TOWARD A VIRTUAL ACCELERATOR CONTROL SYSTEM FOR THE MYRRHA LINAC

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Abstract

The `MYRRHA` project currently under development at Mol, Belgium, is an Accelerator Driven System expected to be operational in 2025 with the primary purpose to study the feasibility of efficiently transmuting nuclear waste products into isotopes with much shorter lifetimes. The reactor may be operated in subcritical mode when fed by spallation neutrons obtained from a 600 MeV superconducting proton linac hitting a Liquid Pb-Bi target with a maximum current of 4 mA. The challenging aspect of the `MYRRHA` linac resides in its very high reliability with a Mean Time Between Failure expected to be higher than 250 hours. This paper presents the strategic approach taken during the design of the linac and its foreseen operation to fulfill this stringent requirement. In particular we describe the concept of a beam dynamics based control system called Virtual Accelerator which is mandatory for the linac operation.

INTRODUCTION

The unique aspect of the `MYRRHA` linac consists in its very high reliability. As presented in Ref. [1], it is required that the number of beam interruption longer than 3 seconds remains under 10 during a 3-month operation period of the `MYRRHA` reactor leading to a linac reliability close to 100%. As of today, typical reliability of superconducting (SC) proton linacs like the Spallation Neutron Source (1 GeV, 26 mA) currently in operation at Oak Ridge is reported in Ref. [2] to be slightly above 90%. Such a reliability fits within the requirement of SC H^- or proton linacs currently under development like the FNAL ProjectX (1 mA at 3 GeV, [3]) or the ESS Linac (62.5 mA at 2 GeV, [4]). A strategic approach has been taken during the design of the `MYRRHA` linac and its foreseen operation to push its reliability close to 100%. The design of the `MYRRHA` linac is based on the Fault-Tolerance Concept [5] which allows, in the event of an element failure, a rematching of the lattice using the neighboring elements. The operation of the `MYRRHA` linac is expected to be monitored by a Virtual Accelerator control system, based on a beam dynamics code, which will be able to upload some pre-defined matched lattices or find some new optimal set points after a linac element failure. Nominal operation of the linac could then be resumed within 3 seconds of the fault detection. After a brief description of the `MYRRHA` linac, this paper describes a possible architecture for a Virtual Accelerator control system foreseen for its operation.

THE MYRRHA LINAC

A schematic layout of the `MYRRHA` linac is shown in Fig. 1 together with the transport line to the reactor.

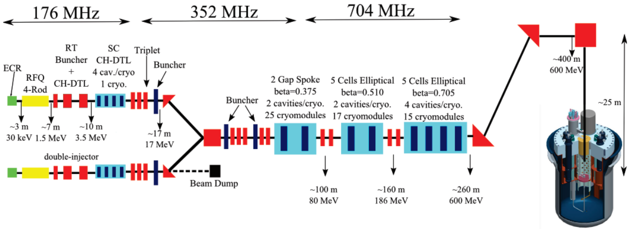

Figure 1: Layout of the `MYRRHA` Linac.

As depicted in Fig. 1, 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 copper multicell CH-DTL cavities further accelerate the beam to 3.5 MeV. At that energy the transition from room-temperature to SC stuctures takes place with the beam accelerated to 17 MeV by 4 SC CH-DTL cavities. The injector (RFQ, buncher, RT and SC CH-DTL) operates at a frequency of 176 MHz. To boost the beam from 17 MeV to 80 MeV, SC Spoke Resonators operating at 352 MHz are used. Final acceleration to 600 MeV is provided by 2 types of 5-cells elliptical cavities operating at 704 MHz. The total length of the linac and the transport line to the reactor is ∼400 m. The 3 type of cavities in the main SC linac are foreseen 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 procedure. Focalization in the main linac is performed with doublets and in the injector with triplets and solenoids. To maximize the reliability, it is foreseen to double the injector (as shown in Fig. 1).

