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BASIS FOR THE RELIABILITY ANALYSIS OF THE PROTON LINAC FOR AN ADS PROGRAM

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Abstract

In the framework of the ADS projects (Accelerator Driven System) developing worldwide, a reliability activity is on going to validate and qualify the linac accelerator design with focus on the general operational and design characteristics that shape the accelerator performance. Further quantitative results should be based on estimations mostly deriving from operational surveys at existing accelerator facilities. Currently, a validated accelerator component reliability data base has not yet been assembled, and because of the early stage of the ADS design in which several systems are not established at this time the topic can be addressed by the application of a preliminary FMEA (Failure Mode and Effect Analysis) methodology, helpful in the identification of reliability-critical areas, where modifications to the design can help to reduce the probability of system failures. In this paper, the preliminary results of this activity are presented together with possible solutions to improve the reliability of the reference linac design.

INTRODUCTION

The request of high availability linac, to be coupled to subcritical reactor for waste transmutation and energy production [1,2,3], puts strong demands on future accelerators. Synchrotron light sources lead the state of the art in accelerator availability reaching availability of more than 99% [4]. However, the request of few beam trips longer than few seconds per year of continuous operation requires the development of new strategies and procedures for the design of accelerator. This paper is mainly devoted to assessment of the basis for a linac design where the reliability and availability (‘fault tolerance’) are the driving guidelines. In the following section, we present tools available for reliability assessment and possible design approaches to implement reliability in linac design, with special care to ‘fault tolerance’ machine design.

Among the different methodologies for reliability assessment, we found that FMEA (Failure Mode and Effect Analysis) is the more appropriate in early stages of accelerator design when a complete and detailed scheme of the machine is not available. We describe the implementation of FMEA to a possible linac design. Whenever the machine layout reaches a more detailed description, quantitative approaches - based on a formal mathematical approach to reliability - are available and their implementation in the accelerator design is the scope of our future work, as mentioned in the last section.

RELIABILTY TOOLS AND DESIGN APPROCHES

The design of a new system driven by reliability issue usually follows an iterative process. From an initial technical design, one evaluates its possible failure modes, discovers critical parts and may draw a first order estimation on the reliability of the system. The technical design is then reviewed trying to improve the weak areas of the system. This procedure continues till the required reliability and availability goals are reached.

The two main approaches to reliability assessment follow either a “top-down” or “bottom-up” approach. The former is the basis for techniques such as FTA (Fault Tree Analysis) and RBD (Reliability Block Diagram) where the system is analyzed starting from big blocks describing major systems and then going down to the details. If, instead, one follows the system from the details up in the hierarchy to the top (“bottom-up”), techniques such FMEA (Failure Mode and Effect Analysis) or FMECA (Failure Mode and Effect and Criticality Analysis) may be applied.

The “top-down” approach may be difficult for large and complex systems where the knowledge of the single component reliability or the logical connections between different elements of the system may be not precise enough for the assessment of the overall system reliability. This approach can be difficult also in the case of systems in the early stage of the design when a detailed description of the complete system is still missing.

A more valuable approach, specifically for system not fully developed, is the “bottom-up” approach. In this case, even an incomplete description of the system can be used to start a preliminary analysis of the system. In the case of FMEA, its aim is to identify all the possible failure modes of components, analyze their effects on the system performance, and suggest solutions and improvements. In the analysis, it is important to include also severity ranking for the failures and possibly their frequency.

The design of a reliable accelerator, besides the use of reliability tools, can benefit also from some general guidelines, common sense and experience that can valuably drive proper design. Among many of them, the most effective in improving reliability and availability of the system are **part derating** and **redundancy/spares**.

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Derating consists in operating a component with a load lower than the maximum rated from its specifications. This solution allows putting less stress on the component - generally guaranteeing a longer lifetime and hence a higher reliability.

Redundancy can be applied to key elements of the system that may induce its failure and it consists in using several identical components (in hot/warm parallelism, depending on the failure rate of the standby component) and/or **spares components** (cold parallelism) to improve the reliability of that particular element.

