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# MYRRHA ACCELERATOR DRIVEN SYSTEM PROGRAMME: RECENT PROGRESS AND PERSPECTIVES

**H.A. Abderrahim, D. De Bruyn, M. Dierckx, R. Fernandez, L. Popescu, M. Schyns, A. Stankovskiy, G. Van den Eynde, D. Vandeplassche**
*Belgian Nuclear Research Centre SCK•CEN*
*Boeretang 200, B-2400 Mol, Belgium*

ABSTRACT

The purpose of the MYRRHA programme is to demonstrate the ADS concept at pre-industrial scale, to prove the transmutation efficiency in ADS and to serve as a flexible and multipurpose irradiation facility. The MYRRHA sub-critical core fueled with highly enriched MOX fuel and cooled with LBE will be operated by a high-power superconducting linear accelerator delivering a proton beam of 600 MeV, 4 mA to an LBE spallation target. In September 2018, the Belgian government has approved the construction of the MYRRHA facility and its operation until 2038. In this paper, we describe the present status of the MYRRHA programme and the perspectives for implementation through a first infrastructure in 2026 to the full MYRRHA operation in 2036.

**Key words:** accelerator-driven system, lead-bismuth, superconducting linear accelerator.

## INTRODUCTION

The Multi-purpose hYbrid Research Reactor for High-tech Applications, MYRRHA, is being designed at SCK•CEN since 1998 [1 – 3]. In 2010, the Belgian government has granted a dedicated five-year budget to support the MYRRHA programme and this support has been renewed for 2015 – 2019. In the meantime, the MYRRHA team has developed a detailed implementation strategy, with a phased approach in order to reduce the technical risk, to spread the investment cost and to allow a first R&D facility available by 2026. As detailed in [3], in this new approach the MYRRHA facility will start with the 100 MeV accelerator (phase 1) and will be followed by the 100-600 MeV accelerator section (phase 2) and by the reactor (phase 3).

Phase 1 is aimed for construction and commissioning by 2026 and will represent a stage-gate for the decision to implement the two following phases that can be executed in parallel or sequentially. This implementation scenario not only allows spreading of investment costs, but it also minimizes the risk to obtain the required accelerator reliability as well as the risk for innovative design options for the reactor. On September 7th 2018, the Belgian government has approved the whole budget proposal for the phase 1 development, construction and operation until 2038 together with additional R&D and design funding for phases 2 and 3.

In this paper, we describe the present status of the MYRRHA programme and the perspectives for implementation through a first infrastructure in 2026 to the full MYRRHA operation in 2036.

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## MYRRHA AT A GLANCE

In 1995-1997, SCK•CEN was developing the ADONIS project (Accelerator Driven Operated New Irradiation System) [4], a small irradiation facility with the production of radioisotopes for medical purposes as its single objective. It was the first project at SCK•CEN where the coupling between an accelerator, a spallation target and a sub-critical core was studied. In 1998, it has been decided to rebrand the project under the name MYRRHA to broaden the application range of the ADONIS machine to become a material testing reactor for material and fuel research, to study the feasibility of transmutation of minor actinides (MAs) and to demonstrate the principle of the Accelerator Driven System (ADS) at a representative power scale.

In 2005, the so-called "MYRRHA – draft 2" design [5] has been developed that was based on a proton accelerator delivering a beam of 350 MeV proton energy and 5 mA proton current to a windowless spallation target coupled to a sub-critical fast core of 50 MWth, Since that time, SCK•CEN and Belgium opened MYRRHA for the EU Member States as well as to the major nuclear power countries for participation in the development of MYRRHA and further on during the construction and operation periods. The 2005 design was used as a starting base within the FP6 EUROTRANS integrated project [6], which resulted in the XT-ADS [7] (experimental demonstration of the technical feasibility of transmutation in an ADS) design, where a linear proton accelerator delivers a 3.2 mA proton beam current at an energy of 600 MeV into the spallation target. The core design was based on mixed oxide (MOX) fuel with a 35% Pu enrichment. The reactor power of XT-ADS was 57 MWth.

The XT-ADS design was taken as a starting point for the work performed in the European Commission's FP7 Central Design Team (CDT) project, which resulted in the MYRRHA-FASTEF (MYRRHA fast spectrum transmutation experimental facility) design. This design has been described in more detail in reference [8]. In the beginning of 2014, SCK•CEN has consolidated a coherent version of the MYRRHA primary system, which was given to an external engineering office as basis for developing the Balance-of-Plant basis engineering.

MYRRHA is positioned as a highly innovative and multidisciplinary research infrastructure that will be used for:

- Testing and developing the transmutation of long-life and most toxic radionuclides in spent nuclear fuel in order to reduce their radiotoxicity in volume (with a factor 100) and in time (from hundreds of thousands of years to a few centuries – a factor 1,000) compared to the current management options. The need for geological waste disposal still exists but transmutation reduces the technical requirements because a smaller volume (reducing significantly the gallery length) is stored for a smaller amount of time that will definitely have a positive impact on safety as well as on the economic cost;
- Securing the continuous production of radioisotopes for medical applications due to an increasing demand worldwide, and in order to produce more efficient and high-quality radioisotopes;
- Carrying out materials research and tests for the current and future nuclear fission reactors as well as nuclear fusion technology;
- Providing a multifunctional accelerator for fundamental and applied research.

