FAULT TOLERANCE AND CONSEQUENCES IN THE MYRRHA SUPERCONDUCTING LINAC*

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Abstract

The MYRRHA project aims at the construction of an ADS demonstrator in Mol (Belgium) which requires a proton flux with a maximum power of 2.4 MW (600 MeV-4 mA). Such a continuous wave beam will be delivered by a superconducting linac which must fulfil very stringent reliability requirements. In this purpose, the accelerator design is based on a fault-tolerant scheme to enable rapid failures mitigations. We here review beam dynamics studies on the RF fault-tolerance capability of the MYRRHA linac and the resulting impact on the R&D.

INTRODUCTION

MYRRHA (Multi-purpose Hybrid Research reactor for High-tech Applications) is a new fast spectrum nuclear facility which is planned to be built at SCK-CEN in Mol (Belgium) [1]. This 100 MW_{th} nuclear reactor is especially designed to demonstrate the ADS (Accelerator Driven System) concept for the transmutation of high level radioactive wastes. To operate, the sub-critical reactor requires a continuous wave (CW) proton beam, with a maximum power of 2.4 MW (600 MeV - 4 mA).

Initiated during previous EURATOM programmes (PDS-XADS and EUROTRANS), the conceptual design of this ADS-type accelerator had been consolidated in the frame of the MAX project (EURATOM FP7) [2]. It is a superconducting linac fed by a 17 MeV injector (details in [4] and [5]). The 17-600 MeV MYRRHA main linac is composed of an array of independently-powered superconducting (SC) cavities. Three different cavity families are used to cover the energy range: a first section with 352.2 MHz Spoke 2-gap cavities (β_{opt}=0.37) and two following sections with 704.4 MHz 5-cells elliptical cavities (β_{opt}=0.51 & 0.70). In the MEBT (Medium Energy Beam Transfer line), between the injector and the main linac, three 352.2 MHz spoke cavities can be used as bunchers. All these choices result of longitudinal beam dynamics optimisations and are more detailed in [6].

This linac was designed to provide large transverse and longitudinal acceptances. The versatility of such design was performed to reach the exceptionally high level of reliability required to operate an ADS. Indeed, frequently-repeated beam interruptions can induce high thermal stresses and fatigue on the reactor structures. In addition, beam interruptions might trigger safety reactor shutdowns that could also significantly affect the ADS availability [7]. Therefore, the number of beam interruption will have to remain extremely low: the current maximum limit is set to 10 beam interruptions, longer than 3 seconds, per 3-month operating cycle. It leads to a global accelerator MTBF (Mean Time Between Failures) of ~ 250 hours [8]. To achieve such a reliability level, the linac design is based on a redundant and a fault-tolerant scheme to enable the rapid mitigation of RF failures.

FAULT-TOLERANCE SCHEME

The followed reliability guidelines for the MYRRHA linac design is: to provide a robust beam optics with operation margins, to elaborate an efficient maintenance scheme with on-line reparation if possible, and to dispose of a maximum redundant elements for failure compensation. For the 17 MeV injector the adopted philosophy is parallel redundancy: by providing a second hot stand-by spare injector able to quickly resume beam operation in case of failure in the main one [9].

In the main 17-600 MeV linac the fault compensation scheme is based on serial redundancy. The present adopted strategy is to use a local compensation method to compensate RF failures (cavities and their associated control and power systems): the faulty cavity (respectively cryomodule) is compensated by acting on the RF gradient and the phase of the 4 nearest neighbouring cavities (respectively cryomodules) operating de-rated (i.e. not already used for compensation).

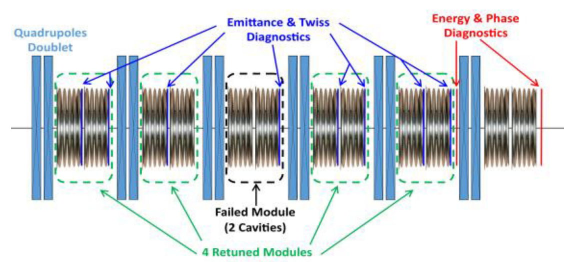

Figure 1: Principle of the local fault compensation method. Example of the retuning strategy used in TraceWin for the failure compensation of one cryomodule in the medium energy section (β_{opt}=0.51).

This retuning scheme can only be achieved by providing significant RF power and gradient overhead throughout the 3 superconducting sections. In the present design, this operation margin in terms of acceleration capability has been chosen to 30% (details in [6, 8]). As a consequence, the operating accelerating gradients (E_{acc}) of the MYRRHA cavities have been chosen on the conservative side to enable these compensation procedures. The average operating point of the SNS β=0.61 cavities in 2008 [10]

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was taken as a reference. And, the maximum E_{acc} were set by keeping E_{peak} < 35 MV/m and B_{peak} < 60 mT. The nominal de-rated operation points were then obtained by removing 30% of these maximum E_{acc}.

