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QUANTITATIVE AVAILABILITY MODELLING FOR THE MYRRHA ACCELERATOR DRIVEN SYSTEM*

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Abstract

The availability of modern accelerators has become a key performance indicator. This is especially the case for accelerator-driven-systems (ADS), such as MYRRHA, which need to deliver beam with very few interruptions longer than a few seconds over a period of several months. Quantification of such beam interruptions at other accelerators such as LINAC4 at CERN and SNS at ORNL show that their fault count would need to be reduced by more than two orders of magnitude to comply with ADS requirements. Redundancy of systems is one viable strategy to achieve this. For MYRRHA, the use of redundant low-energy injectors, modular-redundant RF power amplifiers and serial-redundant RF cavities is presently proposed. The resulting gain in the accelerator availability by the use of these redundant systems has been quantified by simulating the operation of the MYRRHA accelerator with AvailSim4, an availability-modelling tool developed at CERN. The study results highlight the importance to focus on optimizing system design and repair strategies to maximize the effectiveness of such redundancy schemes as well as the value of powerful availability simulation tools.

INTRODUCTION

MYRRHA (Multi-purpose hYbrid Research Reactor for High-tech Applications) is an Accelerator Driven System (ADS) consisting of a proton accelerator and a nuclear reactor core cooled by liquid lead-bismuth-eutectic (LBE), which also serves as spallation target. One of the main benefits of using an accelerator-driven nuclear reactor is that it allows so-called transmutation of nuclear waste, in which long-lived minor actinides are broken down in shorter lived waste. The particle accelerator is required to drive the nuclear reaction with a continuous wave (cw) beam of 4 mA beam current and 600 MeV beam energy.

The particle beam should ideally be delivered continuously to the reactor as any interruptions, so called beam trips, of more than a few seconds lead to thermal stress of the reactor materials. Thermal simulations show that if the beam is absent for longer than three seconds, the reactor needs to shut-down and enter a restart procedure called reactor turnaround (RT), which is estimated to take 12-24 hours. This has a considerable impact on the availability of the entire ADS. Hence, both duration and frequency of beam trips have to be limited. Moreover, the total number of thermal cycles of a nuclear reactor has an impact on its lifetime and must be kept to minimum. This results in a requirement of no more than 10 trips longer than 3 seconds in a fuel cycle (FC) of 90 days

This requirement shall be reached by a range of reliability improvements, among which fault-tolerance is a key measure. This means that a system can continue to operate despite some of its sub-systems failing. This is achieved by redundancy, fault isolation, and (on-line) repair. In the context of MYRRHA, a high-degree of fault-tolerance is ensured by use of (1) redundant injectors, (2) serial redundancy of RF cavities (so-called dynamic compensation) in the main LINAC and (3) modular-redundant RF power amplifiers, as shown in the schematic overview of the MYRRHA accelerator and reactor in Fig. 1.

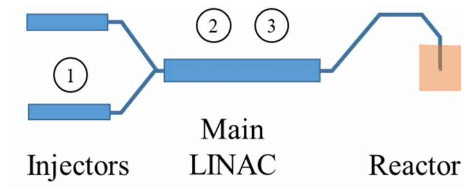

Figure 1: Schematic overview of MYRRHA indicating the foreseen fault-tolerances.

The availability of the MYRRHA LINAC has been studied previously based on a high-level reliability block diagram approach [1], with more detailed reliability input data from the Spallation Neutron Source (SNS) at Oak Ridge National Laboratory (ORNL) in the FP7-MAX4.4 project [2] and using data from the CERN LINAC4 during the H2020-MYRTE D2.9 project [3]. A detailed simulation study of modular-redundant RF power amplifiers of the CERN SPS amplifier upgrade [4] was carried out in preparation for the analysis of MYRRHA amplifiers.

This study aims to build upon the previous projects by a more complete and refined reliability model of the MYRRHA accelerator with a detailed understanding of its fault-tolerance capabilities, which have previously only been studied conceptually. For a detailed treatment the reader is referred to the full project report [5]. The main results are summarized in this paper.

