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Simulation Based Availability Optimization Of Dynamic Fault Compensation For Particle Accelerator RF Systems Applied To The MYRRHA Accelerator Driven System

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Abstract

The availability is a key performance indicator of modern accelerators. This is particularly the case for the MYRRHA linear accelerator, which needs to consistently deliver a particle beam to the MYRRHA reactor with minimal interruptions, each lasting no more than a few seconds, throughout a span of three months. This linear particle accelerator relies on a series of radiofrequency (RF) systems to accelerate the particle beam. These highly complex systems may prove to be a challenge for achieving high availability. A dynamic compensation scheme provides a remedy by allowing to continue beam operation despite the failure of individual RF systems, provided that they have sufficient power margin. The beam physics aspects of dynamic compensation have been studied in detail. However, its availability gains have only been quantified conceptually. An availability simulation model is introduced, which allows to quantify the availability gain of dynamic compensation whilst considering the findings of beam physics studies for optimizing power margins versus availability gain. For the MYRRHA linear accelerator, it is shown that a scheme of using four compensating per one faulty RF system provides a good balance between availability and power margin. Using more than four compensating RF systems would lead to a reduction in required power margins but also reduced fault-tolerance effectiveness and worse accelerator availability. Immediate repair of RF systems instead of repair during beam stops would only marginally improve availability under the foreseen operational scenarios of MYRRHA. These findings have been made possible due to improved and more detailed modelling. The study results highlight the importance of powerful availability simulation models and tools to maximize the effectiveness of advanced redundancy schemes. The developed model can be applied to optimize RF dynamic compensation schemes and helps advancing availability of particle accelerators.

Keywords: availability simulation, fault tolerance, redundancy, particle accelerators

1. Introduction

Particle accelerators drive charged particles to high and precise velocities and energies. These particles are contained within particle beams with carefully controlled characteristics, such as energy, phase, chromaticity to name a few. These tailored beams may be used for diverse purposes, such as particle physics research, radiotherapy for cancer treatment, or ion implantation in semiconductor device manufacturing. For all these purposes, a high availability of the beam is a key requirement of modern particle accelerators.

MYRRHA (Multi-purpose hYbrid Research Reactor for High-tech Applications) is a so-called Accelerator Driven System (ADS), which combines a proton accelerator and a nuclear reactor core, cooled by liquid lead-bismuth-eutectic. This configuration allows for transmutation of nuclear waste by breaking down long-lived minor actinides into shorter-lived waste (Abderrahim et al., 2001).

a) b)

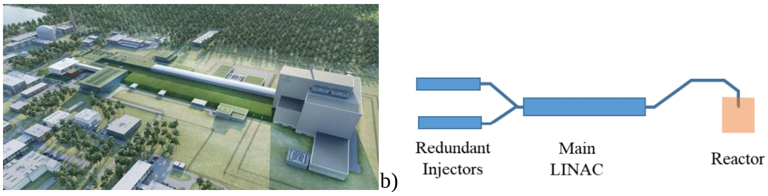

Fig. 1. a) Rendering of the future MYRRHA ADS facility (MYRRHA, 2023). b) Schematic overview of MYRRHA.

Figure 1a shows a rendering of the future facilities and Figure 1b a schematic overview of MYRRHA. The protons are accelerated up to an energy of 16 MeV in the parallel redundant injectors. Afterwards, they enter the main linear accelerator, where they are accelerated to the final energy of 600 MeV, before entering the sub-critical nuclear reactor. The nuclear reaction is propelled through the continuous wave (cw) proton beam of 4 mA current. Continuous delivery of the beam is critical for reactor stability as any disruption, known as beam trips, lasting more than a few seconds induce thermal stress on the reactor materials. Simulations indicate that a beam absence exceeding three seconds requires a reactor shutdown, initiating a restart protocol referred to as reactor turnaround (RT), requiring an estimated 12-24 hours. Such interruptions significantly impact the availability of the entire ADS. Hence, restricting both the duration and frequency of beam trips is imperative. Additionally, minimizing the total number of thermal cycles in a nuclear reactor is crucial for its longevity. This results in an availability requirement of no more than 10 trips longer than 3 seconds within a 90-day fuel cycle for the accelerator. (Vandeplassche et al., 2011)

Charged particle beams are accelerated by employing radiofrequency (RF) systems, which use resonant electromagnetic waves with a frequency that is synchronized with bunches of particles traversing RF cavities. The synchronization ensures that the passage of the charged particle bunches is aligned with the electrical field component of the electromagnetic wave. The higher the amplitude of the electromagnetic wave, the stronger the acceleration of the particle beam. To remove electrical losses arising from very strong electromagnetic fields in these cavities, they can be made of superconducting materials and immersed in a bath of liquid helium within a cryogenic module. Linear accelerators are mainly composed of such RF systems. Being highly complex and specialized, they often represent the main downtime contributor to linear accelerators (Felsberger et al., 2021; Morozov et al., 2022; Geng et al., 2023).