The nominal design power of the MYRRHA reactor is 100 MWth although in the sub-critical mode with $k_{\mathrm{eff}} = 0.95$ the operation power range would be 65 – 70 MWth [9]. The core in subcritical mode is driven by a high power proton linear accelerator (linac) delivering a proton beam in CW mode of 600 MeV proton energy and up to 4 mA intensity. The core is also conceived to operate in a critical mode at 100 MWth when the beam line is removed and a number of fuel assemblies is added to the core periphery to reach criticality. The basic design elements of MYRRHA are sketched in Figure 1.

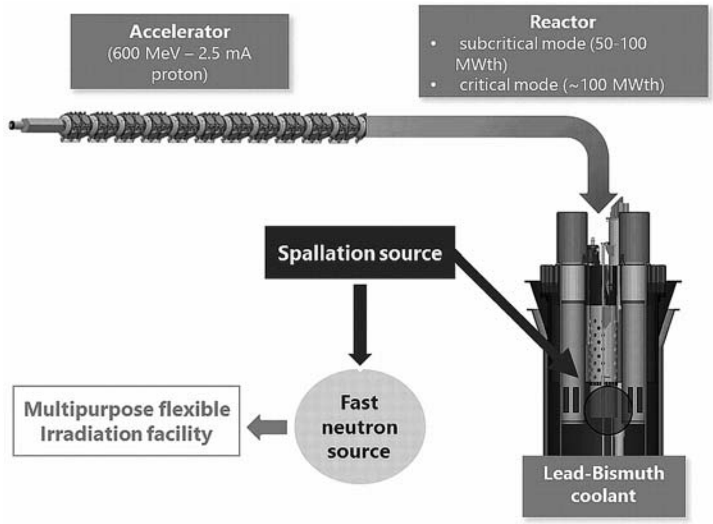

Figure 1: The three components of the MYRRHA facility

## THE MYRRHA REACTOR

The MYRRHA design as worked out in the FP7 Central Design Team project served as a starting point for the further design work of the MYRRHA primary system, the accelerator as well as for the design of the auxiliary systems. This resulted in mid-2014 in an updated MYRRHA primary system design called “Release 1.6” [2]. This version takes into account stringent safety requirements imposed after the Fukushima accident as well as a more advanced design of the primary system based on design mechanical codes after the conceptual stage. The main components/systems of this design are still of the same type as the previous versions. The general design includes a pool-type primary circuit LBE (Lead-Bismuth Eutectic), a secondary circuit with water/steam and a tertiary circuit with air. The primary and secondary systems have been designed to evacuate a maximum core power of 100 MWth.

The power increase compared to 57 MWth of XT-ADS is justified to reach the objectives of the applications catalogue listed in the section above. All the components of the primary system are optimized for the extensive use of the remote handling system during components replacement, inspection and handling. Table 1 summarizes the main physical characteristics of the MYRRHA core and primary system and a section of the MYRRHA reactor in the current design with its main internal components is plotted in Figure 2. It is worth to note that the average hot plenum temperature is 325°C which is lower than 270+90 = 360°C deduced from Table 1, due to all by-pass flows (lead-bismuth not flowing through fuel assembly) in and out of the core.

The current “Release 1.6” answers the difficulties encountered in the previous versions; however, the price to pay is a dramatic increase in size and weight of all components, and consequently the projected cost of construction (1.6 G€ 2014). As example:

- The reactor vessel diameter increases from 8.2 to 10.4 m (which is a challenge both for manufacturing and transportation);
- The LBE inventory increases from 4500 to 7600 ton, which means a non-negligible impact on the initial investment cost.

This led the SCK•CEN Board of Directors to request at the end of 2014 the MYRRHA design team to revisit “Release 1.6” with the objective to reduce the total cost [3]. Some intermediate results in this field have already been published [10]. At the same time, it has been also requested to consider various implementation scenarios for the realization for spreading the investment costs and mitigating the technological, cost and planning risks namely:

**scenario 1** – Accelerator first and reactor later;
**scenario 2** – Reactor first and accelerator later;
**scenario 3** – Accelerator and reactor jointly deployed.

As mentioned before, scenario 1 has been adopted in the phased approach.

Table 1

**Main MYRRHA characteristics**

| | |
|---|---|
| Total reactor power, MWth | 110 |
| Total primary mass flow rate, kg/s | 13800 |
| LBE mass inventory, ton | 7600 |
| Core inlet temperature at full power, °C | 270 |
| Hot plenum temperature at full power, °C | 325 |
| Average core temperature difference at full power, °C | 90 |
| Cold shut down temperature, °C | 200 |
| Temperature of secondary cooling loop, °C | 200 |
| Number of fuel assemblies in subcritical / critical core | 72 / 108 |
| Number of penetrations for experiments and other applications | 55 |
| Total neutron flux in first 6 experimental positions, $\times 10^{15}$ n·cm$^{-2}$·s$^{-1}$ | 2.6 |
| Fast neutron flux in first 6 experimental positions, $\times 10^{15}$ n·cm$^{-2}$·s$^{-1}$ | 0.42 |

