Results of the RAMI analyses performed for the IFMIF accelerator facility in the engineering design phase

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This paper presents a summary of the RAMI (Reliability Availability Maintainability Inspectability) analyses done for the IFMIF (International Fusion Materials Irradiation Facility) Accelerator facility in the Engineering Design Phase. The methodology followed, the analyses performed, the results obtained and the conclusions drawn are described. Moreover, the consequences of the incorporation of the RAMI studies in the IFMIF design are presented and the main outcomes of these analyses are shown.

Keywords: Availability, Reliability, Accelerator, RAMI, IFMIF

1. Introduction

The planned International Fusion Materials Irradiation Facility (IFMIF) has the mission to test and qualify materials for future fusion reactors. IFMIF will employ the deuteron-lithium stripping reaction to irradiate the test samples with a high-energy neutron flux. IFMIF will consist mainly of two linear deuteron accelerators, a liquid lithium loop and a test cell. Accelerated deuterons will collide with the lithium producing a high-energy neutron flux that will irradiate the material samples in the test cell.

The IFMIF accelerator facility is composed of two independent linear accelerators, each of which produces a 40 MeV, 125 mA deuteron beam in a continuous wave mode at 175 MHz. These beam characteristics pose several unprecedented challenges: the highest beam intensity, the highest space charge, the highest beam power and the longest RFQ (Radio Frequency Quadrupole). As a result of these challenges, many design characteristics are counter to high-availability performance: the design is reluctant to accept failures, machine protection systems are likely to stop the beam undesirably, cryogenic components require long periods for maintenance, and activation of components complicates maintenance activities. These design difficulties, together with the high availability requirements and the demanding scheduled operational periods, make RAMI analysis an essential tool in the engineering design phase.

2. IFMIF RAMI analyses

The IFMIF accelerator facility design was analyzed from the RAMI point of view, estimating its future availability and guiding the design towards a high reliability and availability performance. An iterative process was followed to match IFMIF design and availability studies [1,2]. These iterations made it possible to include recommendations and design change proposals coming from the RAMI analyses into the accelerator reference design. Iterations consist of gathering information from the design, creating or updating the RAMI models, obtaining and analyzing results, and proposing ways to improve the design.

Three different approaches were carried out in the iterative process. First, a comparison with other similar facilities was performed. Second, an individual fault tree analysis was developed for each system of the accelerator. Finally, a Monte Carlo simulation was performed for the whole accelerator facility considering synergies between systems. These approaches make it possible to go from detailed hardware availability analyses to global accelerator performance, to identify weak design points, and to propose design alternatives as well as foresee IFMIF performance, maintenance and operation characteristics.

These studies were performed in collaboration with system designers, enabling the creation of RAMI models that reflect current accelerator design. This feedback was of the utmost importance to propose plausible design modifications in order to improve the availability performance of the machine. Parallel activity on the design and construction of the Linear IFMIF Prototype Accelerator (LIPAc) provided the detailed design information needed to conduct these studies properly.

2.1 Comparative analyses

The difficulty of achieving IFMIF accelerators' beam parameters and RAMI requirements becomes clear when compared with other facilities. Operation and

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maintenance cycles, availability requirements, and beam dynamics constrains make the design an arduous challenge. The knowledge gathered from other facilities (e.g., major problems encountered in similar accelerators, typical reliability and maintainability values and other useful data) was used to guide the RAMI analyses towards the most critical systems, components and parameters. Moreover, this information was treated to populate the reliability databases and was used for the inputs of the models.

2.2 Probabilistic analyses

Individual probabilistic analyses were the principal studies done to estimate and improve the availability of the accelerator systems [3]. Many design changes were included in the reference design; however, other major changes were proposed for the principal unavailability contributors in order to achieve the high requirements.

