IMPLEMENTATION STATUS OF MYRRHA PHASE 1 (MINERVA)

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Abstract

The MYRRHA design for an accelerator driven system (ADS) is based on a 4 mA, 600 MeV CW superconducting proton linac. The construction of the first stage (called MINERVA) by the Belgium Nuclear Research Centre SCK CEN was approved in 2018. It consists of a 100 MeV superconducting RF linac as well as 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 presents the main design choices and current status of the overall project parts (civil engineering, particle accelerator and target facilities).

INTRODUCTION

An accelerator driven system aims to root out the downsides of current fission reactors: Accumulation of long-lived nuclear waste, operation of a critical system and the need for weapons-grade material. The main objective of MYRRHA [1, 2] is to design, construct and operate an ADS as a technology demonstrator for the transmutation of nuclear waste but also e.g. for the production of medical radio-isotopes material studies. For this purpose a superconducting RF (SRF) linac will deliver a high power proton beam into a subcritical reactor core that is loaded with the nuclear waste from other facilities. The main accelerator and reactor parameters are summarized in Table 1.

Table 1: Main Accelerator and Reactor Specifications

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particle type</td>
<td>Protons</td>
</tr>
<tr>
<td>Final Energy (MeV)</td>
<td>600</td>
</tr>
<tr>
<td>MINERVA stage Energy (MeV)</td>
<td>100</td>
</tr>
<tr>
<td>Beam current</td>
<td>4mA</td>
</tr>
<tr>
<td>RF-operation</td>
<td>CW</td>
</tr>
<tr>
<td>Beam operation</td>
<td>Pulsed to CW</td>
</tr>
<tr>
<td># beam trips &gt; 3s within 90 days</td>
<td>&lt; 10</td>
</tr>
<tr>
<td>Reactor thermal power (MW)</td>
<td>70</td>
</tr>
<tr>
<td>Reactor technology</td>
<td>Lead Bismuth</td>
</tr>
</tbody>
</table>

ADS concepts are studied at multiple labs worldwide [3]. While this idea has also been pursued at SCK CEN for several decades with explorative design studies, the Belgium government has decided its construction at the end of 2018 and approved the budget for the first implementation stage with the proton accelerator up to 100 MeV. It will be used to practically develop the required fault tolerance concepts to match the extraordinarily high MTBF required for an ADS and at the same time to deliver beam to two user stations (see Fig. 1) – The ISOL facility “PTF” and the full power facility “FPF”. The ambitious schedule aims to have the first beam accelerated to 100 MeV by the end of 2027.

The nuclear license for MINERVA has been requested by the end of 2021 and the Federal Agency of Nuclear Control (FANC, Belgium) has issued the approval by Nov. 2022.

PARTICLE ACCELERATOR

While an accelerator team located in Louvain la Leuve (≈ 100 km south of the final location, Mol) had performed activities together with collaboration partners - exploratory studies for a decade, the hiring for the final accelerator team at the final location started at the end of 2019. While the emerging Corona pandemic had delayed this, the team has grown to just above 20 persons by now with only a few more positions remaining to be filled.

Updated Layout & Beam Optics/Dynamics

As the previous pre-studies [4] had not been performed implementation focused, the first step was to critically review [5] the beam optics design, overall machine layout and existing component design proposals in view of a) the requirements b) reliability c) beam optics/dynamics simplicity and d) simplicity of the design/construction/commissioning. The main purpose of this review was to ensure that the reliability objectives will be met as close as possible by the machine with fault-compensation strategies only being required in operation in a minimal number of cases. Examples of the resulting changes are mentioned in the following sections. Significant progress has since been made on the non-tangible aspects, e.g. establishment of requirements, reliability modeling in collaboration with CERN [6], overall accelerator operational concept including fault tolerance.