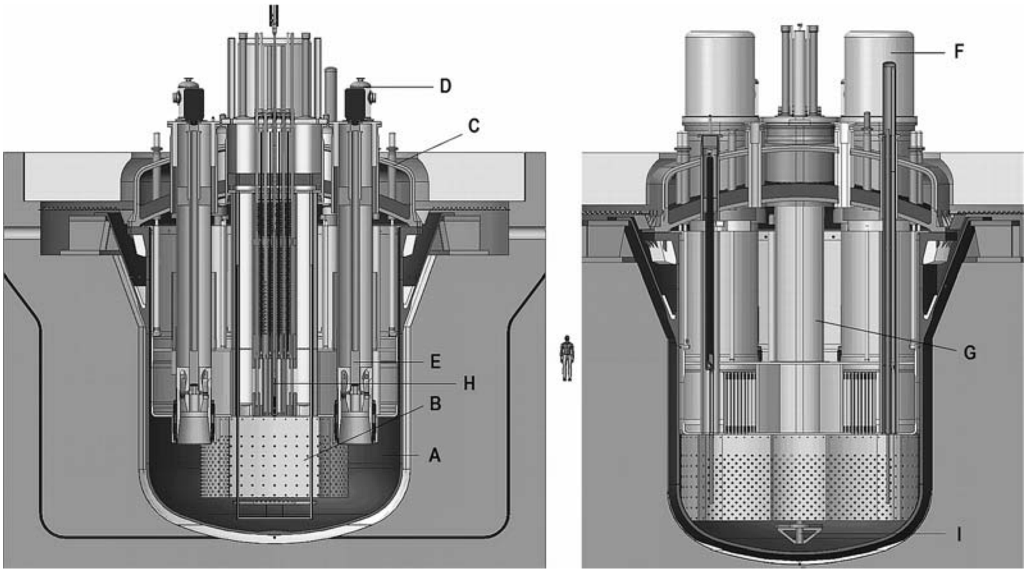

Figure 2: Overview of the MYRRHA reactor: A – Reactor vessel; B – Diaphragm; C – Reactor Cover; D – Primary Heat Exchanger; E – Primary Pump; F – In-Vessel Feel Handling Machine; G – Core Barrel; H – Reactor Core; I – Core Restraint System

## REACTOR CORE

Already in the final stretches of the CDT project, it became clear that the sub-critical core loaded with MOX having a 35% Pu enrichment would be too compact (i.e. too high power peaking factors) to allow to reach sufficiently high neutron flux in the irradiation positions (~$3\cdot10^{15}$ $n\cdot cm^{-2}\cdot s^{-1}$) [9]. Therefore, the decision was taken to reduce the plutonium content to 30%. Based on this boundary condition, a core optimization study was performed and it became clear that an increase of the active height of the core from 600 to 650 mm could be advantageous. In its present form, the “Release 1.6” critical and sub-critical core configurations look as is sketched in Figure 3.

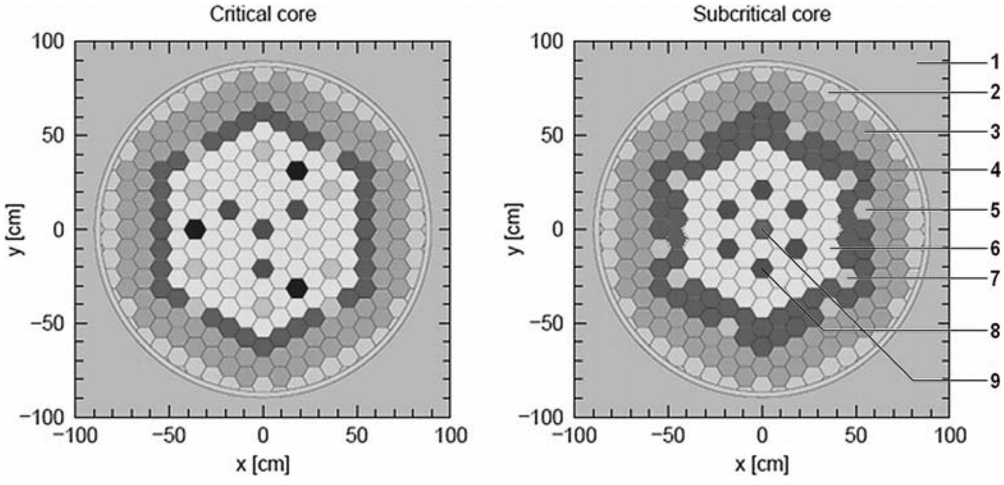

Figure 3: Critical and sub-critical core layouts: 1 – LBE; 2 – SS jacket and core barrel; 3 – Reflector SA; 4 – Dummy SA; 5 – SA with control rods; 6 – FA active part; 7 – Radioisotope production IPS; 8 – Fuel and material testing IPS; 9 – Spallation target

