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Reliability studies of a high-power proton accelerator for accelerator-driven system applications for nuclear waste transmutation

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Abstract

The main effort of the present study is to analyze the availability and reliability of a high-performance linac (linear accelerator) conceived for Accelerator-Driven Systems (ADS) purpose and to suggest recommendations, in order both to meet the high operability goals and to satisfy the safety requirements dictated by the reactor system. Reliability Block Diagrams (RBD) approach has been considered for system modelling, according to the present level of definition of the design: component failure modes are assessed in terms of Mean Time Between Failure (MTBF) and Mean Time To Repair (MTTR), reliability and availability figures are derived, applying the current reliability algorithms. The lack of a well-established component database has been pointed out as the main issue related to the accelerator reliability assessment. The results, affected by the conservative character of the study, show a high margin for the improvement in terms of accelerator reliability and availability figures prediction. The paper outlines the viable path towards the accelerator reliability and availability enhancement process and delineates the most proper strategies. The improvement in the reliability characteristics along this path is shown as well.
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1. Introduction

Each new breakthrough in technology has always presented new challenges and new opportunities for reliability and maintainability professionals, who are demanded to respond consistently to assure system high quality and performance. The need for high availability with a reduced number of beam interruptions for new applications of accelerators is a challenging task not only on the technological viewpoint in the accelerator development phase, given existing accelerators are not primarily optimized with respect to reliability. Furthermore, reliability has only relatively recently been given a high priority in accelerator design, and for very few specific applications (e.g. nuclear waster transmutation, synchrotron radiation sources, medical accelerators of future huge facilities for high-energy physics exploration), as compared to proce-dures routinely employed in industry for many years. This is particularly relevant as far as accelerator-produced neutron facilities and the development of accelerator-driven subcritical systems technology for transmutation of waste purpose are concerned.

For an operational production level accelerator such as is needed for the Accelerator Driven System (ADS) concept, performance and reliability are outstanding attributes, in order both to meet high operability goals and to satisfy the safety requirements dictated by the nuclear reactor system coupled to the accelerator [1]. These requisites entail the evaluation of the accelerator machine in terms of its reliability and availability over the design phase progress, aiming at its improvement to achieve the required goals. Within the ADS-related activity developing worldwide, this crucial point is being addressed to provide a consistent frame to support accelerator reliability analysis and enhancement [2]. Initially a qualitative methodology, as Failure Mode and Effect Analysis (FMEA), helpful in the identification of reliability-critical areas, where

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modifications to the design can help reduce the probability of failure, has been applied as first step of an overall reliability assessment process [3]. Beyond this step, a phase including a quantification process needs to be accomplished: the main scope of the present study is to analyze the reliability of a linac (linear accelerator) for ADS purpose and to suggest the most properly suited strategies in order to achieve the high reliability requirements. The paper is conveniently subdivided into two main parts: in the former one a very preliminary study, with the characteristics of an exploratory effort, is presented, while the second part provides the results of a more detailed and consistent analysis.

2. System description

From a functional point of view, we can describe the high-power proton accelerator configuration under consideration as composed by the following main systems and components [4]:

(1) An *injector*, that is a proton source followed by a 5 MeV Radio Frequency Quadrupole (RFQ) and a (possibly normal conducting) intermediate accelerator stage to the transition energy from 5 to 50 MeV. Possibly, as will be considered in this paper, 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 linac*, based on independently phased cavities, split in a spoke section (with two different structure types) and an elliptical section (with three different structure types), accelerating the beam, respectively, to intermediate and high energies (notably 100 and 600 MeV). The main linac, according to the beam dynamics simulations presented in Ref. [4], exhibits a natural redundancy and fault tolerance capabilities due to its modularity.
(4) The *beam delivery system*: an array of magnetic elements that provides the necessary beam size and pattern at the target at the final energy of 600 MeV.

3. Reliability requirements

In the following, a mission time of 3 months of consecutive operation (2190 h), followed by a month for major maintenance where ideally all accelerator components will be brought back to their initial state, is considered. During this mission time the number of system faults has to be limited as much as possible.

According to the ADS accelerator goal of 10 faults per year, a goal of three system faults during the mission, is

Table 1
Reliability assumptions and goals

Mission time	2190 h
Goal MTBF	∼700 h
Goal number of failures	∼3
Reliability parameter	Unconstrained

established [2], implying a design requirement of a system with a Mean Time Between Failure (MTBF) of approximately 700 h.

The components faults assumed here are the common components faults resulting 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 which wear 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 is worth noting that actually the reliability requirements for the machine performance is set in terms of MTBF or alternatively number of faults per period of operation and no conditions are posed for a high reliability parameter, since indeed the wished values of a MTBF of 700 h for a mission time of 2190 h would imply a nearly null reliability value.

The following table resumes the reliability goals and assumptions (Table 1).

4. Reliability oriented design

The current operational experience at accelerator facilities worldwide surely exceeds by a great factor these requirements on the allowed accelerator faults, but none of the existing accelerators has been until now designed with similar demanding requirements.

Suitable strategies, envisioning reliability oriented criteria, need to be followed early in the design in order to reach the extremely low fault rates expected from the ADS accelerator.

As a starting point of any reliability oriented design, it is necessary to identify the causes of all possible failures that

anyhow occur in the system. Where possible, these causes should be removed (either by a suitable design or operation of the components) and, for the ones that are impossible to avoid, strategies for dealing with the corresponding failures should be identified (e.g., by adding redundancies in the system or providing fault tolerance capabilities).

In addition to systematic application of reliability approaches to new components design, as superconducting cavities, and "commercial" component development as klystrons, part de-rating and component redundancy/spares on line are identified as main strategies, dictated by common sense and experience, suitable to drive a proper design [3].

The former implies the component operating below its nominal specification, thus putting less stress on the component and guaranteeing a longer lifetime. The latter concerns key element in the system that may induce its failure and it consists in adopting redundant configurations (either parallel or stand-by connections) and/or spare to take over the function of the failed components.

