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THE MYRRHA PROJECT*

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Abstract

The main objective of MYRRHA (Multi-purpose hybrid Research Reactor for High-tech Applications) at SCK•CEN, the Belgian Nuclear Research Centre, is to demonstrate the large scale feasibility of nuclear waste transmutation using an Accelerator Driven System (ADS). It is based on a high power cw operated 600 MeV proton Linac with an average beam power of 2.4 MW. Due to the coupling of the accelerator with a fast reactor, a major concern is reliability and availability of the accelerator. Only 10 beam trips longer than 3 s are allowed per 3-month operation cycle, resulting in an overall required Mean Time Between Failure (MTBF) of at least 250 hours. The MYRRHA Linac consists of a room temperature 17 MeV Injector based on CH-cavities and the superconducting main Linac using different RF structures as Single Spokes, Double-Spokes and elliptical cavities. In 2017 it has been decided to stage the project and to start with the construction of a 100 MeV Linac (Injector and Single Spoke section) including a 400 kW proton target station. This facility will be operational in 2026 aiming to evaluate the reliability potential of the 600 MeV Linac. The Front-End consisting of an ECR source, LEBT and 1.5 MeV RFQ is already operational while the first 7 CH-cavities are under construction. The presentation gives an overview about the MYRRHA Project, its challenges and the status of construction and testing.

INTRODUCTION

The Belgian nuclear research centre SCK•CEN has been working for several years on the development of an accelerator-driven multi-purpose neutron source to replace the ageing BR2 reactor. This project, known as MYRRHA, couples a high power proton accelerator with a fast 50-100 MW_{th} reactor [1]. The 600 MeV beam delivered by the accelerator hits a liquid metal spallation target (Pb-Bi). A focus of MYRRHA is the demonstration of the large-scale feasibility of nuclear waste transmutation. In addition, far-reaching possibilities open up in materials research, component testing and the production of radioisotopes. Furthermore, it is planned to make part of the beam available for an ISOL-target. The MYRRHA accelerator must be able to deliver the 600 MeV beam with a beam current of up to 4 mA in cw operation with a beam power of up to 2.4 MW. Particular attention was paid to the reliability of the accelerator. The MTBF shall be at least 250 hours. This was also taken into account in the design of the accelerator. The design philosophy was that the accelerator should be as conservative as necessary and as efficient as possible. This applies to both the hardware components and the beam dynamics. The latter is particularly important with regard to methods for increasing reliability (Dynamic Fault Compensation Scheme) [2]. In a first step the construction of the MYRRHA Linac up to an energy of 100 MeV has started. In parallel, a proton target facility (PTF) will be built to use the beam for first experiments from 2026 [3]. This first stage of MYRRRHA is named MINERVA. Table 1 summarizes the top level requirements for MYRRHA and MINERVA. The development of the MYRRHA project has been supported in recent years by various funding programmes from the European Union between 2001 and 2019 (PDS XT-ADS, Eurotrans, MAX, MYRTE). In 2016 the decision was taken to divide the MYRRHA project into different phases. Phase 1 (2019-2026) includes the design and commissioning of MINERVA and further R&D on the 600 MeV Linac. Phase 2 includes the construction of the Linac up to 600 MeV and phase 3 the reactor. At a later stage it will be decided whether phase 2 and phase 3 will be executed sequentially or in parallel [3]. The reasons for this

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Table 1: MINERVA and MYRRHA Top-level Requirements

Parameter	**MINERVA**	**MYRRHA**
Particle type	Protons	Protons
Frequency (MHz)	176.1-352.2	176.1-704.4
Peak beam current (mA)	4	4
Final energy (MeV)	100	600
Beam duty factor (%)	$2{\cdot}10^{-4}$-100	$2{\cdot}10^{-4}$-100
Beam power (MW)	0.4	2.4

approach are to construct, test and operate a representative section of the MYRRHA accelerator with MINERVA. This is particularly important with respect to reliability of the MYRRHA Linac and to demonstrate the feasibility of fault compensation.