The hexagonal core lattice consists of two kinds of channels. The first type of channels, such as hosting in-pile-section (IPS), shutdown systems and, in the central position, the spallation target assembly, that is the mechanical–functional interface between the proton beam and the sub-critical core, is accessible from the top of the reactor. The other channels are accessible from the bottom by an in-vessel fuel handling machine to host fuel assemblies and dummy or lateral reflector/shielding sub-assembly. Beyond the outer channels, a kind of steel-jacket helps to keep the various sub-assemblies together and reduces the neutron-induced dose on the core barrel. The beginning-of-life (BoL) fresh, sub-critical core consists of 54 fuel assemblies (FA) while the critical one contains 78 FAs. In order to compensate burn-up reactivity losses during operation history of the core (consisting of 90 days of irradiation followed by 30 days of shutdown) few assemblies need to be added. Along with “in-to-out” fuel reshuffling strategy using batches of 6 fuel assemblies each (to preserve hexagonal symmetry) this results in 72 and 108 FA in quasi-equilibrium conditions for sub-critical and critical cores, respectively.

Besides in the number of FAs, the sub-critical and critical cores differ in the number and layouts of control and safety sub-assemblies, as well as irradiation devices (IPS). The sub-critical core can host 6 IPS for material irradiations in fast spectrum, while the critical core employs only three plus the central one liberated from the spallation target sub-assembly. On the other side, the sub-critical core does not need SA with safety rods, since in “Release 1.6” the irradiation conditions are maintained by tuning the beam power while control rods are withdrawn from the core and play role of safety rods in case of sudden increase of neutron multiplication. The core power is determined by the admissible clad temperature of 466°C. The major neutronic characteristics of both cores are summarized in Table 2.

Table 2

**Neutronic characteristics of critical and sub-critical cores**

| | Critical BoC | Sub-critical BoC |
|---|---|---|
| Number of FA | 108 | 72 |
| Effective neutron multiplication factor $k_{eff}$ | 1.02167±0.00002 | 0.96677±0.00012 |
| Effective delayed neutron fraction $\beta_{eff}$, pcm | 330±7 | 325±7 |
| Core power, MWth | 96 | 70 |
| Beam current, mA | – | 1.74 |
| Fuel residence time, cycles | 18 | 12 |
| Fuel burn-up at discharge, MWd/kgHM | 57.4 | 59.1 |
| Peak total flux in central position (IPS or target), $\times 10^{15}$ n·cm$^{-2}$·s$^{-1}$ | 2.6 | 3.8 |
| Peak fast flux (>0.75 MeV) in central position (IPS or target), $\times 10^{15}$ n·cm$^{-2}$·s$^{-1}$ | 0.41 | 1.1 |
| Radiation damage in central position (IPS or target), dpa/EFPY[1] | 22 | – |
| Peak total flux in off-center IPS, $\times 10^{15}$ n·cm$^{-2}$·s$^{-1}$ | 1.8 | 2.6 |
| Peak fast flux (>0.75 MeV) in off-center IPS, $\times 10^{15}$ n·cm$^{-2}$·s$^{-1}$ | 0.26 | 0.41 |
| Radiation damage in off-center IPS, dpa/EFPY | 14 | 31 |
| [1] Effective Full Power Year (EFPY) = 365 days at nominal power | | |

As it is seen from the table, both cores offer very attractive irradiation conditions for fuel and material research in terms of radiation damage metrics such as dpa (number of displacements per atom). The sub-critical core results in higher dpa values due to presence of high-energy tail in its neutron spectrum up to the energy of primary protons 600 MeV. Regarding neutron kinetics characteristics, due to high Pu content in MOX fuel (30%) the effective delayed neutron fraction is low in both cores. However, in the case of the subcritical core it does not have direct impact on the postulated reactivity insertion accidents studied in the safety files.

## MYRRHA PRESENT STATUS AND PLANNING

In 2010, the Belgian Government took the decision to support MYRRHA for further development with a specific endowment of 60 M€2010. Furthermore, it was envisaged to contribute to its construction at a level of 40% of the total cost.

When considering the different scenarios described above, external evaluation panels have recommended to choose scenario 1 for realization of MYRRHA, i.e. a phased implementation with accelerator first & reactor later [3]. In this scenario, the construction of the MYRRHA accelerator happens in two consecutive phases: 0-100 MeV (phase 1) followed by the 100-600 MeV sections (phase 2). The reactor (phase 3) is a separate phase and can be executed in parallel with or after phase 2. This strategy was then confirmed by the SCK•CEN Board of Directors.

Based on the Final report of the Ad-hoc evaluation group for the period 2010–2014, the Belgian Government decided in the meantime continuing to support MYRRHA and granted SCK•CEN a new dedicated MYRRHA endowment of 40 M€ for 2016 – 2017.

Discussions with representatives of the Belgian government have been launched early 2018 and many reports (related to progress of design, progress in R&D and licensing) have been delivered by SCK•CEN in order to obtain a multi-year funding commitment for research, design and operation of the facility. Finally, a good agreement has been found on September 7th, 2018, in which:

- Belgium (read: the Belgian government) decides to build MYRRHA, a new large research infrastructure at Mol;
- A 558 M€ budget is allocated for the period 2019 – 2038, split into three parts:
  - 287 M€ for the construction of the whole Phase 1, now called MINERVA, within the period 2019 – 2026;
  - 115 M€ for further design, R&D and Licensing for the Phases 2 and 3, in order to become fully mature in 2026;
  - 156 M€ for the operation of the MINERVA installation for the period 2027 – 2038;
- Belgium requests the MYRRHA programme to establish an International non-profit organization (in French: AISBL; in Dutch: IVZW) in charge of the MYRRHA facility for welcoming the international partners;
- Belgium continues to mandate Secretary of State for Foreign Trade Mr Pieter De Crem for promoting MYRRHA and negotiating international partnerships.

