Approach of a failure analysis for the MYRRHA linac

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Abstract

The MYRRHA project currently under development at SCK•CEN (Mol, Belgium) is a subcritical research reactor that requires a 600 MeV proton accelerator as a driver. This linac is expected to produce a beam power of 1.5 MW onto a spallation target for the reactor to deliver a thermal power around 70 MW. Thermomechanical considerations of the spallation target set stringent requirements on the beam trip rate which should not exceed 40 trips/year for interruptions longer than three seconds. This paper presents a first approach of developing a method that allows rematching the beam online in the MYRRHA linac upon the failure of accelerator components.

Introduction

About 2500 tonnes of nuclear wastes are produced every year in Europe by the 145 nuclear reactors currently under operation. Some of this material (mainly minor actinides) remains radioactive for thousands if not millions of years [1]. The MYRRHA project currently under development at Mol, Belgium, is an accelerator-driven system expected to be operational in 2023 with the primary purpose to study the feasibility of efficiently transmuting such nuclear waste products into isotopes with much shorter lifetimes (about three orders of magnitude shorter). After transmutation, the nuclear wastes would then be stored underground, 300 to 1000 meters deep, for a period ranging from a few hundred to a few thousand years.

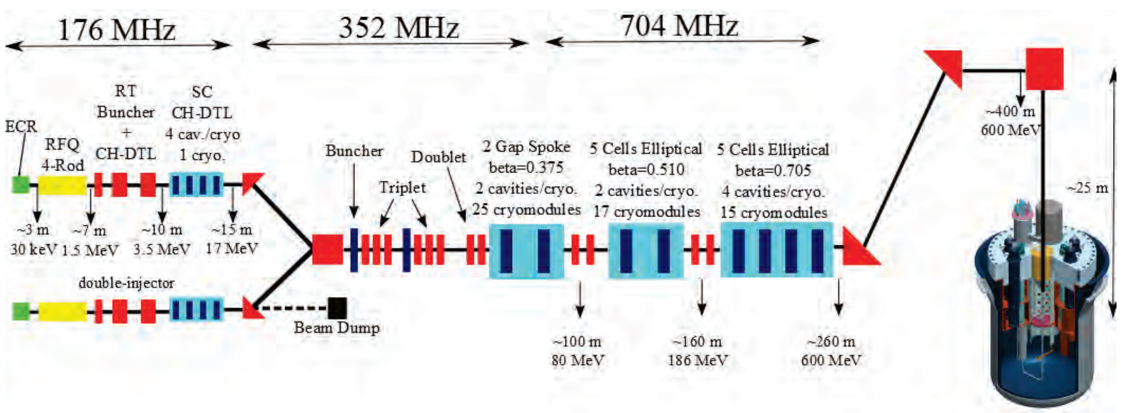
Liquid Pb-Bi eutectic (LBE) alloy has been selected as a coolant and neutron spallation source for the development of the MYRRHA reactor. The reactor is expected to have a thermal power of ~70 MW and may be operated in both critical and subcritical modes. In the latter case, the core is fed by spallation neutrons obtained from a 600 MeV superconducting proton linac beam hitting the LBE coolant/target with an average current of 4 mA. The accelerator providing this beam needs to be compatible with the steady state character of the reactor operation and as a consequence the beam has to be delivered in CW mode (with 200 µs empty gaps at 1 Hz repetition, for subcritical monitoring).

The major issue that needs to be taken into account during the design and the operation of the MYRRHA linac concerns the acceptable rate of unwanted beam interruption, commonly called beam trips. A recent study performed by AREVA and reported in [2] shows that, due to thermal stresses on structural materials (beam window, inner barrel, reactor vessel), no more than 10 beam trips longer than three seconds should take place in the linac per operational period of three months. This paper presents a strategic approach during the design of the linac and in its expected operation to fulfill this stringent requirement.

Layout of the MYRRHA linac

Figure 1 shows the schematic layout of the MYRRHA linac and the transport line to the reactor.

