DESIGN OF THE MYRRHA 17-600 MeV SUPERCONDUCTING LINAC*

J.-L. Biarrotte[#], CNRS/IN2P3, IPN Orsay, France
D. Uriot, CEA Saclay, France
F. Bouly, CERN, Switzerland
J.-P. Carneiro, Fermilab, USA
D. Vandeplassche, SCK•CEN, Belgium

Abstract

The goal of the MYRRHA project is to demonstrate the technical feasibility of transmutation in a 100MWth Accelerator Driven System (ADS) by building a new flexible irradiation complex in Mol (Belgium). The MYRRHA facility requires a 600 MeV accelerator delivering a maximum proton flux of 4 mA in continuous operation, with an additional requirement for exceptional reliability. This paper will briefly describe the beam dynamics design of the main superconducting linac section which covers the 17 to 600 MeV energy range and requires enhanced fault-tolerance capabilities.

INTRODUCTION

MYRRHA ("Multi-purpose Hybrid Research reactor for High-tech Applications") is a new flexible fast spectrum research reactor that is planned to be operational around 2023 in SCK•CEN Mol (Belgium) [1]. Composed of a proton accelerator, a spallation target and a 100 MW_{th} core cooled by liquid lead-bismuth, it is especially designed to demonstrate the feasibility of the ADS concept in view of high-level waste transmutation. To feed its sub-critical core with an external neutron source, the MYRRHA facility requires a powerful proton accelerator (600 MeV, 4 mA) operating in continuous mode, and above all featuring a very limited number of unforeseen beam interruptions.

The conceptual design of such an ADS-type proton accelerator has been initiated during previous EURATOM Framework Programmes (PDS-XADS and EUROTRANS projects). It is a linac (linear accelerator) based solution that brings excellent electric efficiency thanks to the use of superconductivity and high potential for reliability by the use of several redundancy schemes. R&D on ADS-type accelerators is presently being pursued in the frame of the MAX project [2], supported by EURATOM FP7. This project aims at delivering an updated consolidated reference layout of the MYRRHA linac with sufficient detail and adequate level of confidence in order to initiate in 2015 its engineering design and subsequent construction phase. To reach this goal, advanced beam simulation activities are being undertaken and a detailed design of the major accelerating components is being carried out, building on several prototyping activities. A strong focus is also put on all the aspects that pertain to the reliability and availability of this accelerator, with the development of a detailed reliability model of the MYRRHA accelerator and with dedicated R&D, to experimentally prove in particular the feasibility of the innovative "fault-tolerance" redundancy scheme.

LINAC DESIGN

The architecture of the 17-600 MeV MYRRHA main SC linac is summarized in Table 1. It is composed of an array of independently-powered superconducting cavities with high energy acceptance and moderate energy gain per cavity (low number of cells and very conservative accelerating gradients), the goal being to increase as much as possible the tuning flexibility and to provide sufficient margins for the implementation of the fault-tolerance scheme. Three distinct cavity families are used to cover the full energy range: the first section uses 352.2 MHz Spoke 2-gap cavities (β_{opt}=0.37), while the two following sections use 704.4 MHz elliptical 5-cells cavities (β_{opt}=0.51 & 0.70). Such a choice is based on the results of a longitudinal optimization using the GenLinWin simulation code [3]; this analysis actually clearly shows that 3 sections is a straightforward choice for such a 17-600 MeV SC linac, and that playing around with cavities beta & number of cells doesn't change much the picture. It is nevertheless to be underlined that using ESS-type β=0.5 double-spoke cavities [4] could be an interesting back-up option for section #2.

The main RF characteristics of the MYRRHA accelerating cavities are also summarized in Table 1. The design of the elliptical cavities has been performed through previous dedicated R&D programs, including prototyping and RF tests [5, 6]. The design of the MYRRHA spoke cavity [7] has been recently achieved within MAX and prototyping should begin very soon. The operating accelerating gradients of the MYRRHA cavities have been chosen on the conservative side, taking in particular as a reference the actual average operating point of the SNS β=0.61 cavities in 2008 [8]. The chosen rules for the operation of the MYRRHA superconducting cavities are the following: 1. the RF fields at the inner surface of the SC cavities is always kept under 35MV/m peak electric field and 60mT peak magnetic field; the nominal "de-rated" operation points are then obtained removing 30%, to be used as a margin for fault compensations. These rules lead to nominal accelerating fields of 6.4, 8.2 & 11.0 MV/m in the 3 different sections, with a required maximum E_{acc} capability of 8.3, 10.7 & 14.3 MV/m respectively.