Figure 4 shows the most recent version of the planning for the whole MYRRHA programme. If phase 1 receives the most urgent attention, phases 2 and 3 are certainly not forgotten, as these should become fully mature in 2026, in order to take the decision to launch their construction.

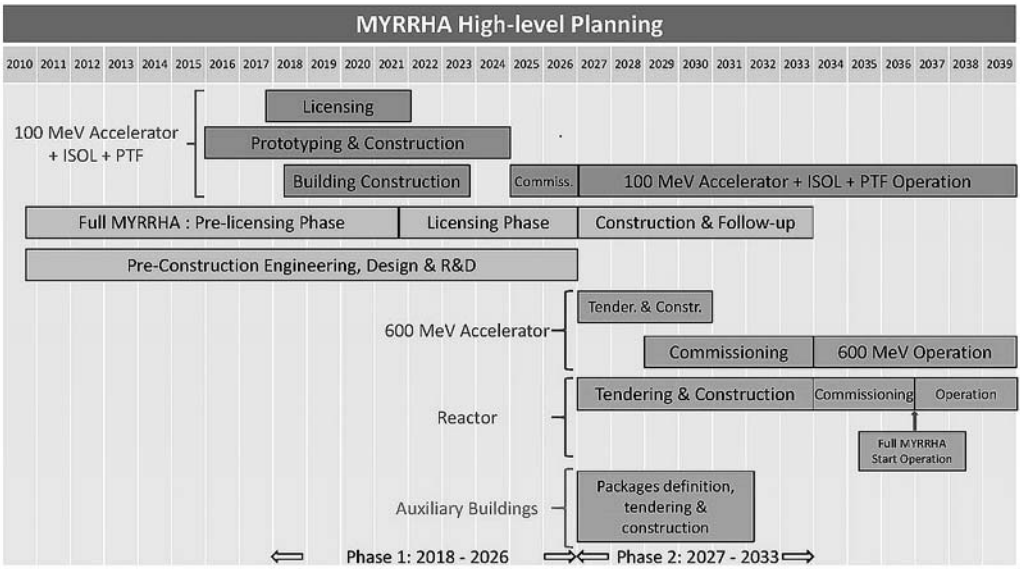

Figure 4: MYRRHA planning today

## MINERVA, MYRRHA PHASE I

At the level of the proton accelerator the first phase consists of building and operating the linac limited to 100 MeV final beam energy. It is well known that beam reliability is the main challenge of the ADS driver. In MYRRHA's case this challenge is expressed as a beam-MTBF (Mean Time Between Failures) of 250 hours. Hence, the principle aim of phase 1 is to experimentally investigate the feasibility and efficiency of the reliability and fault tolerance schemes that are envisaged for the 600 MeV linac. Also in phase 1 it is foreseen to transport a ~10% fraction of the 100 MeV beam to a target station for innovative medical radioisotopes by an Isotope Separation On-Line (ISOL) technique. MINERVA is the name of the project that combines the phase 1 100 MeV linac, the ISOL target station, the target station for fusion materials research and all the associated services and buildings.

## ACCELERATOR

The MYRRHA Injector is a room temperature linac that accelerates a 4 mA CW proton beam to 16.6 MeV [11]. The protons achieve their final energy of 600 MeV in the following sections of a superconducting linac. Then they are deflected to the spallation target inside the MYRRHA reactor core. For the operation of MYRRHA a high reliability and availability of the proton beam is required [12]. To demonstrate the acceleration of the linac in compliance with the reliability requirements the injector will be constructed to an energy of 5.9 MeV in a first stage, see Figure 5. Meanwhile the design of the second stage up to 16.6 MeV will be finalized [13]. Further steps will be constructing and operating without beam of one fully equipped single spoke cryomodule which is the basic building block of the 100 MeV superconducting linac and construction and operation without beam of the beam extraction system that will allow to feed the ISOL target station.

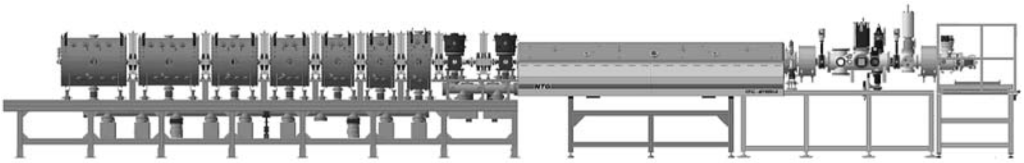

Figure 5: MYRRHA Injector construction scheme up to 5.9 MeV

This 5.9 MeV entirely normal conducting injector is being set up in a specially constructed bunker within the Centre de Ressources du Cyclotron at UCL, Louvain-la-Neuve, Belgium. It combines the following linac elements [14]:

- The ECR (Electron Cyclotron Resonance) proton source, commercially procured from the company Pantechnik [15], able to deliver up to 20 mA and operated at 30 kV.
- The LEBT (Low Energy Beam Transport), designed, assembled and commissioned by LPSC Grenoble [16], using 2 magnetic solenoids for proper beam matching and featuring a diagnostic chamber with Faraday cup, beam slits and Allison-type emittancemeters.
- The beam chopper and its associated water cooled collimator, with a typical repetition rate of 250 Hz and a rise time in the ms range (to be optimized).
- The injection cone for connecting to the RFQ (Radio Frequency Quadrupole), with an electron repeller and an ACCT (AC Current Transformer).
- The 4-rod RFQ accelerating to 1.5 MeV over 4 m, RF frequency of 176 MHz, designed by IAP Frankfurt and built by the company NTG [17].
- The RF power amplifier in Solid State technology, entirely developed by the company IBA [18], delivering up to 192 kW CW at 176 MHz.
- The LLRF (Low-Level RF) controls being developed by IPN Orsay.
- A short matching section named MEBT1 (Medium Energy Beam Transport 1), consisting of 2 quarter wave rebuncher cavities and a magnetic quadrupole triplet.
- A series of 7 individual room temperature CH-type (Crossbar H-mode) accelerating cavities with magnetic quadrupole doublet focusing between the cavity tanks. The

global design is from IAP Frankfurt, the practical execution is supported by the company Bevatech [19].

- A versatile diagnostic test bench, allowing for obtaining the fundamental beam characteristics, applicable at several levels of beam energy.

Further details on the features of MEBT1, the CH series and the diagnostic test bench are given in [20].

For the reliable beam operation of the MYRRHA Injector the specified stability parameters in Table 3 need to be measured and verified with various beam diagnostic elements. An ACCT and a BPM (Beam Positioning Monitoring) are integrated in both MEBT sections. MEBT-2 has an additional space reserved for an emittance measurement device (tomographic tank or slit-grid-scanner). On the end flange of each CH cavity a phase probe is mounted. During the commissioning phase a movable diagnostic bench will be positioned behind every new mounted pair of a cavity and a magnet.

Table 3

**Stability Parameters for Stable Beam Operation and the Appropriate Beam Diagnostic Device**

| Parameter | Tolerance | Device |
|---|---|---|
| Energy stability | < ±1% | Phase probe |
| Current stability | < ±2% | Current transformer |
| Position deviation | < ±10% | BPM |
| Beam size variation | < ±10% | Tomographic tank |

The 100 MeV linac has 30 cryomodules, each housing 2 single spoke cavities. Each cryomodule is connected to the cryogenic supply via its individual cold valve box. Although from an industrial point of view the series are small, an industrial approach to the activities of cavity preparation and of clean room assembly of the complete cryomodules is compulsory. The investigation of this approach is another task of the cryomodule’s integrated prototyping.

The goal of the 100 MeV linac is to establish the feasibility of the 600 MeV ADS driver linac satisfying the reliability requirements. This needs to

- Confirm experimentally the fault recovery procedure(s).
- Feed a reliability model allowing extrapolation.

The former is based on 2 fast procedures:

- A virtual accelerator-based reconfiguration tool (fast beam simulation).
- A global hardware reconfiguration tool (fast setpoint changes and readback).

Both these procedures may be initiated at the prototyping level on the 5.9 MeV injector.

## PROTON TARGET FACILITY

Thanks to the high intensity of the MYRRHA proton beam, a small fraction (up to 10%) can be used to produce Radioactive Ion Beams (RIBs) using the Isotope Separator On-Line (ISOL) technique [21]. Those beams will be produced at the ISOL@MYRRHA facility planned to operate in parallel to the ADS. In addition to the high purity, ISOL@MYRRHA will also provide RIBs of high intensity. Amongst other research fields, the availability of pure and intense RIBs is of interest to medical research. The wide spectrum of RIBs that can be produced and the fact that they can be obtained essentially carrier free makes ISOL facilities a unique tool for preclinical studies of innovative radio-isotopes. As shown in Figure 6, ISOL@MYRRHA is an extension of the MYRRHA ADS [22].