Figure 1. Overview of the MYRRHA linac and reactor



The 30 keV proton beam from the ECR source is bunched and accelerated by a 4-rod Radio-Frequency Quadrupole (RFQ) to an energy of 1.5 MeV with an average current of 4 mA. Downstream the RFQ, a buncher and 2 cooper multicell CH-DTL cavities further accelerate the beam to 3.5 MeV.

At this energy, the transition from room-temperature (RT) to superconducting (SC) structures takes place with the beam accelerated to 17 MeV by 4 SC CH-DTL cavities. The front-end of the linac (RFQ, buncher, RT and SC CH-DTL) operates at a frequency of 176 MHz. In the linac front-end, between the RFQ and the SC CH-DTL cavities, transverse focusing is achieved using RT quadrupole triplets and in the cryomodule hosting the 4 SC CH-DTL cavities using SC solenoid magnets.

At the exit of the dual-injector, two dipoles direct the selected beam into the SC main linac for final acceleration to 600 MeV. To boost the beam from 17 MeV to 80 MeV, SC 2-gap spoke resonators (β=0.375) operating at 352 MHz are used. Further acceleration to 600 MeV is provided by 2 types of 5-cells elliptical cavities (β=0.510 and β=0.705) operating at 704 MHz. The matching from the injector to the main LINAC is performed by 2 bunchers and 2 RT quadrupole triplets. In the 352 MHz and 704 MHz sections, RT quadrupole doublets located between the cryomodules are selected as focusing elements. At the end of the SC linac, the beam is vertically bent in the transport line by two 45° dipoles and reaches a height of ~25 m before injection into the nuclear reactor by a 90° dipole, as presented in Figure 1. The total length of the linac and the transport line to the reactor is ~400 m.

Approach towards a very high availability of the MYRRHA linac

The challenging aspect of the MYRRHA linac consists in its very high availability. It is required that the number of beam interruption longer than three seconds remains under 10 during a three-month operation period of the MYRRHA reactor. The corresponding Mean Time Between Failure (MTBF) is expected to be higher than 250 hours and the linac availability close to 100%.

As of today, the typical availability of superconducting proton linacs in operation like the Spallation Neutron Source (SNS) at Oak Ridge National Laboratory is reported to be slightly above 90% [3]. Some other accelerators like the ProjectX hydrogen ion linac currently under development at Fermilab must demonstrate that it can meet the requirement of 90% availability [4] for a 1 mA beam in CW operation at 3 GeV which turns to be well within reach taking into account the reported availability of the SNS linac.

The technology to build multi-GeV proton superconduting linacs with average currents of few mA and operating with availability in the order of 90% is available today. The strategic approach taken towards the very high required availability of the MYRRHA linac concerns not only the design of the linac but also its operation and this approach is summarised in the 4 principles below:

- element redundancy;
- use of linac components far from their limits;
- design of the linac following the fault-tolerance concept [5];
- operation of the linac under the virtual accelerator concept [6].

Element redundancy

Figure 1 presents the example of element redundancy. A dual-injector is foreseen in the MYRRHA linac to maximise the reliability of its front-end. The beam is expected to be injected in the linac from one injector, while the second injector is on stand-by mode with all elements operating at nominal power. With the dipole magnet turned off at the end of the second injector, the beam is directed into a beam bump. If abnormal beam losses are detected in the first injector, the Machine Protection System (MPS) stops the beam in both injectors using the LEBT choppers (typically in less than 0.1 msec). Once the beam is stopped, attempts are made to recover, if possible, the faulty component. If recovery fails, the beam is resumed in the second injector and sent to the main linac (in typically one or two seconds) by changing the polarity of the injector dipoles.

The linac components and their ancillary equipment need to be selected with the highest MTBF value and some of these components (like power converters, RF generators or quadrupole power supplies) may need to be doubled in the linac.

Use of linac components far from their limits

The three types of cavities in the main superconducting linac are to operate at a derated value, about 30% lower than the nominal values at which these cavities could safely operate. This safety margin is considered primarily for fault-compensation procedures.