As there are limits to increasing the inherent reliability of an RF system, a way to overcome this availability limitation is to employ fault tolerance. In the context of RF systems, this is referred to as dynamic compensation (Biarotte et al., 2008). The idea is illustrated in Figure 2. It shows a chain of RF systems (red) which are contained in cryo modules (blue boxes). When one of the RF systems fails (marked by 'X'), the other RF systems increase the amplitude of the RF field and adjust its phase (marked by 'C') to compensate for the loss of the failed RF system.

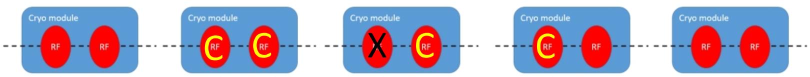

Fig. 2. Schematic overview of dynamic compensation of an RF cavity failure in a superconducting linear accelerator.

This concept has been investigated in more detail from a beam physics perspective for the MYRRHA main LINAC (Bouly et al., 2014; Bouly, 2021) and other accelerators (Xue et al., 2016; Morozov et al., 2022). The main findings will be detailed in Section 2. Its availability aspects have been studied using a high-level reliability block diagram approach (Burgazzi et al., 2007). The paper investigated different LINAC architectures, including one without any fault-tolerance, one with theoretically infinite fault-tolerance for the injectors and the main LINAC, and one with partial fault-tolerance on the injectors and the main LINAC. The latter can be considered closest to the foreseen MYRRHA implementation. The model assumes that repairs on the main LINAC's out-of-tunnel equipment can be carried out while beam is being produced, which is currently not foreseen. Moreover, cryo module failures are not modelled and switching from a nominal to a fault-compensating configuration is assumed to work every time. Lastly, it is assumed that any distribution of faulty cavities in the main LINAC can be compensated as long as the fraction of faulty cavities is below a certain threshold. However, beam physics simulations indicate that certain failure configurations cannot be compensated and that the location of failures within the chain of RF systems is crucial.

A simulation model for dynamic fault compensation is presented in this paper, which integrates recent findings from beam physics investigations in the availability study. It models whether a dynamic compensation is possible depending on the location of faults, consider delayed repair, imperfect switching to compensating configurations, and single points of failure.

The dynamic compensation scheme foreseen for MYRRHA is discussed in more detail in Section 2. The developed availability simulation model and its implementation are explained in Section 3. The results from applying this model to the MYRRHA main LINAC are presented in Section 4. A conclusion is given in Section 5.

2. MYRRHA main LINAC dynamic RF compensation

The MYRRHA main LINAC mostly consists of a chain of superconducting RF cavities, which are housed in cryo modules. They are grouped into three different sections. The first section has 62 single-spoke cavities in 32 cryo modules, the second section has 18 double spoke cavities in 9 cryo modules and finally the third section has 72 elliptic cavities in 18 cryo modules. Each cryo module has a valve box attached, which is the link to the cryo plants via a cryogenics distribution system. The RF tuning mechanism, consisting of an electro-mechanical and a piezo actuator, is integrated in the cryo module (Pompon, 2021).

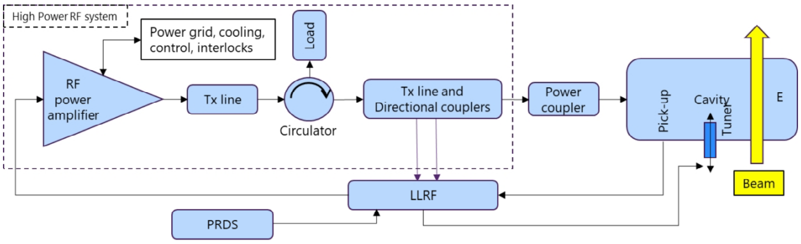

Fig. 3. Schematic overview of an RF circuit. The beam is represented by the yellow arrow. (Pompon 2021)

Each RF cavity is individually powered and controlled. This means that for each cavity there is an RF power amplifier, circulator, feeder line, power coupler to the cavity, and Low-Level RF controls (LLRF), forming an independent RF circuit as shown in Figure 3. The phase reference distribution system (PRDS) helps to synchronize the RF circuits along the LINAC. A tuner controls the resonating frequency of the cavity.