Lastly the fault tolerance concept is introduced [4]: it consists of the capability of the system to perform its duty within the required specifications even if some of its components are defective or are not working at all and it overcomes the previous approaches, even if it entails a strong interaction with the beam dynamics studies. Fault scenarios analysis involving single component fault effects studies on the beam dynamics have been performed in order to assess the effectiveness and applicability of this concept [5]. The solution based on a superconducting linac [5] represents the simplest solution for the accelerator design, it shows a very high degree of modularity—a repeated pattern of transversely focusing elements alternated with independently phased accelerating cavities—which allows a natural implementation of component de-rating, redundancy capabilities and (at least partially) fault tolerance with respect to radiofrequency failures.

A special effort can be dedicated to improving considerably the availability by considering all the elements that influence the repair times: the fault detection and diagnosis process; the preparation time needed to conduct the repair; the fault correction time itself; the post-repair verification strategies and finally the time to restart the system once the fault is corrected. Time needed to localize the exact cause of a failure can be reduced by proper installation of (redundant) diagnostic tools and the use of a dedicated control system. The time needed for repair depends also on policies concerning spare parts, redundant systems and fast access to failing components. Finally the components mean time between failures can be increased by preventive maintenance, in addition to a strong design and de-rated operation.

5. Need for a consistent database

The original goal of the reliability and availability analysis is to estimate the expected machine availability for each project based on projected reliability of components and subsystems and overall operability considerations. However, a survey on pre-existing work on the matter pointed out a deficiency in a relevant set of data required for accelerator reliability assessment, given the quantification accomplished through the current reliability models. The availability of a relevant reliability database and the consequent need for its assembling has been identified as one of the main issues related to accelerators reliability assessment, since data bases are very limited and data are too sparse due to the wide site-to-site variability in causal mechanisms [1].

Thus, while it is possible to use the reliability standard methodologies to model the accelerator systems and to perform the relative reliability/availability assessments, there is no formal and "robust" reliability database for accelerator components available, leading thus to large uncertainties in the results (i.e. high EF if lognormal distributions are assumed for component reliability parameters like failure rate, probability of failure on demand and so on). Thus an enlargement of the sample data is envisaged in order to add credibility to the analysis and to have more confidence in the prediction of the results.

Previous FMEA [3] structured procedure, which provided a complete picture of all the failure modes of the accelerator components, pointed out two broad categories of key accelerator components. The first class concerns the "industrial" components which are found mainly in the support systems as cooling systems, vacuum devices (pumps, valves), cryogenic components, or standard accelerator magnets and magnet power supplies, for which failure data are available from a large operating experience or other areas of applications as, for instance, fission and fusion field, medical accelerators, aerospace or cryogenic industry. The second category concerns major "ad hoc" accelerator components (HV sources, RF systems, cavities …) for which reliability parameters are inferred on the basis of either operational data of existing similar facilities (accelerator for High Energy Physics or Synchrotron Radiation user facilities) or from literature, vendors, previous studies, where applicable, and the practice of "expert judgement". Clearly, many worldwide accelerator facilities have huge databases with many years of operating performances of components which are a useful source of information, but the data organization in a coherent database has not been performed so far, mainly due to the great differences in the data collection and log keeping between laboratories and in the needed manpower for such an effort [6].

6. Failure mode and effect analysis

As mentioned earlier, the topic is first addressed by the application of a preliminary FMEA [3], which allows to identify the reliability-key systems and components of the accelerator, the relative potential failure modes and the consequences on the system performance, in terms of beam

delivery and finally to devise design improvements to reduce the number of critical items and enhance the overall reliability.

The need for such a qualitative analysis stems from the considerations in the previous section and from the early stage of the design, in which many systems are not yet established: the main goal being to suggest future directions for addressing, in an iterative process, the critical issues and to provide an input consistent with more detailed reliability analysis, as illustrated in the forthcoming chapters of the paper.

By analyzing the linac configuration of Section 2, we have identified three main systems of the accelerator: the accelerator hardware, the cryogenic plant and the service infrastructures. These systems are either large functional blocks of the accelerator systems, as the ones reported in Table 2, or large facilities needing buildings or areas physically separated with respect to the linac building (such as cryogenic plant, the service infrastructures and the power network).

The FMEA has been used in order to address the failure identification task: for each one of the scrutinized systems/ components all the possible failure modes that could occur during the operation are evaluated in terms of: failure causes and possible actions to prevent the failure, consequences on the system and actions to prevent and mitigate the consequences. Severity levels have been ranked in a standardized way for all faults. Obviously the beam stop and consequent beam loss is the most relevant consequence taken into account, according to the requirements imposed on the accelerator performance.

The identification of all failure modes is an important source of information, which will guide the more detailed subcomponent engineering that will be performed by future R&D activities aimed at prototype development and reliability studies.

From the analysis of the FMEA tables [3], it is clear that the region of the accelerator where we can find the majority of failure modes that can potentially lead to the full beam loss is the injector (at least up to the RFQ). This has raised the need for a redundant injector with fast beam switching capabilities, as indicated in Table 2. For most of the rest of linac, a small number of failure modes leads to beam stops. Most of them are due to vacuum loss events. Also all the failure mode effects can be limited with a proper strategy, using either the natural redundancy of the superconducting linac or some actively redundant system. This applies for example to the faults associated with the Radio Frequency (RF) units, for which studies have demonstrated the properness of the fault tolerance concept [4,5].