The chosen rules for the operation of the MYRRHA superconducting cavities are the following:

- The RF field at the inner surface of the SC cavities is always kept below 35 MV/m and the peak magnetic field below 60 mT.
- The corresponding maximum accelerating field (given at optimal beta and normalised to the length of the cavities) is then 8.3 MV/m (for the beta=0.375 spoke), 10.7 MV/m (for the beta=0.51 elliptical) and 14.3 MV/m (for the beta=0.705 elliptical).
- The derated operating points are then obtained removing 30%, leading to 6.4 MV/m (for the beta=0.375 spoke), 8.2 MV/m (for the beta=0.51 elliptical) and 11 MV/m (for the beta=0.705 elliptical).

The SNS (beta=0.61) elliptical cavities are reported in [7] to operate with an average accelerating gradient in the order of 12-13 MV/m, which is lower than the derated accelerating field for the MYRRHA elliptical cavities. Therefore, the above-mentioned derated operating fields for the cavities of the main linac seem well within reach.

Following the same idea, the magnetic field of the pole is always kept below 0.3 T in all the linac quadrupoles, giving some comfortable (~30%) room for gradients increase if needed. Also, the RF power amplifiers are derated by ~40%.

Design of the linac following the fault tolerance concept

The main superconducting linac has been designed based on the fault tolerance concept. The philosophy behind this concept [5] is that if an element fails during the operation of the linac, proper compensation and re-matching can be achieved with the neighbouring elements and beam operation under nominal conditions can be resumed after a short (<3 sec) beam interruption.

Namely, the fault tolerance procedure is expected as follows [8]:

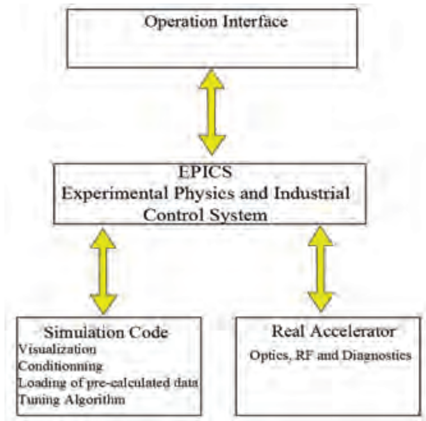
- If abnormal beam losses are detected along the linac then the MPS stops the beam in the injector using the LEBT chopper.
- The origin of the fault is analysed. If the fault cannot be cured, the fault-recovery procedure is initiated. In the case of a faulty cavity, the 4 nearest neighbouring cavities are used for compensation, while the faulty cavity is being detuned. If a quadrupole is faulty, the whole doublet is switched off and the 4 neighbouring quadrupoles are used for compensation.
- New values for cavity phases and fields and/or quadrupole settings need to come either from a predefined table or from a predictive and fast "online" beam dynamics calculation.
- The beam is resumed in the linac, first with very short pulses to check the behaviour of the lattice, then with full power for nominal beam operation.

The machine control system of the MYRRHA linac will need to work very fast to ensure the detection and compensation of any failure in the accelerator in less than three seconds. A beam dynamics code will need to be associated with the machine control system to accurately predict the new matching set points in the event of any accelerator element failure. The association of the beam dynamics code to an accelerator control system is often mentioned in the literature as a "virtual accelerator".

Virtual accelerator concept: Architecture and examples

Figure 2 presents the structure of a virtual accelerator based on the EPICS control system.The virtual accelerator includes a beam dynamics simulation code that is able to run in parallel with the real accelerator. In this configuration, it is possible with the virtual accelerator to visualise the operation of a real accelerator and control some new accelerator set points from a dryrun before implementing these set points on the real accelerator. It is also possible during the operation of the real accelerator to load some pre-calculated data set points to compensate for a component failure. Ultimately the simulation code would be able to find, through a tuning algorithm, a new optic to bring the accelerator back onto nominal operation in every fault configuration.