Figure 2 presents the evolution of the transverse and longitudinal emittance as predicted by `TRACEWIN` [6] and `TRACK` [7] along the linac, from the ion source up to the exit of the last cryomodule (∼260 m). An excellent agreement has been obtained between the two codes. A detailed error analysis has also been performed with `TRACK` from the RFQ exit up to the exit of the last cryomodule. Static transverse misalignment error of 500 μm on solenoids, quadrupoles and cavities have been implemented in the code together with dynamic RF jitter of 0.2% and 0.2° on all the cavities. No losses were observed on 100 randomly generated

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error runs using $5{\cdot}10^4$ macroparticles. These runs were corrected using 1 corrector and 1 BPM per solenoid, doublet or triplet.

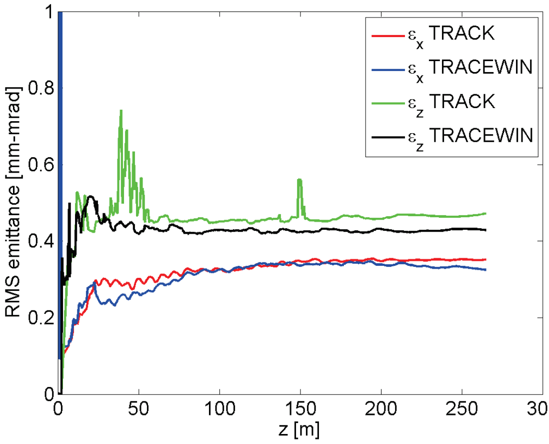

Figure 2: `TRACEWIN` and `TRACK` evolution of the transverse and longitudinal emittance along the `MYRRHA` linac (from the ion source to the exit of the last cryomodule).

Failure of the First Doublet and First Cryomodule

In the event of the failure of the first doublet or the first cryomodule (with 2 cavities), the code `TRACEWIN` has been used to find a new optic (varying upstream and downstream elements within their maximal values of operation). The triplet upstream the first doublet and the second doublet have been used for the matching after zeroing the first doublet. The phase and field of the two bunchers upstream the first cryomodule and of the cavities of the second cryomodule have been used for matching after zeroing the field on the first cryomodule. For these 2 scenarios, a new optic has been found by `TRACEWIN` and validated with error analysis using `TRACK`.

Figure 3 shows the beam maximum horizontal excursion (starting from the RFQ) of the rematched lattice after failure of the first doublet, as predicted with `TRACK` on 100 seeds with the same error and correction algorithm abovementioned for the baseline lattice. No losses were observed on this rematched lattice. The same results were obtained on the rematched lattice after failure of the first cryomodule. These results confirm the Fault-Tolerance Design of the lattice which enables the operation of the linac even in case of failure of one of its elements. 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 linac is expected to operate with the failure of any cryomodule or quadrupole doublet in the main linac.

VIRTUAL ACCELERATOR CONCEPT

The machine control system of the MYRRHA linac will need to work very fast to compensate for a single component failure in less than 3 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. The structure of a Virtual Accelerator based on the EPICS control system is presented in Fig. 4 and described in detail in References [8] and [9].

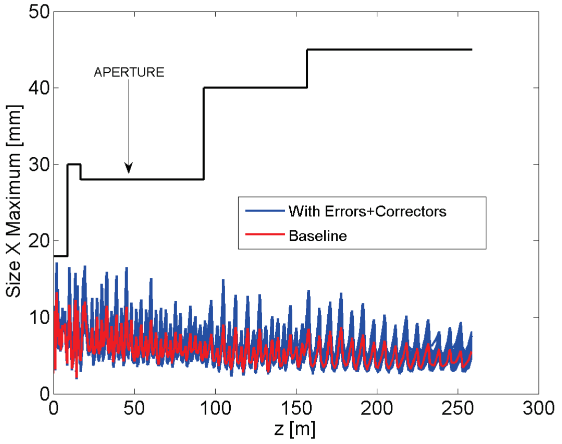

Figure 3: Maximum horizontal beam excursion along the `MYRRHA` linac for two configuration: 1/ the baseline design and 2/ for the rematched lattice after failure of the first doublet. From `TRACK` with 100 seeds.

