conservative but realistic synchronous phase and accelerating field values are used, simulations show that in almost every case, the fault of a cavity induces a sufficient phase slip to rapidly drop the beam out of the phase stability region. The beam can then not be correctly handled longitudinally in the subsequent cavities, and it is finally completely lost later in the linac (see example on Figure 4-2). This kind of behaviour with a final 100% beam loss is encountered for any cavity fault in the linac, except in the specific case of the first spoke cavity's failure (where only 40% of the beam is lost thanks to the low synchronous phase and the very low accelerating field used in this first cavity) and in the case of the last elliptical cavities' failure, at the very end of the linac, where the induced beam phase slip doesn't have any more consequences.

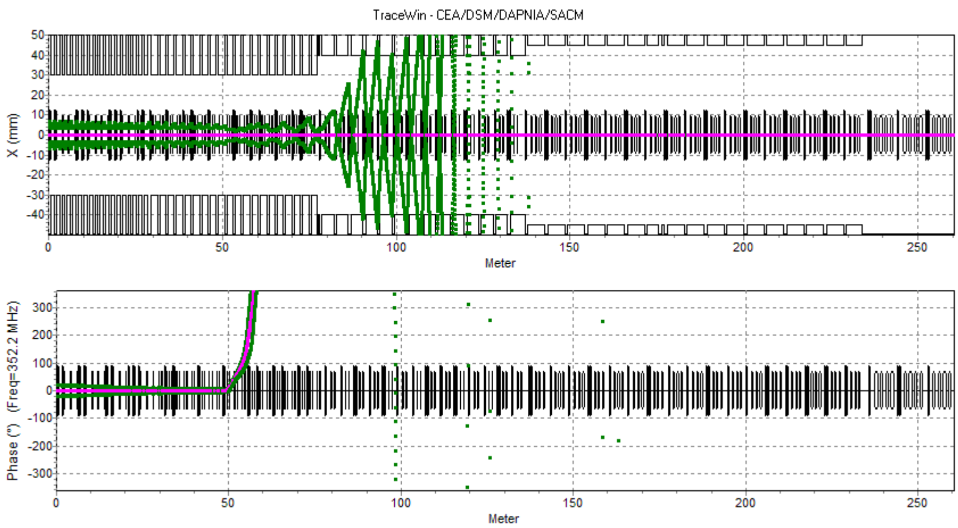


Figure 4-2 – Beam envelopes (x-transverse, phase) in the 5 MeV – 600 MeV XADS reference linac if spoke cavity #62 (40 MeV, 50 m) is lost and no compensation action is performed.

Linac retuning after the failure of a RF cavity ---

From this first analysis, it is clear that in case of a cavity's failure, some kind of retuning has to be performed. The aim of this retuning is to recover the nominal beam characteristics at the end of the linac, and in particular its energy, while ensuring the same level of transmission (and of emittance growth) than in the reference linac case.

To achieve this compensation, the general philosophy is here to re-adjust the accelerating fields and phases of the linac cavities to recover the required longitudinal behaviour of the beam. One simple way to achieve such a retuning is to make a local compensation using the accelerating cavities neighbouring the failing one. This method has especially the advantage of involving a small number of elements, simplifying the retuning procedures and limiting the possible induced errors. It is illustrated on Figure 4-3: if cavity #n is faulty, the 4 surrounding cavities (#n-2, #n-1, #n+1, #n+2) are retuned to recover the nominal beam energy & phase at the end of the following lattice (point M). It can of course be done with more (or less) cavities if necessary. Practically, the retuning of the cavities is made only acting on their accelerating field amplitude and/or phase. On the transverse beam dynamics' side, the gradients of the 4 focusing quadrupoles located inside the retuned lattices can also be adjusted if needed. Here again, more quadrupoles can be used if necessary.

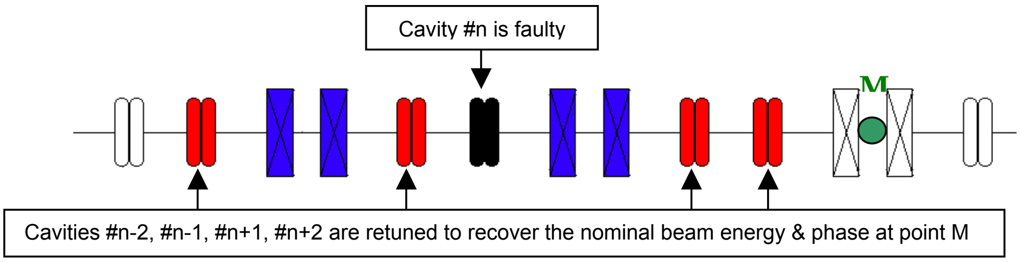


Figure 4-3 – Principle of local compensation to recover the beam energy and phase. Of course, in the case of the failure of cavity #1, cavities #2, #3, #4, #5 are used, and in the case of the failure of the last cavity, the 4 preceding cavities are used.

This retuning has of course to be done properly in order to reach a reasonable compromise between the three following goals.

- Reach the nominal energy and phase at point M (and consequently at the target). In principle, this can be done by simply rising the accelerating field in the surrounding cavities (this is possible because the compensation is made both before and after the failed cavity; this is thus not true for the 2 first cavities of the linac). This method leads to a very acceptable situation (even at very low energies, see Figure 4-4), but of course, with such a basic retuning, some beam mismatch often appears both in the longitudinal and transverse planes, inducing emittance growth and halo creation.
- Avoid any beam loss to ensure a 100% transmission, and keep the emittance growth as low as possible. This is made first by trying to keep phase advances as smooth as possible, but also by limiting as much as possible the longitudinal size of the beam around the faulty cavity area, so as to keep the whole bunch inside the phase stability region (this is

mainly true in the low energy sections). To achieve all this, an adjustment of the RF phases in the retuned cavities and of a few quadrupole gradients is mandatory.

- Ensure that the accelerating field of the retuned cavities (and the corresponding needed RF power) will not have to be increased too much compared with the nominal operation point. We chose in the study not to exceed a + 30 % field increase in the cavities, that leads to maximum allowed peak fields of E_{pk} =33 MV/m for the spoke sections (nominal “derated” operation point: 25MV/m), and of B_{pk} = 65 mT for the elliptical sections (nominal “derated” operation point: 50 mT). Of course, the more cavities are used for the retuning procedure, and the more this field increase can be limited. Note that this requirement has been (hopefully!) relaxed at the beginning of the linac where cavities are working at very low peak field in nominal operation.

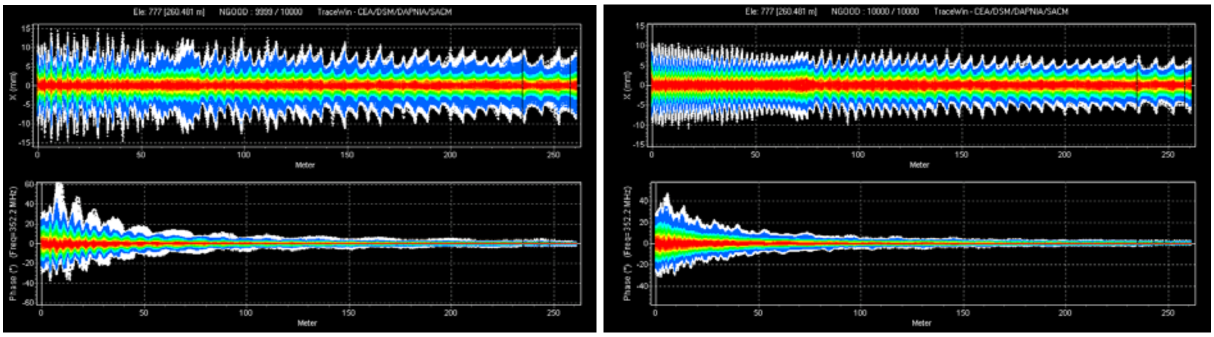


Figure 4-4 – Multiparticle beam envelopes (x-transverse, phase) in the 5 MeV – 600 MeV XADS reference linac if spoke cavity #4 (5.5 MeV, 3 m) is lost and compensation is achieved by: (Left) only rising the field in the 4 surrounding cavities; (Right) applying the optimal tuning as reported in Table 4-1.

A reasonable compromise between these 3 requirements is not always easy to reach, especially in the very low velocity section (spoke β=0.15) where the beam is “debunching” very rapidly at the fault cavity position, leading to halo creation and beam losses if a refined retuning is not carried out. In this case, a strong longitudinal focusing (i.e. high field increase, more than + 30 %) has to be performed in the retuned cavities to compensate for this effect – but not too much to keep a good longitudinal matching.

Above 10 MeV, the situation becomes far easier. It is then always possible to recover the beam within the nominal parameters at the end of the accelerator without exceeding a + 30 % field rise, even if this limitation can be quite difficult to manage in the case where the number of cavities per lattice is small. The levels of emittance growth are always very low, and even meet the nominal values in the elliptical sections (see Table 4-1). Note that the situation is a bit more complicated when the faulty cavity is located at the transition between 2 sections (especially at the frequency change).

Based on these considerations, a systematic study of the XADS linac fault-tolerance has been performed, optimizing the retuned values to be applied for local compensation in the case of the failure of most of the linac cavities. Table 4-1 reports some of the obtained results. The conclusion of the study is that **in every case, with an appropriate retuning, the beam can be transported up to the high-energy end without any beam loss (100 % transmission, reasonable emittance growth), and within the nominal target parameters.**

Table 4-1 – Optimised retuning parameters and corresponding beam dynamics behaviour for a few cavity fault conditions. In all cases, the transmission is 100%; the optimisation level is different depending on the cases.

# faulty cavity	section	Final energy	Emittance growth (%)		Number of retuned cavities (before + after)	Max ΔEacc (%)	Max E_{pk} (SP) or B_{pk} (EL)	Max ΔPower (%)	Nb of retuned quads (before + after)
			Transv.	Long.					
0	-	Nominal	+ 5 %	0 %	-	-	-	-	-
1	SP 0.15	Nominal	+ 7 %	+ 4 %	0 + 4	+ 67 %	19 MV/m	+ 67 %	0 + 4
2	SP 0.15	Nominal	+ 9 %	+ 12%	1 + 3	+ 90 %	19 MV/m	+ 68 %	0 + 4
3	SP 0.15	Nominal	+ 10%	+ 12%	2 + 3	+ 94 %	21 MV/m	+ 56 %	4 + 2
4	SP 0.15	Nominal	+ 9 %	+ 4 %	3 + 3	+ 46 %	15 MV/m	+ 35 %	2 + 4
19	SP 0.15	Nominal	+ 6 %	+ 6 %	2 + 3	+ 38 %	24 MV/m	+ 48 %	2 + 2
20	SP 0.15	Nominal	+ 9 %	+ 4 %	3 + 2	+ 37 %	26 MV/m	+ 58 %	2 + 2
35	SP 0.15	Nominal	+ 6 %	0 %	2 + 3	+ 20 %	32 MV/m	+ 27 %	2 + 2
36	SP 0.15	Nominal	+ 7 %	+ 4 %	3 + 3	+ 22 %	34 MV/m*	+ 32 %	2 + 2
37	SP 0.35	Nominal	+ 6 %	0 %	3 + 2	+ 22 %	35 MV/m*	+ 34 %	2 + 2
38	SP 0.35	Nominal	+ 7 %	+ 6 %	3 + 4	+ 29 %	31 MV/m	+ 26 %	2 + 2
39	SP 0.35	Nominal	+ 5 %	+ 5 %	4 + 2	+ 24 %	36 MV/m*	+ 35 %	4 + 2
61	SP 0.35	Nominal	+ 6 %	+ 2 %	2 + 3	+ 25 %	31 MV/m	+ 26 %	2 + 2
62	SP 0.35	Nominal	+ 6 %	0 %	2 + 2	+ 26 %	31 MV/m	+ 28 %	2 + 2
63	SP 0.35	Nominal	+ 5 %	+ 1 %	3 + 2	+ 25 %	31 MV/m	+ 27 %	2 + 2
94	SP 0.35	Nominal	+ 6 %	+ 2 %	3 + 3	+ 16 %	29 MV/m	+ 18 %	4 + 2
95	SP 0.35	Nominal	+ 7 %	- 1 %	3 + 3	+ 22 %	31 MV/m	+ 29 %	4 + 2
96	SP 0.35	Nominal	+ 5 %	+ 1 %	4 + 2	+ 21 %	30 MV/m	+ 25 %	4 + 2
97	EL 0.47	Nominal	+ 6 %	0 %	3 + 3	+18 %	59 mT	+27 %	4 + 2
98	EL 0.47	Nominal	+ 6 %	0 %	3 + 2	+ 23 %	62 mT	+ 31 %	4 + 2
109	EL 0.47	Nominal	+ 6 %	0 %	3 + 3	+ 20 %	60 mT	+ 28 %	4 + 2
110	EL 0.47	Nominal	+ 6 %	0 %	3 + 2	+ 20 %	60 mT	+ 29 %	2 + 2
123	EL 0.47	Nominal	+ 6 %	0 %	2 + 4	+ 20 %	60 mT	+ 26 %	4 + 2
124	EL 0.47	Nominal	+ 6 %	0 %	3 + 3	+ 19 %	60 mT	+ 28 %	4 + 2
125	EL 0.65	Nominal	+ 5 %	0 %	2 + 3	+ 18 %	59 mT	+ 27 %	4 + 2
126	EL 0.65	Nominal	+ 5 %	0 %	3 + 4	+ 21 %	61 mT	+ 20 %	4 + 2
127	EL 0.65	Nominal	+ 5 %	0 %	3 + 3	+ 21 %	61 mT	+ 25 %	4 + 2
146	EL 0.65	Nominal	+ 5 %	0 %	3 + 3	+ 18 %	59 mT	+ 22 %	4 + 2
147	EL 0.65	Nominal	+ 6 %	- 1 %	3 + 4	+ 19 %	60 mT	+ 22 %	4 + 2
148	EL 0.65	Nominal	+ 6 %	- 1 %	3 + 3	+ 20 %	60 mT	+ 22 %	4 + 2
173	EL 0.65	Nominal	+ 5 %	0 %	3 + 4	+ 17 %	59 mT	+ 19 %	4 + 2
174	EL 0.65	Nominal	+ 5 %	0 %	3 + 3	+ 18 %	59 mT	+ 22 %	4 + 2
175	EL 0.65	Nominal	+ 5 %	0 %	4 + 4	+ 17 %	59 mT	+ 18 %	4 + 2
176	EL 0.85	Nominal	+ 5 %	0 %	3 + 5	+ 18 %	59 mT	+ 22 %	4 + 2
177	EL 0.85	Nominal	+ 5 %	0 %	4 + 4	+ 18 %	59 mT	+ 20 %	4 + 2
178	EL 0.85	Nominal	+ 5 %	0 %	5 + 4	+ 18 %	59 mT	+ 19 %	4 + 2
179	EL 0.85	Nominal	+ 5 %	0 %	6 + 4	+ 17 %	59 mT	+ 16 %	4 + 2
184	EL 0.85	Nominal	+ 5 %	0 %	4 + 3	+ 17 %	59 mT	+ 29 %	4 + 0
185	EL 0.85	Nominal	+ 6 %	0 %	5 + 2	+ 19 %	60 mT	+ 30 %	4 + 0
186	EL 0.85	Nominal	+ 7 %	0 %	6 + 1	+ 21 %	61 mT	+ 33 %	4 + 0
187	EL 0.85	Nominal	+ 6 %	0 %	7 + 0	+ 25 %	63 mT	+ 37 %	4 + 0