Although this approach improves the system reliability, it increases the number of components and hence the failure rate, requiring a more complex organization of the system logistic.

Finally a necessary approach in designing a system like a linac for and ADS is the '**fault tolerance**'. By this, we mean the capability of the system to perform its duty within its specifications even if some of its components are defective or are not working at all.

FAULT TOLERANCE

As mentioned previously, 'fault tolerance' is the key element in the design and operation of a linac for an ADS. To guarantee the availability request for coupling a linac to a sub critical reactor, the beam trips have to be about one per month for a 24 h operation in a period of at least three months up to one year - depending on the core details and fuel operation procedures. The possible approaches that can be followed to reach such availability requirements are: demand very high reliability on the single components or design the system to be fault tolerant. In the first case, an enormous technological effort is required to improve the reliability of both newly developed systems and "commercial" components. For example, the Mean Time Between Failure (MTBF) of a klystron is about 50000 h and if 100 of them are in series, the MTFB of the system is 500 h (about 21 days). After that period, the faulty klystron has to be changed and the linac stopped if no fault tolerance is implemented.

A 'fault tolerance' strategy, instead, relies on redundancy and parallelism. However, these are not enough to guarantee that the system will continue to work within specifications with faulty components. Indeed the system has to **detect** the faulty component, **isolate** it and **readjust** itself to provide fault tolerance.

The application of 'fault tolerance' to an accelerator system implies also a strong interaction with the beam dynamics studies. The failure of a component may have different consequences, depending on the component location along the beam line, on the beam parameters on the target and the system has to react properly to deal with it. The reaction time, it is worth to remember, has to be less then 1 second to prevent thermal stresses on the reactor elements. The control system of the accelerator, and the Low Level RF system in particular, have to cope with it and readjust the machine in order to guarantee the beam specifications at the target. This is only possible if a complete analysis of the fault scenarios is done in advance, the impact of the single component fault has been studied regarding beam dynamics effects and improvements on the control system allows reacting time faster then few milliseconds. In other words, the fault tolerance capabilities need to be included in the design of a new generation of accelerator control systems.

THE LINAC CASE

The application of the aforementioned strategies (FMEA and 'fault tolerance') to a linac requires the setup of a reference design. For the ADS case, the accepted scheme foresees a Source, a Low Energy Section, a Medium Energy Section and a High Energy Section. Proper beam transport lines match each of the accelerating sections. A final beam delivery system transports the beam into the reactor vessel.

The proton source is one of the most critical item both for its complexity and because its failure determines the stop of the beam. The same considerations hold also for the Low Energy Section where a Radio Frequency Quadrupole is used. In this first part of the linac is then difficult to implement a complete 'fault tolerance' scheme. Nevertheless, redundancy and derating on critical parts of the system are necessary to increase the reliability of this critical section.

The Medium Energy Section accelerates the beam up to energies about 100 MeV. Also in this case different solutions are possible even if with a larger preference for the SC (superconductive) solution. The same technology is also the preferred one for the High Energy Section. In fact, many advantages characterize SC cavities and among them: high modularity, independent RF feeding and phasing and large bore radius. These features allows a natural implementation of redundancy (modularity), a relaxation of constrains on alignment and beam losses (large bore radius) and the possibility to implement 'fault tolerance' (independent RF feeding and phasing). Moreover, the operation of the structures at cryogenic temperature allows a very stable linac. It is also a general rule to operate the cavities at lower gradients with respect to the maximum achievable, in order to reduce the stress on the cavity operation (part derating).

The 'fault tolerance' of the SC sections mainly relies on the independent feed of the cavities. The failure of a single cavity can be detected by the control system and an automatic procedure can readjust the neighboring elements in order to compensate and maintain the beam within specifications on the target. This procedure implies knowledge of the effect of each single component failure on the beam characteristic on target. A faulty SC cavity on the first part of the High Energy Section has a different impact on the beam in respect of a faulty cavity at the end of the linac. Beam dynamic studies need to help in defining proper procedures to implement 'fault tolerance' during acceleration operation. Moreover, the machine control system and the LLRF system have to react in very short time to keep the machine running.

