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OPTIMIZED BEAM OPTICS DESIGN OF THE MINERVA/MYRRHA SUPERCONDUCTING PROTON LINAC

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Abstract

The MYRRHA design for an accelerator driven system (ADS) is based on a 600 MeV superconducting proton linac. The first stage towards its realization is called MINERVA and was approved in 2018 to be constructed by SCK CEN in Belgium. This 100 MeV linac, will serve as a technology demonstrator for the high MYRRHA reliability requirements as well as a driver for two independent target stations, one for radio-isotope research and production of radio-isotopes for medical purposes, the other one for fusion materials research. This contribution gives an overview of the latest accelerator machine physics design with a focus on the optimized medium (17 MeV) and high energy (100 MeV) beam transfer lines

INTRODUCTION

The MINERVA project at SCK CEN, Belgium, is the fully funded first implementation stage of the MYRRHA project, which aims to demonstrate transmutation of nuclear waste in a subcritical nuclear reactor driven by a high power accelerator (ADS). This use case also dictates the high reliability requirements to the accelerator of maximal 10 beam trips longer than 3 sections within a 90 day run period.

While the accelerator has been studied in the context of several design studies [1], with the decision by the Belgium government to implement MINERVA, the accelerator design was critically reviewed in terms of a) beam physics robustness b) reliability c) practical feasibility and d) cost and schedule-effectiveness. The final overall layout which is currently being implemented with the aim of operating a first beam at 100 MeV by the end of 2027, is shown in Fig 1.

The main linac beam parameters are given in Table 1.

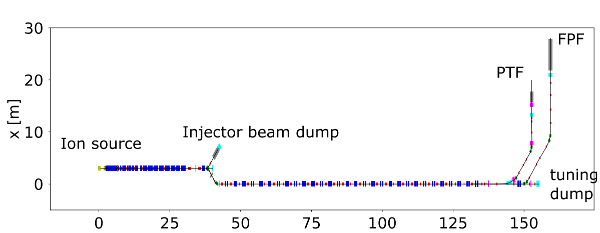

Figure 1: Layout of the 100 MeV MINERVA linac including the transfer lines to the two user facilities (PTF, FPF). The blue boxes indicate RF cavities.

Table 1: MINERVA Linac Specifications

Parameter	Value
Particle	Protons
Energy	100 MeV
Beam current	4 mA
Duty factor	CW (or pulsed with 4ms cycles)
Inj. RF	Normal conducting 176 MHz CH-cavities
Main linac RF	Superconducting 352.2 MHz single spoke

INJECTOR

The injector starts with an ECR ion source (providing a 30 keV beam) coupled to a LEBT containing two solenoids, a fast beam chopper and various beam diagnostic devices e.g. an Allison emittance meter. The subsequent 4 vane 176.1 MHz RFQ [2-3] bunches and accelerates the beam to 1.5 MeV. The following two normal conducting quarter wave cavities re-bunch the beam.
SCK CEN currently operates these elements in a dedicated injector test stand [Fig 2.] which is about to be extended with an emittance meter and a longitudinal bunch shape measurement device [4-6].

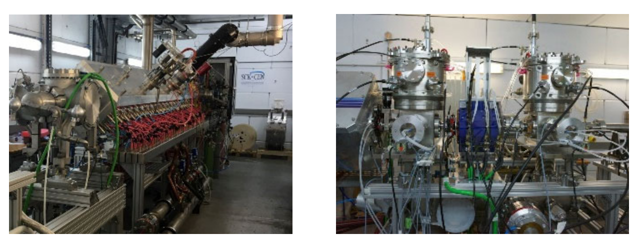

Figure 2: The Injector test stand featuring an ECR ion source, a LEBT, the RFQ and 2 quarter wave rebunching cavities

The following series of 15 normal conducting CH-type cavities accelerates the beam to 17 MeV. The beam optics remained mainly unchanged in this design iteration except for an elaboration of the beam diagnostics and orbit correction scheme.

In order to achieve the required reliability objectives, the final design foresees the installation of two parallel injectors which can be alternatively delivering beam to the SC-

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linac. This beamline merging requires the use of a dog-leg. The hot-standby injector can deliver the beam to an injector beam dump to tune and monitor its operational readiness. As shown in Fig. 3, in the new layout the beam dump had to be positioned at 45 degree to allow for the required shielding without geometrical conflict with the other tunnel areas.