* these values are exceeding the 33 MV/m maximum allowed value because the tuning acts on a cavity (#38) that is already working at 29 MV/m nominal conditions (this cavity is used for the transition matching between the 2 spoke sections)

***Case of a quadrupole failure* ---**

Calculations have been also performed to analyse the consequences of a quadrupole failure on the beam dynamics in the XADS reference linac. Here again, the consequences of such a failure depend on the position of the failed quadrupole. The situation is more critical in the sections where the safety ratio between the beam tube aperture and the beam size is smaller (see Table 4-2): the failure of one of the very first quadrupoles of the β=0.15 spoke section leads to a beam loss of about 30 %, the same failure in the middle of the β=0.35 spoke section only leads to a beam loss of about 10 %, while the beam loss induced by a quadrupole failure in the elliptical sections is always lower than 5 %. Of course, in every case, the beam is strongly mismatched in the transverse planes from the failure position up to the linac end, but the induced longitudinal mismatch is very small as expected.

The second interesting conclusion is that in the case of a quadrupole failure, the situation is clearly better if the other quadrupole of the doublet is also switched off (see Figure 4-5). As a matter of fact, the induced mismatching in that case is better balanced between the 2 transverse planes than if nothing is done. **It is thus recommended to switch off the whole doublet if one quadrupole fails**.

Finally, with an adequate retuning of surrounding quadrupole doublets, it is possible to rematch the beam to the linac and obtain beam envelopes very similar to the nominal case's ones. The situation is a bit more complicated in the very low energy section where we didn't succeed to recover a 100% transmission; the situation should probably be improved by including the MEBT quadrupoles (not modelised in the present study) in the matching procedure.

Table 4-2 – Beam losses for a quadrupole or a doublet failure, and possible solutions to recover the beam.

		Beam losses		After retuning (case of doublet failure)			
# faulty quadrupole	Section	Quadrupole failure	Doublet failure	Nb of retuned quadrupole doublets	Beam losses	Transversal emittance growth	Longitudinal emittance growth
1	Spoke 0.15	28%	0.33%	0 + 7	0.33%	More than 100%	More than 100%
2	Spoke 0.15	26%					
17	Spoke 0.15	18%	0.16%	3 + 3	0.02%	100%	10%
18	Spoke 0.15	22%					
35	Spoke 0.15	9.5%	0%	3 + 3	0%	20%*	-10%*
36	Spoke 0.15	12%					
37	Spoke 0.35	24%	0%	2 + 2	0%	66%*	-12%*
38	Spoke 0.35	22%					
55	Spoke 0.35	12%	0%	2 + 2 or 3 + 3	0%	12%	0%
56	Spoke 0.35	9%					
75	Spoke 0.35	7.5%	0%	2 + 2	0%	5%	0%
76	Spoke 0.35	6%					
77	Ellipt 0.47	0.3%	0%	3 + 3	0%	11%*	-2%*
78	Ellipt 0.47	1%					
89	Ellipt 0.47	3.5%	0%	2 + 2 or 3 + 3	0%	20%*	-10%*
90	Ellipt 0.47	3%					
103	Ellipt 0.47	0.6%	0%	2 + 2	0%	5%	0%
104	Ellipt 0.47	0.5%					
105	Ellipt 0.65	1%	0%	2 + 2	0%	7%	0%
106	Ellipt 0.65	1%					
121	Ellipt 0.65	0.5%	0%	2 + 2	0%	5%	0%
122	Ellipt 0.65	0.5%					
137	Ellipt 0.65	0%	0%	2 + 2	0%	5%	0%
138	Ellipt 0.65	0%					
139	Ellipt 0.85	0%	0%	3 + 1	0%	5%	0%
140	Ellipt 0.85	0%					
143	Ellipt 0.85	0%	0%	4 + 0	0%	5%	0%
144	Ellipt 0.85	0%					

* coupling resonance

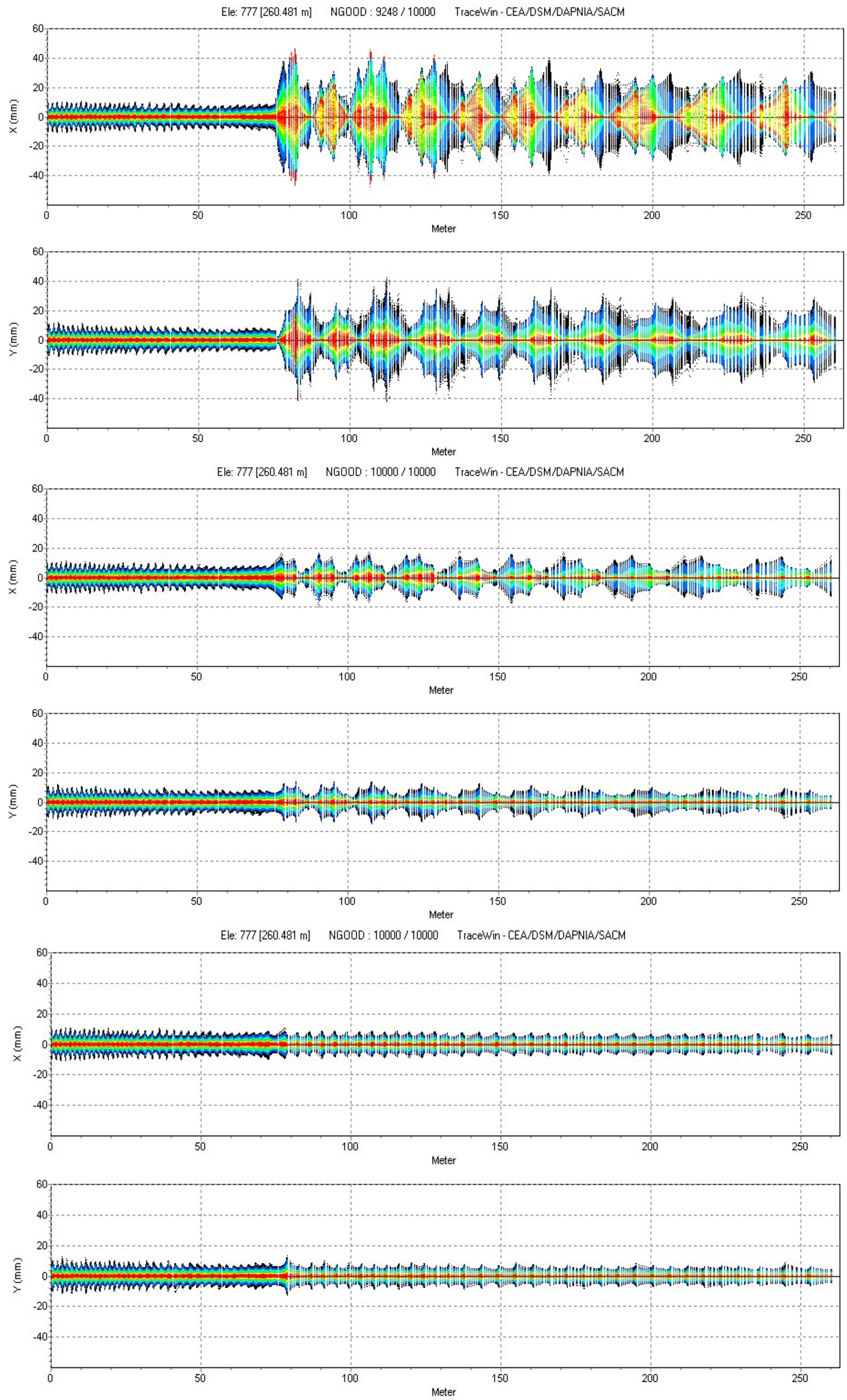


Figure 4-5 – Beam in the 5 MeV-600 MeV XADS linac: (Up) failure of quadrupole #75; (Middle) the whole doublet is switched off; (Down) the 4 surrounding doublets are retuned.

Conclusion and preliminary considerations for a full transient analysis of the problem ------

The systematic analysis performed to evaluate the fault-tolerance capability of the XADS superconducting linac leads to the following conclusions.

- If a cavity fails and if nothing is done, the beam is (almost) always completely lost.
- If a cavity fails and if an appropriate local compensation is done (retuning of a few surrounding cavities' field and phase + adjustment of a few quadrupoles gradients if needed), the nominal beam parameters at the target can be restored.
- If a quadrupole fails, the whole doublet has to be switched off to limit the beam losses along the accelerator. For power supply failures, it is thus convenient to power both quadrupole in the doublet by a single power supply. The nominal beam parameters at the target can generally be restored by re-adjusting a few surrounding quadrupole gradients.
- The situation is substantially more difficult in the low energy section of the linac (below 10 MeV).

This analysis is anyway not complete because it only takes into account the beam behaviour before the failure, and after local compensation. The remaining part of the problem consists now in analysing what happens during the transient state, and in optimizing the way the retuning procedure is carried out in order to minimize the possible beam losses due to these transients. In particular, this study will have to establish, in case of a cavity fault, if both RF and beam have to be switched off before re-starting (approach n°1, see Figure 4-6), or if RF has to be maintained while micro-switching the beam (approach n°2, see Figure 4-7). The second approach seems more adequate for mitigation, continuously keeping a smooth and compensated beam. However, it is important to study under which conditions it can be effectively implemented (failure type or component, impact on beam, cavity type) in a safe manner (minimizing beam losses).

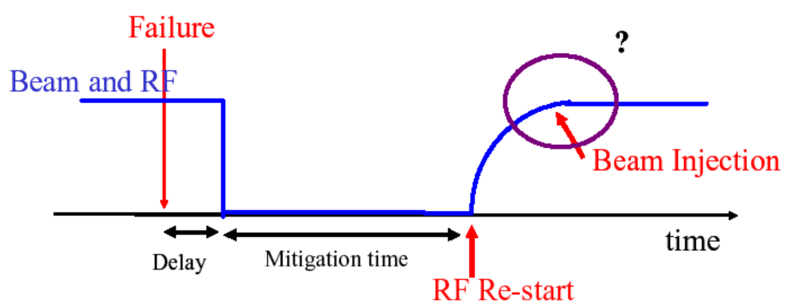


Figure 4-6 – First approach for dealing with a RF failure. The beam and the RF power are stopped everywhere, and the faulty cavity is immediately detuned. After a mitigation time while which some cavity parameters (amplitude, phase and frequency) are retuned, RF is re-started, and the beam is then re-injected at full power. This approach is quite similar to a new beam start-up.

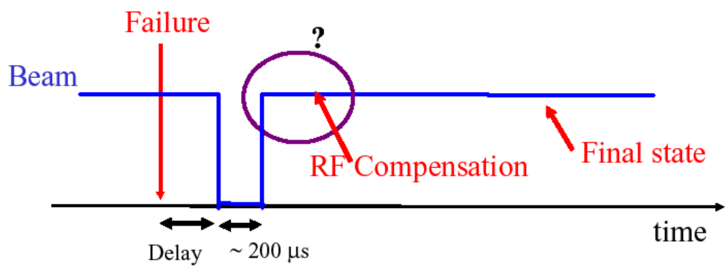


Figure 4-7 – Second approach for dealing with a RF failure. Even though the cavity is not working properly, the beam is maintained through it while action is taken to reduce the failure impact on the beam. First, a very short beam hole is implemented, quite similar to the one usually available for subcriticality measurements. Then, while rapidly detuning the faulty cavity (with a piezoelectric actuator), the parameters (amplitude, phase and frequency) of some adjacent cavities are continuously changed in order to achieve the best beam delivery onto the spallation target.

This full analysis of the problem will really start in the 6th Framework Program with the development of a new simulation code coupling both beam dynamics and RF feedback loops calculations. A first approach of such a "transient analysis" tool is summarized in Figure 4-8. R&D activities on superconducting cavities, to definitely demonstrate performances that ensure the "over-design" criteria required by the reliability requirement, and on the development of adequate digital LLRF systems are also foreseen (see section 5.2).