7. Preliminary accelerator reliability studies

7.1. Model

According to the current methodologies, the Reliability Block Diagram (RBD), which works in the "success space" as compared to the Fault Tree (FT) which works in the "failure space", is identified as suitable technique for the accelerator reliability assessment. The RBD hierarchially represents unit interactions and/or dependencies according to the system toponomy: the RBD model represents the functional/logical relationship of the components and systems and includes reliability values of the components. The RBD tool, reducing complicated series and parallel systems to a visible sequence of series and parallel blocks,

Table 2
Configuration of the accelerator

Subsystem	Main components	Redundancy	Comments
Ion source	1 lumped unit	2 systems in parallel	
RFQ	1 RF structure		
	2 RF systems		
Intermediate energy	36 cavities	None	18 focussing lattices
Beta = 0.15 Spoke cavity	36 RF systems		
	36 magnets		
Intermediate energy	60 cavities	None	20 focussing lattices
Beta = 0.35 Spoke cavity	60 RF systems		
	40 magnets		
High Energy	28 cavities	None	14 focussing lattices
Beta = 0.47 Elliptical cavity	28 RF systems		
	28 magnets		
High energy	51 cavities	None	17 focussing lattices
Beta = 0.65 Elliptical cavity	51 RF sources		
	34 magnets		
High energy	12 cavities	None	4 focussing lattices
Beta = 0.85 Elliptical cavity	12 RF sources		
	8 magnets		

calculates an exact reliability for the network and creates an efficient encoding of the topology of the system. The analysis is being pushed according to the present stage of definition of the design—since many systems are not yet setup—hence the RBDs are developed mostly by using simplified—i.e. consisting mainly of "lumped" elements— models for each apportioned system: because the analysis is being developed for top-level reliability evaluation, modeling the machine state at system or subsystem level is usually adequate and thus acceptable.

With reference to the configuration outlined in Section 2, the main systems for the ADS accelerator are: the hardware components of the accelerator (cavities, magnets, vacuum connections, etc.), the cryogenic production and distribution plant for the Superconductive Cavities and the infrastructures (water, compressed air, electrical power). The control system together with the vacuum and the RF systems, due to the modularity of the SC solution, are distributed systems included in the accelerator hardware and are not considered as distinct systems. The RBDs are thus built at functional/logical system level: the reliability results from the contributors deriving from the various subsystems, which comprise the Ion Source, the RFQs, the Medium Energy Section Spoke Cavities, the High Energy Section Elliptical Cavities, whose main characteristics are reported in Table 2 [6], the Cryogenic System and any other support systems like the Electrical Power Distribution System and the Water Cooling System.

7.2. Exploratory "parts count" reliability assessment

Along the path to provide a basis for the development of a high-performance accelerator through the reliability and availability figures of merit, initially a rough "parts count" reliability estimation has been performed, assuming no fault tolerance is provided in the accelerator, which is modelled effectively as a series connection of all its components, besides a redundant injector (ion source and RFQ). Thus, any single component failure will produce complete system failure: under these assumptions obtaining an upper bound for the system probability of failure is straightforward. Obviously in this case, due to the considerations expressed in the preceding paragraphs, the reliability of such a system is practically zero, for any practical mission time.

The model has been fed with a preliminary set of MTBF data collected mainly from International Fusion Materials Irradiation Facility (IFMIF) or Los Alamos Neutron Science Centre (LANSCE) experience, [1], and complemented with engineering judgment where data was missing. Given the subjectivity at this preliminary stage of the input data, especially in the Mean Time To Repair (MTTR) data, that do not include logistic and waiting times, the results are only intended as a guideline for the identification of critical areas, and the study needs a further iteration after a cross check with other component sources, as the one described in the preceding paragraph.

The results, predicting a reliability value around zero and a number of failures of around 70 totally incompatible with the ADS goal, although sounding rather "awkward" for a reliability study, are however consistent with the outcome of preceding similar work as found in [7,8], focused on the Reliability, Availability and Maintainability (RAM) analysis of the linear accelerator of the IFMIF project. Besides the warnings expressed above on the credibility of the results, this very rude parts count estimations performed for a 3-month mission time lead to a system MTBF of 28 h with a MTTR of 5 h, resulting in an 85% inherent availability. An analysis of the percentage contribution to the overall failure rate is shown in Table 3. Clearly in this extremely oversimplified "parts count" estimation the critical points are found in the regions with the higher number of components (notably the 0.35 beta spoke and 0.85 beta elliptical cavities), since we have considered, very conservatively, that a single RF unit failure within any super conducting section constitutes a system and accelerator failure [6].

The identification of reliability-critical areas assists the designer in the appropriate allocation of resources towards achieving the most benefit from the reliability improvement process. Therefore, the main strategies devoted to accelerator reliability improvement should be implemented on RF systems, since they are identified as critical components, within the superconducting sections. In Fig. 1 and Table 4, respectively, the RBD model and the results of the analysis relative to the RF system are reported, with reference to the 0.35 beta Spoke Cavity Section (60 cavities): the table highlights the sensitivity of the reliability values to the number of cavities/sections. This stems directly from the reliability analysis rules which predict the product of the single reliability values for series wise configuration.

Finally, it is worth highlighting that the mission reliability of the system implies the evaluation of the probability that the system will properly accomplish its function without failing over the specified mission time,

Table 3
Percentage contribution to the overall failure rate from the subsystems

Subsystem	FR contribution (%)
Proton injector	0.6
Intermediate energy section low beta	19.0
Intermediate energy section high beta	31.7
High-energy section low beta	14.6
High-energy section intermediate beta	26.2
High-energy section high beta	6.7
High-energy beam transport system	0.1
Beam delivery system	0.1
Cryogenics	0.4
Water system	0.1
Compressed air	0.2
Electrical power	0.3
Total for accelerator	100

which conditions the relative reliability figure, based on the negative exponential model, but not the mean time between failure estimation, which is actually the figure of merit of interest: the 1 week mission time (i.e. 168 h) has been actually assumed in this specific system related analysis according to analogous works [7,9].