RELIABILITY AND FAULT TOLERANCE

If the MYRRHA reactor is operated in subcritical mode, the spallation target provides the necessary external neutrons. If the beam is interrupted, the reactivity of the reactor core and its temperature drops rapidly. In order to minimize thermal stress and thus long-term damage and material fatigue, especially to the fuel rods, unwanted beam interruptions must be avoided as far as possible. This has serious consequences for the required reliability of the accelerator. In the operational MYRRHA context, the beam is considered to fail if its delivery to the subcritical core is interrupted during a time period that lasts longer than 3 s [4]. Such a beam interruption leads to the shutdown of the reactor, which takes several hours to restart. Frequent interruptions would drastically reduce the availability of the entire facility. To achieve an availability of 80%, the present provisional limit for the number of allowable beam interruptions of t>3 s is 3 per month. It should be noted that shorter beam trips are tolerated at a virtually unlimited occurrence frequency. A number of measures are necessary to achieve the required reliability of the MYRRHA Linac. Basically, all components have been developed conservatively, so that they are operated well below their physical limits. Examples are the minimization of thermal stress in the normal conducting cavities and the gradients in the superconducting cavities. In addition, the MYRRHA accelerator has been designed to be fault tolerant. Fault tolerance means that the function of a faulty element (e.g. amplifier module or cavity) can be taken over by one or more other elements in order to continue to deliver the proton beam with nominal parameters to the target. The basic precondition for a high degree of fault tolerance is redundancy. Redundancy can be ensured in parallel or in series. To be noted that in the case of parallel redundancy one or more independent systems can provide the requested functionality. In series redundancy, the requested functionality of a given element is ensured by means of dynamic failure compensation by non-failed elements, taking over the load of the failed one. This implies that all elements must be operated well below their nominal performance. Nevertheless, there's a maximum number of failure cases that can be compensated thanks to the available margins. In the low energy section up to 17 MeV, two injectors are currently planned to ensure parallel redundancy. In the medium- and high-energy section, serial redundancy is used by means of the Dynamic Fault Compensation Scheme. If a superconducting cavity fails, other cavities will be adjusted in phase and gradient in such a way that the failure is compensated and the beam interruption is avoided [4]. This requires powerful and low-error diagnostics (e.g. beam, RF, vacuum) in order to be able to detect failures reliably and quickly or predict their future occurrence. Furthermore, a fast Low Level RF (LLRF) system is required to reconfigure the compensating cavities with respect to phase and amplitude. Simulation tools running in parallel to support optimization of the new configuration. Additionally, it is mandatory to implement a powerful and fast control system to reach the required reliability level [5].

BEAM DYNAMICS

Beam dynamics plays a major role in the design of MYRRHA. It is obvious that beam loss of a 600 MeV Linac with an average beam power of 2.4 MW should be as low as possible to prevent possible damage to components and to minimize activation. In addition, excessive beam loss can result in a shut down and lower availability of the facility. The Linac should provide large acceptance and high flexibility in tuning for normal operation as well in case of cavity failures. Extensive beam dynamics studies have been performed to optimize the Linac and to find best strategies in case of cavity failures. End-to-end simulations have been done using realistic 3D field maps. In addition, error studies have been performed. These studies lead to an estimation of required number of additional elements as steerer and slits. An error study with failing cavities has been performed simulating 1000 linacs with $3{\cdot}10^6$ particles each. Figure 1 shows a cumulative plot of all linacs. 90% of the linacs do not show any losses, 99% have maximum losses below 0.2 W/m. The maximum loss of the worst case was 0.85 W/m.

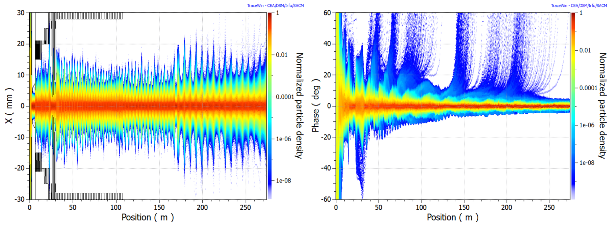

Figure 1: End-to-end simulation of the MYRRHA Linac with errors and cavity failures (cumulated particle density x- and z-plane).