Individual powering and controls are required for the dynamic compensation scheme in which the failure of one RF circuit does not impact beam operation for more than a few seconds. This is achieved by detuning the faulty RF circuit and ramping up the accelerating fields of neighbouring cavities. Detuning is required so that the particle beam can traverse the cavity of the failed RF circuit without electromagnetic coupling between beam and RF circuit. In case of a cryo module failure, the two or four cavities within the cryo module cannot be used anymore and need to be detuned. The power must be compensated by neighbouring cavities.

To compensate for a failed RF circuit (Step 1 in Figure 4), a sequence of steps needs to be executed so that dynamic compensation allows the continuation of beam operation (Step 2 in Figure 4):

1. The fault is detected & the beam is stopped.
2. The fault is localized & the faulty cavity is detuned by moving the tuning mechanism.
3. The compensating configuration is fetched from a database of pre-defined compensation settings.
4. The settings of neighboring cavities are changed accordingly and RF fields are ramped up.
5. A probe beam is sent, and iterative tuning corrections are applied to the RF circuit settings.
6. The beam current is ramped-up in a controlled manner until nominal conditions are established.

Given the MYRRHA requirements, these steps must be carried out fast enough to not interrupt beam operation for more than three seconds. Otherwise, the reactor must enter a lengthy reactor turnaround (RT) procedure with a heavy impact on the availability of the system.

In a compensating configuration, the LINAC is in a degraded state and additional RF circuit failures in the direct surrounding of the failed cavity can potentially not be compensated any more. Hence, repair of the faulty RF system should be done as soon as possible (Step 3 in Figure 4) and the original LINAC configuration should be restored (Step 4 in Figure 4).

Most faults cannot be immediately repaired but require the beam to be off. This is the case during RTs or at the end of a 90-day fuel cycle. Even if a repair could be carried out while beam operation continues, the repaired

RF circuit would need to be brought back "online" within a reverse dynamic compensation procedure. This is deemed feasible in principle but has not been developed in detail nor shown experimentally. The foreseen scheme will be to postpone the repairs until the next beam stop or the end of a fuel cycle. This means that faults may accumulate before a repair can be carried out. The effect this has on the availability will be quantified in Section 3.

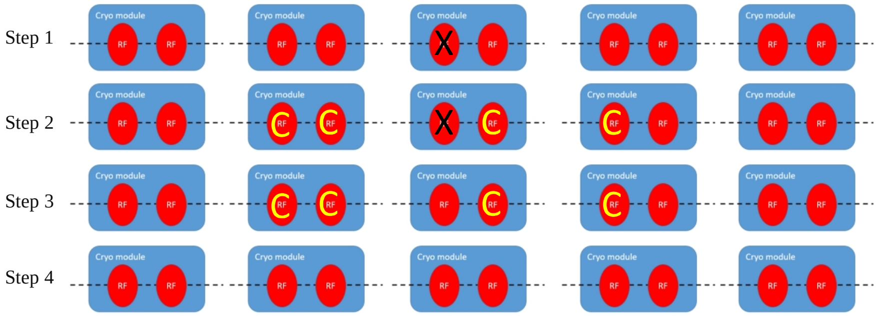

Fig. 4. Illustration of the sequence of steps involved in the dynamic compensation scheme.

The scheme can compensate most faults of individual RF circuits. However, the following scenarios are not covered:

- Too many failures accumulate and cannot be compensated anymore.
- The switching from normal to compensating configuration does not succeed in under three seconds.
- RF controls (LLRF) systems are giving wrong instructions.
- The tuning mechanism gets stuck in a way that does not allow to detune a faulty RF circuit.
- Other single and common mode failures.

All these aspects can be modelled in an availability simulation, considering the expected failure behaviour of the involved systems as well as the flexibility of the compensation scheme as governed by the beam physics studies.

Regarding this flexibility of the compensation scheme, beam dynamics simulations have confirmed that the accelerator can compensate a range of fault configurations (Bouly, 2022), which should be able to cover up to two faulty RF circuits in series in the low-energy section (first stages of the LINAC) and up to four faulty RF circuits in series in the higher energy section (later stages of the LINAC). This has already been demonstrated in practice at the Spallation Neutron Source at the Oak Ridge National Laboratory, albeit at a transition time from normal to compensating mode which exceeds the three seconds required for MYRRHA (Morozov et al., 2022).