Figure 2. Structure of a virtual accelerator based on EPICS



In 2006, a first test of a virtual accelerator was performed at CEA-Saclay [6], using the code TRACEWIN [9] to optimise the transmission of the SILHI proton injector. While after several days of manual optimisation, the transmission achieved 79%, using the virtual accelerator, it reached 87% within half an hour. More recently, this TRACEWIN based virtual accelerator was successfully used for the conditioning of the SPIRAL2 injector with heavy ions at Grenoble and proton/deuteron at Saclay.

A virtual accelerator based on the code TRACK [10] was also proposed in 2008 in [11]. Since the beginning of 2013, a special interface [12] has been developed at ANL to connect the ATLAS LINAC control system to the code TRACK. The interface is now capable of producing TRACK inputs from the actual element settings (read directly from the control system) and the reverse is under development. Finally, the operation and optimisation of the ATLAS LINAC will be possible through the TRACK based virtual accelerator.

Beam dynamics aspect of the fault tolerance design

It is generally accepted that the fault-recovery procedure cannot be applied at low energies (below 10 MeV). This is the actual main reason for the choice as input energy of 17 MeV for the main linac. It is also important to point out that once the proper compensation and re-matching is found by the beam dynamics code, the new lattice needs to be tolerant to typical accelerator misalignments and jitter. In other words, this new lattice should be able to correct typical errors with losses that need to be below 1 W/m, the threshold taken as a reference to insure "hands-on" maintenance on the linac [13].

The main superconducting linac i.e. from the injector exit (17 MeV, upstream of the dipoles) up to the end of the last cryomodule (600 MeV) has been designed with the code TRACEWIN and the corresponding baseline lattice has been translated as TRACK input for sensitivity studies. First, the behaviour of the baseline lattice of the MYRRHA linac will be presented in the presence of typical errors and correctors and then three fault tolerance cases (failure of the first spoke cryomodule, failure of the first doublet and failure of the first quad of the first doublet) will be studied.

Baseline design with errors and correctors

Static transverse misalignment error of quadrupoles and cavities and dynamic RF jitter (field and amplitude) have been implemented into the beam dynamics code TRACK. The transverse misalignments δ_{xy} are setup in the code such that the element ends are randomly misaligned (with a uniform distribution) horizontally and vertically by the same value which does not exceed the maximum input δ_{xy}. Concerning the dynamic RF jitter, TRACK generates Gaussian distributions truncated at 3 sigma. The TRACK correction algorithm aims to steer the beam so that the transverse displacements measured by the BPM's are minimised.

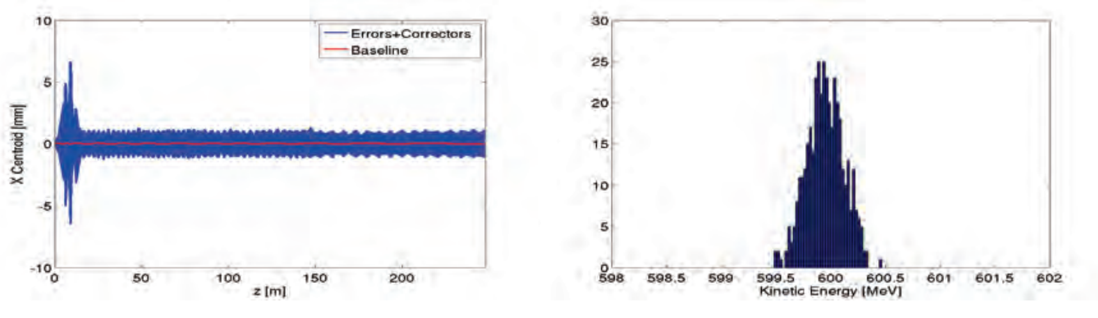
Figure 3(a) presents TRACK beam dynamics simulations of the beam centroid in the main superconducting linac with transverse misalignment of cavities and quadrupoles of δ_{xy} = 500 µm, RF dynamic jitter of 0.2° and 0.2% and quad roll of 5 mrad around the z-axis. A set of 400 randomly generated error runs were performed with TRACK using $5 \cdot 10^4$ macroparticles with 3D space charge routine. These 400 randomly generated error runs were corrected using 1 corrector (acting in both the horizontal and vertical plane) and 1 BPM per triplets (located downstream the second injector dipole) and per doublet (located between the main linac cryomodules). The corrector maximum strength is set to 5 mrad and the resolution and the offset in position of the BPM's are 30 µm and 1 mm. As depicted in Figure 2 (a), after correction the beam centroid motion keeps below 1 mm along the main superconduting linac and no losses due to element misalignments and RF field jitter are observed. This study confirms that the actual baseline design of the MYRRHA superconducting linac is tolerant to typical errors.