Conversely, the availability of the systems seems not to be affected significantly by the number of the components: this is due to the fact that the MTTR is not so notably influenced by the number of the components as MTBF parameter, when in series configuration (for n identical components the MTTR is even the same, while the MTBF is the nth fraction of the single component value), making the correspondent value in any case much smaller than that of the MTBF and resulting in a quite acceptable availability value. Despite the fact that if on one side the reliability (i.e. if no maintenance action occurs) of the system decreases very rapidly to unacceptable values with the number of components, on the other side the maintainability holds constant, thus reducing the system availability but still keeping at acceptable values. It is worth noticing that the above calculations refer to the inherent steady state availability considering only the corrective downtimes of the system and not accounting for all experienced sources of downtime due, for instance, to administrative time, logistic time and waiting time, which should be inputs to the operational availability measurement, defined as the ratio of the system uptime and total scheduled time.

For instance, with reference to a week of operation (168 h) with a MTBF of around 30 h and a MTTR of around 4 h (as inferred from the results of the parts count analysis), the state of the system is illustrated in the following figure, in terms of MTBF and MTTR pertaining to the accelerator system as a whole: each time the system fails a renewal occurs and the system is restored to working order, in a sequence of alternating functioning and repair states (Fig. 2).
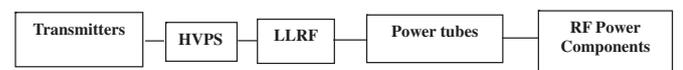
From this example it appears clear how the system is subject to a relevant number of failures featuring a short MTBF and consequently a very low reliability over the time span, but a quite acceptable availability, in terms of combination between the reliability and maintainability (notably the ratio of the MTBF to the sum of the MTBF and MTTR) and as far as the MTTR is relevantly less than the MTBF.

7.3. Step forward to reliability enhancement

The pessimistic results presented in the previous section, mostly deriving from the conservative assumptions taken in the analysis show a large extent for reliability improvement of the machine. In fact, the adoption of an appropriate reliability improvement process during the design phase is devised, making reasonably feasible and not too optimistic to reach a 25 times improvement of the system MTBF in order to achieve the MTBF reliability figure of merit of 700 h.

With this respect an analysis simulating a more realistic system configuration with "k out of n" redundancy for the SC cavities has been exploited: this means that not all RF units in the two linac SC portions are necessary in order to provide the required function. As a simple hypothesis one ($n-1$ out of n) or two ($n-2$ out of n) RF units in each superconducting linac section (either spoke or elliptical) can fail at any time, implying a moderate level of fault tolerance of the system. The results of both cases are shown in Table 5.

From the table one infers that consideration for a quite realistic and simple fault tolerance concept application leads to an improvement, albeit moderate, in the reliability figure of merit of the system, with reference to the present model. As mentioned before other provisions to deal with the task consist of the critical component redundancy (and
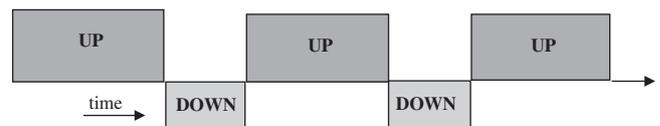
Fig. 1. RBD model for RF system.

Fig. 2. System behavior over mission time.

Table 4
Reliability and availability results for RF system (for a standard mission time of 168 h)

Component	MTBF (1/h)	MTTR (1/h)	Failure rate (1/h)	Reliability	Availability
Transmitters	10000	4	1.0E-4	0.98	0.99
High-voltage power system	30000	4	3.3E-5	0.99	0.99
Low-level radio frequency	100000	4	1.0E-5	0.99	0.99
Power amplifiers	50000	4	2.0E-5	0.99	0.99
Power components	100000	4	1.0E-5	0.99	0.99
1 comp./system	5769	4		0.97	0.99
60 comp./system	96	4		0.17	0.96

diversification in order to cope with the common cause failures) that have yet been accounted for the Injector system.

Table 6 shows the gradual increase in reliability values for the specific RF systems in both cases.

7.4. Poisson process

As ultimate step of this "exploratory" study, a specific probability model, such as the Homogeneous Poisson Process (HPP), has been assumed for describing the physical process on the probabilistic standpoint, that is the event count has a Poisson distribution.

This model has a constant event occurrence rate λ: the number of events in time t is a Poisson random variable with parameter $\mu = \lambda t$.

In addition to the assumption that the failure rate does not change over time this kind of distribution implies that exactly two simultaneous events do not occur, thus excluding common cause failures, and the events are independent (occurrence of an event does not influence the occurrence of another event).

Under the above assumptions the number of events X in some fixed time t is a Poisson random variable with mean $\mu = \lambda t$ and variance $\sigma^2 = \lambda t$:

$$Pr(X = x) = e^{-\mu}\mu^x/x! \qquad (1)$$

The Poisson distributions have been considered for these different values of the parameter μ (or correspondently λ, being $t = 2190\,h$, fixed) from the worst case (parts count) to the wished value (MTBF = 700 h), as in Table 7.

The distributions of the accelerator failures for different values of μ, which represent the number of failures over the mission time, are reported in Figs. 3 and 4 (representing, respectively, the probability and cumulative distribution functions), which show the improvement in system reliability as the parameter μ and hence the number of failures decreases (in both figures the parameter μ is denoted as m and a is the number of failures).

8. Reliability analysis

The "exploratory" analytical studies illustrated in the previous section provided only any useful insights to deal with the task, being the analysis carried out on the basis of quite generic numerical values assigned to a simplified model of the system.

These limitations clearly suggested that additional work aimed, first of all, at a refinement of the analysis was needed in order to add credit to the model quantification, on the path towards quantitative assessment of the reliability characteristics by means of standard methodologies.

By using all the considerations expressed in Ref. [3] and the further work on beam dynamics synthesized in Refs. [4,5], 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, consistent with the accelerator arrangement delineated in Section 2 and Table 2.