Table 1: MYRRHA Main Linac Parameters

Section #	#1	#2	#3
E_{in} (MeV)	17.0	80.8	184.2
E_{out} (MeV)	80.8	184.2	600.0
Focusing type	NC quad doublets		
Cav. Technology	Spoke	Elliptical	
Cav. freq. (MHz)	352.2	704.4	704.4
Cavity optimal β	0.375	0.510	0.705
Nb of cells / cav.	2	5	5
B_{pk}/E_{acc}* (mT/MV/m)	7.3	5.5	4.6
E_{pk}/E_{acc}*	4.3	3.3	2.5
R/Q** (ohms)	217	159	315
E_{acc_nom}* (MV/m)	6.4	8.2	11.0
E_{acc_max}* (MV/m)	8.3	10.7	14.3
Nb cav / cryom.	2	2	4
Total nb of cav.	48	34	60
Synch. phase (°)	-40 to -18	-36 to -15	
4 mA beam load per cav. (kW)	1.5 to 8	2 to 17	14 to 32
Required Q_L	2.2 10⁶	8.2 10⁶	6.9 10⁶
Nominal Qpole gradients (T/m)	5.1 to 7.7	4.8 to 7.0	5.1 to 6.6
Beam aperture (mm)	⌀56	⌀80	⌀90
Section length (m)	73.0	63.9	100.8

*E_{acc} is given at optimal beta and normalized to $L_{acc} = N_{gap}.\beta_{opt}.\lambda/2$
**R/Q is given at optimal beta with the "linac" definition

The linac architecture is based on the use of regular focusing lattices, with not-too-long cryostats (about 6 metres maximum) and room-temperature quadrupoles doublets in between. Such a scheme provides several advantages: easy maintenance and fast replacement if required, easier magnet alignment at room-temperature, possibility to provide easily reachable diagnostic ports at each lattice location, nearly perfect optical lattice regularity (no specific beam matching required from cryostat to cryostat) and last but not least, possibility to operate the beam with a full cryomodule missing.

The quadrupole magnets have been chosen sufficiently long to minimize fringe field effects, and with low operating gradients to ensure reliable operation. In nominal operation, the magnetic field on the pole is always kept below 0.3 T, giving some comfortable room for gradients increases if needed. Additional coils are to be included in the quadrupole magnet design to ensure the required dipolar steering capability for beam orbit correction. In association with these steerers, about 60 beam position monitors (BPM) will be located at each lattice warm section for beam alignment purposes.

As far as beam instrumentation is concerned, beam profilers and bunch shape monitors will also be needed in the typically 3 or 4 first lattices of each linac section, in order to be able to perform a suited beam matching. Other possible needs, still to be assessed, could concern additional beam current measurements from place to place and an intermediate energy Faraday cup to be used as a low power beam dump for very early beam commissioning purposes. Finally, several (about 100) beam loss monitors will have to be located all along the linac to detect any abnormal beam loss and trigger the machine protection system.

BEAM DYNAMICS

Even if the pulse current is rather low (4mA) hence leading to quite safe tune depression ratios (>0.75), the main tunings of the beam dynamics through the MYRRHA linac (see Figure 1) have been determined according to the standard rules usually considered for high-power ion linear accelerators [9].

The synchronous phase at the linac input is chosen sufficiently low to bring a very large and safe longitudinal acceptance, able in particular to cope with the different longitudinal settings to be used by the compensation schemes. The synchronous phase law through the linac is optimized to keep constant this acceptance, especially at the RF frequency transition [10].

The longitudinal & transverse phase advance at zero-current are always kept below 90° per lattice, so as to avoid any structure & space-charge driven resonance and subsequent emittance growth and halo formation [11]. This especially implies limitations on the allowed accelerating voltage per lattice. The dangerous $\sigma_T = \sigma_L/2$ parametric resonance [12] is avoided by keeping the transverse phase advance always above 70% of the longitudinal one and any energy exchange between transverse and longitudinal planes is minimized by tuning the linac lattices set-points as far as possible from the space-charge driven parametric resonances, by operating when possible near the equipartitioned regime [13].