Noteworthy in Figure 3(b) is the corresponding energy distribution at the end of the linac, which shows that with an RF jitter of 0.2° and 0.2% the energy distribution keeps well below +/- 1 MeV, as recommended, during the design phase of the transport line from the linac to the reactor. Studies have shown that an RF jitter of 0.5° and 0.5% does bring some of the 400 seeds at an energy exceeding the threshold of +/- 1 MeV.

Fault tolerance design: Failure of the first cryomodule

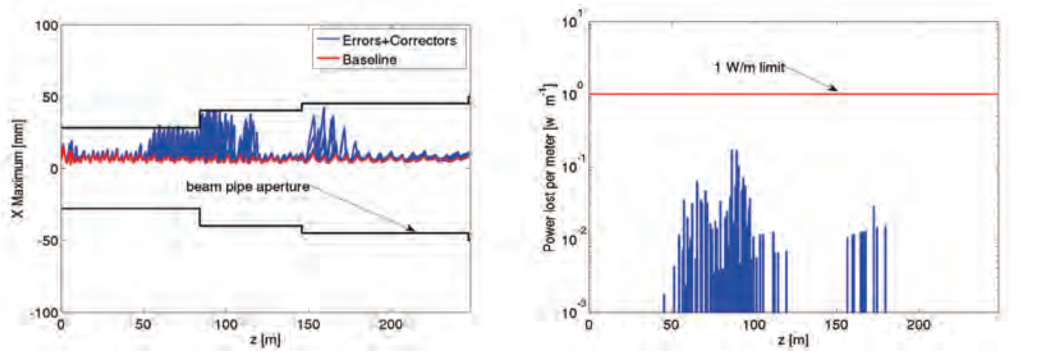
In the event of the failure of the first cryomodule, the code TRACEWIN has been used to find a new optic taking the phases and the fields of the two downstream bunchers and two upstream cryomodules (4 cavities) for matching. During the matching procedure, it was not specified to recover the energy due to the loss of the first cryomodule (slightly lower than 1 MeV). The new optic found by TRACEWIN has been converted into TRACK for typical error and corrector studies following analysis performed with the baseline design lattice. Figure 4(a) shows that some of the 400 TRACK runs are not fully corrected with macroparticles having a maximum excursion larger than the beam pipe aperture radius, leading to losses, as depicted in Figure 4(b). The losses present a maximum of ~0.1 W/m at the intersection between the spoke cavity section and the β=0.501 elliptical cavity section and therefore are acceptable, being by one order of magnitude lower than the 1 W/m threshold. As a result, this study shows that the actual design of the MYRRHA main superconducting linac is able to operate in the event of the failure of its first cryomodule.

Figure 3. (a) TRACK simulations of corrected horizontal beam centroid motion along the linac for static transverse misalignments of 500 microns (quadrupoles and cavities), dynamic RF jitter of 0.2/0.2% and quad roll of 5 mrad along the z-axis (b) corresponding energy distribution at the end of the linac



(a) (b)

Figure 4. Figure 5: TRACK simulations of the fault-recovery of the first cryomodule with errors and correctors