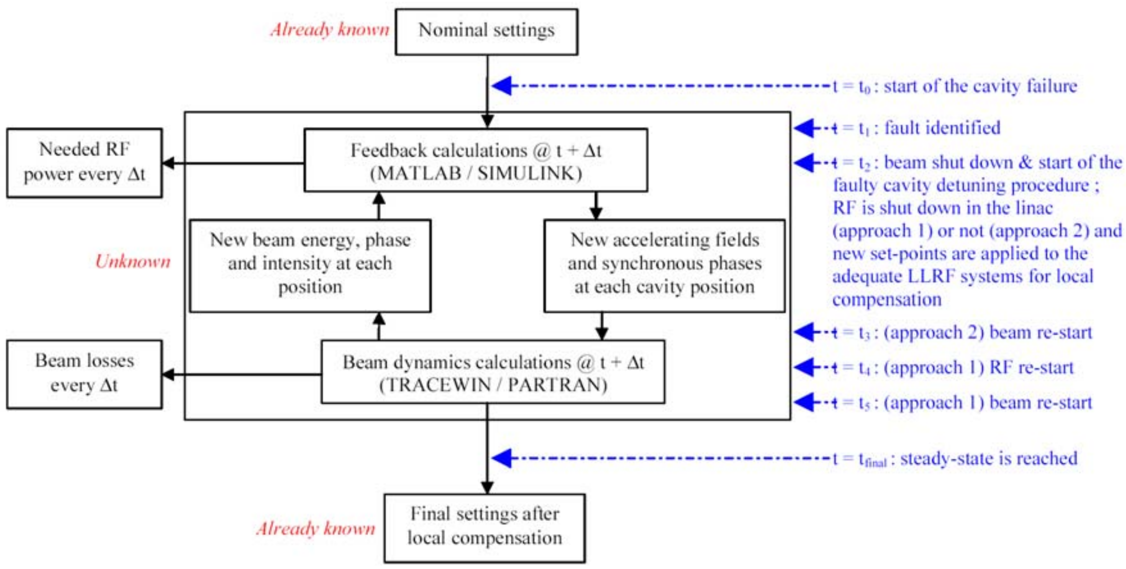


Figure 4-8 – Proposed approach for a full transient analysis of the local compensation procedure.

4.2 COMMISSIONING, ROUTINE OPERATION, RAMPING UP AND BEAM SHUTDOWN

Running an XADS accelerator can be performed under three different ways of operation.

The first phase, called the "commissioning", concerns mainly the first months of operation of the accelerator part, during which all the beam tuning and setups procedures should be determined.

A second phase can be considered as the "routine operation", in which the beam is delivered to the subcritical assembly under "normal conditions". It is quite obvious that the main goal will be to try to operate most of the time in that operational phase.

A last way of operation should be considered whenever the accelerator is in "off-normal" conditions, either due to a specific requirement for the beam (current, energy or time structure) or due to some abnormal failure of critical components or parts. In that case, it is important to define very precisely how to deal with these conditions. In particular, the ramping of the beam power from zero up to its "normal condition" or the shutting down of the beam in case of an interlock signal should be done under absolute control.

4.2.1 Commissioning

The commissioning is a very important phase for the accelerator operation. Not only it helps to qualify and debug all the equipment, either hardware or software, but it is of prime importance for the knowledge of the beam parameters all along the linac. Commissioning plans have already been developed for other high current proton linacs comprising superconducting cavities (SNS, APT Linac **[102,103**,**104,105,106,107]**).

Each machine section should be commissioned in sequence, from the source to the target, in order of increasing energy. By using specific diagnostics (see section 3.2.4) that could eventually be removed during routine operation, the beam would have to be fully characterized at any point of the linac. In fact, the influence of any parameter modification, like for example the value of the focusing magnetic fields or the quadrupoles misalignments, would have to be very precisely assessed and experimentally checked. While doing so, that would help establishing future operational procedures used whenever the linac will be in the running mode when additional diagnostics cannot be anymore installed or used.

These operational procedures are important to establish, because the machine has to be tuned each time a given basic parameter is changed. For example, assuming that in a running mode, the operator (or the corresponding automatic task system) asks for an increase in the beam current to raise the reactor thermal power. Then, all the components will have to be re-tuned in order to deliver the proper beam to the target. Each RF input power in every superconducting cavity will have to be increased while adjusting at each time the amplitude, phase and cavity frequency in order to keep a clean beam through it. These operational procedures (like a complete machine tuning) are to be checked, automated, implemented and experimentally demonstrated during the commissioning phase. Also some specific component failures could be simulated and mitigation procedures found that could maintain the beam through. That would be of prime necessity to achieve the tremendous reliability requirement asked for this accelerator.

Most of the time, the commissioning operation will be done in pulsed mode, with a very low duty cycle (and eventually sending the beam on a dedicated low power target). But, when all parameters will be set at low average power, higher power tune-up will be required prior to regular operation. That could be achieved by increasing the repetition rate and the peak current. A step-by step increase will eventually lead to the full peak current using, of course, the spallation target. The repetition rate should also be increased before reaching the full power continuous-wave beam. Higher currents might mean higher losses and different beam profiles, allowing for better understanding of beam dynamics, including unforeseen physics effects and component errors. Beam halo might indicate beam mismatches and a need to tune-up the lattice. Space charge and other non-linear effects might appear and require its measurement, understanding and integration in the simulation codes. Major unexpected performance problems should be detected and fixed during this period.

A particular attention should be given to the initial stage of commissioning of the injector. Beam properties at low energies define the beam at higher energies and influence the calibration and tune-up of subsequent modules. It is also important to pay attention to beam losses, which should be minimized, not only because of the strict limits imposed on beam current fluctuations, but also because losses induce activation of components, restricting hands-on maintenance and reducing the reliability of some components.

During the whole commissioning period, careful comparison with simulations must be performed, including a careful monitoring of all beam properties: beam energy, size, position, transverse match, transmission, halo, etc. Work might be required in order to be able to make such a comprehensive characterization of the beam at several locations in an easy and straightforward way, including a requirement for availability of space for in-line diagnostic tools (a moveable diagnostic package was envisaged for some machines **[105]**). This should allow for correction of the physics model and validation of the simulation codes with experimental data. Automatic generation and periodic update of beam properties databases corresponding to each machine component might become a very useful tool to later identification of problems and a much better knowledge of the machine as well as input for computer codes.

4.2.2 Routine operation

In the operating mode, the accelerator will be delivering beam to the spallation target inside the reactor vessel, through a bending magnet and a beam line containing rastering magnets. While running, the accelerator will equally have to deal with additional constraints coming from the subcritical core. In particular, its operation will be directly coupled to the level of desired neutron flux inside the reactor. It may also act as active safety equipment, because a beam shutdown is equivalent to an extremely fast negative reactivity insertion (almost instantaneous when compared to classical reactors).

Operation procedures --

Operation procedures defined during the commissioning phase will be applied for any modification in the accelerator set-up. Most (if not all) of the procedures can be implemented in the accelerator control-command system as automatic routines in order to prevent any manual wrong manoeuvre. Operational procedures should give the ability to swiftly move from one set point to another without requiring a complete shutdown. As an example, a raise in beam power can be gradually and smoothly done by continuously tuning all the accelerator components without destroying the beam quality. An easy way to operate would be at a given energy to slowly raise the beam current. That should be the simplest and more efficient way to minimize beam loss, taking advantage of the continuous wave operation of the XADS accelerator, always reducing the peak current to the lowest possible value for a given beam power. Operation procedures should also be defined and implemented in case of a component failure, whenever the failure could be handled without leading to a major beam interruption (interlock needing a long recovery time, see preceding section 4.1). In that case, a mitigation sequence can be launched for each failure thoroughly analyzed during the commissioning phase and for which a process has been determined. Here again, the tuning procedure should automatically allow to recover the beam while slowly bringing the accelerator back to its “normal condition” operation.

Beam current ---

The main concern during daily operation of the feedback system is to maintain the beam power within the 2% stability limit from its nominal value. The choice is to keep the beam energy fixed and to stabilize the beam power through control of the beam current intensity. This means keeping the intensity also within a 2% fluctuation limit. Beam intensity stabilization can be obtained by adjusting at the same time and continuously all the accelerator transport elements, from the source down to the target.

In the injector part of the linac, the tuning could be adjusted using the source as described in section 3.2.4.2. In principle, under normal conditions, with a beam stabilized at a given current level (in the range from 70% to 100% of its maximum value), operation of the feedback system in the low-energy part means merely a regulation of the source input RF power, with little or almost no modification of all other beam characteristics (energy, emittance, etc…).

In the intermediate and high-energy parts the situation is more complex, due to the detuning of the superconducting cavities, their high sensitivity to perturbations or phase slippage. A fast feedback system can address these problems (refer to section 3.2.4.2.) and several approaches for hardware implementation like digital I-Q demodulation are proposed, based on the current knowledge of these systems. In principle, no major problems are foreseen for small fluctuations of the current intensity, as long as no major beam or machine component disruptions occur.

The final parts of the XADS linac are the transport line and the target. However, this section will be used mainly for monitoring and control, maintaining the required beam characteristics and particle distribution (including the raster scanning system).

4.2.3 "Off-normal" conditions

A major characteristic of the XADS will be its ability to maintain operational parameters within very strict limits under major perturbations, like unwanted components failure. That ability is essential to achieve the very stringent requirement on reliability and beam trips, as well as the high availability. Besides what has been labelled as "normal condition" operation, particular attention should be paid to what happen under "Off-normal conditions". An "Off-normal" operation will happen whenever a transient phase is needed to switch from a normal operation condition to a different one. As such, any transient appearing from a given situation (either voluntarily or accidentally) should be mitigated in order to move the system back towards a known "normal operation" set point.

Also, during the transient phase, beam characteristics should be temporarily relaxed. For example, while under normal operation, beam current is stabilized to within 2% and beam loss to less than 1 nA/m in the high energy section, higher beam current fluctuations and higher beam losses could be allowed during an "Off-normal" regime, as long as the corresponding time duration is not too long.

A good example of a transient phase is given by the regular short beam interruptions needed for criticality measurements. It is foreseen to cut holes in the beam current with a time length of approximately 200 μs and a repetition rate of 1 Hz. This interruption translates in a shutdown of the full beam current source (100%) on purpose, generating consequently two transient regimes at each hole, the first at the cut down and the other when resuming back the current up to its nominal value. In particular, the understanding of the SCRF cavity behaviour with respect to these fast transients is still incomplete and further studies are required. But the low level RF feedback system will have to cope with the current gaps and swiftly respond to those transients, while temporarily maintaining a reasonably low level of beam halo. Beam monitoring might eventually require a level of communication between the RF feedback system and the current source feedback control.

Another point is the effect of a cavity fault. The linac is intended to operate even if a superconducting cavity fails. Any failure scenario will have to be predicted and set points pre-calculated and provided to the feedback and control system, which will need to develop a fast re-phasing and compensation on the remaining operating cavities. The already described option for independent phasing of the cavities is a requirement for this scheme to work. Other effects resulting from beam dynamics are also not yet fully understood, but known to cause instabilities and might alter beam parameters during transients.

Ramping up ---

In order to reach the operating accelerator normal conditions, a suitable procedure for ramping up the beam power up to the nominal, multi-MW level, needs to be identified **[102]**. The procedure is necessary in order to check at each start-up all the control system predefined set points and make local calibration adjustment, while avoiding the possibility to lose a significant fraction of the beam on the accelerator hardware, for activation and machine protection issues. The power grading procedure will be deeply investigated during a suitably long period during the commissioning of the high power accelerator. That will help to develop a complete physics model of the whole linac. This model, which will include beam dynamics and RF systems considerations, will be at the basis of the control system tuning procedures described in the routine operation mode.

Ideally, both the commissioning period and the regular beam start-up will be initiated by launching a very short pulse with low duty factor and low current (consistently with beam diagnostics and source control capabilities) for the purpose of checking the correct beam trajectory and setting the necessary steering. In the commissioning phase, the same low power beam should be used to perform the RF phase and amplitude scans for all the linac cavities, for calibration and to determine the set points of each cavity operation. The use of low beam power will prevent component activation during this phase where beam can be potentially lost during the scans. When all the cavities have been characterized in this way, the peak pulse current can be gradually increased while maintaining a low beam duty factor. This procedure is essential for validation of the combined beam dynamics-RF simulation models described previously and to determine the RF control set points for fault tolerance implementation. Finally, in the final stage, the beam, now at the nominal pulse peak current, but with reduced average current due to the pulsing of the source, should be brought to full continuous current operation. It must be stressed here that during all these different beam time structure changes, even at very low duty cycle, all the radiofrequency cavities are maintained at full CW power operation. Consequently, all electromagnetic fields in all SCRF cavities are continuously adjusted to their nominal values thanks to the RF feedback, so that any adverse pulsing effect (like Lorentz force detuning) should be precluded.

From the considerations expressed here, it is clear that the commissioning stage will play a major role in the identification of the suitable start-up procedure and in the setting of the proper control system defining the required time necessary for the establishment of the nominal beam parameters. The experience that should be gained in the next few years at the SNS **[103]**, a MW-range of average beam power superconducting proton accelerator, will also be relevant on the path towards the engineering design of an XADS-class accelerator system.

It is therefore after these considerations that a strategy needs to be selected for the power ramping of the XADS accelerator. As mentioned above, the commissioning and the system start will be performed with pulsed beams while maintaining CW RF power operation. During the commissioning phase different beam pulse formats (in terms of duty cycle and peak pulse current) need to be run through the linac, in successive phases in order to arrive to the full power CW operation.

Shutdown --

Basic safety hazards (radiation, contamination, power level, criticality, etc…) will induce either accelerator or reactor interlocks usually leading to a complete shutdown of the beam. Resuming beam power will only be possible after the corresponding default is fully analyzed and the problem solved.

In parallel to safety interlocks, a proper operation of the accelerator will require its internal interlocks. Any abnormal operation resulting from the detection of a wrong parameter either in a hardware component or from a diagnostic item will generate a default. Analyzing this default would induce an interlock signal, usually leading to a beam stop order. If the default can be corrected without stopping the beam, then specific procedures can be followed to set-up the right process, resetting the default.

4.2.4 Summary

In conclusion, the accelerator operation has to be an integral part of the global operating system, including the nuclear core control and the overall safety management. The commissioning will be a very important phase during which both the normal running conditions and the "off-normal" set points should be completely determined. In each mode, operating procedures should be established and automatically implemented together with specific interlocks, including the power ramping up and the beam shutdown management.

4.3 ACCELERATOR RELIABILITY ANALYSIS

The reliability goals for the XADS have been briefly discussed in section 2.2, where we also introduced the main difficulties – namely the lack of a well established component database - on the path towards quantitative assessments of the reliability characteristics by means of standard methodologies. However, as we have anticipated in Deliverable 57 **[3]**, the intrinsic modularity of the superconducting linac can provide the necessary fault tolerance required in order to meet the tight reliability goals. Section 4.1 of this deliverable discussed in some details the preliminary work towards a full assessment of the fault tolerance characteristics of the XADS linac from the beam dynamics point of view.