The main improvements proposed are shown in Table 1 together with their qualitative impact on the global accelerator facility availability:

System	Component or subsystem	Improvement or recommendation	Availability increase	Comments
Injector	Power supplies	Multilayer coils, automatic switch or permanent magnets	Low	If access time to vault increases this recommendation would have more relevance
	Extraction electrodes	Improved isolation	Medium	Preventive maintenance should fit within scheduled maintenance periods
	Vacuum pumps	Redundancy	Medium	Design change needed
MEBT	Buncher tuning system	Redundant step motors	Low	
	Scrapers	Easily extractable module	Medium	Cooling time can be high. Easy maintenance is essential
SRF linac	Leak-related components	Quality control	High	Every failure can lead to very large downtimes
	RF vacuum window	Double window	Medium	RF couplers design change needed
	Tuning system step motors	Redundancy	Medium	Possible technical problems
	Cryomodules	Hot spares	High	Expensive
	Isolation vacuum pumps	Overdesign for possible leaks	Medium	Easy improvement
	Cavities and focusing elements	Failure acceptance	High	Reduction of beam parameters. Specific beam studies required
HEBT	Scrapers	Easily extractable modules	Medium	Cooling time can be high. Easy maintenance is essential
RF system	Amplifying chain	Solid-state	High	Change the design, technology not yet mature
Auxiliaries	Cryoplants	Higher capacity	Medium	
Other	Power Supplies	Automatic switch	High	Many power supplies could use this fast failure recovery design
	Control system	Redundancies and 2-out-of-3 configuration	Medium	Minimize false trips

Table 1. Mean hardware availability and mean beam intensity results

Moreover, RFQ modules can be very problematic due to their high likelihood of wear-out. An easy and quick maintenance procedure should be foreseen to replace the modules.

RiskSpectrum results show that the hardware availability requirements could be achieved with the improved design model. Hardware availability results obtained with RiskSpectrum for the reference design are 78.10%, while the improved design results are 91.57%, achieving the 91.10% of hardware availability requirement.

It is important to make clear that these results were achieved as a result of the acceptance of operating with beam degradation. The hardware availability requirement was fixed considering a beam degradation of only 2%, and then assuming that the mean intensity would be 98% of the nominal intensity [4]. As this degradation cannot be calculated with RiskSpectrum, an estimation was made based on the reliability results [5]. Considering the probability of the failure of each component that could affect the intensity, and taking into account the intensity degradation that each component failure could cause, a rough mean intensity of 91% was obtained. This intensity value implies to have a Beam Effectiveness (which includes beam current and beam trips) of 88.73% and therefore a Beam Availability (product of Beam Effectiveness and Hardware

Availability) of 81.25%. With these values, the 95.5% Beam Effectiveness requirement and the 87% Beam Availability requirement cannot be achieved; however, the product of hardware availability and intensity cannot be balanced with RiskSpectrum.

Probabilistic analyses are a very useful way to improve the design and to obtain detailed and specific results of each system but not to obtain global availability results for the accelerator facility as a whole. In the next subchapter, the simulations performed for the accelerator are described.

2.3 Availability simulation

When analyzing the accelerator facility as a whole and when considering degraded operation and beam intensity and hardware availability product optimization, an availability simulation software was needed. AvailSim [6] became the perfect software to fulfill these needs after a laborious adaptation and improvement of its features [7,8]. Thanks to these modifications, AvailSim permitted to take into consideration synergies between systems, degraded operation modes and realistic maintenance plans among other specific features.

The AvailSim simulation has been very useful to obtain more adequate results for such a complex system. The relationship between hardware availability and beam parameters, and the balance between the two, make it possible to obtain realistic and interesting results. At the same time, these analyses became extremely useful to estimate the future operation, maintenance and logistics of the IFMIF accelerators

The beam availability results obtained with AvailSim for the whole accelerator facility for the reference and improved design models, along with the requirements, are shown in Table 2.

	Hardware availability	Beam effectiveness	Beam availability
Reference design	80.85%	89.94%	72.72%
Improved design	90.75%	93.48%	84.83%
Requirements	91.10%	95.55%	87.00%

Table 2. Mean hardware availability, beam effectiveness and beam availability results obtained with AvailSim for the reference and improved designs, together with the requirements.