The transition from normal to compensating mode in under three seconds is expected to pose challenges. It requires a very rapid movement of the tuning mechanism, but has been estimated to be feasible. The tuning will first be set to a pre-defined compensation setting, which must be identified 'off-line' during extended testing in the commissioning period of the accelerator. After cavities have been adjusted to this pre-set configuration, iterative fine-tuning will be necessary within the three second period. Extensive off-line testing during commissioning will be essential to reduce further on-line fine tuning as far as possible.

For both the off-line and on-line optimization the number of compensating cavities requiring re-phasing is critical as more of them imply more possible combinations of configurations to optimize during off-line testing and possibly more iterations during on-line fine-tuning. Hence, fewer compensating cavities would promise a faster and more reliable transition from normal to compensating mode. However, distributing the compensation across fewer cavities requires a stronger increase in RF field amplitude per compensating cavity and this directly translates to a higher power margin of the RF powering of the cavities. This means that the RF power rating is significantly higher than what is needed in nominal conditions, strongly impacting the cost of the system requiring higher up-front investment. Operating RF systems further away from their rated power reduces the efficiency of RF amplifiers and increases the operating costs in nominal operation conditions. From a cost point of view, it would be better to distribute the compensation across as many cavities as possible. Lastly, when compensating with more cavities the difference in the RF field amplitudes between normal operation and compensating operation is smaller - and as such it is considered easier to manage.

To balance these aspects, it has been proposed to apply a scheme in which four RF circuits are used to compensate for one faulty. This implies a relatively low number of cavities requiring re-phasing during a dynamic compensation and reasonable RF power margins. The margins have been evaluated (Bouly, 2022) and are between 40% and 70% of the required RF power for nominal operation. A detailed overview of the power margins for dynamic compensation is shown in Fig. 5. It shows the power per RF circuit (y axis) along the chain of 152 cavities. The power requirements at nominal operation without failures is plotted in blue. The case of a dynamic compensation is represented by red dots, with few RF systems considered faulty with a power of 0 kW. One can see that the neighbouring cavities adjust their power accordingly. An upper envelope function representing the required power margin is shown in green. Averaged over the entire MYRRHA main LINAC, the required margin for dynamic compensation is approximately 45%. Since margins are leading to significant cost increases, the goal of the availability modelling is also to assess whether the chosen scheme of four compensating RF circuits is optimal or if the margins can be reduced by using more compensating cavities.

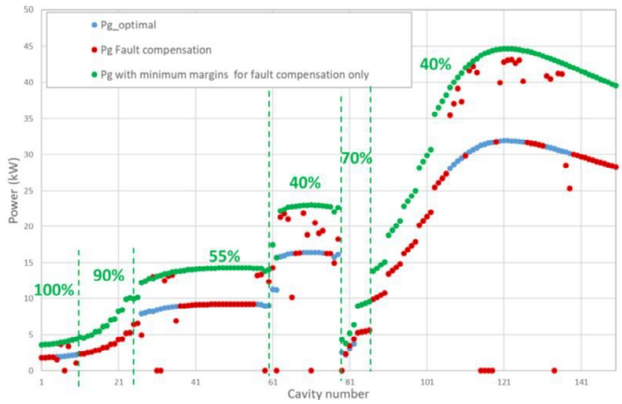

Fig. 5. Estimation of required RF power margins for dynamic compensation when four compensating cavities are being used. Estimated by beam-dynamics simulations (Bouly, 2022).

3. Availability simulation model

The modelling described in this section allows to find an optimum between RF margins, compensation flexibility, system failure rates, the MYRRHA reliability goals and the fault-tolerance effectiveness. To do so, the following aspects are modelled:

- The failure rates of sub-systems;
- The repair accessibility of sub-systems;
- The flexibility of the compensation scheme reflecting latest findings of beam physics simulations and different RF power margins. The possibility to compensate faults is explicitly evaluated for all RF circuits in the LINAC;
- The consideration of failures at the beginning and the end of the accelerator chain, where no symmetric compensation can be done and consequently faults are more difficult to compensate;
- The inclusion of failures of cryo modules, the imperfect execution of the scheme, as well as faults not covered by dynamic compensation;
- RT & fuel cycle procedures and associated repair policies;

This is addressed by a model with the following design choices:

- Cryo modules & RF circuits are modelled as single components with a single failure mode. A failure of a cryo module will also put the RF circuits it contains into fault.
- All other systems that are not part of dynamic compensation are modelled as a single component triggering RTs, which give opportunities to repair cryo modules and RF systems.
- The three different accelerating stages (single-spoke, double-spoke, elliptic) are modelled separately.

