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SUPERCONDUCTING LINAC DESIGN UPGRADE IN VIEW OF THE 100 MeV MYRRHA PHASE I*

F. Bouly†, M. Baylac, Laboratoire de Physique Subatomique et de Cosmologie, Université Grenoble-Alpes, CNRS/IN2P3, Grenoble, France
A. Gatera, SCK-CEN, Mol, Belgium
D. Uriot, CEA Saclay/DRF/IRFU, Gif-sur-Yvette, France

Abstract

The goal of the MYRRHA project is to demonstrate the technical feasibility of transmutation in a 100 MW_{th} Accelerator Driven System by building a new flexible irradiation complex at Mol (Belgium). The MYRRHA facility requires a 600 MeV accelerator delivering a maximum proton current of 4 mA in continuous wave operation, with an additional requirement for exceptional reliability. Supported by SCK•CEN and the Belgium government the project has entered in its phase I (MINERVA): the construction of the linac first part, up to 100 MeV. We review the design updates of the superconducting linac.

CONTEXT

MYRRHA (Multi-purpose Hybrid Research reactor for High-tech Applications) is a fast spectrum research reactor that is planned to be operational around 2033 at SCK•CEN Mol (Belgium) [1]. The facility is especially designed to demonstrate the feasibility of high-level waste transmutation with an Accelerator Driven System (ADS). MYRRHA requires a powerful proton accelerator (600 MeV, 4 mA) operating in CW mode. The accelerator must, above all, fulfil very stringent reliability requirements to ensure the safe ADS operation with a high level of availability. The actual maximum limit is set to 10 beam interruptions (longer than 3 seconds) per 3-month operating cycle.

The conceptual design of such an ADS-type accelerator has been initiated during previous EURATOM Framework Programmes (PDS-XADS and EUROTRANS projects) and consolidated in the MAX project** [2] [3]. It is a linac based solution (see Figure 1) that brings good electric efficiency thanks to the use of superconductivity and high potential for reliability by the use of several redundancy schemes. It is composed of two distinct sections.

A low energy (normal conducting) injector where a 30 keV beam is transported through the Low Energy Beam Transport line (LEBT) [4] and matched to a 176 MHz 4-rod RFQ [5]. The 1.5 MeV bunched beam at the RFQ output is then accelerated up to 16.6 MeV by CH-cavities [6]. In the injector modularity and fault tolerance are not easily applicable because of the low beam velocity. Here redundancy is applied in its parallel form, and so two similar compact injectors with fast switching capabilities are foreseen. A medium and high energy section (main SC linac), highly modular, based on individual, independently controlled accelerating superconducting cavities. In this section, serial redundancy is applied to guarantee a strong tolerance to faults, thanks to a fault compensation scheme [7]: a cavity fault is mitigated locally and taken over by retuned adjacent cavities.

The MYRRHA construction is now following a phasing approach. The first phase consists in building and operating the linac limited to a 100 MeV final beam energy [8]. The principle aim of phase I is to experimentally investigate the feasibility and efficiency of the linac reliability and fault tolerance schemes. It is foreseen to transport the 100 MeV beam to different irradiation stations to produce innovative medical radioisotopes and radioactive beam with an ISOL production target for innovative medical radioisotopes. MINERVA corresponds to the phase I of the project that combines: the 100 MeV linac, the target station and the associated services and buildings.

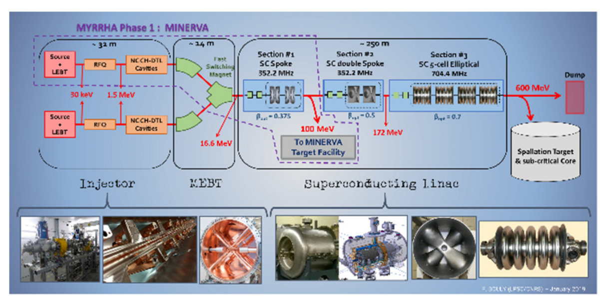

Figure 1: MYRRHA & MINERVA linac scheme.

SC LINAC ARCHITECTURE

The architecture of the SC linac is summarised 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: single and double spoke (ESS type) cavities at 352.2 MHz and 5-cells elliptical cavities at 704.4 MHz. Such a choice is based on the results of a longitudinal optimisation using the GenLinWin simulation code [9].

Compared to the previous design [3] it has been decided to: use ESS double-spoke cavities [10] in section #2, to decrease the synchronous phases of the first cavities and to increase the nominal accelerating gradient, especially in section #1. Such choices are the result of errors studies

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† frederic.bouly@lpsc.in2p3.fr
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showing that improvements were still necessary to increase the robustness of the design. Indeed, for some fault compensation cases, especially when a full cryomodule is lost [7], the tuning of the neighbouring cavities might be too aggressive and decreases the longitudinal acceptance. While the retuning method has to be improved it was also noticed that a linac with a larger acceptance would help for the fault compensation feasibility and even for the linac operation in nominal conditions [11]. In addition, the longitudinal matching between sections could be improved [11]. And finally experimental results showed that due to very high mechanical softness of the β=0.51 elliptical cavity [12], they are extremely sensitive to all perturbations (pressure variations, vibrations, Lorentz forces, field flatness degradation…). It led to severe difficulties to achieve stable and reliable operation at high RF fields and relatively low bandwidths in CW operation [13].