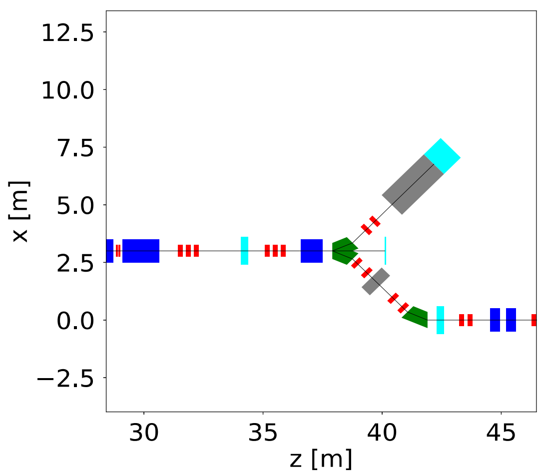

Figure 3: The updated layout of the 17 MeV section between the normal conducting injector (last CH-cavity at z=30m) and the start of the superconducting linac (first two cavities at z = 45 m): RF cavities in blue, dipoles in green, quadrupoles in red, beam dump and vacuum valves in turquois, and shielding wall in grey.

In past designs, three super conducting single spoke cavities were installed in this section to match the beam longitudinally into the SC-linac. Apart from the problematic (in view of the vacuum system) proximity of the first SC-cavity to the normal conducting ones, special cryo module designs would have been needed with one cavity only, instead of the standard linac cryo module with 2 cavities. Finally, there was the interest to increase the number of beam diagnostic devices in the injector to be able to fully characterize the beam when used as a hot-spare delivering beam to the injector beam dump. This includes the collimation system, which was originally foreseen in the dogleg and thus only available once the injector is switched to the linac. A solution could be found where the required field in the cavity is sufficiently low, such that a single normal conducting cavity can be used instead. By increasing the distance between the last accelerating CH-cavity and the first dipole, sufficient space for diagnostic and collimation is available. The revised transverse and longitudinal beam optics can be seen in Fig. 4.

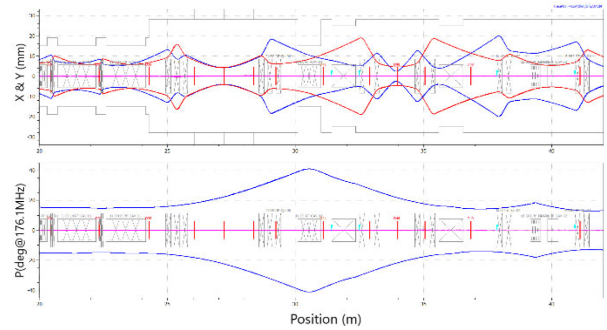

Figure 4: Transverse and longitudinal beam optics of the new diagnostic and dogleg section showing the 6σ transverse beam sizes and 6σ phase extension.

SUPERCONDUCTING LINAC

The beam optics design of the SC-linac itself has not been changed (see Fig. 5) [7], keeping the 30 repetitions of a cryomodule enclosing two 352.2 MHz single spoke cavities [8-11] and an intermediate warm section containing a doublet and varying beam diagnostic devices.

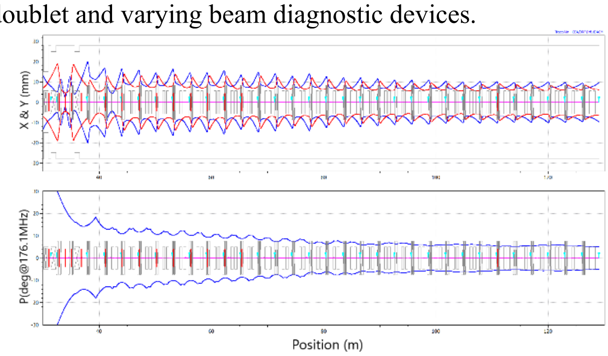

Figure 5: 6σ transverse and longitudinal beam size and phase extension (phase relative to the 176 MHz injector frequency).

As commonly done in other linacs, it is intended to compensate the loss of an RF-cavity by the other cavities. The challenge at MINERVA/MYRRHA will be to achieve full beam power recovery (0.4 MW at MINERVA, 2.4 MW at MYRRHA) within three seconds after the beam trip [12-13]. The required RF-overhead in the remaining active cavities has been recently re-evaluated and seen to be up to 100% in the first MINERVA cavities. The anticipated RF-overhead for the full 600 MeV MYRRHA linac can be seen in Fig. 6 and are also studied for an alternative global compensation approach