To explicitly model the compensation scheme, two parameters are used. The first one is the number of compensating cavities per detuned cavity, Nc. If Nc = 4, this means that if a cryo module containing two RF circuits stops working, the two cavities therein need to be compensated by two times four cavities, making eight compensating cavities in total. This parameter has a strong influence on the required RF powering margin for RF circuits since the power that is missing in the faulty RF circuit needs to be distributed across the Nc compensating circuits. This scales approximately with 1/Nc. The more compensating cavities per detuned cavity, the fewer additional power needs to be provided by the compensating cavities, resulting in a smaller RF power margin requirement. In practice, beam dynamics simulations indicate that there are limits to reducing the margin by distributing the compensation over more and more cavities since the direct neighbours of the detuned cavity will often have to bear a bigger part of the compensation load.

The second parameter is the maximal compensation distance to the detuned cavity, Cd. If Cd = 4, this means that the compensating cavities can be located up to four cavities away from the detuned cavity. For the case of a faulty cryo module described above, which requires eight compensating cavities, a Cd of four is necessary so that four compensating cavities can be placed to each side of the faulty cryo module. This is also shown in the fourth row (Nc = 4, Cd = 4) of Figure 6, which shows a few examples of fault configurations that can or cannot be compensated with the parameters Nc and Cd, indicated in the respective row.

Generally, lower Nc and higher Cd values allow for a more flexible fault compensation scheme. Beam physics simulations suggest that Cd = 4 is feasible in low-energy sections of the LINAC and Cd = 8 in high-energy sections (Bouly, 2022). However, even larger values may be possible and their potential benefit in terms of availability should be studied.

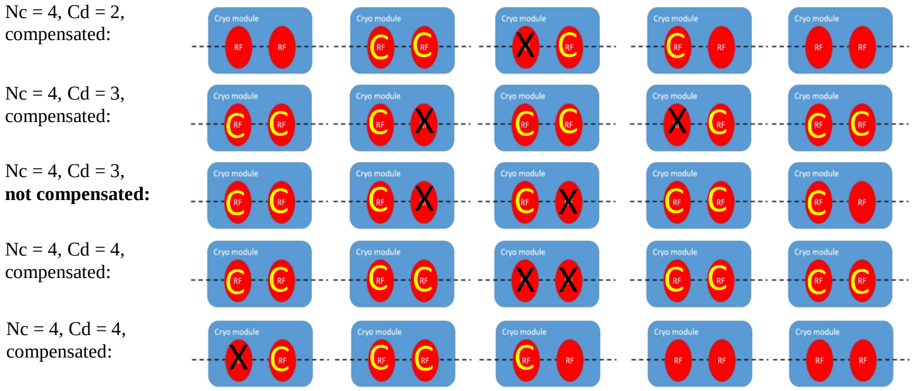

Fig. 6. Examples of fault configurations, which can or cannot be compensated by a compensation scheme with the respective parameters for Nc and Cd, indicated on the left.

Figure 7 shows the state diagram governing the simulation model. It starts in the normal operation state (OP). When a possibly compensatable fault of an RF circuit or a cryo module happens the dynamic compensation state (DC) is entered for three seconds. In this state the model evaluates whether a possible compensating configuration exists, given the chosen parameters for Nc and Cd and the distribution of faults in the LINAC. If the fault cannot be compensated, the simulation enters the RT state, stopping beam production for 12 hours. If a compensating configuration has been found, it is evaluated whether the switching succeeds or not using a pre-set failure probability. If it fails, the system enters a RT for 12 hours. If it succeeds, operation continues in compensation mode in the state “degraded OP”. Whenever another possibly compensatable fault happens, the steps involving the dynamic compensation are repeated. Once a non-compensatable fault is encountered, the system transitions to a RT and RF repairs can be initiated, including repairs of previously compensatable faults. After the set time of a RT, the system returns to “normal OP” if all repairs have been finished, to “degraded OP” if not all repairs could be finished but it is possible to run in compensating mode, or to a Long Repair state if sufficient repairs could not be finished to return to any operational mode. The long repair state exists to consider cryo module failures that are normally only repaired after the 90 days fuel cycle unless operation cannot resume without the repair. In this case the Long Repair state is initiated to complete the normally lengthy cryogenics repairs. Note that the latter two options are not shown in Figure 7 to ease readability.