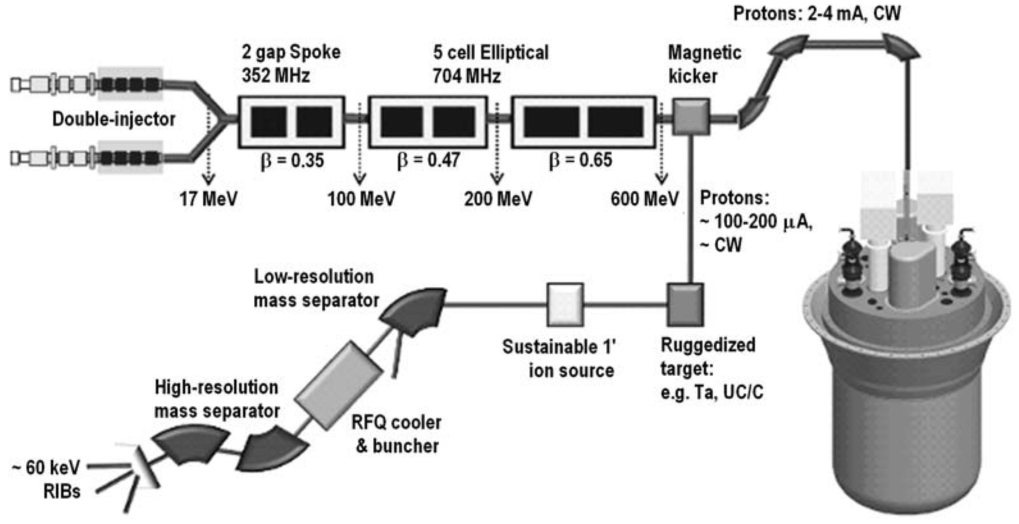

Figure 6: Schematic view of the MYRRHA and ISOL@MYRRHA [22]

The ISOL system will consist of a primary beam tube, a target/ion source, a mass separator, and a separated beam transport system. Radioactive atoms will be produced by bombarding the target with high-intensity beams of protons. The radioactive products will be stopped in the target material at high temperature (~2000°C) in order to speed the diffusion of the exotic atoms inside the target material to the surface from which they desorbed [23]. Radioactive atoms diffused and desorbed from the target material will effuse through a transport tube into an ion source, where they will be ionized, and subsequently extracted, mass-separated on-line and (in some cases) reaccelerated. Formed high quality beams of isotopes will be used for the low-energy experimental areas. A top-view of the ISOL@MYRRHA target station conceptual design is shown in Figure 7.

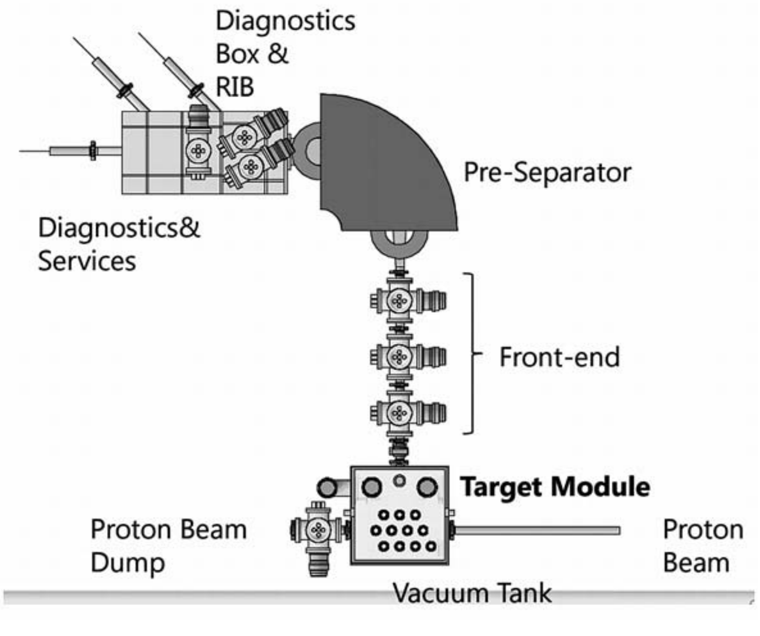

Figure 7: Top-view of the ISOL@MYRRHA target station conceptual design

Already in the first phase of the project (MINERVA), ISOL@MYRRHA can profit from the availability of a high power proton beam [24]. Therefore, high power target concepts for operation at 100 MeV and beam currents up to 500 mA are under investigation [25], see Figure 8. The concepts build on strategies like a beam profile adaptation, internal radiant heat transfer and increased external radiant cooling surface. Besides the target itself, specific additional challenges for this low-energy high-power target are the design of a beam window and a beam dump behind the target.

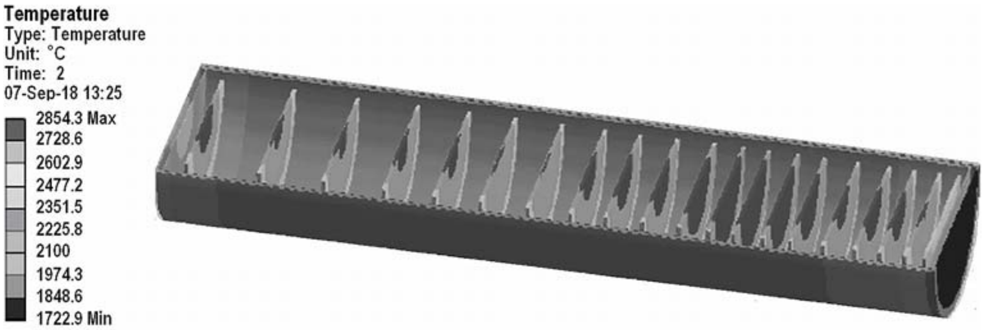

Figure 8: Thermal profile in a TiC target under development for ISOL@MYRRHA-phase 1. The target discs are holded by a graphite insert, which is encapsulated in a 20-cm long 5-cm diameter Ta container. The computational exercise was focused on optimization of TiC target-discs distribution that offers a good thermal distribution in the target. (Picture from ref. [25])