The structure of this paper follows the order of the methodology applied: An estimate of the expected failure rates of the different accelerator sub-systems were obtained by performing a quantitative availability evaluation of existing, comparable accelerators. These serve as reference input to the more detailed availability models of the fault-tolerance schemes, which address the core objectives of this project. Based on the results of these investigations, conclusions related to the MYRRHA availability goals were drawn.

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AVAILABILITY COMPARISON AND REQUIREMENTS MODEL

To obtain an updated and more complete overview of reliability challenges in existing, comparable accelerators, a quantitative analysis of existing availability data was carried out in a top-down manner. Three accelerators and operational time-frames were selected on the basis of similarity to the MYRRHA accelerator and accessibility to reliability data: ORNL SNS data from 2011/2, CERN LINAC2 data from 2018 and CERN LINAC4 data from 2021.

In the following, the analysis of the available data will be split in data on short and long beam trips, with the former being longer than two minutes and the latter shorter than two minutes. This separation is done since the data for longer faults is of significantly better quality, as longer faults usually require a human intervention to be repaired, contribute more to downtime, and are better documented. Short beam trips are often self-correcting problems or remotely resettable and are often not followed-up in detail. Moreover, without automated fault tracking solutions in place, short beam trips may even go unnoticed unless they significantly impact a user of the beam.

With regards to short beam trips, Table 1 provides an overview of their frequency within 90 days for the three reference accelerators and compares it to the requirement for MYRRHA. Note that faults of a few seconds are studied as these are relevant for the MYRRHA requirement.

Table 1: Comparison of Short Beam-Trip Frequency

Accelerator	Beam trips per 90 days
SNS 2010-2013 (early operation)	1800 interruptions > 6 seconds
CERN LINAC4 Oct. 2021	3942 interruptions > 6 seconds
CERN LINAC4 Oct. 2021	5241 interruptions > 6 seconds
MYRRHA requirement	10 interruptions > 3 seconds

The fault count for the existing accelerators is more than two orders of magnitude above the MYRRHA requirement. However, it needs to be considered that short beam trips contribute little to unavailability for the existing accelerators. Hence, there is less intention to reduce the frequency of short beam trips in comparison to longer faults for accelerators aiming for high availability.

With regards to long beam trips, more information about the sub-systems in fault is available. Across the three reference accelerators, the top-contributing systems to downtime are (1) RF, (2) Power Converters, (3) Cryogenics (only present in SNS). Other notable contributors are electrical network perturbations, Beam Instrumentation, Controls and Vacuum.

Based on the relative distributions of faults across systems, a top-down requirements model for MYRRHA was derived. The full models can be accessed in the final project report. In the context of this paper, the following requirements were derived: one beam trip (longer than three seconds) for the redundant injectors and 3.3 beam trips for the dynamic-compensation of RF systems in the main LINAC per 90 days. These numbers will have to be updated once more concrete design and first testing data is available for these systems. At the moment, they serve as reference targets for the fault-tolerance analysis.

FAULT TOLERANCE ANALYSIS

To quantify the effectiveness of the fault-tolerance schemes and to identify their key dependencies, more detailed models are required. Due to limitations of analytic modelling, the models were implemented as Monte Carlo simulations in AvailSim4 [6]. The software has been made open source and is accessible on the pypi package repository with a link to the source code and a detailed user guide. It is a Monte-Carlo based availability simulation software specifically made for the particle accelerator domain. It was extended by a range of MYRRHA-specific features, which are e.g. needed to model the complex logic for the dynamic compensation of RF circuits in the main LINAC. It includes numerous features to model complex system behaviour including different phases of operation with associated failure modes, blind failures that can only be detected by inspections, different repair policies depending on system accessibility during beam, etc.

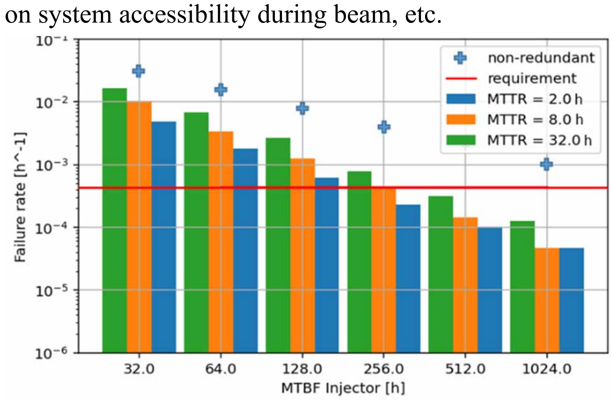

Figure 2: Failure rate of the injector redundancy (y-axis) at 95% chance of switching success under different individual injector MTBF (x-axis) and MTTR (different colours) compared to requirement and no redundancy.

