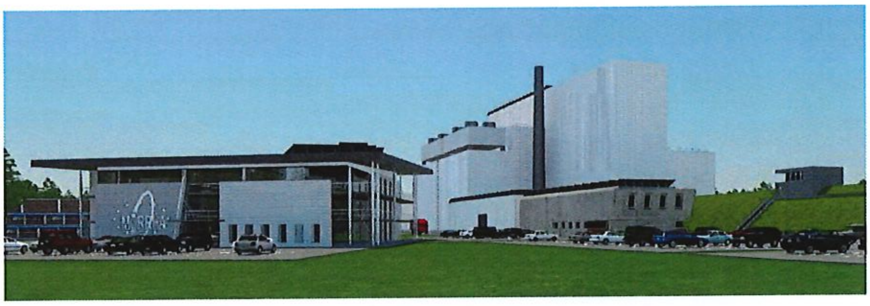
MYRRHA: Multipurpose hYbrid Research Reactor for High-tech Applications

Communication investment project in application of the Council regulation No 2587/1999 of 2 December 1999 defining the investment projects to be communicated to the Commission in accordance with Article 41 of the Treaty establishing the European Atomic Energy Community



MYRRHA
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Belgium

Contents

Introduction

SCK•CEN, the Belgian Nuclear Research Centre, is an internationally renowned Centre of Excellence in nuclear research with an excellent track record in safely and efficiently operating many nuclear research facilities on its technical site at Mol in Belgium. Since 1998, SCK•CEN has been developing the MYRRHA research infrastructure. Conceived as an Accelerator Driven System (ADS) with experimental target stations, MYRRHA consists of a proton accelerator of 600 MeV with a 4 mA proton current intensity coupled through a spallation neutrons source using liquid Lead-Bismuth Eutectic (LBE) to a sub-critical nuclear reactor cooled also by LBE.

These preparatory developments were conducted by SCK•CEN with international partners, via bilateral collaborations or under multi-annual EURATOM R&D programs of the European Commission (FP5, FP6, FP7 and H2020).

MYRRHA has been submitted regularly and nearly every 2 years to international peer reviews (see Annex 1) on various aspects of project; at strategic, technological and technical level as well as its relevance to the international research communities in the various fields targeted by MYRRHA.

After 10 years of R&D, the Belgian Federal Government requested an independent project review to OECD/NEA that mandated a panel of international independent experts to assess the MYRRHA project technical readiness level for a decision on investing specifically in this project. The MYRRHA International Review Team (MIRT) published its report and recommendations to the Belgian government in November 2009[1].

On 5 March 2010 following the first option of the MIRT recommendation, the Belgian Federal Government decided to support the MYRRHA program and to grant a dedicated budget of 60 M€$_{2010}$ for the period 2010-2014 to develop in greater detail the Front-End Engineering Design (FEED) of MYRRHA; to secure its licensing; and to establish an international consortium that would fund the 60% of the construction budget of MYRRHA complementing the 40% engagement to be covered by Belgium.

Since 2006, MYRRHA was listed by the European Strategy Forum on Research Infrastructures (ESFRI) on its roadmap as an emerging project. In 2010, MYRRHA was included as a priority research infrastructure in the category Energy projects of the "Strategy Report on Research Infrastructures Roadmap 2010". Since then MYRRHA has been re-evaluated bi-annually by the ESFRI Energy Working Sub-Group and stayed listed as a priority project in the roadmap report of 2018[2].

MYRRHA's pan-European dimension and its multidisciplinary impact are also illustrated by the fact that MYRRHA is part of the European Sustainable Nuclear Industrial Initiative (ESNII)[3], one of the pillars of the Sustainable Nuclear Energy Technology Platform (SNETP) and was included in the implementation plan of the Key Action 10 of the SET-Plan. ISOL@MYRRHA, one of the target stations of MYRRHA, is also included by the Nuclear Physics European Collaboration

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[1] Report by an International Team of Experts (MIRT) organised by the OECD Nuclear Energy Agency. (OECD 2009, NEA No. 6881, ISBN 978-92-64-99114-9).

[2] http://roadmap2018.esfri.eu/

[3] http://www.snetp.eu/esnii/

Committee (NuPPEC) of the European Science Foundation in the "NuPPEC Long Range Plan" since 2010 and re-confirmed in its most recent edition of 2017[4].

In 2010, the Belgian Federal Government established a monitoring and control committee, the MYRRHA Ad Hoc Committee (MAHG), whose mission it is to control the progress of the program's development and to make recommendations to the Belgian Federal Government related to the future direction of the MYRRHA program.