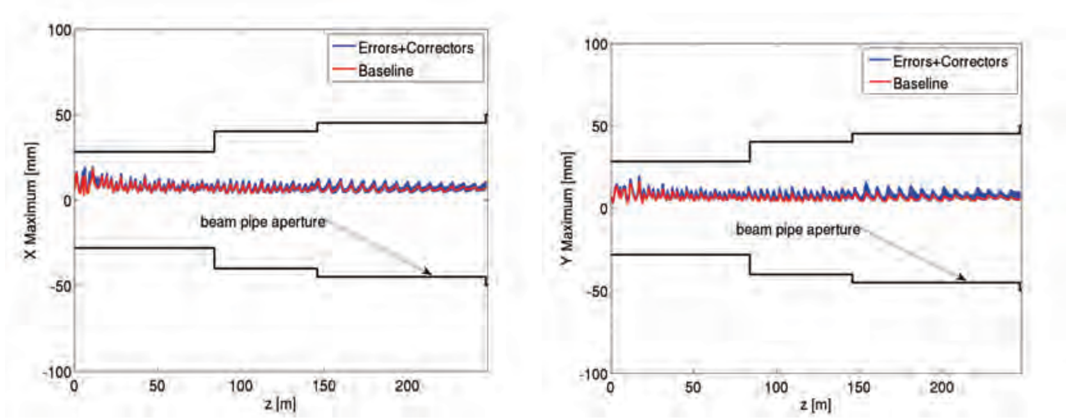
(a) (b)

(a) Maximum horizontal beam excursion along the linac, (b) corresponding average power lost per metre along the linac.

Fault tolerance design: Failure of the first doublet

The behaviour of the baseline lattice has been studied in the event of the failure of the first quadrupole doublet, located upstream the first cryomodule. A new optic was found using TRACEWIN and the two upstream triplets together with the two downstream doublets for matching. Figures 5(a) and 5(b) present the maximum horizontal and vertical beam excursion along the linac in the presence of typical errors and correctors, as previously discussed. These figures show that the re-matched lattice is tolerant to errors with all the 400 seeds computed by TRACK being properly corrected, insuring a maximum beam excursion well below the beam pipe aperture radius (by at least a factor of 2). These studies confirm that the operation of the MYRRHA main superconducting linac is possible even in cases of failure of its first doublet.

Figure 5. Maximum (a) horizontal and (b) vertical beam excursion along the linac after fault-recovery of the first quadrupole doublet with errors and correctors



(a) (b)

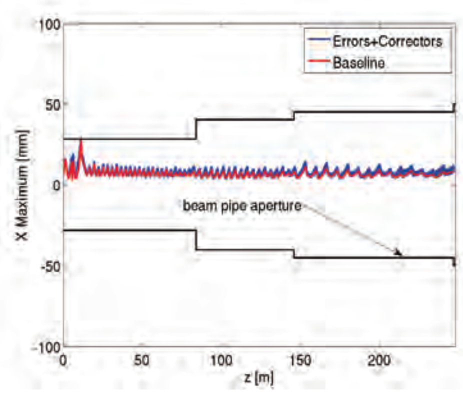
From TRACK.

Fault tolerance design: Failure of the first quadrupole of the first doublet

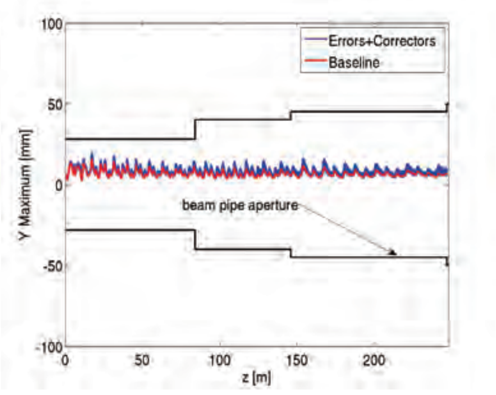
In the event of a failure of the first quadrupole of the first doublet, TRACEWIN was in charge of finding a new optic, taking into account the upstream two triplets, the remaining quadrupole of the doublet and the downstream doublet for matching. TRACK simulations of the corresponding new TRACEWIN lattice including the usual errors and correctors are presented in Figures 6(a) and 6(b) for the maximum horizontal and vertical beam excursion along the linac. Figure 6(a) shows that, at the location of the failed quadrupole, the beam presents a strong asymmetry in the horizontal plane while this asymmetry is not present in the vertical plane, as shown in Figure 6(b). For some of the 400 runs, the maximum beam excursion in the horizontal plane at this location goes slightly above the beam pipe aperture radius in the presence of errors leading to some limited losses (<0.05 W/m).