By using all the considerations expressed in Deliverable 57 and the further work on beam dynamics synthesized in this deliverable, we can start exploring the role of redundancies and fault tolerance on the reliability characteristics of the linac, by using a simplified – i.e. mainly consisting of “lumped” elements - reliability modelling.

In the following paragraphs, we show the evolution of the reliability characteristics of a simplified linac from the simplest (and unreliable) case of all components in series, to the highest possible degree of parallelism (infinitely fault tolerant system). All the analysis is based on a given set of reliability characteristics of the baseline components, and the comparison is intended to show the effect of their connection on the resulting system. Different reliability block diagrams (RBD) configurations are analyzed and discussed.

4.3.1 The "lumped" linac and component data

From a functional point of view, we can describe the accelerator configuration as composed by the following main components:

1. The **linac front end** (or injector), that is a source followed by an 5 MeV RFQ and a (possibly normal conducting) intermediate accelerator stage to the transition energy in the range from 5 to 50 MeV (still needing to be precisely defined by further work). Possibly, as described elsewhere in this deliverable, the injector can be doubled in order to have a parallel "hot" redundancy.

2. The **main support systems**: namely a cryogenic plant to provide the necessary cryogenic fluids, a cooling systems providing cooling water to all magnets and the control system, dedicated to the management of all the accelerator components "set points" and to the handling of the component faults.

3. The **superconducting lina**c based on independently phased cavities, split in a spoke section (with two different structure types) and an elliptical section (with three different structure types). The main linac, according to the beam dynamics simulations presented in a previous paragraph, exhibits a natural redundancy due to its modularity.

4. The **beam delivery system**: an array of magnetic elements that provides the necessary beam size and rastering pattern at the target.

4.3.1.1 The "Mission Time" and reliability goals

Any analysis aimed at the prediction of the reliability characteristics of a given system should define its "Mission Time", i.e. the period during which the design reliability characteristics should be met. In the following we have assumed a mission time of three months of consecutive operation (2190 hours), which will be followed by a month of major maintenance, where ideally all accelerator components will be brought back to their ideal initial state. During this mission time the goal is to limit, as much as possible, the number of system faults. A goal of 3 system faults during the mission will be compatible to a XADS accelerator goal of 10 faults per year. Hence, the design requirement is a system with a MTBF of approximately 700 hours.

The components faults assumed here are the common component faults that result in a loss of the component function for a relatively long period (that is, needing human intervention on the component for fixing or replacement), thus assuming that the strong design of the linac deals with component fault in the sub-second timescale, which are not taken into account. Also, catastrophic failures associated to extremely long corrective actions that impact the overall system availability, like a huge and abrupt unprotected vacuum break in the beam line or the physical damage to accelerator structures or the loss of the complete cryogenic gas inventory, are not considered here and need to be analyzed separately from the normally distributed random subcomponent failures. For the analysis of these failures a quantitative FMEA or a Fault Tree analysis seems more appropriate. The analysis also, as usual, does not include the contribution of components that wears in a predictive fashion, as the lifetime of these components needs to be chosen to be compatible with the mission time and their periodic substitution needs to be planned during the scheduled shutdowns every operation cycle (e.g. klystron filaments, mechanical pumps, etc.).

It should be noted again that no requirements are made in order to achieve a high reliability parameter R, and indeed the requirement of an MTBF of 700 hours for a mission time of 2190 hours will imply a nearly null reliability value, as usual in non mission critical operations.

Table 4-3 resumes the reliability goals and assumptions.

Table 4-3 – Reliability assumptions and goals.

Mission Time	2190 hours
Goal MTBF	~ 700 hours
Goal number of failures	~ 3
Reliability parameter	Unconstrained

4.3.1.2 The linac components

The linac front end --

The injector configuration analyzed in all RBD is simply a series configuration of its three components: the source, RFQ and NC or SC accelerator intermediate stage (in the RBD identified as NC DTL) and shown below.

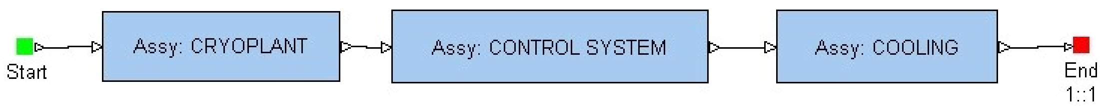
Each of these components is treated as a “lumped” element, and the implicit assumption here is that we are considering systems designed for high reliability levels, that will include redundancies in its subcomponents in order to aim at an overall MTBF figure which is not drastically shorter with respect to the mission time. By that, we assume that, for example, redundancies will exist in the high voltage power supplies, vacuum pumping capabilities in the RFQ, etc. However, in order not to make too unrealistic requirements on the design of these components, overall MTBF of approximately 1000 hours for each component have been used, even more conservative with respect to what has been used in similar analyses in other applications (cf. IFMIF **[108]**).

The RBD analysis of such a simple series system, using the reliability figures summarized in Table 4-4, predicts an MTBF of ~ 350 hours, yielding 6.2 expected failures per mission. If the injector stage is doubled and a hot parallelism is introduced, with the ability to perform the necessary maintenance action on one of the injectors while the other is operating, an MTBF in excess of 2400 hours is achieved, dropping the injector contribution to less than a tenth of a failure (0.09) per mission time. In this particular case, even with a moderately reliable injector chain, the hot-maintainable parallelism guarantees the compatibility with the low failure rate specifications.

***The main support systems* ---**

The systems in this class represent rather big infrastructures needed by the accelerator complex for its correct operation. We have deliberately omitted to include the electrical power system providing the on-site electricity to the accelerator complex, since this system will be shared with the subcritical assembly need and will be designed according the specific guidelines for a nuclear plant. The reliability experience at similarly sized accelerators for physics investigations is not relevant for this subsystem.

The XADS accelerator will anyhow require a rather large cryogenic plant, that produces, stocks and distributes the cryogenic fluids (LHe, LN) to the superconducting accelerator, a water cooling plant, that will provide the chilled and clean (low resistivity) water for the cooling of the magnets and normal conducting sections, and finally a hardware/software complex, the control system, that will manage automatically the accelerator operation under normal and abnormal conditions. The RBD of the support systems is depicted below.

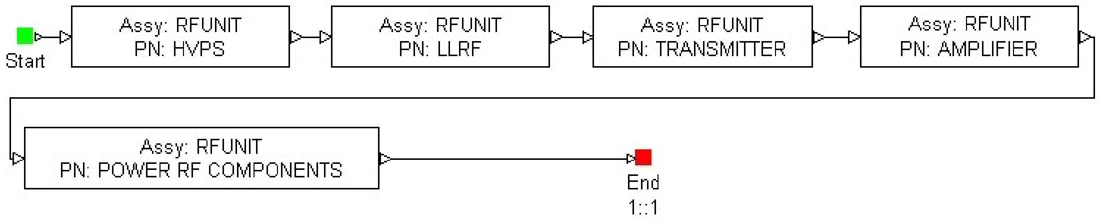


All these subsystems can be, and indeed nearly always are, designed with a high degree of redundancy. Large cryogenic plants with extremely good availability records exist in several laboratories, which are naturally redundant and allow their routine maintenance without the need of complete shutdowns. For these reasons, we have assumed that these three systems are designed each with a goal MTBF in excess of the mission time, and with a high availability. Assuming a goal MTBF of 3000 hours for each subsystem, the predicted MTBF is ~ 1000 hours, yielding the contribution of nearly 2.2 failures per mission time. Thus, this number of failures represents the lowest value for any analysis based on the reliability characteristics found in Table 4-4.

A second support system that we did not include in the analysis is the extremely complex system needed to provide the necessary vacuum conditions in the beam line and in the cryostats. By nature the vacuum system is a distributed system and in a superconducting accelerator, with large surfaces at cryogenic temperatures acting as cryopumps, very redundant and fault tolerant. The loss of individual pumps will be a minor event that will not require the system shutdown. A minimal vacuum pumping capability needs to be guaranteed by planning redundancy in the design in order to avoid the risk of hazard situations (e.g. complete loss of insulation vacuum in a cryomodule or sudden loss of beam line vacuum, due to large leaks). The potential occurrence of these situations should not be analyzed in a standard reliability prediction aimed at deriving the potential system MTBF under the hypothesis of standard component faults.

***The superconducting linac* ---**

The superconducting linac is a periodic array of focusing magnets and accelerating cavities. The linac is composed of two sections based on two different cavity structures (the spoke cavities in the first linac section, up to nearly 90 MeV, and the elliptical cavities in the second section, up to the final design energy of 600 MeV). In section 4.1.2, we summarized the fault tolerance capabilities of the independently phased superconducting linac, with respect to RF failures (low of the function provided by one cavity) and to magnet failures. The outcomes of these analyses are: a proper handling of the RF signals will allow to provide system fault tolerance with respect to cavity failures; and a nearly ideal fault tolerance with respect to quadrupole magnets is naturally achieved provided that the failure of a quadrupole in a doublet will trigger immediately the switching of the remaining quadrupole. With this simplification, the superconducting linac reduces to a number of accelerating elements that we will denote in the following as RF units. Here we stress again that we are dealing only with failure modes that determine the loss of function of the component, and hence the functional layout of each RF unit can be summarized by the following diagram, consisting of a series connection of a high voltage power supply, a block of low level RF electronic components, a set of support components (indicated in the transmitter block, including power supplies, vacuum components, control sensors and interlocks, preamplifier stages, etc.), the high power RF amplifier itself and a set of power RF components (waveguides, loads, circulators, the coupler and the cavity with its active tuning mechanism.). The MTBF for these components are listed in Table 4-4 and have been taken both from SNS predictions and the USLCTOS estimates. In the following, for the sake of simplicity, we will not make any distinction between the RF units in the spoke or elliptical sections, even if they operate at different frequencies and, more important, at different rated power levels. In the spoke linac section, where the required RF power is lower, components with longer MTBF could be used, by employing solid-state amplifiers. The RBD of such RF units is depicted below.



A series connection of these components determines an overall MTBF for the RF unit of ~ 5700 hours, that is a projected number of failures of 0.38 per unit during the mission time.

The spoke linac (in the assumption of covering the full 5 – 90 MeV energy range) is composed of 96 of such RF units (36 in the low beta portion and 60 in the high beta), whereas the elliptical linac is split in three portions of 28, 51 and 12 RF cavities, for a total of 91 RF units. Hence, in our RBD modelling, the superconducting linac is reduced to a set of 187 RF units, each with an MTBF of ~ 5700 hours.

It is clear that, if the functional connection between these components would be a series connection, the MTBF of such a superconducting accelerator would drop to ~ 30 hours, resulting in 72 failures per mission due only to RF failures. Hence, parallelism and fault tolerance in this section needs to be guaranteed, in order to be compatible with the XADS reliability objectives.

In the following paragraph different degrees of fault tolerance will be investigated in a series of RBD configurations, showing how a careful planning of a minimal level of fault tolerance can allow reaching the desired goal without asking for more reliable components.

The beam delivery system ---

The beam delivery system is composed by a set of electromagnets needed to gently bend the beam from the linac trajectory to the spallation target, and to distribute the beam power uniformly on the target by a rastering pattern. Experience at huge accelerator facilities worldwide, which accumulated dozens of years of operation, show us that these components have usually high reliability characteristics. For our simple model we have assumed a series connection of 20 magnets and associated power supplies, with the reliability characteristics listed in Table 4-4.

4.3.1.3 Summary of the data used in the RBD analyses

In the following table we list all the reliability characteristics of the components we have used in all the RBD analyses in order to assess the system MTBF of the different configurations of the XADS linac. Some of the MTBF listed below have been selected from existing literature (like the US Linear Collider Technology Options Study, SNS or APT published material), others, like the values for the support systems, have been set as design goals for major subcomponents and are needed for the compatibility with the envisaged long mission time of the XADS operation cycles, aiming at very low system failure rates. It is necessary, however, to point out that the use of the same numbers in all RBD analyses, assuming different component connections and different degrees of planned fault tolerance, can result in completely different system reliability characteristics. **The scope of this activity is to thus to prove that the system layout is much more important than the role of the reliability characteristics of the individual components and, even in the case of moderately reliable components, the system can be made more reliable by means of increasing either parallelism or its fault tolerance characteristics, as it will be clear in the discussion of the result.**

Table 4-4 – Reliability characteristics of the components used for the RBD analysis.

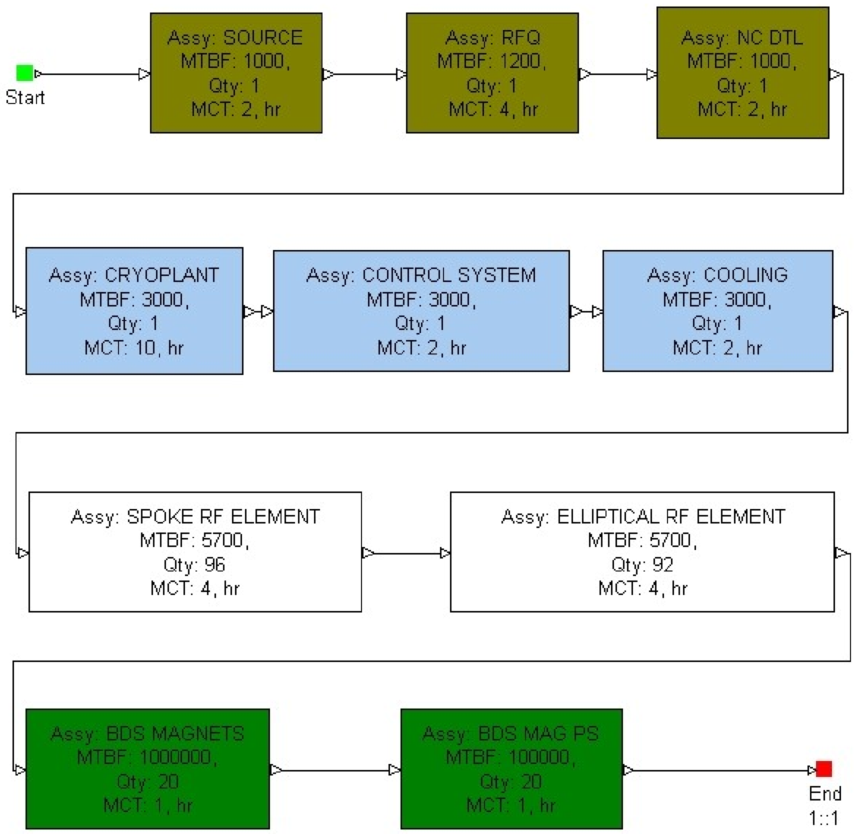
System	Subsystem	MTBF (h)	MTTR (h)
Injector	Proton Source	1,000	2
	RFQ	1,200	4
	NC DTL	1,000	2
Support Systems	Cryoplant	3,000	10
	Cooling System	3,000	2
	Control System	3,000	2
RF Unit	High Voltage PS	30,000	4
	Low Level RF	100,000	4
	Transmitters	10,000	4
	Amplifier	50,000	4
	Power Components	100,000	12
Beam Delivery System	Magnets	1,000,000	1
	Power Supplies	100,000	1

4.3.2 Analysis of different linac configurations

Having described all the components in our model linac, and having listed all the reliability characteristics that we have assumed, we can now arrange the functional connection of all these elements in an accelerator RBD, in order to determine its reliability characteristics. We have used a commercial RAMS software (Relex™ from Relex Software Corporation) in order to perform the RBD analysis either using analytical modelling (when possible) or Monte Carlo modelling (when the system could not be evaluated analytically due to the complex repair strategies).