A major concern is the longitudinal dynamics because it can lead to uncontrolled beam loss along the Linac. The Dynamic Fault Compensation Scheme seems to be necessary to achieve the reliability goals but there is a drawback. It could be shown that the longitudinal acceptance is shrinking

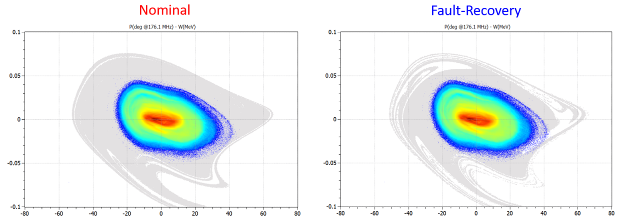

Figure 2: Example of the decrease of longitudinal acceptance (gray shaded area) due to the compensation of failing cavities (Spoke cavity #19, full cryo module #7 in section 2, one cavity in cryo-module #10 in section 3).

when this scheme is applied. This effect is all the greater the more cavities are failing. However, multi-cavity failures and even the loss of a complete cryo module in the high energy section can be compensated with enough longitudinal acceptance. Figure 2 shows the longitudinal acceptance for nominal operation and in exemplary case of cavity failures (4 cavities in total). It is clearly visible, that some parts of the beam halo are outside the acceptance. For this simulation 10^8 macro particles have been simulated.

17 MeV INJECTOR

The injector serves to accelerate the beam to an energy of 17 MeV. It consists of an ECR source, a magnetic Low Energy Beam Transport (LEBT), a 4-Rod RFQ, a Medium energy Beam Transport (MEBT) and a total of 17 normal conducting CH-cavities. Originally it was planned to use superconducting CH-cavities above 6 MeV. Due to the decision for the construction of MYRRHA and the tight schedule, it was decided to realize the injector completely with normal conducting cavities. Before the availability of the buildings at SCK•CEN in Mol, the first part of the injector up to 5.9 MeV is presently being installed at the Cyclotron Resource Centre in Louvain-la-Neuve. Figure 3 shows the layout of the first part of the injector.

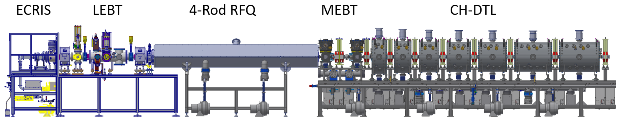

Figure 3: Layout of the MYRRHA injector up to 5.9 MeV which is presently being under construction.

Front-End

The Front-End consists of the proton source and a LEBT-section with integrated chopper system. As proton source an ECR source has been chosen because of their high reliability, easy handling and maintenance and because of its high proton fraction. The extraction energy has been set to 30 keV. This value is high enough for the beam transport and low enough to achieve a sufficiently high bunching efficiency in the RFQ. The M1000 source can deliver up to 20 mA. In the LEBT section which has been developed by LPSC Grenoble there a two solenoids for focusing the proton beam, cleaning the beam from unwanted species ($H_2{}^+$, $H_3{}^+$) and for matching the beam into the acceptance of the RFQ [6]. Between the solenoids various diagnostics devices (Faraday cups, ACCT, Allison scanner) are installed to monitor the beam properties. Motorized collimators are used to intercept the beam halo and to control the beam current. In front of the RFQ a chopper system has been installed to create a pulse structure required for commissioning and monitoring the sub-criticality of the reactor. Figure 4 shows the setup of the Front-End.