3. Results

The results obtained with RiskSpectrum are compared to those obtained with AvailSim. Some differences between both models are caused by the different limits of hardware availability acceptance. While only static limits are imposed for the RiskSpectrum model, for the AvailSim simulation an optimization on the product of beam intensity and hardware availability is followed.

The consequence of such difference in the analysis implies divergences in the hardware availability and intensity parameters. The AvailSim result gives a better value for the beam intensity and Hardware Availability product due to its parameter optimization, which is closer to real operation decisions.

RiskSpectrum does not improve the beam effectiveness like AvailSim does, which implies to obtain results with higher hardware availability but lower beam availability. AvailSim’s capability to make realistic maintenance decisions and to simulate degraded operation modes makes it the preferred software for analyzing the behavior of a complex machine like IFMIF. Beam parameter results are more accurate and trustworthy than those obtained through probabilistic analysis.

From the reference design to the improved design, the corresponding mean annual dpa production would increase from 5,969 to 6,963 full power hours (maximum of 8,208 hours annually considering scheduled maintenance periods). This would mean reducing the non-productive time from 2,239 to 1,245 full power hours, a decrease of nearly 45%.

The beam effectiveness results obtained with AvailSim are similar to the requirements. This parameter optimization should be pursued to improve IFMIF beam availability.

Noteworthy, the results of these analyses are also related to operation and maintenance considerations, which can have an impact on the final performance of IFMIF. Some considerations and recommendations that have been proposed are: (i) beam dynamics studies and tests during commissioning are recommended to identify degraded operation modes and their consequences on beam parameters; (ii) possible problematic spots for maintenance and logistics have been highlighted and should be adequately planned; (iii) high quality control is recommended for components that have been selected as likely to become problematic; and (iv) possible problematic parameters, such as vault access time, cooling time for hands-on maintenance, restart systems time, and beam turn-on time and steps have been identified and should be carefully considered.

4. Conclusions

Even with several uncertainties, RAMI analyses have been performed in great detail. The results show that the hardware availability of the reference design (78.10% with RiskSpectrum and 80.85% with AvailSim) is insufficient to achieve the requirements (91.10%). However, if the proposed design changes to improve availability are considered, then the results come close to the requirements (91.57% with RiskSpectrum and 90.75% with AvailSim).

Several design changes are proposed. The ones that will have an important impact on the availability are to change the RF power system to solid-state technology [9], to have hot spare cryomodules for the SRF linac, and to include multiple redundancies in many ancillary systems. These proposals should be further evaluated before being included in the IFMIF accelerator reference design (e.g., feasibility and cost).

Moreover, to achieve such improvement, it is necessary to consider the capability of continuing operation with some failed components in the accelerator. Such failures would degrade the beam but would allow continued operation until the scheduled maintenance period. This option improves the hardware availability parameter but decreases the beam effectiveness. Beam effectiveness of the improved design obtained with AvailSim is 93.48%, while the estimation used to establish the requirements was 95.55%.

The beam availability results of the improved design obtained with the AvailSim analysis (84.83%) are close to the accelerator facility requirement (87%). The improvements and changes required to accomplish the 87% can be hard to achieve (technically and economically).

Many assumptions made in this analysis should be confirmed in future analyses or calculations. Final conclusions should not be drawn without considering the data, assumptions and estimations used to obtain the results.

The repercussion of the RAMI analyses in IFMIF should not only be estimated in terms of the availability results of the calculations and simulations performed. The inclusion of the availability requirements to each system and the incorporation of a RAMI team to monitor and look after its achievement made it possible to guide the design to a high RAMI performance. Thanks to the precociousness of these studies in the accelerator design, many possible future problems were eliminated from the root of the problem through initial iterations with the designers. Moreover, other possible problems were identified, and future analyses will ensure that they do not affect the global availability performance.

Finally, it is noteworthy that these studies do not have precedents in experimental accelerator facilities from their early design stages. This made it difficult to obtain data and to find similar approaches but permitted to open the way to develop new methodologies and tools in order to include the RAMI analyses into the IFMIF accelerator design [10].

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