The phase advance per meter is kept as smooth as possible through the linac so as to minimize the potential for mismatch and ensure a current-independent lattice as far as possible. This especially implies limitations on the allowed accelerating voltage after the frequency jump. Finally, a clean beam matching at the linac input and between sections is performed in all planes to avoid envelope oscillations and minimize emittance growth.
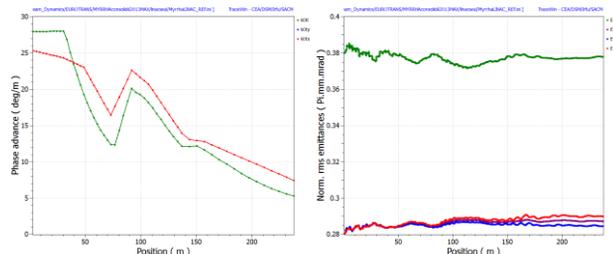

Figure 1: Phase advance laws and emitance growth through the MYRRHA main linac.

02 Future projects

C. Future Project

Beam multi-particle simulations have been performed with TraceWin [3] using 3D field-maps models for accelerating cavities and with an input matched beam distribution of 10^5 macro-particles with a Gaussian shape truncated at 4σ and RMS normalised emittances of 0.28 (transverse) and 0.38 (longitudinal) π.mm.mrad, according to the preliminary injector results obtained so far [14]. The results (see Figure 1) show no significant emittance growth and negligible halo growth. Moreover several conclusive tests have been performed to check the robustness of the design, showing very low sensitivity to input beam distribution, to input beam mismatch, to cavities gradient spread or to beam current fluctuations. The requirements for the stability of RF fields have been also defined (better than ±0.2% ±0.2° RMS).

In its nominal operating conditions, the MYRRHA linac design also provides a very large transverse acceptance with a ratio beam tube to RMS envelope always substantially higher than 10 and even 20 in the high energy end. The longitudinal acceptance is also quite large thanks to the safe synchronous phase law, giving the possibility to accelerate a beam with a longitudinal full emittance up to 50 times the nominal RMS one. These choices are mandatory to try to reach a safe operation in all possible envisaged conditions (i.e. with or without fault conditions and in presence of errors).

TOLERANCE TO FAULTS

The MYRRHA main linac is designed to ensure enhanced fault-tolerance capabilities, which is absolutely necessary to try to reach the reliability goal [15] i.e. an MTBF of 250 hours. This is done 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 was fixed to 30%, leading to a main linac overcost estimated to about 20%. This value was chosen considering an average MTBF value of about 10 000 hours for RF systems units leading to a global MTBF for the whole main linac accelerating RF system of about 70 hours: about 30 to 35 failures are therefore to be expected (and compensated) simultaneously during the foreseen 3 months MYRRHA mission time if no on-line repair can be performed, that corresponds to 25% of the total number of cavities.

The present reference scheme for recovering RF units failures is to use a local compensation method (while stopping the beam for not more than 3 seconds): the RF fault is compensated by only acting on the RF gradient and phase of the 4 nearest neighbouring cavities operating de-rated (i.e. not already used for compensation), the maximum allowed number of consecutive failed cavities being 2 (in sections #1 & #2) or 4 (section #3). Based on the initial studies made a few years ago [16, 17], new simulations have been performed on the up-to-date MYRRHA main linac design to better assess its fault-tolerance capability in terms of RF failures and evaluate more accurately the induced requirements: amplifiers power needs, power couplers coupling factors, LLRF and

tuner regulation strategies, machine reconfiguration procedures. For this new analysis, the TraceWin code has been used with the following constraints for the cavities retuning scheme (Figure 2): recover the nominal beam phase and energy at the first "un-retuned" linac lattice, rematch the beam through the 4 first following lattices, both in the transverse and longitudinal dimensions (keeping all the quadrupoles gradients unchanged), while limiting the cavity voltage & the RF power (beam loading) increase below 30% and 40% respectively.
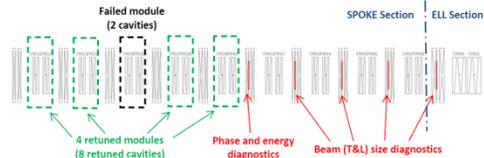