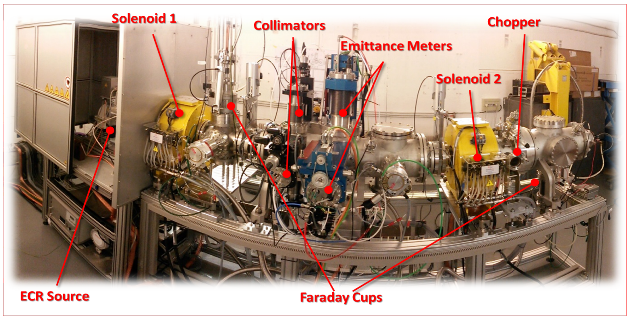

Figure 4: The MYRRHA Front-End with ECR source and LEBT.

The Front-End has been fully characterized at LPSC. It could be shown that the transverse emittance $\epsilon_{RMS,N}$ is less than 0.2π mm mrad at the RFQ entrance as required [6]. Figure 5 shows the beam current through the tuned LEBT as function of the solenoid currents. The red dot indicates the working point where the beam is matched to the RFQ. Meanwhile the Front-End has been shipped to Louvain-la-Neuve and first tests have started.

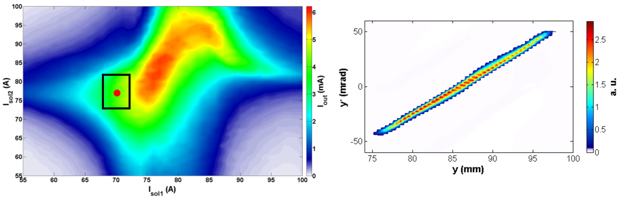

Figure 5: Measured beam current through the tuned LEBT as function of the solenoid currents. The red dot indicates the working point.

RFQ

As first accelerating structure a 4-Rod RFQ has been chosen because of the excellent possibilities of frequency and field tuning, the modular design and the possibilities for maintenance and repair. In recent years, the 4-Rod RFQ has been further developed in terms of high duty cycle up to cw operation [7]. New fabrication technologies have been developed to optimize the cooling. The RFQ accelerates the beam from 30 keV to 1.5 MeV at a frequency of 176.1 MHz. To limit the thermal load, a rather low electrode voltage of

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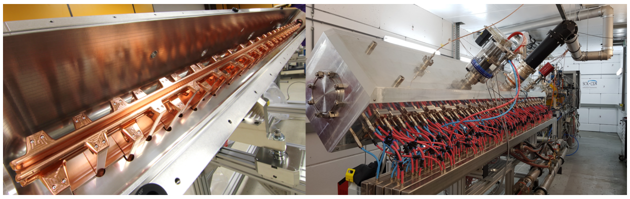

Figure 6: The MYRRHA RFQ with open lid (left) and the setup for the high power test in Louvain-la-Neuve (right).

44 kV has been used. The shunt impedance is 73 kΩm resulting in a specific power requirement of 26.5 kW/m, the total RF power without beam loading is 107 kW. 4-Rod RFQ-structures have an intrinsic dipole component. In case of the MYRRHA RFQ this dipole component could be reduced from 25% to -4% by asymetric widening of the stems [8]. Figure 6 shows the RFQ with open lid and the setup for the high power tests. After a pre-conditioning with 10 kW at IAP [9] the RFQ was shipped to Louvain-la-Neuve. Meanwhile the RFQ is conditioned with a power of up to 145 kW cw. Figure 7 shows exemplarily the conditioning of the RFQ. The belgian company IBA has developed the solid state amplifier for the RFQ (Fig. 8). The amplifier delivers up to 192 kW of RF power. With respect to reliability, Solid State Amplifiers (SSA) have a great advantage because of their modular design and thus increased redundancy (RF modules, power supplies). In early 2020 first beam tests are foreseen.

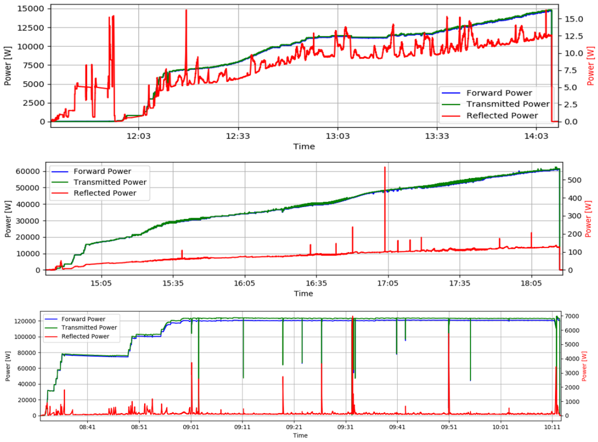

Figure 7: Exemplary measurements of the RFQ during the high power tests.