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 RBD configurations are analyzed and discussed. Since analytical

Table 7
MTBF values for different values of μ for Poisson distributions under consideration

$\mu = \lambda t$	MTBF
78	28
38	56
26	84
15	140
8	280
5	420
3	700

Table 5
Accelerator system reliability values for k/n configuration

System configuration	System MTBF (h)	Number of failures	Reliability
$(n-1)$ out of n	72	30	0.1
$(n-2)$ out of n	152	14	0.34

Table 6
RF system reliability values for k/n configuration

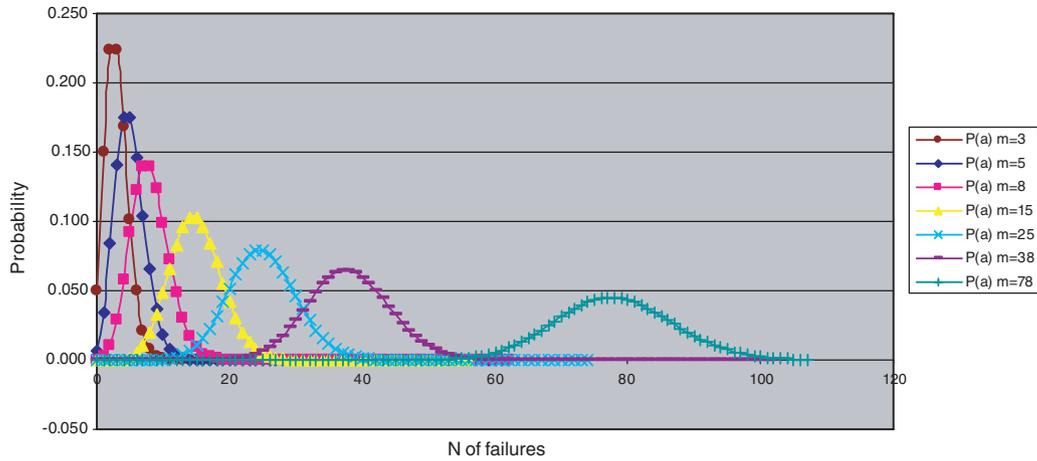| System	Number	Reliability	Reliability $(n-1/n)$	Reliability $(n-2/n)$
RF System	1	0.97	—	—
RF Beta = 0.15 Spoke Cav.	36	0.35	0.72	0.92
RF Beta = 0.35 Spoke Cav.	60	0.17	0.48	0.75
RF Beta = 0.47 Elliptical Cav.	28	0.44	0.80	0.95
RF Beta = 0.65 Elliptical Cav.	51	0.22	0.56	0.82
RF Beta = 0.85 Elliptical Cav.	12	0.70	0.95	0.99

Fig. 3. Probability distribution functions of the number of failures for different values of μ.
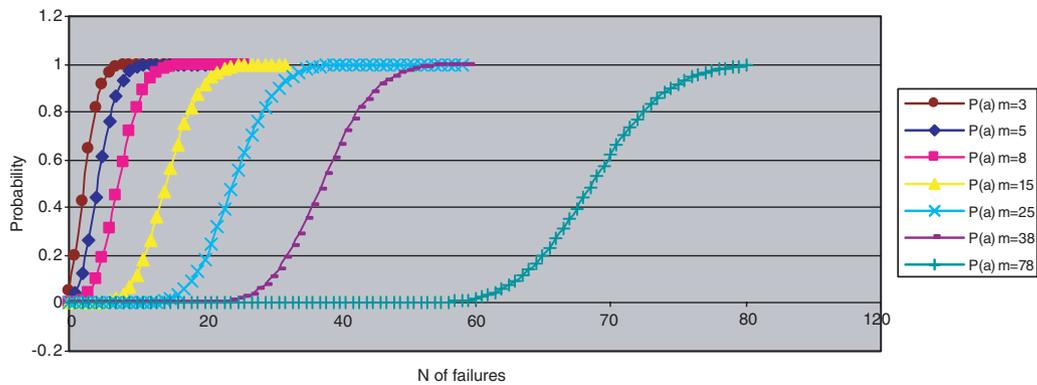

Fig. 4. Cumulative distribution functions of the number of failures for different values of μ.
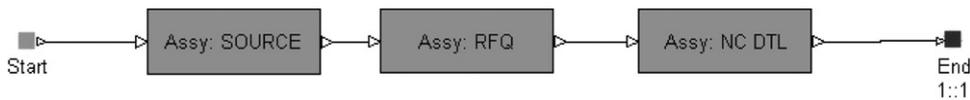

Fig. 5. RBD model for the injector.

methods are not suitable to deal with the complexity of the models including repairable components, a commercial software package, which uses both analytical calculations and numerical simulations capabilities, has been used to accomplish the task.

8.1. The linac components

8.1.1. The injector

The injector configuration analyzed in all RBD is simply a series configuration of its three components: the source, RFQ and NC accelerator intermediate stage (in the RBD identified as NC DTL) and shown below (Fig. 5).

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 h for each component have been used, even more conservative with respect to what has been used in similar analyses in other applications [9].

The RBD analysis of such a simple series system, using the reliability figures summarized in Table 8, predicts a MTBF of ~350 h, 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 h 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.

8.1.2. 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 nuclear reactor 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 ADS 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 whole support system is depicted below (Fig. 6).

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.

Table 8
Reliability characteristics of the components used for the RBD analysis

System	Subsystem	MTBF (h)	MTTR (h)
Injector	Proton source	1000	2
	RFQ	1200	4
	NC DTL	1000	2
Support systems	Cryoplant	3000	10
	Cooling system	3000	2
	Control system	3000	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

Assuming a goal MTBF of 3000 h for each subsystem, the predicted MTBF is ~1000 h, 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 8.

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 beamline 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.

8.1.3. 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 Refs. [4,5] the fault tolerance capabilities of the independently phased superconducting linac are summarized, with respect to RF failures (loss 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 providing 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,

Fig. 6. RBD model for the support systems.