When any other MYRRHA system fails, the simulation enters an externally triggered reactor turnaround (Ext. RT), which allows for repairs of the explicitly modelled RF systems. If the simulation has spent 90 days in operational modes, the fuel cycle is over, and the simulation is terminated. The described state diagram represents the reference configuration of the system. For the analysis alternative configurations are tested, such as having repairs during beam production, which would alter the state diagram.

The parametrization of the model and its failure parameters reflect the expected behaviour as derived from an evaluation of comparable systems and expert estimations, described in more detail in (Felsberger et al., 2022). Given uncertainties of the estimations, a pessimistic and optimistic reference model are chosen. The simulations are carried out with the parameters of the low-energy section of the LINAC as it is considered the most demanding for dynamic compensation. The complete set of parameters is listed in Table 1.

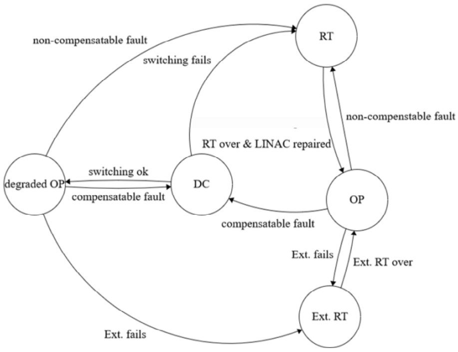

Fig. 7. State diagram illustrating the simulated behavior of the system. Abbreviations: RT – reactor turnaround, DC – dynamic compensation, OP – operations, Ext. RT – Reactor turnaround triggered by systems other than main LINAC RF systems & cryo modules.

Table 1. Parameters of the Availability Model. Note that the optimistic and pessimistic model are identical except for the last two rows.

Component	System count	Failure behaviour	Triggering	Repair policy
RF circuit	60	MTBF = 32000 h	DC	Repair every RT
Cryo module	30	MTBF = 256000 h	DC	Repair after fuel cycle (or when blocking operations)
Other MYRRHA systems not covered by dynamic compensation	‘1’	MTBF = 1080 h (twice per fuel cycle)	Ext. RT	Providing repair opportunity for RF circuits and cryo modules
Single RF circuit and cryo module failures (only present in pessimistic model)	‘1’	MTBF = 1300 h	RT	Repair every RT
Failure of switching to compensating mode (only present in pessimistic model)	‘1’	15% of DCs	RT	Repair every RT

The model was implemented in the Monte-Carlo Simulation code AvailSim4 (Blaszkiewicz et al., 2024), which was developed at CERN from 2020 on and is open source. It is a powerful and versatile availability simulation software that includes numerous features to model complex system behaviour including different phases of operation with associated failure modes, different repair policies depending on the accessibility of systems during operation, etc. The system definition is based on spreadsheets. Arbitrarily complex system dependencies can be defined in Python code, which the tool accepts as additional input. This enabled an explicit definition of the model’s complex logic for the dynamic compensation of RF circuits, by recursively iterating through the chain of RF systems to identify whether a compensating configuration can be found given the parameters Nc and Cd.

The AvailSim4 model has been simulated on a personal computer with the following simulation parameters:

- Simulation terminated after 90 days of delivered beam (time spent in any operational state);
- 2000 Monte Carlo iterations for each set of parameters (one iteration took ~0.03 seconds on an office PC).

On average 10.3 RF and 0.6 cryo module faults occur during one fuel cycle. The reported performance metric is the number of RF & cryo faults that are not covered by dynamic compensation and trigger a RT. This does not include external MYRRHA system faults triggering Ext. RTs. The results are multiplied by 152/60 to scale the modelled single-spoke section up to the full length of the MYRRHA accelerator. This is a deliberate choice to make them comparable to the requirement of no more than 3.3 failures from RF systems and cryo modules in the entire main LINAC. This was defined in the global MYRRHA availability requirements (Felsberger et al., 2022).

4. Results

In the following, the availability simulation model is used to identify the impact of key parameters on the effectiveness of the dynamic compensation scheme. These are:

- The compensation distance Cd as governed by the beam physics simulations.
- The number of compensating cavities Nc determining the required power margins and associated costs.
- The possibility to carry out repairs during beam operation.