4.3.2.1 All series connection

The simplest case to analyze is the case of a single injector and all components in series, as in the following RBD where we have highlighted the component failure (MTBF) and repair (MCT, mean correction time) characteristics, along with their quantity.

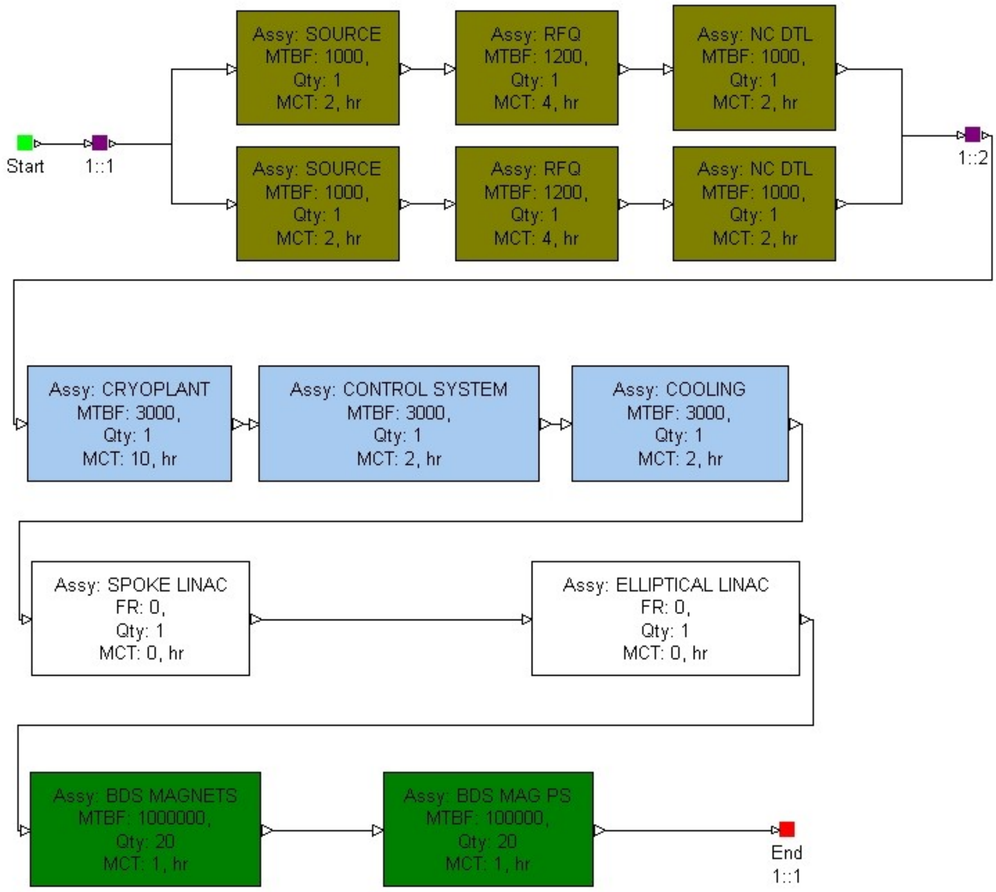


System MTBF	31.19 hours
Number of failures	70.23
Steady State Availability	86.6 %

Clearly, this system is dominated by the series connection of 188 RF units that have each an MTBF of 5700 hours, thus determining the very low system MTBF. Clearly in this case the doubling of the injector will not reduce by much the total number of predicted failures. As we have already mentioned above, the injector system has an MTBF of ~ 350 hours, contributing to 6.2 failures per mission time. Assuming a redundant injector, accessible for maintenance during system operation, only increases the computer system MTBF to 33.48 hours, with a predicted number of failures of 65.41 per mission time. This situation, where the failure of each component in the RF unit causes a system failure, is totally incompatible with the XADS goals and would imply to require much higher MTBF characteristic to all RF components, by at least a factor greater than 20.

4.3.2.2 Infinitely fault tolerant linac with a double injector

The opposite situation is found where we assume an infinite fault tolerance with respect to cavity faults. In this idealized case, we assign a zero failure rate to the superconducting linac and we include the injector redundancy, as in the following RBD.

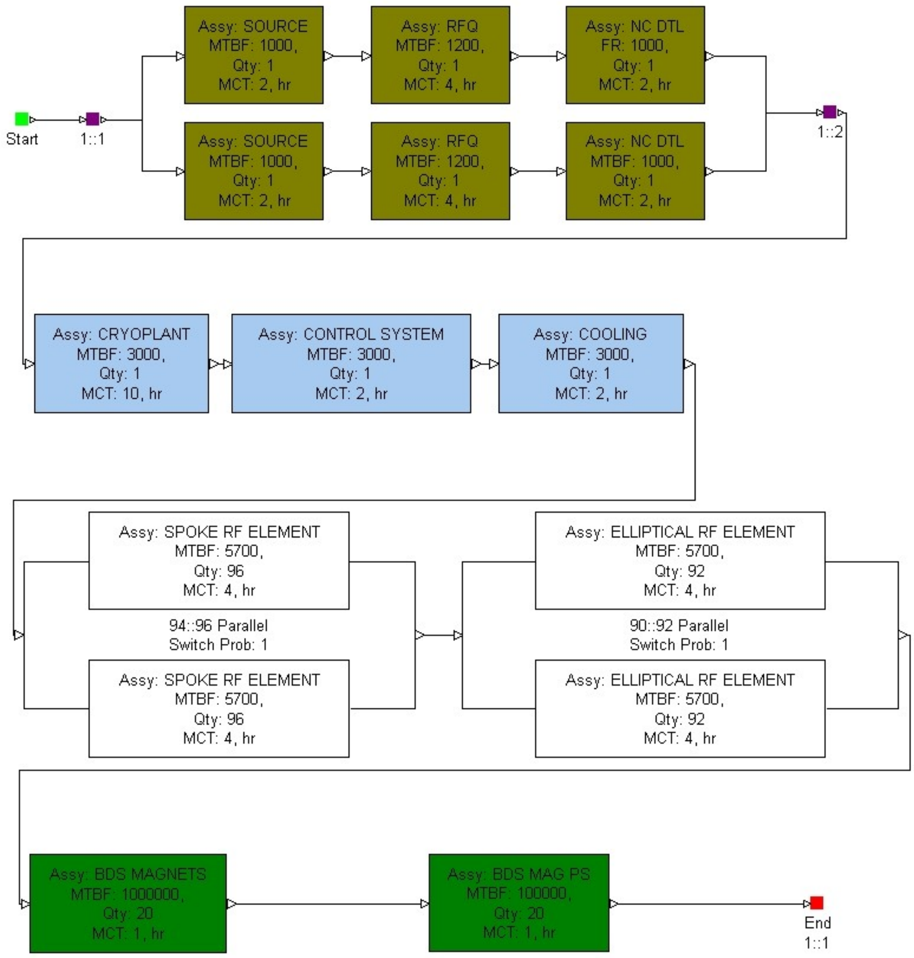


System MTBF	796.91 hours
Number of failures	2.75
Steady State Availability	99.5 %

This case represents the highly desirable situation where the number of failures is nearly entirely due to the three support systems (accounting for 2.2 failures due to their series MTBF of ~ 1000 hours). Clearly this is an idealized situation, but in the following we will show that an intermediate level of fault tolerance, keeping the same characteristics for all components, can reach similar system MTBF values.

4.3.2.3 Moderately fault tolerant linac with a double injector

We can now examine the case of a different functional connection of the RF units in the system. We can assume that not all RF units in the two linac portions are necessary in order to provide the correct beam specifications on the target. As a simple hypothesis we assume that only two RF units in each superconducting linac section (either spoke or elliptical) can fail at any time ("moderately" fault tolerant linac). On average this will imply a maximum energy loss of 1.8 MeV for the spoke linac and 11.0 MeV for the elliptical linac, and we assume that the system can increase a few neighbouring cavities gradients to compensate for it, as described in the previous sections. The system described above is illustrated in the following RBD.



System MTBF	757.84 hours
Number of failures	2.89

Steady State Availability	99.5 %

We have therefore assumed that all RF units in a linac sections are in a “k out of n”, that is 94 out of 96, and 90 out of 92, parallel redundancy. We have to stress here that maintenance can occur on the failing systems without needing a system shutdown. This model is clearly optimistic, since a number of components in the RF units – namely the majority of the power RF components – are located in the accelerator tunnel (e.g. couplers, tuners, …) and are not accessible while the system is in operation. We will deal with these components in a further analysis. By assuming “hands-on” maintenance for all components in the RF unit, we have reached an MTBF of 757.84 hours, which is nearly the MTBF of the previous case, where no failures were assumed for the RF system. **We have therefore shown here that even a moderate “hands-on” parallelism in the RF unit area can nearly fully recover the ideal situation of an infinitely reliable superconducting linac, without any increase of the components characteristics**.

4.3.2.4 Split RF system repair provisions

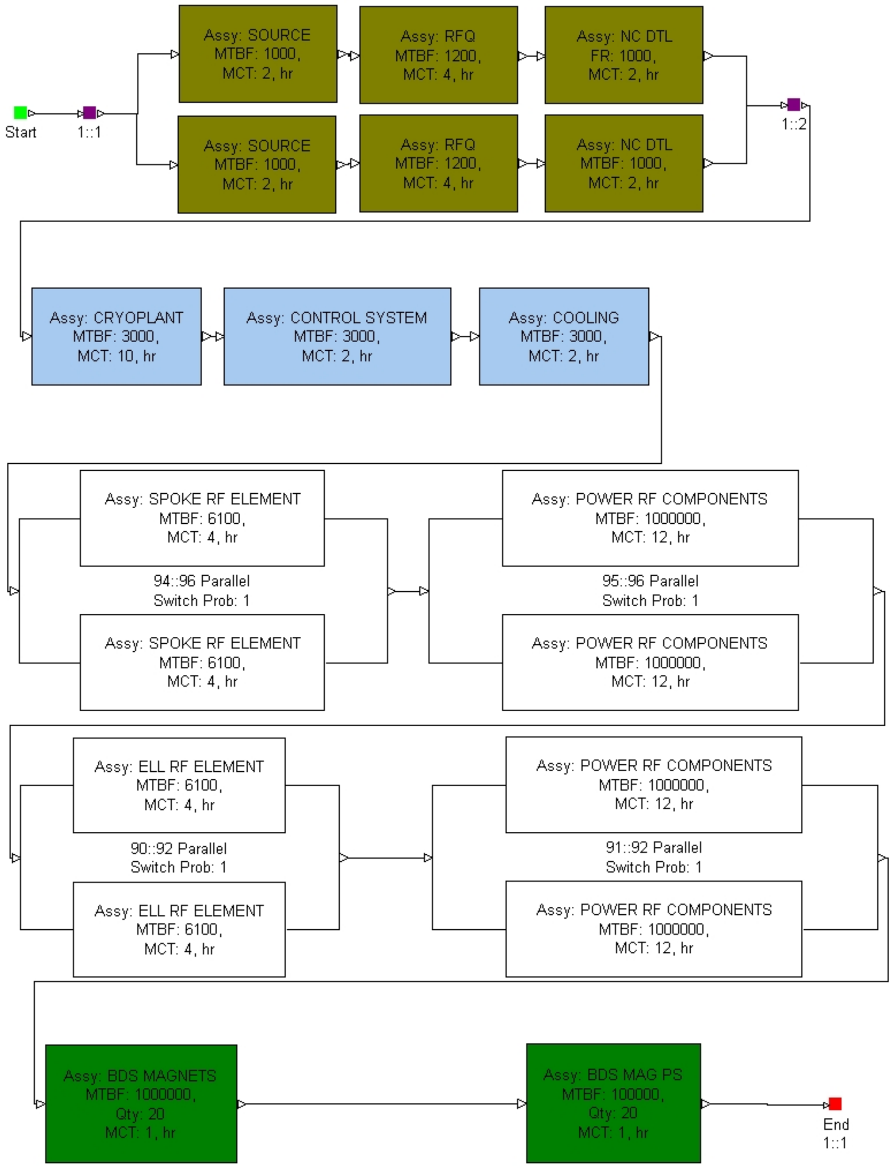
The previous model assumes that all of the RF components can be repaired during the system operation. We can now split the RF unit in two parts, with different repair provisions and type of redundancies in order to deal with a more realistic situation.