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) (Fig. 7). The MTBF for these components are listed in Table 8 and have been taken both from the Spallation Neutron Source (SNS) predictions and the US Linear Collider Technology Options Study (USLCTOS) estimates [10]. In the following, for the sake of simplicity, we will not make a 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.

A series connection of these components determines an overall MTBF for the RF unit of ~5700 h, 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 h.

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 h, 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 ADS 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.

8.1.4. 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 character-

istics. For our simple model we have assumed a series connection of 20 magnets and associated power supplies, with the reliability characteristics listed in Table 8.

8.2. Summary of the data used in the RBD analysis

In the following table we list all the reliability characteristics of the components we have used in all the RBD analyses in order to asses the system MTBF of the different configurations of the ADS linac. Some of the MTBF listed below have been selected from existing literature (like the USLCTOS, SNS or Accelerator Production of Tritium (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 ADS 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.

8.3. 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 commercial RAMS software (Relex™ from Relex Software Corporation) in order to perform the RBD analysis either using analytical modeling (when possible) or MonteCarlo modeling (when the system could not be evaluated analytically due to the complex repair strategies).

8.3.1. 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
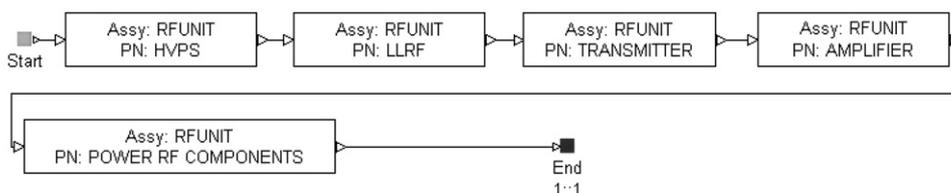

Fig. 7. RBD model for the superconducting linac.

(MTBF) and repair (MCT, mean correction time) characteristics, along with their quantity (Fig. 8).

The results are comparable with the outcome of the preliminary assessment based on the parts count approach in Section 7 (Table 9).

Clearly, this system is dominated by the series connection of 188 RF units that have each an MTBF of 5700 h, 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 h, 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 h, 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 ADS goals and would imply to require much higher MTBF characteristic to all RF components, by at least a factor greater than 20.

8.3.2. Infinitely fault tolerant linac with 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 (Fig. 9).

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 h). 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 (Table 10).

8.3.3. Moderately fault tolerant linac

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

Table 9
Results of the all series connection configuration

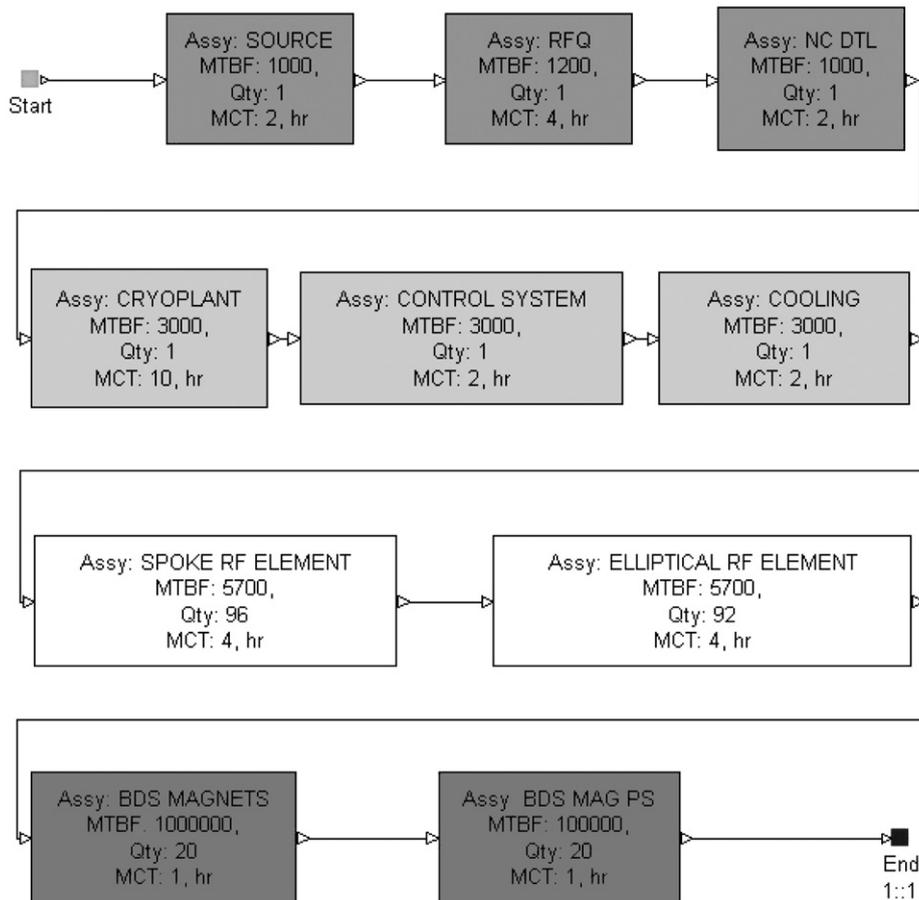| System MTBF	31.19 h
Number of failures	70.23
Steady state availability	86.6%

Fig. 8. RBD model for all series connection configuration.

in order to provide the correct beam specifications on the target. As a simple hypothesis we assume that two RF units in each superconducting linac section (either spoke or elliptical) can fail at any time. 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 neighboring cavities gradients to compensate for it, as described in Refs. [4,5]. The system described above is illustrated in the following RBD (Fig. 10).

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 h, which is nearly the MTBF of the previous case, where no failures were assumed for the RF system (Table 11). 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.

8.3.4. Split RF system repair policies

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 (Fig. 11).