Redundant Injectors Switchover Analysis

The injectors are around 40 meters long and produce a beam of 17 MeV protons. They consist of a range of specialized accelerator systems, such as the source, LEBT (Low-Energy-Beam-Transfer) line, RFQ (Radio Frequency Quadrupole), MEBT (Medium-Energy-Beam-Transfer) line and CH RF-cavities.

The proposed fault-tolerance scheme is to duplicate the entire injector and use a fast switching magnet to switch from the faulty to the hot-spare injector in less than three seconds, to not interrupt the reactor operation.

The implemented AvailSim4 simulation assumes a certain success rate of the switching and that repairs on the spare injector can be carried out while beam is produced

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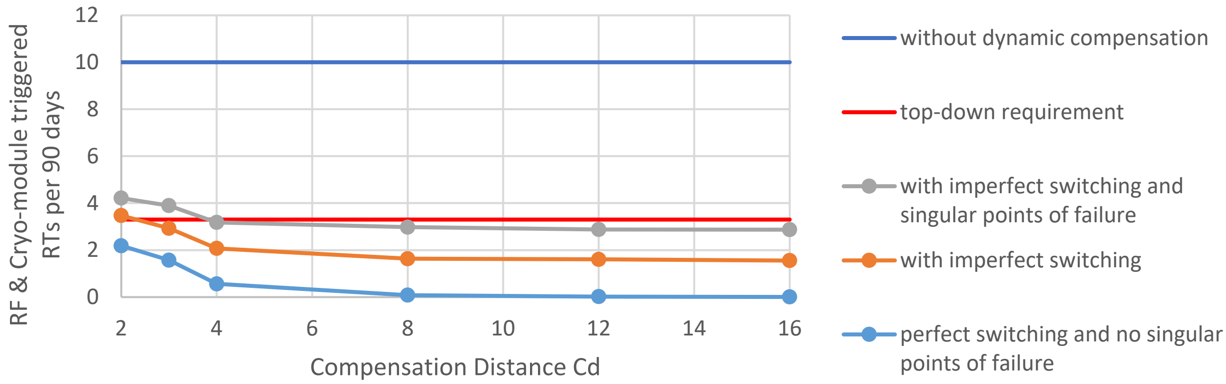

Figure 3: Failure rate of the main LINAC RF systems and cryo-modules (y-axis) as a function of the maximal compensation distance Cd for different model configurations.

by the operational injector. A range of feasible MTBFs (Mean Time Between Failure) and MTTRs (Mean Time To Repair) for the individual injectors was studied. Figure 2 shows the results of the sensitivity analysis of the redundant configuration with imperfect switching (95% chance of switching success) based on the AvailSim4 simulation. The results show that with a high switching success rate, the redundant configuration reduces the failure rate requirement for an individual injector by an order of magnitude in comparison to a single non-redundant injector.

Main LINAC Serial-RF Redundancy Analysis

The main LINAC consists of a chain of superconducting RF cavities, which are housed in cryo-modules. The spoke section has two cavities per cryostat and the elliptic section four. Each RF cavity is individually powered and controlled. This allows a dynamic compensation scheme in which the failure of one RF circuit does not impact other circuits and can be compensated by ramping up the accelerating fields of other (neighboring) cavities, given they are equipped with sufficient margins. In case of a cryo-module warm-up, the cavities within the cryo-module are detuned and can also be compensated by neighboring cavities.

The transition from normal to compensating mode, the so-called dynamic compensation, has to happen in under three seconds. This is posing several challenges but has been estimated to be feasible, in principle [7]. The more cavities are involved in the compensation, the less likely the switch to a compensation mode will succeed on time. The fewer cavities are involved, the bigger the required power margins and the more expensive is the implementation. As trade-off it was suggested to use four compensating cavities per faulty one.