Updated injector layout & optics design

While the final full MYRRHA accelerator will feature two 17 MeV injectors for parallel redundancy, MINERVA will currently only implement one. The first part of the injector - consisting of a commercial ECR ion source, a 4 rod 176 MHz RFQ and two quarter wave re-bunching cavities as shown in Fig. 2 - have been successfully beam-tested in a dedicated test stand [7, 8]. This part and the subsequent section accommodating 15 accelerating and 2 re-bunching cross-bar-H-mode (CH) cavities [9] required only minor updates. Extending the distance between the end of the CH-section up to the dogleg and reducing the distance from the exit of the dogleg to the start of the SRF linac allowed to significantly improve the diagnostic capabilities.

Furthermore, it allowed replacing two re-bunching low-beta SRF spoke cavity cryomodules of special design by one standard normal-conducting re-bunching cavity, while at the same time reducing the maximal phase extension of the beam.
Before start of production of RF cavities, blue = vertical bars (green = horizontal), up to the PTF target

Figure 1: Layout of the 100 MeV accelerator (blue = cavity, red = quadrupoles, green = dipole) and RIB lines (red).


ds = dipole, 

c = quadrupole

Hardware Status

Normal conducting injector CH Cavities (176.1 MHz) While the first two 176.1 MHz CH cavities were already built by industry (NTG and PINK), the contract for the remaining 13 accelerating and two rebunching CH cavities was recently awarded to RI Research Instruments GmbH (RI). While the overall RF design of the CH-cavities has not been changed significantly, e.g. the need of a second vacuum pumping port was identified. Currently, the water-cooling design - primarily the cooling of the cross-bars - is being critically reviewed before start of production.

Low-beta single-spoke cavities (352.2 MHz) 60 identical 352.2 MHz low-beta (geometrical beta ~0.35) single-spoke cavities (at 2 K) will be installed. After the development and production of four prototype single cavities by JICLab - successfully tested in a vertical dewar to meet the MINERVA requirements - the industrial fabrication at RI was initiated by end of 2021. By now the first three pre-series cavities have been fabricated (Fig. 4) and are currently undergoing the surface post-processing via Buffered Chemical Polishing (BCP) in a new rotary BCP facility established at RI. For the final design, a critical review has uncovered the need for a several modifications i.e. improved 2 K heat load capacity, improved achieving of the target frequencies during and after fabrication or minimizing the stack-up of longitudinal tolerances.

Cryomodule A test-cryomodule (housing two cavities) had been designed and assembled by IJCLab in 2022. While initial testing – without RF – had successfully been done in 2022, high-power RF testing is foreseen to be performed only within the first half of 2023.

The design had been critically reviewed and a series of critical design issues are currently being resolved, e.g.

Figure 4: First MINERVA pre-series SC-cavity.

New HEBT layout & optics design A design for a HEBT that allows the deflection to the two newly added user facilities at 100 MeV was developed. A fast deflector in the High Energy Beam Transfer line (HEBT) can direct the beam for up to 500 μs to the first user facility with a repetition rate of 250 Hz. The feed-down effect of a single quadruple is used to amplify the effect of the fast kicker (see Figure 3).

Figure 3: Beam envelope (green=horizontal, blue = vertical) from the doublet in front of the last cryo-module (blue boxes), up to the PTF target.

Consolidated SC-linac layout & optics design While the optimal transition energy from the SRF low-beta single spoke cavities to the envisaged future medium beta double spoke ones would be at ~70 MeV, the PTF user facility requires 100 MeV. In order to limit the currently needed development efforts, it was decided to use the low-beta cavities up to 100 MeV at the cost of a slightly reduced acceleration efficiency. The general design of the SRF linac – featuring the commonly used warm-quadrupole doublet section between the ~2 m long cryomodules (containing two single spoke cavities) - remained largely unchanged. New simulations showed an significantly increased RF-overhead for fast fault compensation of RF-failures in the SC-linac [5].

Figure 2: The injector test stand consisting of the ECR ion source, the 176 MHz RFQ and two quarter wave re-bunching cavities.
• Resolving limitations in the cryogenic routing
• As Minerva will be a test facility where failures of cavities will be artificially induced to test the functioning of the RF-fault compensation mechanism, the motor of the mechanical tuning system (CTS) of the SRF cavities will need to safely detune the deactivated cavities several orders of magnitude more often compared to other linacs. As prototype tests at JINLab uncovered serious lifetime issues with motors failing within 2-3 days [10], SCK CEN is investigating a warm motor solution.
• While the RF-aspects of the RF-coupler have been validated in simulations and experimental tests [11], the cooling and mechanical design required a complete redesign.
• The achievable alignment precision and mechanical interferences are being consolidated. While the foreseen heat-exchanger has been validated in the prototype test, the design of the final valve box is only starting at ACS [12].