CH-DTL

After the RFQ the beam is injected into a short Medium Energy Beam Transport (MEBT) section to match it into the acceptance of the following drift tube Linac. It consists of two quarter wave rebunchers, transverse focusing elements and various beam diagnostics devices. The rebunchers have been produced and are presently high power tested.

Figure 8: 192 kW Solid State Amplifier driving the MYRRHA RFQ.

The drift tube Linac has to accelerate the beam to an energy of 16.6 MeV. Basically, the Linac should be as efficient as possible in terms of power consumption. Furthermore, beam dynamic aspects, modularity, maintenance, repair, R&D effort, availability of suitable amplifiers and investment costs also play a role. It has been decided to use normal conducting CH-cavities operated at 176.1 MHz [10]. CH-cavities are efficient RF structures operated in the TE_{211} mode [11]. They offer excellent cooling possibilities. All cavities are made from stainless steel with subsequent copper plating. Each cavity is equipped with one static and one dynamic tuner. Due to the cw operation, power consumption and cooling is a major issue. A prototype cavity has been tested with full power before the construction of the MYRRHA cavities has started [12].

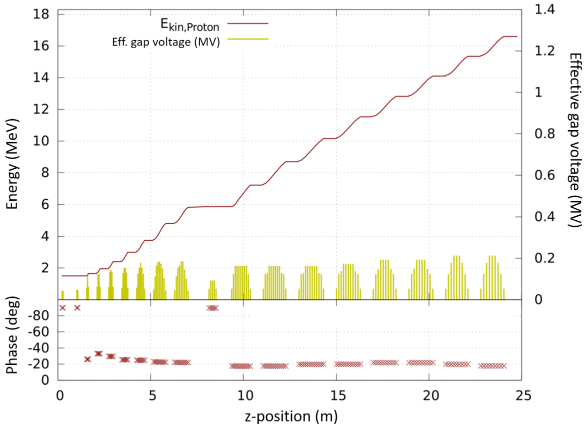

Figure 9: Energy gain, gap voltages and synchronous phase along the CH-Linac.

The Design of the CH-Linac was driven by two main factors, applicable gradients (RF power, cooling) and beam dynamics, especially longitudinally. In many cases, H-mode structures (CH, IH) are using KONUS beam dynamics which often leads to a significant emittance growth in the longitudinal plane. Although it is less efficient, it has been decided to apply a conservative beam dynamics with constant syn-

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chronous phase in each cavity. The RF phase and the number of accelerating cells have been optimized to minimize the emittance growth. Figure 9 shows the energy along the Linac, the gap voltages and the synchronous phase in the different cavities. In total 15 CH-cavities are used to accelerate the beam. Between cavity 7 and 8 there is a diagnostics section and a 5-gap CH-cavity acting as rebuncher. The CH-Linac is realized by a quasi-periodic lattice. There are magnetic quadrupole doublets between the cavities for transverse focusing. The quasi-periodicity leads to a smooth course of the phase advance and thus to low emittance growth. Two CH-cavities have been produced already. After low level RF characterization the cavities have been tested with full power at IAP. The power level could be reached within a few days without problems. Figure 10 shows CH-1 and CH-2 and the setup at the high power test stand [13].

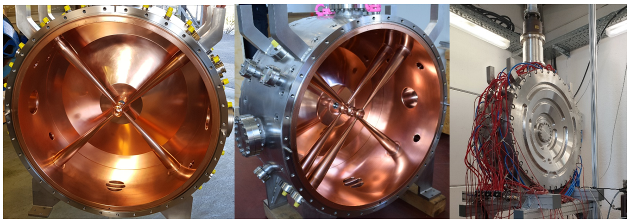

Figure 10: CH-1 (left), CH-2 (center) and high power test stand (right).