RETUNING STUDIES

Simulation studies have been carried to evaluate the feasibility of the local failure-compensation method and are based on initial works presented in [11, 12]. Our goal is to better assess, in terms of beam dynamics, the feasibility of multiple RF failures compensation and to evaluate more accurately the requirements for the RF systems.

In this purpose the TraceWin [13] code, with its matching internal algorithm, have been used. The most difficult type of scenario studied is the failure of one complete cryomodule: i.e 2 adjacent cavities for section #1 and #2 and 4 adjacent cavities for section #3. Figure 1 shows one of the methods used to "guide" TraceWin through this local re-matching. It is clearly a theoretical approach since, in this simulation, the Twiss parameters are checked after each compensation cavity. In this way we reached a compromise by minimising the transverse and longitudinal mismatching, and still recovering the nominal energy at the output of the retuned area with the beam arriving at the "right time" in the following lattice (i.e. with the nominal RF phase). We also try to keep the synchronous phase (ϕ_s) as low as possible to keep a sufficiently large longitudinal acceptance.

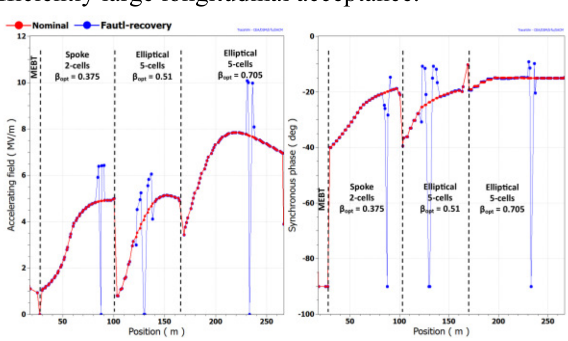

Figure 2: Example of multiple RF failures compensations with the local retuning method: accelerating fields (left) and synchronous phases (right).

In each of the three accelerating sections, several failure scenarios have been individually assessed with success. Recently, we have been exploring scenarios with multiples failures in each sections of the linac. The results of one the most advanced multiple failures study are presented on Figure 2: 1 failed cavity in sections #1 and #3, 1 failed module in section #2. The red dots curves gives E_{acc} and ϕ_s for every cavity in nominal condition while the blue dots curves are the fault-recovery settings. They were calculated by limiting the E_{acc} increase at 30 % in every retuned cavity, while the maximum ϕ_s change could not be kept below 58 %, especially in the case of a full cryomodule failure.

Nevertheless, no losses are observed in the global beam transport through the linac and the transverse envelope periodicity is conserved as illustrated by multiparticle simulation on Figure 3. Still, The RMS emittances growths between the nominal and this fault-recovery scenario are: ~ 28% in the horizontal plane, ~ 40% in the vertical plane, and ~ 45% in the longitudinal one. The input beam is a distribution tracked from the injector and the MEBT. It is very close to a Gaussian distribution truncated at 4 σ with RMS normalised emittances of: ~ 0.18 mm.mrad (transverse) and ~ 0.33 mm.mrad (longitudinal).

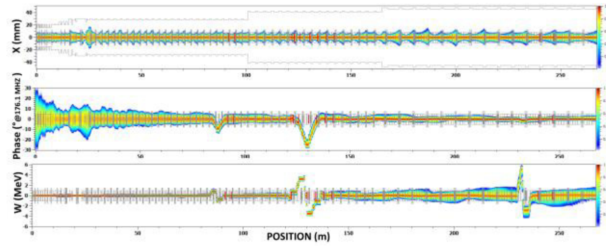

Figure 3: Beam dynamics with failures compensation.

In such a scenario, the longitudinal acceptance of the SC linac decreases; as expected. The acceptances, for both cases, are plotted on Figure 4. In the nominal case, on can fit an ellipse inside the acceptance which correspond to ~55*ε_{RMS} of the beam, while in the multiple failure scenario it is decreased to ~19*ε_{RMS}; which should remain a sufficient margin for the linac operation.

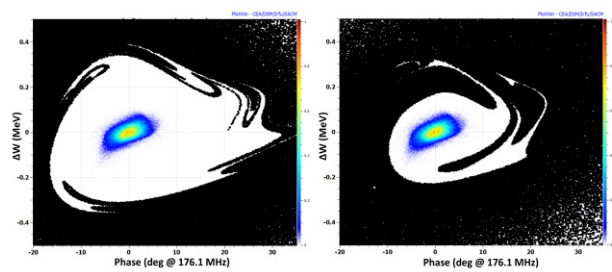

Figure 4: Longitudinal acceptance and input beam. Left: nominal tuning. Right: fault-recovery scenario.