We begin with replacing the single RF unit block with two blocks, representing the out-of-tunnel RF Unit systems (that is the HVPS, the LLRF, TRANSMITTER and AMPLIFIER) and the in-tunnel RF Unit systems. According to the component breakdown in Table 4-4, the out-of-tunnel components MTBF is ~ 6100 hours and the in-tunnel is simply that listed for the power RF components. We have then selected a redundant parallel connection to the out-of-tunnel RF component by allowing 2 units failures in each linac section and assigning a “hands-on” corrective maintenance (that is, the redundant failing component is immediately repaired). Finally, the in-tunnel components are assumed to be in a parallel redundant connection that allows one component failure. However, the maintenance of the failed system can be started only after a system failure, and cannot be performed while the system is operating. By doing so, the following system characteristics are evaluated:

System MTBF	557,80 hours
Number of failures	3.92
Steady State Availability	97.9 %

As expected, this model, which simulates more realistically the different parallelism of the in-tunnel and out-of-tunnel components, results in lower MTBF values and, consequently, a higher number of predicted failures. Note that the availability reported for this calculation does not take into account for the additional logistic time needed for the access to the in-tunnel components, which includes radiation time decay and long preparation times if cryogenic components need to be accessed.

It is therefore interesting to examine a final case. Since we have identified a restricted set of in-tunnel components that limit the «hands-on» parallelism and fault tolerance of the system, because of their physical accessibility, this suggests exploring the sensitivity of the system reliability figures to this class of components. We therefore have increased the MTBF of the power RF components by a factor of 10 and analyzed the following system (identical to the one just described, with the only difference of the increased MTBF of the in-tunnel components).



System MTBF	749.81 hours
Number of failures	2.92
Steady State Availability	99.3 %

Once again, we have shown that reliability characteristics similar to the ideal case of an infinitely fault tolerance superconducting linac can be achieved by requiring a design MTBF increase only to the few in-tunnel components. If the assumed moderate fault tolerance with respect to RF faults can be guaranteed, there is no point in requiring components with higher than average MTBF, besides the few ones that turn to be critical based on their physical accessibility.

4.3.3 Conclusions and perspectives

We have formally shown here by means of RBD analyses that, for given component reliability numbers, the chosen degree of redundancy and fault tolerance in the linac configuration can result in a wide range of system reliability characteristics.

In addition to that, repair provisions should be defined and analyzed for all redundant components, because the larger gain in the systems is achieved in the case of parallel redundancy with "hand-on" repair possibilities. For the components falling in this class, there is no need to request better reliability characteristics than the ones currently expected by the accelerator community, also for the high reliability goals of the XADS linac. Conversely, a proper planning of the reliability characteristics for the few in-tunnel components, which require system shutdown for corrective maintenance, allows reaching performances close to the ideal case of an infinitely fault tolerant system with a minimum design overhead.

4.4 ACCELERATOR MAINTENANCE STRATEGY

The study of the maintenance aspects for the XADS accelerator is precisely described in Deliverable 48 "Accelerator: Radiation Safety and Maintenance" **[5]** which identifies, among other things, the main features of a possible maintenance strategy compatible with the high-reliability requirement of the machine. This chapter is intended to present the global philosophy of the maintenance strategy.

The main goal of the maintenance strategy is to guarantee the reliability of the XADS accelerator for all its period of life, about 20 years. A modular linear accelerator was proposed because it allows implementing three prime criteria needed for a proper maintenance:

- overdesign of the components by the application of a part derating,
- redundancy,
- fault-tolerance.

It has been found that these requirements request the development of an expert system able to precisely identify and locate equipment that has started to loose performance or that is out-of-order and has be replaced or repaired. This fastest possible way of preparing the maintenance procedure is also in-line with the ALARA (As Soon As Reasonably Achievable) principle for the concerned personnel, like enough working place and quick disconnection of sub-equipments.

We have studied the different "systems" of the accelerator, for which we have point out the principal ideas. When it is possible, a table is used in order to gather the main points of maintenance requirements (see the example of Table 4-5), giving the main items (and possibly their function), the failure mode and its severity level, and two types of action: the preventive action with its frequency and time of intervention, and the curative action.

The proton source **---**

Concerning the source design, we need to use adequate materials able to bear the power with sufficient margins, for example 50 %. We have to try to simplify the equipment as much as possible and minimize the number of complex components. The water-cooling will also respect the margins. Do not forget to protect all fragile components like the RF window for example.

EMI hardened devices will have to be used to reduce the damages due to spark and to dramatically enhance the source performance. To avoid spark propagation on the cables, it is important to separate and shield the signals cables paths from the power ones. Galvanic insulation of analog and digital signals greatly helps to avoid troubles.

Table 4-5 – Actions of maintenance for the H+ source.

PDS-XADS-WP3
Deliverable 63
Chapter 4.4
H+ source

Severity Ranking Tables	
Local effect	**Effect on beam**
0: No effect 1: Functionning with reduced performances 2: Loss of function	0: Beam with nominal parameters on target 1: Beam with wrong parameters on target 2: No beam on target

Main Items	Function	Failure Mode	Severity ranking		Preventive action			Curative action		Rem.
			local	beam	action	freq.	time of int.	action	time of int.	
Boron nitride discs		Wear	1	1	Replace	6 months	24 H	Replace	24H	
Vacuum pumps		Wear	1	2	Regenerate	24 months				
		Out of order	2	2	-			Replace	8H	
Power supply filters		Get dirty	0	0	Clean	3 months	few min			
Power supply		Aging	0	0	Overhaul	24 months	few weeks			Use spare while overhauling
Cooling (water): filters, pumps...		Wear / dirty	0	0	Clean					
Plasma electrode		Aging	1	1	Replace	12 months	24H			
Magnetron		Out of order	2	2	Replace	24 months	2H	Replace	2H	Replace at 80% of MTBF
HV power supply		Out of order	2	2	Oil changing	24 months	8H	Replace	8H	
Extraction electrodes		Aging	1	1	Replace	24 months	48H			
Security devices :										
Water flow controller		get dirty			cleaning	12 months	30 min	Replace	2H	
Temperature controller		Out of order			Systematic tests	12 months	few min	Replace	8H	could be doubled
Emergency stop		Out of order			Systematic tests	12 months	1 H	Replace	1 H	
DGPT		Out of order			Systematic tests	12 months	1 H	Replace	8 H	

Concerning the high voltage, the technologies have to be respected with long distances, no angles and great care at triple points to minimize the spark rate. Of course robust power supplies will be preferred and safety margin will be applied. Constructor maintenance notices (cleaning of the filters, exchange of air driers and so on) will be respected. A critical point is the HV transformer: sparks could rapidly lead to its destruction. Great care has to be taken to protect the transformer (use of ferrites, spark gaps, important margins).

The best way to guaranty the requested reliability with constant and continuous beam is to double all the injector. The simultaneous running is preferable.

The RFQ --

Because the cavity is relatively slender, it requires multiple redundant supports both laterally and vertically inside the box structure to maintain the required straightness and to avoid low natural vibration frequencies. The box structure is a stiff cocoon that can be cinematically mounted off the facility floor allowing ease of alignment in the beam line.

The RFQ cavity is an inherently robust structure that is expected to require little in the way of maintenance. There are no active components. The only credible maintenance scenario which may occur once or more during the 40 years lifetime of the facility is the requirement to replace the first physical segment of the cavity due to excessive erosion of the vane tips from beam scrape-off.

Ancillary components associated with the RFQ that will require periodic maintenance are the RF windows in the RF drive lines and pumps and valves in the vacuum system.

The superconducting cryomodules --

Several particle accelerators based on superconducting accelerating structures are under operation since several years and important knowledge on the maintenance aspects can be drawn from the accumulation of operating hours on these superconducting machines, even if the maintenance objectives for accelerators dedicated to physics are of a quite different concern than for an accelerator for an ADS system.

Superconducting cavity performances are very stable over a long operating time. This property is almost intrinsic: due to the extremely low power dissipation within the cavity walls, and the wide beam port aperture (resulting in negligible beam loss), the cavity does not suffer any important aging effect. The only cavity performance degradations reported on operating accelerators appeared after cavity warm up or vacuum break. The need for reliability imposes to minimize the thermal shocks, so to keep the whole cryomodule cold as long as possible, even during the month or so of shutdown time if no maintenance operation on the cryomodule is needed.

Actually, there is not much more to do as maintenance operations on a superconducting cavity itself. The performances of each cavity should be monitored during the whole operation of the linac, by means of RF input and forwarded power, cryomodule cryogenic losses, or dedicated diagnostics like X-rays detectors which could be located outside the cryomodule. If any diagnostic device foreshadows a cavity performance decrease, the next maintenance period should be used to identify the problem. One should point out here that to check the cavity capability to operate in any conditions, the test should be performed on the whole accelerating field range: from zero to the operating gradient plus the margin or even up to the higher gradient needed for the fault-tolerance of the linac.

During the check-up, if any cavity performances deterioration is discovered, then two cures could be performed in-line: high peak power processing and/or helium processing. If the cavity performances are not recovered, the cryomodule should be replaced by a spare. The removed cryomodule could be dismounted, and the faulty cavity undergoes a complete cycle of reconditioning (light chemistry, high pressure rinsing with ultra-pure water).

Like superconducting cavities, power couplers do not require important maintenance operations, and the functioning is very stable under normal operation. Nevertheless, coupler performances degradations may occur after several thermal cycling (de-conditioning): for the couplers also, minimizing the number of thermal cycling is a way to reach a high reliability. The most fragile part of the coupler is the ceramic window: it may happen that the window breaks during operation, or at least starts to crack, resulting in a vacuum leak. In that case, the coupler and the cavity could be polluted and the only solution is to replace the whole cryomodule by a spare.

For the other components of the cryomodule, some of them should follow the general rule for systematic replacement before reaching the Mean Time Between Failure, i.e. replacement at 80% of the MTBF (cold tuning system motors, temperature sensors...).

The beam delivery system --

The last dipole magnet and its associated diagnostics or vacuum devices must operate in the presence of the very intense neutron flux induced by the reactor. As a consequence, the magnet must be designed to be radiation resistant and capable of being handled remotely by means of a quick and reliable disconnection system. Radiation hardness requires that no organic material is used for magnet coils insulation or vacuum seals. It guarantees the equipments from failures due to radiation. Nevertheless, inspections during scheduled maintenance periods will be indispensable to measure the dose absorbed by all critical elements and to identify possible radiation damages. Also activation products like long-lived isotopes that are estimated to be produced in the reactor environment and that have the potential to back stream along the beam line will have to be inventoried periodically to be certain that their production rate and their concentration do not affect heavily the accelerator maintenance operations.

The beam transport line sensitivity to magnet misalignments has been evaluated and is not expected to be a cause of concern. Beam deviations due to unavoidable residual systematic or random errors of a few tenths of millimetres will be easily detected by beam position monitors and compensated for by correction dipoles. Nevertheless, long-term effects like building or grounds movements may induce unacceptable misalignments after a very long period of uninterrupted operation. Periodic hands-on or remote controlled re-alignment of the whole beam line system will have to be scheduled to ensure that these deformations will remain within tolerable values for the correction system. A typical value is in the order of one control and re-adjustment per year of operation.

The cryogenic system --

The cryogenic system should not be a major problem as far as reliability is concerned. Some examples already exist on cryogenic systems for particle accelerators (CEBAF and LEP for instance) showing that a reliable and continuous operation is achievable, providing that a proper maintenance is performed.

Still, periodic inspections and specific maintenance operations are necessary to reach an overall high reliability. The cold box, main part of the helium liquefier is one of the most sensitive elements (presence of high speed rotating turbines) and requires a periodic regeneration to avoid impurities. Part of the system is also composed by rotating systems (screw compressors, helium gas recovery compressors…), which require oil lubrication, filters and oil renewing. An important part of the components (storage dewars, transfer lines) are static elements that need to be periodically checked for leak appearance.

A specific crew should be recruited to be able to perform the maintenance operations. The other possibility could be to have contracts with the constructors.

The RF system ---

All linear collider projects consider the RF system components as the most critical part in the design, and the less reliable. The XADS linac is designed to be fault-tolerant: the consequence on the RF system is that each accelerating cavity or structure is fed by a separate RF source. Even if the MTBF of each component could be quite high (typically ranging between 10 000 hours to 100 000 hours), due the high component number, only a very low overall MTBF could be achieved. The fault tolerant design could react to a RF system failure and maintain in the short term the beam on the target, but still, an active repair and maintenance policy must be implemented.

The first consequence is the need to perform maintenance or to repair during operation. So all critical RF components should be installed in a separate tunnel, running in parallel to the accelerator tunnel, and accessible housing to all components must be allowed to repair or replace as fast as possible the failed system. The other consequence is the need of specific funding to provide sufficient number of spare components.

A preventive maintenance strategy should be followed, consisting in a systematic anticipated replacement of the components, when they reach 80% of their MTBF, in order to avoid the zone around the MTBF presenting an increased failure rate.

During all operation phases, a “log book” policy is essential to understand failures, to detect component trends, and to adapt the regular maintenance activities. During the commissioning period, data gathering of all failures with detailed system behaviour would contribute to adopt a maintenance policy for the long-term operation.

Depending on the failure data analysis, for each RF sub-system or component, an adapted maintenance method could be selected. Failure data from different accelerators show that a preventive or predictive method could fit well for most of the RF components. The sub-systems related to the control, command, survey and diagnostic purposes, will probably need a proactive maintenance method, associating repair and replacement with detection and continuous improvement of critical process.

***The vacuum system* --**

The maintenance operations are well known for all components of the vacuum system, and the vacuum system is here even simplified by the fact that the main part of the linac is superconducting.

Still, the maintenance of the vacuum system is an important amount of work, because each pump requires several days to perform the overhaul. Redundancy and turnover allow to check each component of the pumping system without interfering with the accelerator operation. Apart from systematic overhauling, the only preventive maintenance consists in the replacement of each component after they reach 80 % of their MTBF.

Operating experience showed that the vacuum system could be reliable providing that all components are tested prior to their installation on the accelerator (to detect manufacturing problems), but also carefully prepared (bake-out): these operations are mandatory to avoid early problems (infant mortality).

***The diagnostics* ---**

Preventive and systematic replacements, especially for irradiated exposed components, are likely the best possible maintenance for beam instrumentation of the accelerator. Systematic and periodic calibration of electronic instrumentation is also an important part of the maintenance aspect.