SUPERCONDUCTING LINAC

The superconducting Linac consists of an array of independently phased cavities with moderate energy gain per cavity (small number of cells and very conservative accelerating gradients) [14] [15]. This increases the tuning flexibility as much as possible and creates sufficient margin for the implementation of the Dynamic Fault Compensation Scheme. Three different cavity families are planned to cover the entire energy range from 17 MeV to 600 MeV: Single and double spokes (ESS type) cavities at 352.2 MHz and 5-cell elliptical cavities at 704.4 MHz (β=0.7). Compared to the previous design [14], it was decided to use the ESS double-spoke cavities in section 2 instead of elliptical cavities with β=0.5 in order to reduce the number of cavities and to increase longitudinal acceptance. For the 100 MeV MINERVA Linac, the first MYRRHA section, consisting of 60 spoke cavities (β=0.35)will be completely constructed.

Two 352.2 MHz, β=0.35 Spoke cavities have been constructed and tested (see Fig. 11) [16]. Special attention has been paid to the optimization of the surface preparation. The best recipe is BCP+heat treatment without any post BCP treatment. So we demonstrated that, even with a titanium tank, this post BCP is not required and moreover better performances are obtained in term of Q_0 [17]. But this implies additional care during heat treatment by installing Nb caps on cavity openings. At low fields, unloaded Q-values between 4 and $5{\cdot}10^{10}$ and gradients of 20 MV/m and 14 MV/m could be achieved (see Fig. 12) [16]. All prototypes are far above the requirements for MYRRHA and offer enough margin to compensate for the failure of individual cavities.

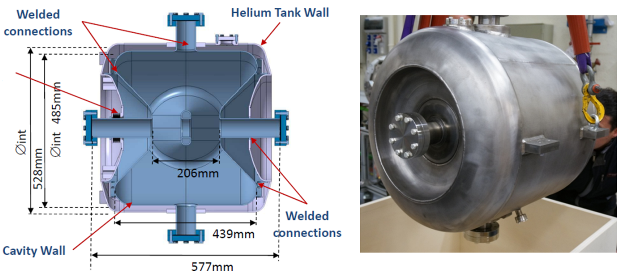

Figure 11: Sectional view of the β=0.35 spoke cavity (left) and realized protoype with helium vessel (right).

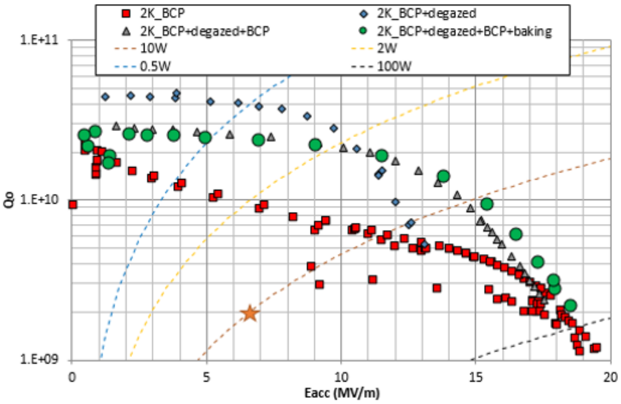

Figure 12: Experimental results of the spoke prototype cavities.

CONCLUSION

In the MYRRHA project, a 600 MeV, 2.4 MW proton linac will be coupled with a fast reactor. The Linac will have to meet special reliability requirements. The high required reliability had a big influence on the design of the accelerator. An overall conservative approach with high modularity was pursued. It was decided to divide the project into several phases, the first of which, called MINERVA, is currently under construction. First beam tests are foreseen in early 2020. The 100 MeV Linac with target facility is the most critical part of the MYRRHA accelerator. Goals are the demonstration of its reliability and the optimization of tuning procedures due to component failures. In addition, this facility will allow a wide range of experiments to be carried out before MYRRHA is completed.

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