During the period 2010 to 2014, SCK•CEN further developed the engineering design of the MYRRHA primary system, resulting in an advanced, integrated and consistent engineering design for the reactor and a frozen design of the MYRRHA accelerator.

In 2015, a phased construction implementation approach of MYRRHA was decided to spreading the investment cost and to mitigating the technological, financial and planning risks.

Following this phased implementation approach, MYRRHA will be constructed in 3 phases:

- Phase 1: construction of the first part of the MYRRHA accelerator up to 100 MeV with the full intensity of 4 mA complemented by a Proton Target Facility (PTF),
- Phase 2: upgrade of the MYRRHA linear accelerator from 100 MeV to 600 MeV,
- Phase 3: construction of the MYRRHA nuclear system.

Considering the progress booked on the period 2010-2014, the MYRRHA Ad Hoc Group (MAHG) recommended to the government to continue supporting the MYRRHA project for a period of 4 years on the basis of an annual budget of 20 M€ with an intermediate milestone after two years. Furthermore, the MAHG recommended nominating a MYRRHA "High-level Representative" acting in name of the government to promote MYRRHA on the international and national scene and to secure international participation in the MYRRHA consortium.

These recommendations were formally endorsed by the Council of Ministers at its meeting of 16 October 2015, which granted an additional financial support of 40 M€$_{2015}$ for the period 2015-2017.

At the end of 2017, a new in-depth MYRRHA program progress evaluation by the MAHG was complemented by various additional studies and evaluations as listed below:

- A comprehensive business plan for MYRRHA for both the construction periods (2018-2026 for phase 1 extended up to 2033 for phases 2 & 3) and operational period (partially from 2027 for phase 1 and fully from 2034 till 2065)
- [redacted]
- the letter of the safety authority FANC/AFCN's first opinion of November 2017, saying that no show stopper was identified in the pre-licensing process conducted by MYRRHA Program since 2011,

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[4] http://www.nupecc.org/pub/lrp17/lrp2017.pdf

- the positive evaluation conducted by the Belgian Federal Council of Science Policy of the scientific case of MYRRHA as a Large research infrastructure of pan-European dimension,
- the positive evaluations conducted by PMV of the MYRRHA business case for its financial part and by EWI/FWO for its scientific case on behalf of the Flemish ministry of Innovation

On 7 September 2018, following the recommendations of the MAHG, the Belgian Federal Government took the decision to build the new large research infrastructure MYRRHA at the site of SCK•CEN. The details of the decision are summarized below:

- The decision by the Government endorses the financing of Phase 1 of the MYRRHA project for a total budget of 558 M€$_{2018}$, i.e. the establishing of the MYRRHA AISBL/IVZW[5] and the construction of the first part of the accelerator up to 100 MeV supplemented with the PTF, as well as the continued support for the design, licensing and R&D for Phase 2 and Phase 3 of the MYRRHA program.
- The objective of the international non-profit organisation MYRRHA AISBL/IVZW is to design, to develop, to build and to operate the MYRRHA research infrastructure with an international and pan-European dimension for contributing as a "Centre of Excellence" for the benefit of society (in the broad sense) through scientific research and technological developments in the fields of advanced management of high level nuclear waste through transmutation, medical and aerospace applications of radioisotopes, fundamental physics, applied research in the field of materials for materials research for fusion and fission energy and for non-energetic applications, particles accelerator technology and education and training of new generations of scientists and engineers in these fields.
- The prime mission of the MYRRHA AISBL/IVZW is to promote the MYRRHA facility internationally and to act as a control and reception structure for international partners. In addition, it shall attract partners in the MYRRHA AISBL/IVZW that shall be composed of Member-States. The MYRRHA AISBL/IVZW will be the owner of the Research Infrastructure. The MYRRHA AISBL/IVZW shall designate/delegate the construction and the exploitation of MYRRHA to SCK•CEN. The Research Infrastructure shall be built on the technical site of SCK•CEN in Mol.

The MYRRHA AISBL/IVZW is currently under creation by the Belgian State and SCK•CEN, the Belgian Nuclear Research Centre, following this decision of the Belgian Government.

The MYRRHA AISBL/IVZW is the legal vehicle intended to welcome the international partners who will be contributing to the construction period (2019-2033) of the facility as well as for using the research facility during the operational period (starting partially from 2027 (phase 1 of the project) and fully from 2035 until 2065).

In the first years, the prime mission of the MYRRHA AISBL/IVZW is to promote the MYRRHA project internationally and to act as a control and reception structure for international partners.