## CONCLUSIONS

Belgium is contributing to an innovative approach for the treatment of the spent nuclear fuel of present nuclear power plants. This approach is under development within the EU strategy for Partitioning & Transmutation through the unique facility MYRRHA. This facility is based on a sub-critical reactor Generation IV LBE technology requesting very unique expertise and facilities in reactor as well as accelerator technologies. MYRRHA Project will be realized according to the phased approach approved by Belgian government. At the first phase the high-power superconducting linear accelerator delivering proton beams of 100 MeV with the intensity of up to 4 mA, will be constructed and tested. In parallel to that, a proton target facility dedicated for medical isotope production based on ISOL technology that takes advantage of high stability and intensity of the proton beam, will be constructed. At later stage, the accelerator will be extended to 600 MeV and coupled to the sub-critical reactor.

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### Authors

Prof. Hamid Ait Abderrahim, Deputy Director General of SCK•CEN, Director of MYRRHA Programme
E-mail: hamid.ait.abderrahim@sckcen.be

Dr. Didier De Bruyn, Member of MYRRHA Management Team
E-mail: didier.de.bruyn@sckcen.be

Dr. Marc Dierckx, Leading Scientist, Proton Target Research
E-mail: marc.dierckx@sckcen.be

Dr. Rafael Fernandez, Deputy Director of Advanced Nuclear Systems Institute of SCK•CEN
E-mail: rafael.fernandez@sckcen.be

Dr. Lucia Popescu, Head of Proton Target Research
E-mail: lucia.popescu@sckcen.be

Dr. Marc Schyns, Director of Advanced Nuclear Systems Institute of SCK•CEN
E-mail: marc.schyns@sckcen.be

Dr. Alexey Stankovskiy, Leading Scientist, Nuclear Systems Physics
E-mail: alexey.stankovskiy@sckcen.be

Prof. Dr. Ir. Gert Van den Eynde, Head of Nuclear Systems Physics
E-mail: gert.van.den.eynde@sckcen.be

Dr. Dirk Vandeplassche, Head of Accelerator Design and Tests
E-mail: dirk.vandeplassche@sckcen.be

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# УСКОРИТЕЛЬНО-УПРАВЛЯЕМАЯ СИСТЕМА МИРРА: ПРОГРЕСС И ПЕРСПЕКТИВЫ

Х.А. Абдеррахим, Д. Де Брёйн, М. Диркс, Р. Фернандес, Л. Попеску, М. Схинс, А.Ю. Станковский, Г. Ван ден Эйнде, Д. Вандеплассхе
Бельгийский ядерный исследовательский центр SCK•CEN
Boeretang 200, B-2400 Mol, Belgium

Целью программы по разработке ускорительно-управляемой системы (УУС) МИРРА является практическая реализация УУС с приближенной к индустриальной производительностью для демонстрации эффективности трансмутации радиоактивных отходов в УУС, а также для проведения облучения топлива, конструкционных материалов и производства радиоизотопов. Подкритическая активная зона установки МИРРА с высокообогащённым МОКС-топливом, охлаждаемая свинцово-висмутовой эвтектикой (СВЭ), управляется сверхпроводящим линейным ускорителем, доставляющим пучок протонов с энергией 600 МэВ и током 4 мА к нейтронообразующей СВЭ-мишени. В сентябре 2018 г. правительство Бельгии утвердило полный бюджет по сооружению установки МИРРА и ее эксплуатации на период до 2038 г. В статье описывается текущее состояние НИОКР по программе МИРРА и перспективы реализации проекта от строительства первичной инфраструктуры в 2026 г. до полного ввода в эксплуатацию в 2036 г.

**Ключевые слова:** ускорительно-управляемая система, свинцово-висмутовая эвтектика, сверхпроводящий линейный ускоритель.

**Авторы**

Проф. Хамид Аит Абдеррахим, заместитель генерального директора SCK•CEN, директор программы МИРРА. E-mail: hamid.ait.abderrahim@sckcen.be

Д-р Дидье Де Брёйн, член Совета директоров программы МИРРА
E-mail: didier.de.bruyn@sckcen.be

Д-р Марк Диркс, ведущий научный сотрудник подразделения разработки протонных мишеней. E-mail: marc.dierckx@sckcen.be

Д-р Рафаэль Фернандес, заместитель директора Института перспективных ядерных систем SCK•CEN. E-mail: rafael.fernandez@sckcen.be

Д-р Лючия Попеску, руководитель подразделения разработки протонных мишеней
E-mail: lucia.popescu@sckcen.be

Д-р Марк Схинс, директор Института перспективных ядерных систем SCK•CEN
E-mail: marc.schyns@sckcen.be

Станковский Алексей Юрьевич, ведущий научный сотрудник подразделения физики ядерных систем, канд. физ.-мат. наук. E-mail: alexey.stankovskiy@sckcen.be

Проф., Д-р Герт Ван ден Эйнде, руководитель подразделения физики ядерных систем
E-mail: gert.van.den.eynde@sckcen.be

Д-р Дирк Вандеплассхе, руководитель подразделения разработки и тестов ускорителей заряженных частиц. E-mail: dirk.vandeplassche@sckcen.be

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