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 8 the out-of-tunnel components MTBF is ∼6100 h 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"

Table 10
Results of the infinitely fault tolerant linac configuration

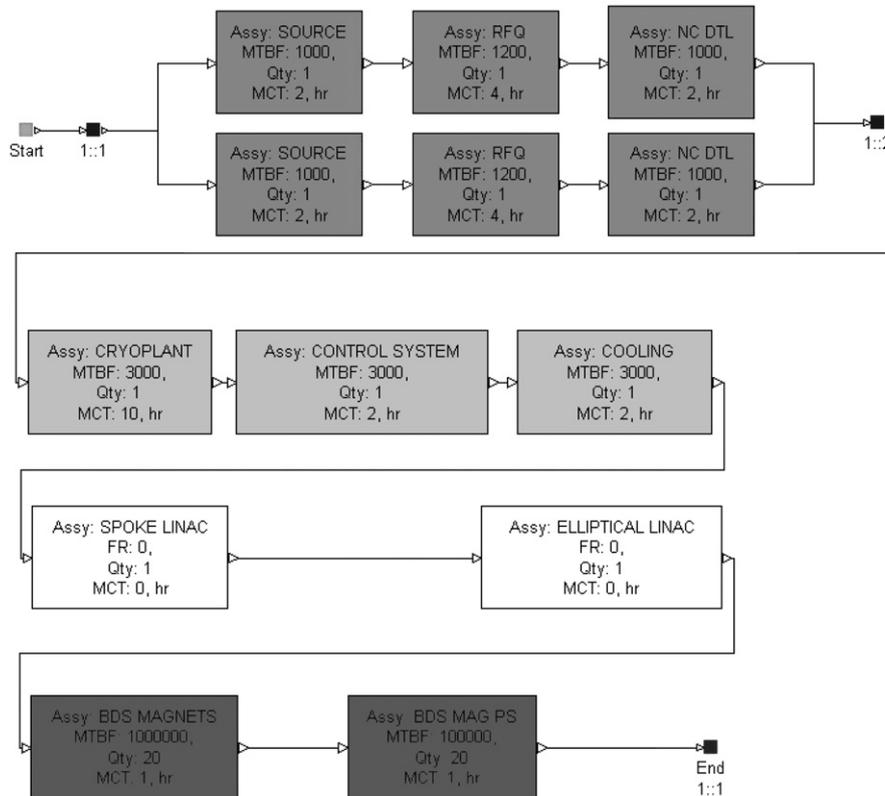|	
System MTBF	796.91 h
Number of failures	2.75
Steady state availability	99.5%

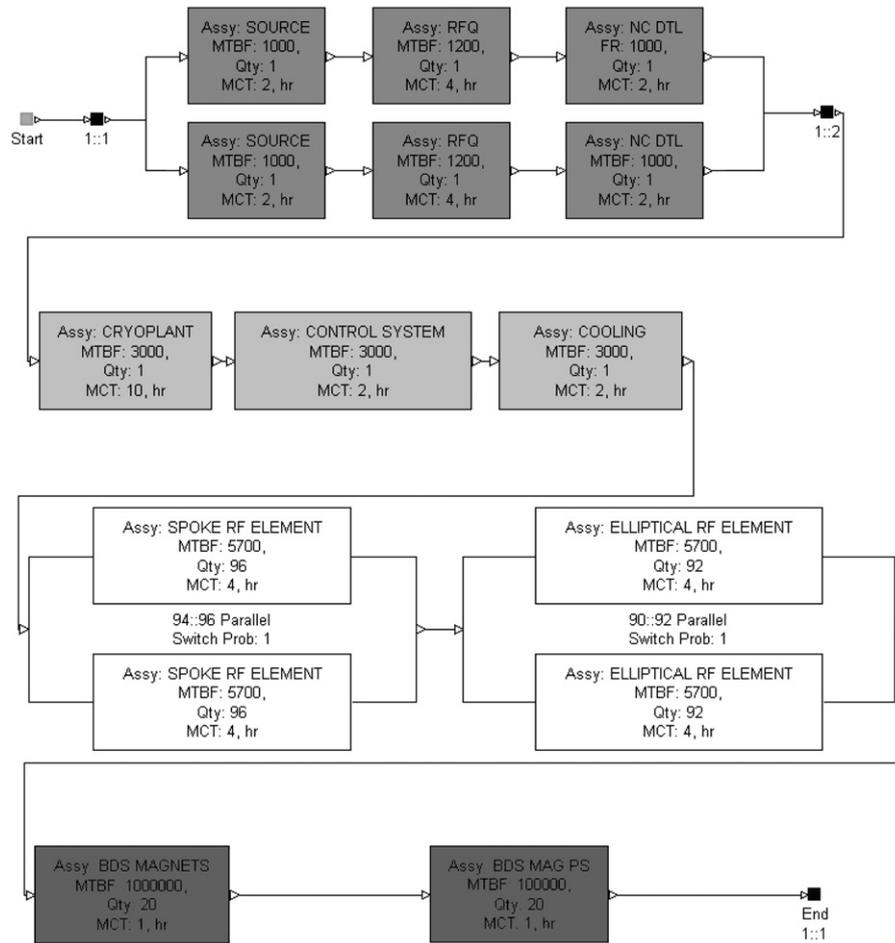Fig. 9. RBD model for infinitely fault tolerant linac configuration.

Fig. 10. RBD model for moderately fault tolerant linac configuration.

Table 11
Results of the moderately fault tolerant linac configuration

System MTBF	757.84 h
Number of failures	2.89
Steady state availability	99.5%

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 (Table 12).

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 the case to examine a final case. Since we have identified a restricted set of in-tunnel components which 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).