Each factor will be discussed individually and a sensitivity analysis is performed by varying them in respect to the optimistic and pessimistic reference models.

4.1. The compensation distance Cd

The compensation distance determines how far a compensating RF circuit can be located from the faulty one. The larger the distance, the more flexible the scheme and the more faults within a local area can be accumulated. The effect of varying Cd is shown in Figure 8, which indicates the number of RTs triggered (y-axis) as a function of the compensation distance (x-axis). In Figure 8, the number of compensating cavities is kept at four (Nc = 4).

One can see that the optimistic model with perfect switching and without single points of failure triggers the fewest RTs. There is a strong dependence with Cd. Going from no dynamic compensation (dark blue) to the least flexible optimistic compensation scheme with Cd = 2, already reduces the triggered RTs from 10 to 2.2. A strong further reduction to 0.6 RTs is observed for the optimistic model with Cd = 4. Going to larger Cd can reduce the number of RTs further, but the gains are relatively small.

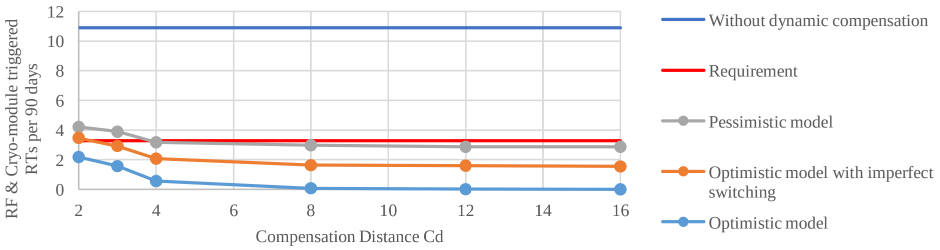

Fig. 8. Impact of the compensation distance on number of triggered RTs.

The optimistic model with imperfect switching (85% success rate) increases the number of triggered RTs significantly. Finally, for the pessimistic model of imperfect switching with 85% success rate and 1.65 single point failures per fuel cycle, the number of RTs are increased to the point that Cd = 4 only just meets the requirements.

Overall, it can be concluded that the expected foreseen compensation distance of Cd = 4 allows for sufficient compensation flexibility reaching a significant coverage of faults. The limitations of the scheme are more likely due to imperfect switching or single points of failure.

4.2. The number of compensating cavities Nc

The number of compensating cavities has a strong impact on the required RF power margin, scaling approximately with 1/Nc. Increasing Nc can in principle reduce power margins and associated costs. However, the number of RF circuits that can be chosen as compensating cavities is limited as shown in beam physics simulations and modelled by the compensation distance Cd. The more compensating cavities are required within this distance, the sooner a situation will arrive in which insufficient compensating RF circuits are available once failures accumulate. This effect is studied by varying the number of compensating RF circuits, while keeping the compensation distance fixed at four (Cd = 4). The sensitivity of the number of RTs triggered (left y-axis) with respect to the number compensating cavities (x-axis) is shown in Figure 9. In addition, the theoretical impact on the relative RF powering margin is shown (right y-axis), where 100% corresponds to the margin required for four compensating cavities (left end of the grey dashed line in the figure). It is important to note that this assumes that the compensation can be distributed equally among the compensating cavities, while in practice this only holds for low values of Nc.

In the investigated range of Nc (4 to 8), the power margin can theoretically be halved. However, this increases the number of RTs triggered due to a reduced coverage of the fault-tolerance scheme. For the optimistic model, the number of triggered RTs goes from 0.6 to 3.3 and for the pessimistic model from 3.3 to 4.7.

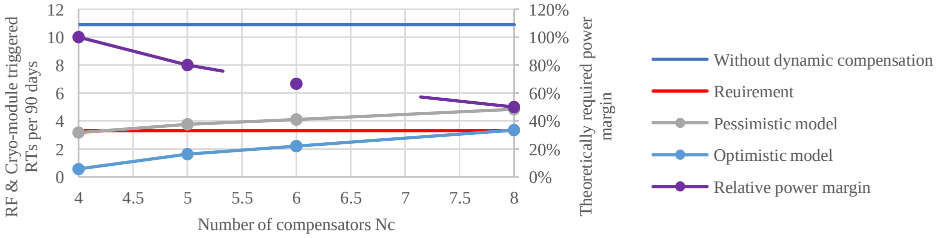

Fig. 9. Impact of number of compensating cavities per faulty RF circuit on number of RTs triggered.