The reliability of the beam delivery system and beam transport lines for such a machine will be dominated by magnets and their power supplies. Redundancy and fault tolerance in the vacuum system and diagnostics can be planned in advance. The extensive experience at existing facilities shows that magnets usually fail due to water cooling failures (in pipes or connections), to cooling channel clogging or to power supply failures. Preventive maintenance and replacement operations may contribute to solve the majority of these issues.

FAILURE MODE AND EFFECT ANALYSIS

The FMEA analysis provides useful information already in the early stage of the design and even in a qualitative approach.

In order to perform such an analysis, the key systems and components of the accelerator need to be identified. Once they are known, a list of all potential failure modes, corresponding failure frequency and analysis of their effects must be compiled. On the basis of critical components found in the previous analysis, the design of the accelerator has to be reviewed.

The four main systems for the accelerator of an ADS are: the hardware components of the accelerator (cavities, magnets, vacuum connections, etc.), the cryogenic production and distribution plant, the auxiliary infrastructures (water, compressed air, electrical power) and the control system. The vacuum and the RF systems, due to the modularity of the SC solution, are included in the accelerator hardware and are not considered as distinct systems.

Following well-known standards, a WBS (Work Breakdown Structure) hierarchical structure is needed to classify all the components of each system, and based on it the possible failure modes and the detection means are identified. For each failure mode, the effects on the faulty system, on the system upper in hierarchy and on the beam properties, which are our main concern, are highlighted. The effects, at each level of this analysis, are ranked based on their severity. Once the effects of the failures are known, possible corrective or preventive actions are suggested and they should be implemented in the reviewed version of the accelerator design.

The FMEA analysis can also be used as a guideline for addressing the task of preventing undesirable failure modes in a more specific technical and detailed analysis of the components.

At present, activities are ongoing in order to develop a complete FMEA analysis for the reference design of the accelerator designed for the PDS-XADS program of the European Community [5].

FUTURE WORK

The present limitations for a complete and quantitative reliability assessment of linacs for ADS are the lack of a detailed accelerator configuration and the uncertainty in the available reliability data (MTTR, MTBF, etc.).

The absence of a formal reliability database for accelerator components makes difficult to perform a mathematical treatment of the reliability problem for the accelerator. Even if many laboratories have own large datasets of failure modes both at the system and at the component level, there is no common way to store and analyze them, and the effort to unify these databases (in terms of manpower and resources) is so large to hinder the benefit of such an action. Hence **“expert” judgment** is the only way, at the moment, to state reliability figures for accelerator components. The situation is different for “commercial” products where data are available; however the application to the accelerator case requires careful consideration on the different operative conditions.

Concerning the detailed description of a reference linac design, studies are still on going worldwide and decisions have still to be taken mainly concerning the initial part of the linac where different solutions and technologies are currently under consideration.

Once this information will be available, a first quantitative reliability assessment of the accelerator system will be possible.

CONCLUSION

The reliability and availability request for the future accelerator to be coupled to subcritical reactors leads to a new philosophy in approaching linac design. Few trips longer than one second during a period of operation of at least some months can be achieved only if redundancy and ‘fault tolerance’ capabilities are included in the design and operation of the machine. A valuable tool during the early design stages of the linac to assess the reliability is the FMEA that provides useful information even if applied on qualitative basis and on a not fully developed scheme of the accelerator.

For a quantitative reliability analysis of an accelerator, a common database for accelerator components is still missing. An effort to coherently integrate the dataset present in all the major labs on failure causes is advisable.

The methodology developed for ADS accelerator can be customized to deal with different requests such as future linear colliders [6] or linac for future light sources machines [7].

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