If a cryo-module with two cavities fails, the 8 necessary compensating cavities have to be up to four cavities away from the failed cavities in both directions. This distance between the faulty and the compensating cavity is denoted as Cd. It defines the flexibility of the compensation scheme. The larger Cd the more faulty cavities can accumulate locally without shutting down the operations.

The dependency of the failure rate of the main LINAC RF systems and cryo-modules on the compensation distance Cd has been studied using AvailSim4 simulations. The main results are shown in Fig. 3. Whenever a failure occurs, the simulation evaluates whether a compensating configuration exists. If so, the switching is executed with 100% (blue line) or 85% (orange line) success probability. 1.65 singular failures per 90 days and 85% switching success are assumed for a pessimistic model (grey line). The MTBF of individual RF circuits and cryo-modules has been assumed to be 32000 hours and 256000 hours, respectively. The assumed MTBF for RF circuits is ambitious but expected to be achievable with redundant solid-state power amplifiers and significant margins in all components of the RF circuit. RF repairs can be carried out during 12-24 hour long RTs and cryo-module repairs after FCs of 90 days. Four compensating cavities per faulty cavity are used. 60 RF circuits and 30 cryo-modules were modelled. The simulation results were linearly scaled to represent the situation of 152 cavities of the entire MYRRHA accelerator.

The results show that the proposed scheme yields a significant reduction of failures even at low Cd values. For higher Cd, the improvements are marginal. This means that an effective fault-tolerance is possible while keeping the compensating cavities close to the faulty cavities, which is expected to increase the switching success rate and is necessary for an effective dynamic compensation scheme.

SUMMARY AND CONCLUSIONS

The analysis of existing, comparable accelerators has shown that the MYRRHA beam-trip requirements pose a significant challenge. Proposed fault-tolerance schemes to address this challenge were studied with Monte-Carlo Simulations in AvailSim4. Results showed that these schemes are effective when properly designed and implemented. The level of detail of the simulation models allowed to find trade-offs that balance reliability requirements, cost targets, and technical feasibility. These results can already be translated into hardware design requirements.

Significant uncertainty remains on the input parameters in terms of system failure rates. Future reliability studies and real-world tests will reduce this uncertainty and more concrete conclusions can be drawn by updating the input parameters of the developed simulation models. This will help ensuring the feasibility of ADS systems.

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REFERENCES

[1] L. Burgazzi, and P. Pierini, "Reliability studies of a high-power proton accelerator for accelerator-driven system applications for nuclear waste transmutation." in *Reliab. Eng. Syst. Saf.*, vol. 92, no. 4, pp. 449-463, 2007. `doi:10.1016/j.ress.2005.12.008`

[2] A. Pitigoi and P. Ramos, “MAX Deliverable D4.4: Reliability model of the MYRRHA Linac*”*, SCK-CEN, Mol, Belgium, Internal report, 2014.

[3] A. Apollonio *et al*. “H2020-MYRTE D2.9: LINAC4 reliability analysis for MYRRHA”, SCK-CEN, Mol, Belgium, Internal report, 2015.

[4] L. Felsberger, A. Apollonio, T. Cartier-Michaud, E. Montesinos, J. C. Oliveira, and J. A. Uythoven, “Availability Modeling of the Solid-State Power Amplifiers for the CERN SPS RF Upgrade”, in *Proc. IPAC'21*, Campinas, Brazil, May 2021, pp. 2308-2311. `doi:10.18429/JACoW-IPAC2021-TUPAB345`

[5] L. Felsberger *et al.*, “PATRICIA_GA945077 D10.1 Accelerator Reliability”, SCK-CEN, Mol, Belgium, Ref.Ares (2022)8607764 - 12/12/2022, Dec. 2022.

[6] Availsim4, `https://pypi.org/project/availsim4/`

[7] A. Plaçais and F. Bouly, “Cavity Failure Compensation Strategies in Superconducting Linacs”, in *Proc. LINAC'22*, Liverpool, UK, Aug.-Sep. 2022, pp. 552-555. `doi:10.18429/JACoW-LINAC2022-TUPORI04`