Other systems The lessons learned during the pre-studies [13] and at our injector test stand are culminating in the development of the final system uTCA based which heavily relies on a collaboration with DESY, e.g. for the use of their currently developed direct sampling RF-SoC.

The development of the beam dumps is done by ESS-Bilbao with basic designs already being established. An external magnet design engineer is currently being contracted to be responsible for the electro-mechanical design of all magnets and the production follow up (except the design of the HEBT kicker and septum which is performed via a collaboration with CERN).

While initial experience with the use of solid state amplifiers was gained as part of the previous studies, the final ones are about to be tendered in the coming months.

Control system The injector test stand is being operated with EPICS heavily relying on extensions done by ESS and adaptations implemented by CosyLab [14].

The MINERVA Control System (MCS) is developed following a modern development life cycle based on agile, DevOps and Test Driven Development (TDD) to improve quality, in particular the challenging reliability requirements. MCS will still rely on EPICS and µTCA4 [15] supplemented with a White Rabbit [16] based Timing and Triggering System and standard industrial solutions to further minimize development and operational costs. Main solution delivery is performed together with Framatome Hungary [17] and EvoPro Innovation [18].

USER FACILITIES

ISOL Facility (PTF)

Due to a collaboration, the ISOL technique and the RIB distribution at the PTF can be based on technology from ARIEL at TRIUMF [19]. The average beam current on the target will be lowered by reducing the duty factor – with 250 Hz up to 500 µs on non-actinide targets or up to 200 µs on actinide targets.

The layout of the RIB distribution network has been established (see red lines Fig. 1) serving three distinguished experimental stations, with potential extension. The design mass resolution is envisaged as 1500 in an initial stage and can be easily upgraded to well above 10000. A yield station will allow continuous online monitoring of the beam quality.

Full Power Facility (FPF)

The FPF can absorb the 400 kW proton beam and will serve as beam dump for accelerator studies and to irradiate samples for fusion material research. Its concept is similar to e.g. IPF at Los Alamos [20], where a target holder is submerged in a 10 m high water column. When used as beam dump facility, a dedicated beam dump module will inserted in order to limit the Tritium production. The efforts are currently focused on the development of beam-dump module, the vacuum-water window and its integrity monitoring by a camera, the remote handling aspects for the replacement of the targets as well as of the vacuum window that is part of the final 6 m long vacuum chamber.

BUILDING & INFRASTRUCTURE

The final overall facility layout can be seen in Fig. 5. While the clearing of the future site from pre-existing cabling/piping has been completed, ground breaking for the first buildings is planned for the end of this year.

The definition/design of the cryogenic plant is performed via a contract with CEA-lab DSBT [21].

![Image](https://via.placeholder.com/559x71)

Figure 5: Design of the MINERVA buildings.

SUMMARY

The first implementation phase of MYRRHA – the 100 MeV SC accelerator project is well progressing. While some progress is made on theoretical fault tolerance studies, the current focus is placed to reviewing/improving the designs with respect to their individual reliability to achieve the ambitious reliability goals set by its future application as a reactor driver. While several significant tenders, e.g. for all cavities, have already been placed and production started, the main remaining ones will be published still this year.

ACKNOWLEDGEMENTS

The authors like to thank all involved SCK CEN team members and all the numerous collaboration partners for their valuable contributions (alphabetical order): CERN, DESY, ESS, ESS BILBAO, University of Uppsala/FREIA, LANL, CNRS/IN2P3/JLab and TRIUMF.
REFERENCES


[6] Lukas Feldberger et. al., „Accelerator Reliability“, Deliverable 10.1 of the EU-PATRICIA project.


doi:10.18429/JACoW-LINAC2022-TUPOJO23