Table 1: MYRRHA SC Linac Parameters

Section #	#1	#2	#3
E_{in} (MeV)	16.6	101.4	172.3
E_{out} (MeV)	101.4	172.3	600.0
Focusing type	Normal Conducting Quad. Doublets		
Cav. Technology	Single-Spoke	Double-Spoke	Elliptical
Cav. freq. (MHz)	352.2	352.2	704.4
Cavity optimal β	0.375	0.495	0.705
Nb of cells / cav.	2	3	5
B_{pk}/E_{acc}* (mT/MV/m)	7.3	8.75	4.6
E_{pk}/E_{acc}*	4.3	4.4	2.5
R/Q** (ohms)	217	427	315
E_{acc_nom}* (MV/m)	7.0	6.8	11.0
E_{acc_max}* (MV/m)	9.1	9.0	14.3
Nb cav / cryom.	2	2	4
Total nb of cav.	60	18	72
Synch. phase (°)	-45 to -15		-35 to -15
4 mA beam load / cav. (kW)	1.1 to 8.4	8.2 to 16.4	2.9 to 31.9
Required Q_L	1.5×10^6	2.1×10^6	6.9×10^6
Nominal Qpole gradients (T/m)	5.1 to 7.9	3.8 to 4.3	4.4 to 6.0
Section length (m)	91.2	36.3	121.0

*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*

Therefore the option with double spoke has been retained. During the optimisation the adjustment of the double spoke cavities β_{opt} was also studied. It showed the ESS design matched [14] for the section #2 of the MYRRHA linac. Such a choice also presents the advantage of having a common development with the ESS project on a proven technology.

The nominal accelerating gradient in section #1 is 7.0 MV/m (compared to 6.4 MV/m in the previous design). This chosen value is quite conservative in comparison to the measured performances of the cavity prototypes [15]. The chosen gradients were also achieved by considering the cryogenic consumption of the cryomodule especially in the fault recovery configuration (E_{acc_max} = 9.1 MV/m). For section #2 the chosen maximum gradient for fault compensation is set to 9.0 MV/m, which is the ESS nominal operating point. The nominal accelerating gradient for section #2 is then chosen at 6.8 MV/m that is: 30 % below the maximum accelerating gradient. The section #3 remains unchanged from previous design. So, basically the E_{acc} choices for the three sections were done according the following rules: the RF fields at the inner surface of the SC cavities is always kept under 35 MV/m peak electric field and 60 mT peak magnetic field; the nominal "de-rated" operation points are then obtained by removing 30%, to be used as a margin for fault compensations.

The linac architecture is based on the use of regular focusing lattices, with rather compact cryostats (about 6 metres maximum) and room-temperature quadrupoles doublets in between. Such a scheme provides several advantages for the maintenance, the alignment, the possibility to provide easily reachable diagnostic ports at each lattice location, and the possibility to operate the beam with a full cryomodule missing.

The quadrupole magnets operate with low gradients to ensure reliable operation and giving some comfortable room for gradients increase, if needed. Additional steerers are to be included in the quadrupole magnet design to ensure beam orbit correction. In association with these steerers, beam position monitors (BPM) will be located at each lattice warm section for beam alignment purposes: typically one steering pair in a quadrupole and one BPM pair in the second quadrupole of the lattice mesh. Ideally, beam profilers and bunch shape monitors may also be needed in the typically 3 or 4 first lattices of each linac section, in order to be able to perform beam matching.

BEAM DYNAMICS AND TUNING

Even if the beam current is rather low (4 mA), hence leading to quite safe tune depression ratios (>0.75), the tuning of beam dynamics has been optimised using standard rules used for high-power ion linear accelerators. The transverse phase advance at zero-current is always kept below 90° per lattice, so as to avoid any structure & space-charge driven resonance and subsequent emittance growth [16]. The $\sigma_T = \sigma_L/2$ parametric resonance [17] is avoided by keeping the transverse phase advance always above 70% of the longitudinal one. Energy exchange between transverse and longitudinal planes is minimised by tuning the linac lattices set-points as far as possible from the space-charge driven parametric resonances; by trying to operate near the equipartitioned regime [18]. The transverse 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 [3]. Finally, a clean beam matching between sections in all

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planes is performed (adjustment of 4 quadrupoles and 2 to 4 cavities tuning) to avoid envelope oscillations and minimize emittance growth.