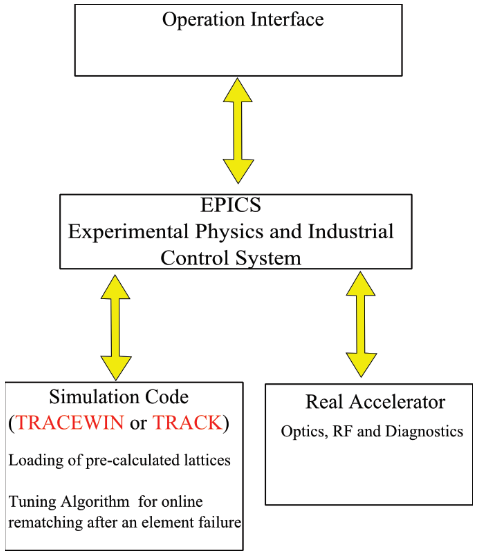

Figure 4: Possible Architecture for the Virtual Accelerator control system of the `MYRRHA` linac.

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 visualize the operation of a Real Accelerator and for instance check some new accelerator set points from a dryrun before implementing these set points on the Real Accelerator. Also it is possible during the operation of the Real Accelerator to load some pre-calculated data set points to compensate for a component failure. For instance, as depicted in Fig. 1, the main linac in its present configuration contains 47 cryomodules (holding 144 cavities) and about 114 quadrupoles. A first set of 258 predefined lattices could be stored and uploaded in the event of a quadrupole failure or a cavity failure. The number of these pre-defined lattices (that would need to be updated after an element failure) could be increased to few hundred to include the cases of doublet failure and crymodule failure. It is obvious that all multiple fault configurations cannot be pre-calculated and it is therefore mandatory for a Virtual Accelerator control system to be based on a beam dynamics code that could perform new matching calculations and implement a new matching in the linac within 3 seconds following a fault. Parallelizing the codes to speed up the matching algorithm might be necessary and is certainly feasible. Ultimately the linac would be operated continuously by the Virtual Accelerator, with the essential condition that the codes are in good agreement with the beam dynamics in the Real Accelerator.

VIRTUAL ACCELERATOR EXAMPLES

Optimization of the SILHI & SPIRAL2 Injectors

In 2006 a first test of a Virtual Accelerator has been achieved at CEA-Saclay [10] using the code `TRACEWIN` to optimize the transmission of the SILHI proton injector. While after several days of manual optimization the transmission achieved 79%, using the Virtual Accelerator it reached 87% within half hour. Most recently the commissioning of the light ions and heavy ions SPIRAL2 injectors have been successfully performed at respectively CEA-Saclay and LPSC-Grenoble using the same Virtual Accelerator control system as for the SILHI injector, validating the tuning procedure defined in `TRACEWIN` [9].

Operation of the ATLAS Linac at ANL

A Virtual Accelerator based on the code `TRACK` was also proposed in 2008 in Ref. [11]. Since the beginning of 2013, a special interface [12] has been developed at ANL to connect the ATLAS linac control system to `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 optimization of the ATLAS linac will be possible through the `TRACK` based Virtual Accelerator.

Future Optimization of the Injector at LLN

The injector presently under construction at Louvain-La-Neuve [13] consisting of an ECR source and two solenoids is an excellent platform to test the concept of Virtual Accelerator. The codes `TRACEWIN` or `TRACK` could be connected to the control system and used to perform the optimization of the injector.

CONCLUSION

A Virtual Accelerator based control system is mandatory for the operation of the `MYRRHA` linac to ensure the very fast implementation (< 3 sec) 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 it through the accelerator control system. In the event of element failure the beam dynamics code would upload pre-calculated matched lattices. The set of pre-calculated configurations has to be kept in coherence with the actual machine. Ideally the Virtual Accelerator could obtain updated set points for any fault configuration in a full on-line mode. A Virtual Accelerator based control system has been successfully tested at Saclay and Grenoble (using `TRACEWIN`) on the SILHI and SPIRAL2 injectors and at ANL (using `TRACK`) on the ATLAS linac and could possibility be tested in the injector currently under construction at Louvain-La-Neuve.

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