Another problem occurs with electronics failure if the beam diagnostic is a part of a beam characteristic regulation control system: intensity position or phase. The only way to circumvent this difficulty consists in hardware redundancy. After automatic detection of failure, a supplementary system takes over the regulation.

The focusing elements ---

Warm magnets are rugged and reliable devices, and most of the failures are likely to originate from the cooling system of the coils, or from the power supplies. Main part of the maintenance consists in regular inspections and visual checks.

Cooling water quality control (purity, pressure) should be performed in-line, and any variation of these parameters on one unit should lead to a complete check-up during next maintenance.

The other "weak" point for the focusing elements is the power supplies, but their maintenance is well known: they should be installed in an area where temperature and humidity level are controlled (to a certain extent). The maintenance actions should follow the manufacturer requirements: fan filter regular cleaning and change, dust removal from the output and input connectors, etc..

As far as preventive maintenance is concerned, the main task consists in regular checking of the coils and supplies characteristics: voltage versus current and magnetic field versus current. These measurements should be stored in a database, and compared with the previous measurements.

If one magnet fails, due to either the coil or the power supply, the beam will probably be lost, or have the wrong parameters on the target. Redundancy could be used for the each magnet, or for the most important ones: each supply could be doubled, with a switch to connect the first one or the second to a load. During normal operation, they could be used alternatively (switch every month for example) to achieve equal aging one each system.

Conventional facilities ---

The maintenance of the conventional facilities required for the XADS is quite straightforward, because these facilities are quite routine industrial standards (electrical power distribution network, demineralised cooling water circuit, compressed air circuit…).

A specific point is the fact that the accelerator tunnel should be air-conditioned in a closed circuit for containment of activation.

Consequences on the facility layout ---

In order to be able to perform an active and efficient maintenance, some constraints are imposed to the facility layout.

The first and most important one is to implant the linac and the RF sources in two separate tunnels. This is the consequence of the overall low reliability of the RF system: despite the fault-tolerant property of the superconducting linac, easy and quick access to the faulty RF source is mandatory in order to be able to repair or replace during operation and to avoid the difficult situation of two RF failures at the same moment. For this particular purpose, the mean time to repair (MTTR) is an important criteria.

The second consequence is imposed by the need to be able to exchange a cryomodule with a spare one as fast as possible. If a cryomodule encounters an important problem (important leak, break of a window power coupler…), the best solution is to replace the cryomodule by a spare one. In order to reduce as much as possible the MTTR (which is for this particular example the Mean Time To Replace rather than the Mean Time To Repair), several conditions should be fulfilled:

- spare cryomodules for each section should be installed in the tunnel, close to their potential replacement location.
- the spare cryomodule should be ready for the exchange at any time as soon as a cryomodule failure occurs. In other words, each spare should be kept cold, to avoid the lost of time for cooling down.
- the accelerator tunnel should be designed taking this need into account, and should allow easy access to a faulty cryomodule to facilitate the spare cryomodule displacement and the replacement of the faulty one.

Maintenance scheme ---

One of the most difficult challenges for the XADS accelerator is to reach a very high reliability. Maintenance becomes of primary importance because it is mandatory to insure a high mean time between failures but also to foresee and prevent early failures.

A preliminary analysis of the maintenance scheme for the accelerator has been studied. For each sub-sections of the linac, the maintenance operations (preventive actions and curative actions) were presented and their timeframe (duration, frequency) has been given. The main goal of this study was to check the compatibility of the maintenance strategy with a possible operation mode of the XADS, which is 3 months of continuous operation, and 1 month of shutdown.

Several fundamental principles could be drawn from this study.

- Maintenance needs should be taken into account during the design phase of the accelerator (for example, integrate into the design of several components the need of quick and easy disconnection).
- The maintenance imposes several constraints on the facility layout (two tunnels, enough space in the accelerator tunnel for ease of component transportation...), but are rather conventional.
- Curative maintenance mainly relies on a precise spare strategy (RF sources, cryomodules, vacuum devices...).
- Preventive maintenance is based on frequent inspections, on in-line measurements of component performances during operation (in order to detect the beginnings of a failure), and on systematic replacement of the key components when they reach 80 % of their MTBF.

Moreover, several important conclusions arise from the analysis of each sub-section of the accelerator by the experts.

- The maintenance to be performed seems perfectly compatible with the considered operation mode 3 months on / 1 month off.
- No essential maintenance actions are required every 3 months: this period could probably be extended to 4 or 5 months.
- The preventive actions to be performed do not require a full month of shutdown time, providing that enough manpower is available. Shutdown time could probably be reduced to 2 weeks if necessary.
- Still, one longer shutdown of 1 month once a year appeared unavoidable.

From the maintenance point of view, it seems possible to increase the duration of one shift, and to decrease the shutdown period to 2 weeks. A "5 months on / 2 weeks shutdown / 5 months on / 1 month off" operation mode seems efficient to ensure that all components are properly maintained, i.e. each MTBF is kept at its nominal value.

But one has to keep in mind that this assessment only applies to the maintenance strategy. The duration of one shift will be also (and mainly) driven by reliability, i.e. by the global MTBF of the machine that may not exceed 3 months. This value will have to be actually determined in the next steps of the project, especially with the completion of the reliability analysis started within Deliverable 57 **[3]**.

5 THE R&D PROGRAM

One of the major requirements for a transmuter demonstrator is the reliability of the driver accelerator, i.e. a very low number of so-called “beam-trips” (unwanted interruptions of the beam that last longer than a certain time: typically the order-of-magnitude is a second). A “reliable” accelerator should not exceed a number of “a few” trips per year.

As already mentioned, the strategy to implement the required reliability relies on over-design, redundancy and fault-tolerance. This approach requires a highly modular system where the individual components are operated substantially below their performance limit. A superconducting linac, with its many repetitive accelerating sections grouped in "cryomodules", conceptually meets this reliability strategy. It further allows keeping the activation of the structures rather low, important for radioprotection and maintenance issues, in turn strongly influencing the capital cost of the machine.

The R&D program will thus be an as much as possible **experimental evaluation of the reliability figures for the main modular components of the XADS reference accelerator** that is presented in this document.

5.1 IDENTIFIED R&D NEEDS FOCUSED ON RELIABILITY

The reference design for the XADS driver accelerator, shown in page 23, is composed of a proton linac front-end (ECR source + normal conducting RFQ structure + eventual additional structure that could be a superconducting CH-DTL or a normal conducting IH-DTL), followed by spoke and then elliptical superconducting cavities that bring the beam energy up to 600 MeV. The front-end section, which does not exhibit any fault-tolerance capability, is duplicated for redundancy, with a fast switching magnet that can bring either beam (but not both) to the rest of the linac.

Several points linked with the high-reliability capability of the solution have to be demonstrated through R&D programs. The main objectives are the following:

- Reach a sufficiently high reliability level for the injector section.
- Reach RF performances for superconducting cavities well above the foreseen operating point (50 mT peak magnetic field, 25 MV/m peak electric field), and at nominal power (up to about 20 kW for spoke cavities, and 120 kW for elliptical cavities), to ensure the de-rating principle.
- Prove the fault-tolerance capability of the solution by developing a fast RF control system able to manage cavity failures.
- Check the compatibility of radioprotection and maintenance procedures with the foreseen operation schedule of the XADS (3 months operation / 1 month maintenance).

During the last years, and related to the foreseen projects for high-intensity proton accelerators, several R&D programs have been started in different laboratories around the world. In the US, these activities were developed around the APT project at Los Alamos, and more recently within the SNS project. In Japan two laboratories KEK and JAERI joined its efforts to prepare a multipurpose facility. Several R&D programs have been also launched in Europe by the partners of the XADS collaboration, or connected to other projects like EURISOL for the nuclear physics, ESS, TRASCO, etc..

Status of the R&D on the injector section (up to 5 MeV) --

The Los Alamos National Laboratory was the first to operate a 350 MHz injector, LEDA, at intensities of the level of 100 mA CW **[30]**. In Europe, two major developments, with characteristics close to the XADS injector requirements, are presently in an active construction and test phase: IPHI in France and TRASCO in Italy. IPHI is composed of an ion source, a 3 MeV RFQ copper structure and a beam analysis system. The source is now operational and reaches very high intensity proton beams (up to 100 mA, see section 3.2.1.1, page 25), the RFQ is under construction, and a complete beam test is planned for 2005-2006 **[32]**. The status of the TRASCO injector is very similar: the source is in operation and the first sections of the 5 MeV RFQ have been constructed **[33]**. Final tests with a 30 mA proton beam are planned in the 2004-2005 period.

Good performances of both RFQ are important milestones for the XADS project. Reliable operation of these complex copper structures relies on sophisticated technological and fabrication techniques. The excellent results obtained with the ion sources must be complemented by similar RFQ performances, in particular to demonstrate the feasibility of a very high geometrical stability for these structures submitted to high RF power and thermal constraints.

Status of R&D on the intermediate section (from 5 MeV up to 90 MeV) ------------------------

The transitional section, between the 5 MeV injector and the high-energy section, is probably the less well-known part of the accelerator. In old projects and even in some more recent, a room temperature (RT) copper section was proposed for the 5 – 100 MeV energy range. Very often this choice was associated to the accelerator pulsed operation mode, which allows accepting moderate structure losses. In the case of the CW beam required by the XADS project, the study of a solution using superconducting (SC) structures was considered from the very early stage of the study. The gain in installed RF power and its associated economy on operating costs were major incentives for this choice. The XADS reference design thus proposes to study an intermediate section composed of SC (or RT copper) DTL structures from 5 to X MeV (X value around 20 MeV, not decided yet) and independently phased SC structures from this value up to around 100 MeV.

Concerning the front-end high-energy part (5 MeV up to X MeV), some prototypes are now under construction and test, as presented in: a SC CH-DTL structure proposed by the Univ. of Frankfurt **[55]**, and a RT copper interdigital DTL structure proposed by IBA (Belgium). Theses proposals, which offer very efficient and compact structures, are now in the construction phase, as reported in sections 3.2.1.4 and 3.2.1.5.

In the first section of the independently-phased superconducting linac, from X MeV up to 90 MeV, the XADS proposal is to use spoke SC cavities, offering high modularity, fault-tolerance capability and, very important, high beam tube diameter reducing the activation risks. After the initial developments and results obtained in two U.S. laboratories (Argonne and Los Alamos), a first prototype has been studied and tested by the CNRS-IPN Orsay laboratory, in close collaboration with the French industry (CERCA-Framatome ANP), who took in charge the cavity fabrication. Cold test results confirmed the excellent performances of such cavities, with accelerating fields exceeding the requirements for a XADS driver accelerator (12.5 MV/m at 4.2K and 16.2 MV/m at 2K, see section 3.2.2.1, page 43). To keep going with the spoke cavities development program for European accelerator projects (i.e. PDS/XADS and EURISOL), the CNRS-IPN Orsay has launched the fabrication of a new spoke cavity, and a design study on the associated power coupler and cryomodule.

In this intermediate energy range, it has to be noted that other types of superconducting resonators are also studied in several laboratories, like the SC re-entrant resonators proposed by INFN Legnaro in Italy **[109]**. These short resonators offer very high modularity, and the initial prototype results confirm the foreseen performances (Eacc > 7 MV/m).

Status of R&D on high-energy section (from 90 MeV up to 600 MeV or higher) -------------

For the high-energy section, starting at 90 MeV, a general agreement of all laboratories involved in this field around the world, confirm the choice of multi-cell elliptical SC cavities. The excellent results obtained by the TESLA (electron-positron collider) project, and the confirmation by the European industry of the technological feasibility of niobium cavities, has been recently confirmed by the successful test of the first series of cavities for the SNS project in construction in the US.

In the XADS project, the cavities frequency and cell geometry have been adapted to the special requirements of the project. A preliminary R&D program was started in the frame of a collaboration between French (CNRS-CEA) and Italian (INFN) laboratories. A first prototype (beta 0.65) was constructed and tested by the CEA-CNRS. During the last test, performed in a horizontal cryostat (CRYHOLAB facility), the cavity was tested with its helium tank at 2K, in a cryogenic environment close to the accelerator, and reached a maximum gradient of 19 MV/m. Two beta 0.47 prototypes have been also constructed and tested by the INFN Milano, showing excellent performances, and confirming the quality of the fabrication and preparation procedures (see section 3.2.2.2, page 46). These performances confirms the feasibility of the cavities for the high energy section, having the capability to cover a wide energy range, and offering accelerating gradient performances well in excess of the XADS requirements.

To operate these cavities some important associated components are needed, in particular a RF power coupler (in the range of 100-150 KW) and a cold tuner for the fine adjustment of the resonant frequency of each cavity. Both developments are now in the preliminary design stage and will become major activities of the foreseen R&D program.

5.2 ROADMAP FOR THE 6TH PCRD

The main focus of a R&D program for the next 6th FWP will thus be an experimental evaluation of the reliability performances of the main components of the reference accelerator configuration that has been elaborated within the PDS-XADS study. In different meetings and technical discussions of the WP3, it was clearly stated the need of a specific R&D program that meets the unique reliability criteria of an HPPA destined to transmutation within a sub-critical system. An overview of the proposal was presented in the ADOPT "InWor" Meeting at Mol **[6]**, and a more elaborated proposal was recently prepared for the submission of the EUROTRANS integrated program. Five essential tasks have been identified.

TASK n°1 - Experimental evaluation of the proton injector reliability **--------------------------**

Task 1 should experimentally determine the reliability of the injector part by means of the 3 MeV, 100 mA accelerator IPHI, presently in construction by CEA and CNRS. Furthermore, the performance of this section with regard to voluntarily beam interruption (neutronic measurements, safety-grade shut-down) will be demonstrated.

TASK 1 GOAL

The injector IPHI, developed in France by CEA and CNRS before being installed at CERN, will be used for a long run test to demonstrate on a real scale the reliability of the first injector part. It is composed of an ECR Ion Source, a RFQ and associated beam diagnostics. The proton beam, with energy of 3 MeV will be continuously operated over a period of several month with current intensity between 20 mA and 40 mA . Other important issues for ADS technology, i.e. the beam time structure with current "holes" for online sub-criticality measurements, will be studied in these tests, as well as the safety-grade shutdown of the source.