The beam dynamics simulations were achieved with the TraceWin [19] code, using field-maps models for accelerating cavities. An input matched beam distribution of 10^5 macro-particles was used, with a Gaussian shape truncated at 4σ and RMS normalised emittances of 0.24 π.mm.mrad (transverse) and 0.27 π.mm.mrad (longitudinal), according to the preliminary results obtained during the Injector and Medium Energy Beam Transfer line design.

The tuning has also been chosen in order to maximize transverse acceptance. Thus, the option of a "strong" focusing has been chosen. It leads to a crossing between the longitudinal and the transverse phase advance as illustrated on Figure 2. The resonances at $k_{xy}/k_z = 1$ have to be carefully crossed to avoid emittance growth effects. After tuning, no significant emittance growth (Figure 3) is experienced and the halo growth remains negligible. 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.

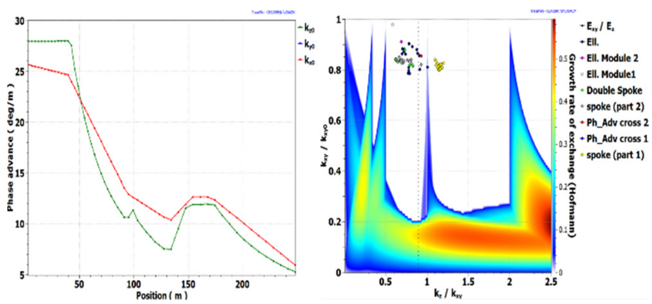

Figure 2: Zero-current phase advance (per meter) law and tuning set-points in the Hofmann diagram (after matching).

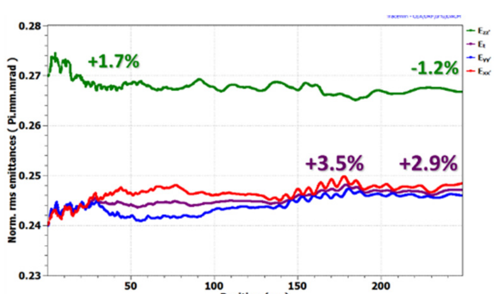

Figure 3: RMS emittances through the SC linac.

Finally the MYRRHA linac design provides a large longitudinal acceptance (see Figure 4) thanks to the safe synchronous phase law, giving the possibility to accelerate a beam with a longitudinal full emittance up to 70 times the nominal RMS one. These choices should allow a safe operation in all possible envisaged conditions (i.e. with or without fault conditions, and in presence of errors), with non-perfectly matched beam coming from the Injector. In any case, the main objective for the superconducting linac design was to provide the most flexible tuning to minimise re-matching efforts as function of the different beam operation conditions.

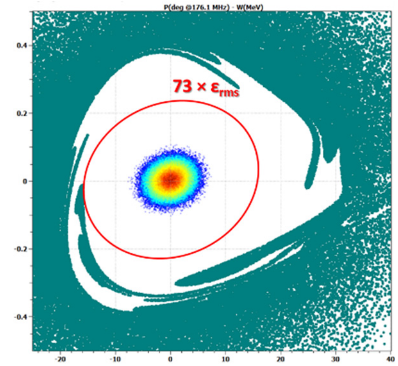

Figure 4: Longitudinal acceptance and considered 16.6 MeV input beam distribution.

CONCLUSION & MINERVA PROJECT

The tuning of the MYRRHA main SC linac was achieved in order to be as acceptant as possible to errors or beam mismatch. This has been confirmed with the MINERVA start-to-end design and errors studies: which showed a good design robustness as regard to longitudinal errors. The gradient spread (due to less performant cavities: multipacting, etc.…) and the HOM excitation risk might also be readdressed. This last effect should be very low for such a CW superconducting linac [20]. Nevertheless, this HOM issue may need in the near future to be accurately evaluated for the MINERVA specific (macro-) pulsed operation mode (commissioning case for instance).

During the SC linac design phase an alternative architecture had also been considered. This second solution, which can be considered as a backup solution for the 600 MeV linac, is optimised to minimise the length and the number of cavities required. It has 144 cavities (instead of 150 for the reference design): 23 single spoke cryomodules, 13 double spokes cryomodules and 18 5-cell elliptical cryomodules. This solution showed a similar sensitivity to mismatch than the reference design, while the section matching appeared to be a bit more flexible. Still, the length gain (5 meters) is rather low as regards the first solution. Here, the energy transition between section #1 and section #2 occurs below 100 MeV. For MINERVA two types of cryomodule would be needed, which cannot be envisaged in the current project development.

Therefore, the MINERVA reference solution will be based on an architecture that needs 60 single spoke cavities (i.e. 30 cryomodules) operating with a maximum accelerating gradient of 7 MV/m in nominal operation. The possible reachable energy has also been assessed to a value higher than 140 MeV. This is under the assumption that the accelerating field for every cavity can be safely increased to 9 MV/m. In that case it was also considered to use a more aggressive synchronous phase distributions (-35° to -10°). But the reliability requirements should be carefully assessed with such a tuning, since devices failures or beam losses could be increased.

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