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 (Table 13).
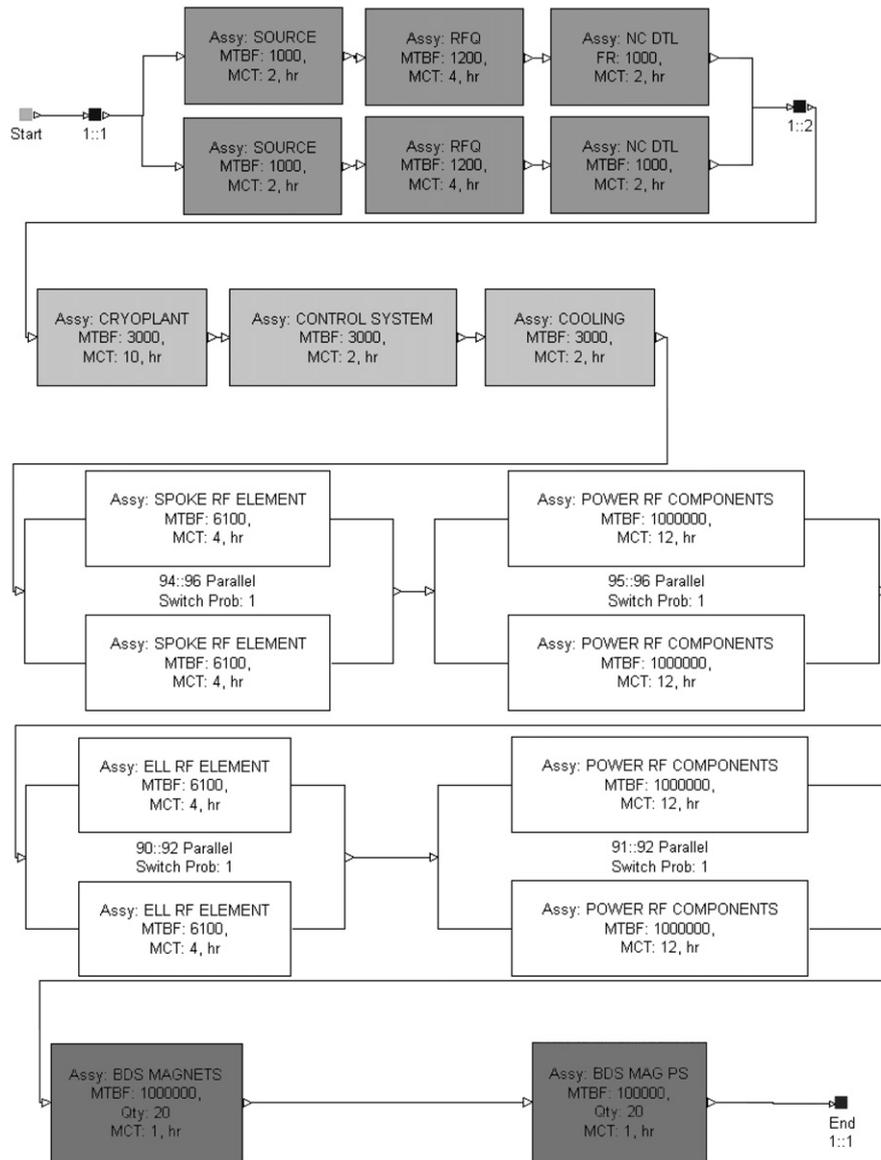
Fig. 11. RBD model for the split RF system repair policy linac configuration.

Table 12
Results of the split RF system repair policy linac configuration

System MTBF	557,80 h
Number of failures	3.92
Steady state availability	97.9%

Table 13
Sensitivity analysis results

System MTBF	749.81 h
Number of failures	2.92
Steady state availability	99.3%

8.3.5. Result summary

In this section we have formally shown by means of RBD analyses that the assumed degree of redundancy and fault tolerance in the linac configuration without changing the reliability figures of the components 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 "hands-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.

9. Conclusions and path forward

In order to meet the challenges and realize the opportunities presented by emerging technologies, accelerator reliability assessment process and consequent development of an accelerator reliability database have been initiated in response to many reliability issues raised in several accelerator projects, where reduction of beam trip events and mitigation of the effects of beam interruptions on accelerator-based facilities, such as Accelerator-Driven Systems, are identified as critical points under the safety and availability point of view.

The stringent requirements pertaining to the accelerator application for new advanced concepts in the nuclear field call for the development of new strategies and procedures for the design of the accelerator where the reliability and availability are the driving guidelines: this arouses the need for addressing the reliability and availability assessment of the machine.

The models presented here are very basic and subject to the limiting assumptions pertaining both to the configuration of the system (the design of almost all the systems id not finally fixed yet) and the component failure and repair rate data, especially for one-of-a-kind large complex system as an accelerator facility (since data bases are very limited and data are too sparse due to the wide site-to-site variability in causal mechanisms): however the concepts related to these models serve as the "building blocks" for more complex and realistic repairable accelerator system models.

So far, a "pioneering" effort has been undertaken and presented in this paper: since the input values and models are very subjective for the reasons illustrated above, the numerical values shown here serve mostly as indicators of the extent of achievement of the task. The present study, performed at first at a rough "parts count" analysis level and further through a more sophisticated model by a commercial software, suggests that the design has the potentials for reaching the extremely low fault rate goal, but more work is needed in developing more realistic reliability models and in the setup of a meaningful reliability component database. Moreover, the study tracks a viable path towards the improvement of the reliability of the accelerator machines, by delineating the strategies to implement early in the system design to guarantee the desired target in terms of the allowed number of interruptions figure of merit. Along this path, valuable results coming out of the analysis are measures as the parallel redundancy for the Injector system and the fault tolerance concept for the RF cavities, by assuming k out of n redundancy, which are envisaged to be introduced at the machine design level, in addition to a proper maintenance strategy. Implementation of the present reliability analysis, notably through the simulation of a series of plant configurations at this beginning stage, is required as soon as a sound failure data is established and a more detailed design is available, because the level of definition of the current design does not allow reaching a final assessment.

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