RF REQUIREMENTS

Until now, the beam dynamics results tend to show that it is possible to apply local fault compensations. To reach the reliability goal, a retuning procedure was defined [14]: when a fault is detected the beam is stopped, the RF cavities are locally retuned, and the beam is switched on again, in less than 3 seconds. This brings some specific requirements for the RF technologies, which we briefly comment here.

SRF cavities and control systems

A key aspect is that the fault compensation strategy rest upon the individual capability of each SC cavity. If the gradient have to be increased in less than 3 seconds a huge R&D effort is required to make the cavities, their power couplers and the surrounding cryogenic systems as performant as possible: to challenge quench limitations and parasitic effect (e.g. Multipacting). Besides, the control systems of each cavity will also have to be extremely performant, especially the tuning systems. It will have to act “quickly” to enable the retuning in less than 3 seconds, and to minimise the RF power consumptions. Even more critical, it will be necessary to avoid beam loading on the faulty cavity to limit perturbations (deceleration) and power dissipations. It was estimated [6, 15] that a faulty cavity have to be frequency detuned by at least 100 times its bandwidth (~ 100*150 Hz). Consequently the tuning system must act on a large frequency range and its minimum “detuning speed” will have to be of ~ 5 kHz per seconds [15]. Within the MAX programme, R&D topics have been dedicated to these aspects [16, 17].

RF power needs

The fault-recovery beam dynamics studies also enabled to estimate the required RF power for every cavity in the linac. To anticipate on the power needed per cavity, a statistical errors study was carried out on every parameters which can be inaccurately controlled and which affect the required RF power [18]. To the maximum power found (worst case in the error study), we added 10 % extra margins to take into account the signal attenuations.

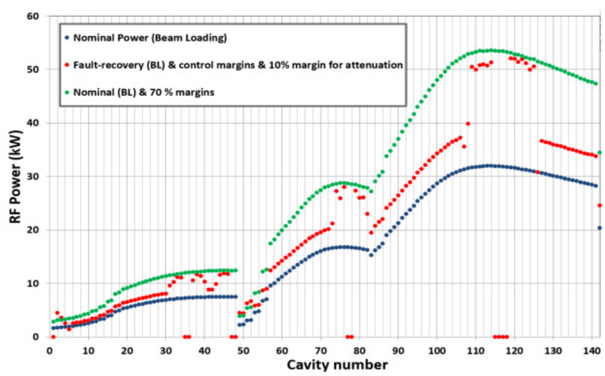

Figure 5: Estimation for the RF power requirements.

On Figure 5, the minimum required RF power in a “perfect” nominal operation – i.e. without any errors - is plotted (blue dots curve). The red dots curve gives the required RF power by taking into account the maximum errors of the control system (from statistical error study), the 10% extra-margins and the retuning of some cavity to compensate full cryomodules failures. This shows that a minimum power margin of 70 %, as regard to the “perfect” nominal case, should be foreseen (green dots curve). Nevertheless, the required CW power per cavity should not exceed 60 kW. Consequently, the use of solid state technology (352 MHz & 700 MHz) is considered as a reference option for the MYRRHA RF amplifier park. It would bring some flexibility with small individual modules which could be replaced during operation.

DISCUSSION & FUTUR PLANS

We presented some studies to evaluate the feasibility of the fault compensation procedures in the MYRRHA linac. This theoretical approach was a first step but the retuning methods used until now can clearly not be directly apply on a real machine. Indeed, even with the optimisation algorithm proposed in TraceWin, this is not a straightforward process to obtain acceptable retuning set points. In addition, the simulation time easily reaches several minutes. So, a next step would be to develop a ‘retuning code’ which uses a systematic method to process the retuning set points. This method, should also take into account the real diagnostics available on the machine and the beam information they provide. The real time set points evolution of each cavity will also have to be considered; knowing that this settings will not be as “perfect” as in design simulations. Moreover, since the time to recalculate the fault compensation set points may take more than 3 seconds, it will be necessary to have a database with the fault compensation settings ready to be used. This database should constantly be updated according to the fluctuating cavities operation point. This can be done inside - or in interaction with - a Virtual Accelerator [19, 20] which will ensure the beam adjustments during the linac operation.

As a conclusion, the successful and reliable operation of the MYRRHA accelerator is challenging and requires a huge beforehand R&D effort. It is necessary to pursue prototyping to an engineering design phase but also to follow up activities on topics related to beam operation: in particular to optimise, and accurately define, the strategies for fast fault compensation procedures.

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