TASK n°2 - Assessment of the reliability performances of the intermediate energy accelerating components **---**

Task 2 should assess the performance of the subsequent accelerating components. The reference design uses a combination of 3 types of structures, but the transition energies between them have to be determined by reliability values and economy. This quantification and optimisation will be done with experimental results from the 3 prototypical components presently studied by the PDS-XADS participants partners.

TASK 2 GOAL

Evaluation of room-temperature cavities and superconducting cavities operating performance. Optimisation of reliability versus construction and operational costs, choice of the transition energy between warm and super-conducting parts of the accelerator. Determination of the energy transition from where on doubling of the injector is no longer required for reliability.

- For the room-temperature structures, a design of IBA (Belgium) of a copper multi-gap structure of the IH type should be constructed and tested. Regarding the reliability concerns for an ADS, this structure offer several major advantages: it avoids focusing elements inside drift tubes, and the low power density facilitates cooling challenge for a CW accelerator. The main goal is to test at full power an IH structure in order to evaluate its reliability performances.
- Concerning the superconducting CH multi-gap structure, a prototype is presently under construction by University of Frankfurt. It will be tested and equipped with auxiliary systems in order to evaluate the reliability performance at high power. This original development offers, together with its inherent low RF power consumption, and very high real estate gradient, reducing the needed number of components.
- Results recently obtained by CNRS IPN Orsay have confirmed that spoke cavities are excellent candidates for replacing room-temperature structures in the 25-100 MeV energy range, and their modularity allows to implement a fault tolerant scheme. A spoke cryomodule, presently under design at CNRS-IPN Orsay, will be connected to the IPN Tandem accelerator, delivering 30 MeV proton beam, for long duration reliability qualification and fault tolerance experiments with associated acceleration of beam (at the maximum intensity, some mA, of the injecting Tandem).

TASK n°3 - Qualification of the reliability performances of a high-energy cryomodule at full power and nominal temperature --

Task 3 should qualify the performance of a high-energy section cryomodule with all subsystems running at rated power and nominal temperature. This task could heavily rely on prior R&D results, existing infrastructures, and investments of INFN, CNRS and CEA.

TASK 3 GOAL

Design, construction and test of a full prototypical cryomodule of the proton linac high-energy section. This cryomodule (see Figure 5-1) is the basic building block of this accelerator section and the high availability/reliability requirements and maintenance considerations impose a special design adapted to the ADS environment. The task is focused at delivering an operational prototype cryomodule for extensive tests (without beam but at full RF power level) to qualify its reliability characteristics. The cryomodule is designed for the 100 - 200 MeV range (beta = 0.47) with 2 (or 3) elliptical niobium superconducting cavities (since for physical reasons, the very similar sections above 200 MeV are becoming less critical with increasing energy). This cryomodule will also be connected and tested with the special digital electronics developed within Task 4, and thus provide a complete proof of principle of the "fault tolerance" feature.

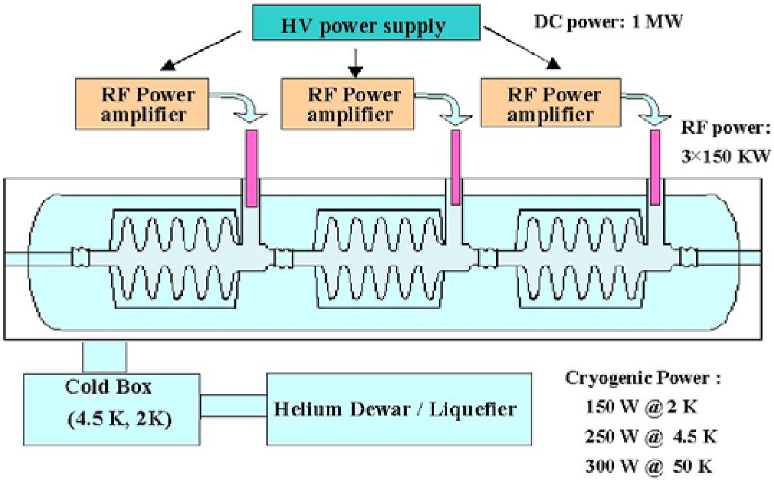


Figure 5-1 – Sketch of a possible prototypical cryomodule for the high-energy section of the XADS linac.

TASK n°4 - Design and test of a prototypical RF control system for fault tolerance operation of the linear accelerator ---

Task 4 should be the design and realisation of a prototypical RF control system. Based on a novel concept using fast digital electronics, this "intelligent" system aims to guarantee the fault-tolerance of the linac.

TASK 4 GOAL

The RF Control System for the superconducting cavities is the "brain" of the linac, because it maintains the beam stability by adjusting the amplitude and the phase of the accelerating field with high accuracy and fast response. Many RF control systems have been developed in different accelerator facilities, but they do not satisfy all the stringent specifications in terms of reliability, robustness and flexibility, as required by an ADS for transmutation. The flexibility appears here as an important feature since the system should be easily and quickly adjusted or reprogrammed in case of a failure in any other RF part, power source or accelerating cavity (fault tolerant design). A digital RF control system, in which a number of key functionalities are implemented on a single chip, offers this high-grade reliability and flexibility, and communications with the accelerator control system are monitored by means of micro-controllers without additional boards. Some conceptual design features have already been developed within PDS-XADS. Prototyping such a RF Control System unit, in a parallel process to the construction of a high energy cryomodule (Task 3), will offer the opportunity to demonstrate coherently the operation of an accelerating module at full RF power, even if the tests are performed without beam. It will also provide accurate cost estimation for the RF system in a global ADS design.

TASK n°5 - Overall coherence of the accelerator design, final reliability analysis, and cost estimation of XT-ADS --

Finally, in Task 5, the overall coherence of the accelerator design will be provided.

TASK 5 GOAL

The final reliability analysis for the whole accelerator will be performed, integrating the experimental results and demonstrated reliability numbers. The deduced and optimised design will provide the basis for the cost estimation for XT-ADS and EFIT and a possible schedule for its realisation. Task 5 will also include the beam-dynamics calculations needed for the full demonstration of the fault tolerance concept. Related to the development of a new RF control system and to the validation of the "fault tolerant" design, specific beam dynamics simulations are needed to investigate the transient beam loss related to a cavity or RF system failure and its recovery. The development of a simulation code that includes a transient analysis of beam stability (longitudinal and transverse) with a realistic model for the RF system and the cavity, which is a critical issue for ADS linac, will be performed.

Funding and schedule --

An initial estimation of the needed funding to develop this R&D program concentrated on reliability was discussed and the laboratories proposed their involvement and responsibility on the different tasks discussed above (see Table 5-1). This initial proposal was presented at the ADOPT "InWor" meeting in Mol **[6]**. It reflects the expression of partners to a potential collaboration at that time. The EU contribution for this R&D program was estimated to 6.5 M€, the total cost of this program supported by the institutions being an order of magnitude higher.

Table 5-1 – R&D needs focused on reliability & possible collaboration scheme as discussed in October 2003 at the ADOPT "InWor" workshop in Mol (Belgium).

	Low Energy Section	Intermediate Energy Section				High Energy Section	RF System	Global Coherence
R&D Topic	Injector Reliability	Spoke cav. (SC)	CH struct. (SC)	IH struct. (NC)	Other cav. (SC)	Beta 0.5 Cryomodule	Control System	
Responsible	CEA	CNRS				INFN	CEA	CNRS
Participants	CNRS, INFN, U.Fra	CEA, FZJ, IBA, INFN, Framatome-CERCA, U.Fra				CEA, CNRS, IBA	IBA, INFN, ITN	CEA, ENEA, IBA, INFN, ITN, U.Fra
Requested EU Contribution	1 M€	2 M€				2.5 M€	0.5 M€	0.5 M€

Some milestones and general schedule were also discussed (see Figure 5-2). A program of 4 years, starting beginning 2005, should allow to implement the different proposed R&D

studies and experiments, aiming to establish a complete reliability assessment and many of the proofs of feasibility for the main components of the proton linear accelerator.

Important part of this program is now proposed to be performed within the 6th FP Integrated Project EUROTRANS.

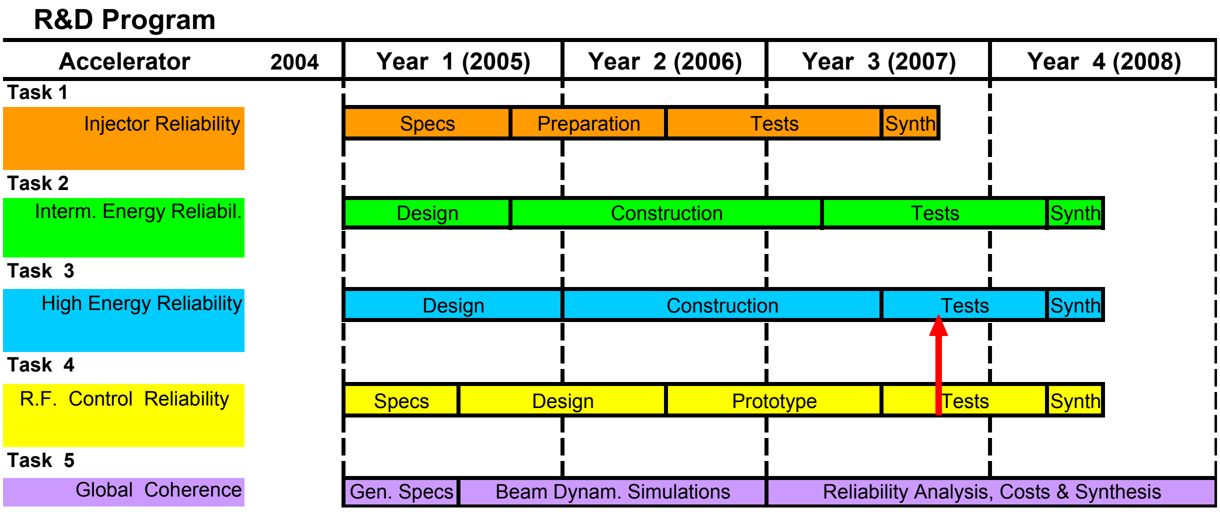


Figure 5-2 – Preliminary 4-year R&D time schedule.

6 CONCLUSION

Notwithstanding the extrapolations for a larger scale (industrial type) ADS, that will be the subject of deliverable D80, the present deliverable D63 constitutes the overall synthesis document for the XADS accelerator.

A robust technical design has been elaborated on the basis of specifications made by other working packages of PDS-XADS. In particular, regular interaction was made with WP1, assuring the "Overall Coherence" of the project, and with WP 5.3 for the special needs of the smaller-scale XADS, including some preliminary investigations concerning infrastructure aspects of SCK-CEN technical site at Mol, Belgium.

A superconducting linear accelerator, with its associated doubly-achromatic beam line, has been found to constitute an optimal technical solution. In fact, this type of concept is substantially superior to other solutions with regard to the established requirements for reliability. Further, this modular concept generically satisfies not only the PbBi- and gas-cooled XADS, which rely on a 600 MeV proton energy. Indeed, by simply withdrawing or adding some more accelerating "cryomodules", an energies ranging from 350 MeV for the smaller-scale XADS ("MYRRHA") to 1 GeV or more for an industrial transmuter can be reached, respectively.

Similarly, a double achromat with active scanning is able to "paint" a large variety of beam profiles. Thus, not only the beam profiles required by the spallation targets of the various XADS versions can be satisfied, but the same concept can also applied to industrial transmuters. The doubly-achromatic feature guarantees two important safety functions. If a small energy variation of the accelerator occurs, that is within the tolerances of specifications, then the beam position on the spallation target will not change. If, on the other hand, the beam energy is considerably below or above the specified value, although such a condition is rather difficult to conceive for other reasons, then, as intrinsic design feature, the achromat will simply block out the beam in the intermediate focal plane.

A critical specification for an XADS accelerator is the absence of beam trips. In this aspect, the proposed solution is a priori very robust, since it relies on a highly modular linac to which very conservative design rules have been applied. In fact, we have formally shown by means of an RBD analysis that, for given component reliability numbers, the chosen degree of redundancy and fault tolerance in the linac configuration can result in a wide range of system reliability characteristics. A large gain in the system reliability is achieved in the case of parallel redundancy with “hand-on” repair possibilities. For accelerator components falling in this class, the current reliability performance is actually sufficient for the XADS need. For in-tunnel components, which require a system shutdown for corrective maintenance, a sufficient degree of fault tolerance has to be applied. Our beam dynamic studies and our conceptual studies for the RF system indeed show that such a level of fault-tolerance can be achieved in a sufficiently modular linac system, in contrast to more compact solutions.

Concerning the required infrastructures, the specifications are proposed and solutions have been discussed. The concept of a small cross-section tunnel, with relatively thin concrete walls and recovering of the excavated earth for additional radioprotection, turn out to be a very elegant and cost effective solution. In fact, from the civil engineering viewpoint, such an elongated layout is actually not more complicated and should also not require more concrete for shielding than an accelerator hall for a more "compact" machine, requiring typically an order of magnitude thicker concrete shielding and a correspondingly reinforced floor to sustain the weight of the machine and the shielding. Of course, such general considerations are dependant on site-aspects.

A roadmap has been elaborated for such an accelerator, which relies on the successful accomplishment on an advanced technology programme dedicated to the reliability issue. Estimated to last about 4 years, the construction phase for the accelerator and its infrastructures, including all the required authorizations, would typically last 7 years, to be followed by a 3-year commissioning period prior to beam delivery in routine operation specifications. From other machine projects, a cost, prior to routine operation, of about 300 M€ has been estimated for the 600 MeV machine, including in-house and external man-power as well as infrastructure investments of 30 M€, but notwithstanding certain assumptions on the site which have been detailed (e.g. land procurement, access roads…). This estimate would be considerably reduced if the energy is lower, and the injector not doubled. As concerning operation costs, the concept of using superconducting technology from a very low energy range on is most cost effective.

The advanced technology R&D program (partly to be financed within the 6th FP Integrated Project EUROTRANS), will not only provide answers related to the accelerator performance in the critical area of reliability/availability, but it potentially may allow to relax on some of the presently rather conservative specifications, which in turn may reduce the present cost estimate.

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