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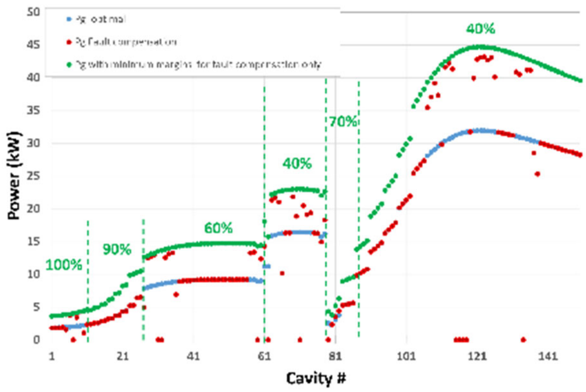

Figure 6: Simulated RF-power needs for: nominal beam operation (blue), a representative case with several failing cavities (red), and the overall expected RF-overhead need to apply failure compensation (green).

USER FACILITY TRANSFER LINES

While MINERVA will at the start be used to develop and prove to meet the stringent reliability requirements, it will in parallel be able to deliver beam to two user facilities, i.e. the "Proton Target Facility (PTF)" and the "Full Power Facility (FPF)", and a beam dump for very first beam tuning in straight extension of the linac.

It is envisaged to be able to kick up to 0.5 ms beam pulses with duty cycle frequencies as high as 250 Hz to the PTF facility, allowing average beam currents up to 0.2 mA on fissile material targets or up to 0.5 mA on non-fissile material targets [14]. The generated high-purity Radioactive Ion Beams (RIB) will be used for physics experiments and as well as radioisotopes collection for e.g. medical research. While the layout of this Isotope Separation On-Line (ISOL) system is strongly inspired by the proton target irradiation facility ARIEL at TRIUMF, the design of the beam line leading to it was developed only recently. As shown in Fig. 7, the quadrupole doublet in front of the last cryo module is already used to prepare the beam for the following section. A fast kicker deflects the beam.

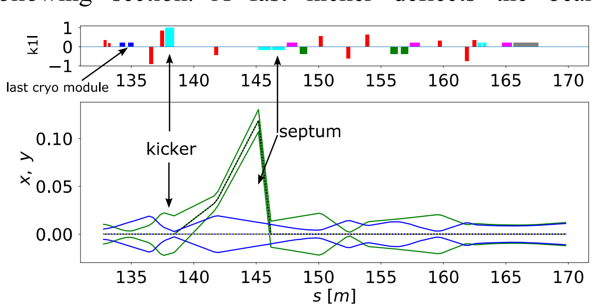

Figure 7: The upper plot shows the element strengths, while the lower one shows the 6σ transverse beam sizes starting in front of the last cryo module up to the PTF target.

The effect of this is enhanced by the additional feed-down effect of the following quadrupole. The separation of the 6σ beam sizes at the septum is around 9 cm. The final three quadrupoles of the beam line can be used to tune the beam size at the target according to the user demands between 1σ = 2 and 8 mm. Two rastering magnets will be able to scan the beam over the target.

The FPF facility is designed to handle the full CW beam (400 kW). The beam will be directed into a water embedded target volume, into which various target configurations can be placed. While the main purpose of the facility will be to perform fusion material research, a dedicated target rig will also be available to be used as beam dump for linac commissioning. The 6 sigma beam size – again starting from the doublet in front of the last cryo-module – is shown in Fig. 8. The cryo module at z = 150 m, will not be installed at the moment but indicates a corresponding space reservation for the later implementation stage, when the beam needs to be longitudinally matched into the subsequent medium beta linac section in the straight extension.

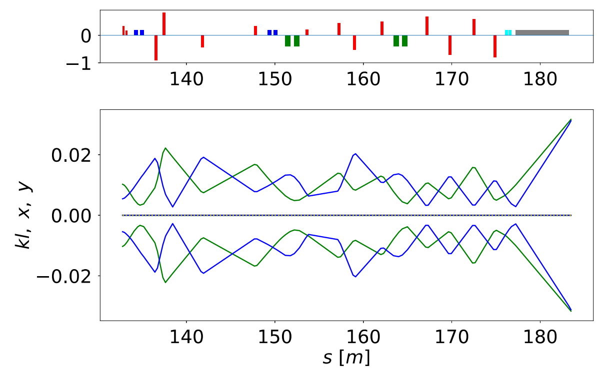

Figure 8: The 6σ beam sizes of the beamline towards the FPF facility. The target is located after a 6m shielding wall indicated by the grey box in the upper sub-figure. The two turquois boxes in front of it indicate the two rastering magnets.

CONCLUSION

The main beam line design of the MINERVA accelerator is completed and the implementation is ongoing with a first 100 MeV beam planned for end 2027.

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