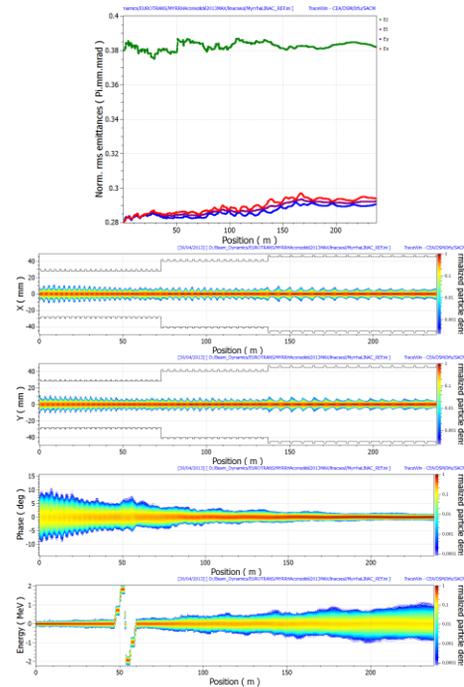Figure 2: Retuning strategy used in TraceWin for compensation optimisation.

Figure 3: Beam dynamics through the MYRRHA main linac with Spoke cryomodule #18 off-line.

This retuning strategy has been successfully assessed in several fault test scenarii [18, 19], as shown in Figure 3, including the case of the lower energy cavities (including MEBT bunchers) and the case of multiple simultaneous faults (1 cryomodule off in each section). The main conclusion of these fault-recovery scenario analyses is that the fault recovery scheme is a priori feasible everywhere in the MYRRHA main linac to compensate for the loss of a single cavity or of even a full cryomodule. This statement should be confirmed by the upcoming advanced beam dynamics studies to be performed in the MAX project, where these compensation schemes will be also assessed through full start-to-end (source to target) simulations including random errors.

In order to practically implement such compensation schemes, a first detailed recovery procedure has been defined [20]. Several steps of this procedure appear to be non straightforward and will require further studies. The switching time of less than 3 seconds will clearly be a critical issue, with probably huge consequences on the required capabilities of the machine control system (efficient and fast fault diagnostic, fast automated beam restart and associated consequences...). Also, an efficient predictive beam simulation code will need to be developed and benchmarked during the machine commissioning phase so as to be able to efficiently predict the optimal retuning set points in every fault configuration.

On the RF cavity side, dedicated LLRF digital systems and fast and reliable cold tuning systems also need to be developed together with suited regulation loops. A R&D program is on-going in MAX at IPN Orsay [21, 22] on these aspects, especially on the tuner design that specifically needs to provide a large detuning range during the duration of the recovery procedure (i.e. a few seconds) to provide a negligible (decelerating) effect on the beam and induce sustainable power dissipation in the helium bath when the beam comes back. To reach this goal, the cavity typically needs to be detuned by more than 100 nominal bandwidths, as illustrated by Figure 4, this statement being still valid if the cavity is quenched.
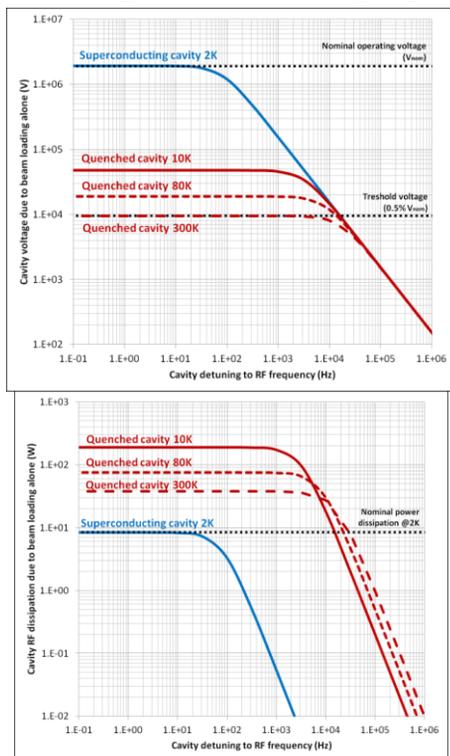

Figure 4: Effect of beam loading on a failed spoke cavity: if the cavity is still superconducting, the important criterium is the induced decelerating voltage (to be lowered below 0.5% of nominal voltage); otherwise, it is the dissipated power, especially for a quenched but still cold cavity.

ACKNOWLEDGEMENTS

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