The reliability requirement can only be met for Nc > 4 if the actual system failure rates, the compensation switching success rate and/or the number of single failures are better than in the assumed pessimistic model. This reflects the lower chance of finding a compensating configuration with increased Nc.

In practice, using more compensating cavities potentially leads to a lower switching success rate as more cavities need to be re-phased and fine-tuned, which would lead to an even less effective fault tolerance. This additional effect is not visible in Figure 9 as the model assumes a constant switching success rate independent of Nc.

Overall, it can be concluded that increasing the number of compensating cavities leads to a relevant reduction of the RF power margin, but the fault-tolerance scheme is losing effectiveness. This can only be used if reliable switching can be guaranteed for more compensating cavities.

4.3. Immediate repair of RF failures

Although immediate repair of RF failures might be difficult to implement, it is important to study its theoretical potential for the dynamic compensation scheme. In Figure 10, the results with immediate RF repairs are compared with the reference models, in which RF repairs are only carried out during RTs and after the fuel cycle of 90 days.

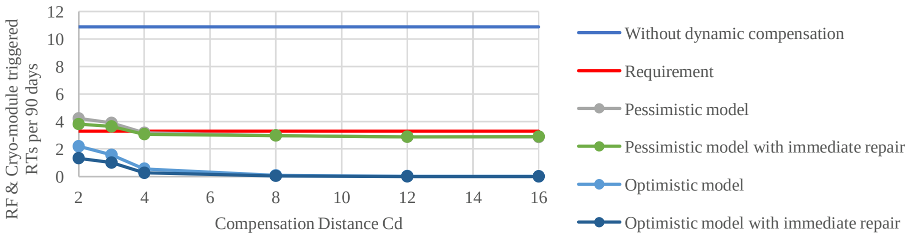

Fig. 10. Difference in number of RTs triggered between repair of RF components during beam or during RTs only.

For the optimistic model with perfect switching and without single failures, there is a significant difference in the number of RTs triggered up to Cd = 4 (lower two curves). For Cd = 2, 3, 4 and 8 the difference of triggered RTs is 0.9, 0.6, 0.3, and 0.0, respectively. For the pessimistic model with imperfect switching and single failures, the difference is less noticeable (upper two curves). For Cd = 2, 3, 4 and 8 the difference of triggered RTs is 0.4, 0.3, 0.1, and 0.0, respectively.

The interpretation of this is that for the pessimistic model the frequency of RTs is high enough to be able to timely repair faulty RF components. However, for the optimistic model RTs are rare and being able to repair RF systems during beam operation increases the effectiveness of dynamic compensation. Moreover, one can see that for inflexible schemes (Cd < 3) the benefit of repairing faulty RF circuits immediately is larger than for more flexible schemes (Cd ≥ 4). The conclusion is that unless the dynamic compensation scheme is inflexible and switching very reliably whilst having almost no single points of failure, repairs during RTs are sufficient and earlier (or immediate) repair of RF components does not provide advantages.

5. Conclusions and future work

An availability simulation model to quantify the benefits of dynamic compensation is presented. It considers constraints identified in beam physics studies and allows trade-offs between required power margins and availability gains. Assessing the MYRRHA linear accelerator, the study demonstrates that employing four compensating RF systems per faulty one strikes an effective balance between availability gains and power margins, leading to an estimated 65-95% reduction of beam outages due to RF systems and cryo module failures in the main LINAC if RF systems have a power margin of approximately 45%. Reducing the margins generally results in availability gain reductions. Concretely, a 25% RF power margin would only lead to an estimated 50-65% reduction of beam interruptions, which is potentially not sufficient to meet the MYRRHA availability targets. Immediate RF system repair offers limited improvements unless the MYRRHA accelerator's availability substantially surpasses its requirements. These findings have been made possible due to unprecedented levels of detail in the models.

With the advancement of the MYRRHA project, further testing of the dynamic compensation scheme will be possible. Experimental verification of key factors, such as permissible compensation distance and switching success rate can then be obtained experimentally. When this information is incorporated into the presented reliability model, more precise estimates of the optimal dynamic compensation configuration for the entire MYRRHA accelerator will be attainable.

This study underscores the pivotal role of robust availability simulation tools in optimizing sophisticated redundancy strategies. The presented model is generic and can be applied to other particle accelerators for which dynamic compensation is envisaged. It offers the potential to refine such RF schemes, which could drive significant improvements in general availability.

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