The study of the failure of the first quadrupole or the first doublet indicates that a new matching can be found using the remaining quadrupole of the doublet, the two upstream triplets and the downstream doublet. This new lattice presents some limited losses when tested with errors, jitters and correctors. Nevertheless, the results presented in Figures 5(a) and 5(b) suggest that it might be preferable, in the event of one quadrupole failure, to switch off the entire doublet to keep the beam symmetric. In this configuration, the re-matched lattice computed by TRACEWIN shows no losses in the presence of typical errors and correctors.

Figure 6. Maximum (a) horizontal and (b) vertical beam excursion along the linac after fault-recovery of the first quadrupole of the first doublet with errors and correctors



(a)



(b)

From TRACK.

Fault-recovery procedure and virtual accelerator control system

The fault-recovery procedure needs to take place within three seconds which is the maximum allowable beam interruption in the MYRRHA linac. Such a short time to resume nominal beam operation in the linac after an element failure implies the coupling of the accelerator control system to a beam dynamics code. This virtual accelerator will then be in charge of the linac operation and ideally the beam dynamics code will find a re-matched lattice for any failure scenarios. Obviously, this re-matched lattice would need to be tolerant to the typical accelerator misalignments and RF jitter with losses below the 1 W/m treshold once the nominal operation is resumed.

Some promising results have been obtained on optimising injectors using the virtual accelerator concept with TRACEWIN or TRACK at Saclay and ANL. Significant R&D is still necessary to have these codes perform an automatic lattice matching to compensate for any element failure in a full LINAC. Furthermore, this automatic matching procedure will need to be very fast to cope with the 3-second allowable beam time interruption. Also, the interaction between the beam dynamics code and the real accelerator through the accelerator control system will need to be very efficient, with some R&D needed in auxiliary systems like the cavity tuners and LLRF digital, as mentioned in [8].

Conclusion

The actual state-of-the-art in the design and operation of multi-GeV superconduting proton linacs with few mA of average current guarantees an availability of about 90%, as measured at the Oak Ridge Spallation Neutron Source linac or expected in the ProjectX linac currently under development at Fermilab. The challenging aspect of the MYRRHA linac is its requested reliability with no more than 10 beam trips longer than three seconds that should take place per operational period of three months, leading to an availability close to 100%. This very high availability needs to be incorporated into the design of the linac.

The three underlying principles in the design of the MYRRHA linac are elements redundancy (like the dual-injector), elements operation at derated values (like cavities operating at about 30% from their nominal operating points) and the fault tolerance concept, which allows the failure of a beamline component to be compensated by its neighbouring elements. Studies presented in this document show that in the event of a failure of the first cryomodule or the first quadrupole doublet the linac can resume nominal operation with a re-matched lattice. Since the fault tolerance procedure is expected to work more efficiently at higher energies (due to lower space charge effects) we can extrapolate from our studies that the MYRRHA linac is expected to operate with the failure of any cryomodule or quadrupole doublet in the main linac.

A virtual accelerator-based control system is mandatory for the operation of the MYRRHA linac to ensure the very fast implementation (<3 seconds) of the fault tolerance procedure. The virtual accelerator uses a beam dynamics code (like TRACEWIN or TRACK) to compute the model of the real accelerator in operation and interacts with this later through the accelerator control command. The beam dynamics code could, for instance, upload some pre-defined matched lattices in the event of element failures or it could ideally find some new optimal set points for every fault configuration. Such virtual accelerator-based control command has been successfully tested at Saclay (using TRACEWIN) on the SILHI injector or the SPIRAL2 injector and at ANL (using TRACK) on the ATLAS linac. Significant R&D is still needed to expand the concept of the virtual accelerator to a full linac like MYRRHA.

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