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[5] International Non-Profit Organization = Association International Sans But Lucratif / Internationale Vereniging Zonder Winstoogmerk

1 Description of the investment project

MYRRHA stands for **M**ultipurpose h**Y**brid **R**esearch **R**eactor for **H**igh-tech **A**pplications. It is conceived as an Accelerator Driven System (ADS). It consists of a proton accelerator of 600 MeV x 4 mA nominal current intensity coupled through a liquid Lead-Bismuth Eutectic (LBE) spallation neutrons source to a nuclear sub-critical reactor cooled by LBE. The 600 MeV x 4 mA linear accelerator of MYRRHA is a high power proton machine, delivering a proton beam of 2.4 MW on the LBE spallation target. The spallation reactions induced in the target create a high intensity neutron source in the centre of the sub-critical reactor core. In their turn, the produced neutrons feed the sub-critical MYRRHA reactor core inducing fission reactions.

The phased MYRRHA implementation consists of:

- Phase 1: construction of the first part of the MYRRHA accelerator up to 100 MeV with the full intensity of 4 mA complemented by a Proton Target Facility (PTF),
- Phase 2: upgrade of the MYRRHA linear accelerator from 100 MeV to 600 MeV,
- Phase 3: licensing and construction of the MYRRHA reactor.

MYRRHA will allow research and development for the following applications:

- Demonstrate, on a semi-industrial scale, the transmutation of highly radioactive waste, in particular of minor actinides, to reduce their radiotoxicity using ADS systems,
- Develop the next generation of therapeutic medical radioisotopes,
- Develop and demonstrate unprecedented accelerator reliability leading to accelerator technology enhancement,
- Enable ground-breaking fundamental physics research thanks to its ISOL@MYRRHA facility and its unprecedented accelerator reliability,
- Contribute the European Fusion roadmap leading to fusion electricity by testing candidate fusion materials supported by the post irradiation facilities of SCK•CEN ,
- Operate as a flexible fast spectrum irradiation facility after completion of Phases 2 & 3, contributing to support the safe and secure of advanced nuclear systems, to support material developments for fusion reactors and the development of reactor-based radioisotopes production for medical purposes.

1.1 Name and address of the person(s) or undertaking(s) notifying the investment project

MYRRHA AISBL/IVZW in creation, which will have its Registered Office in Belgium, Avenue Herrmann-Debroux 40, BE-1160 Brussels and which will be the owner of the new infrastructure

Contact person: Hamid Aït Abderrahim, Director MYRRHA (+3214332596, hamid.ait.abderrahim@sckcen.be or hamid.ait.abderrahim@myrrha.be)

And

The Studiecentrum voor Kernenergie/Centre d'Etude de l'Energie Nucléaire [also known as the Belgian Nuclear Research Centre], Foundation of Public Utility, with its Registered Office in Belgium, Avenue Herrmann-Debroux 40, BE-1160 Brussels and its Operational Office also in

Belgium, Boeretang 200, BE-2400 Mol, with enterprise number 0406.568.867 and VAT number BE0406.568.867 (hereafter "**SCK•CEN**").

SCK•CEN will be the nuclear operator of the new infrastructure, on behalf of the MYRRHA AISBL/IVZW.

1.2 Name of the investment project

MYRRHA which stands for **M**ultipurpose h**Y**brid **R**esearch **R**eactor for **H**igh-tech **A**pplications.

1.3 Relevant industrial activities as per annex II of the treaty:

11: Nuclear reactors of all types and for all purposes.

1.4 Is it to be a new installation, a replacement or a conversion?

MYRRHA is a new installation.

1.5 Reference to documents previously communicated to Euratom in respect of the investment project (date of correspondence).

In October 2018, MYRRHA, through the Belgian Government, asked the Directorate General for Research and Innovation to benefit from the support for fission research & innovation (R&I) investment projects of pan-European relevance through the InnovFin instrument foreseen in the Euratom Work Program 2016-2017[6]. With this financial instrument, the Euratom fission program aims to support fission R&I investment projects, typically in relation to the construction or refurbishing of research infrastructure, specialised equipment or technology demonstrators, through a financial contribution to the InnovFin instrument.

1.6 Name and address of person(s) or undertaking(s)

1.6.1 Operator of the installation

MYRRHA AISBL/IVZW will be the owner and responsible of the MYRRHA nuclear large research facility.

SCK•CEN will be MYRRHA's nuclear operator on behalf of the MYRRHA AISBL/IVZW.

1.6.2 Project preparation

MYRRHA is being prepared by SCK•CEN in association with MYRRHA AISBL/IVZW.

1.6.3 Project supervision and execution

SCK•CEN is responsible for the project supervision and execution, in association with MYRRHA AISBL/IVZW in creation.

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[6] https://ec.europa.eu/research/participants/data/ref/h2020/wp/2016_2017/euratom/h2020-wp1617-euratom_en.pdf

1.6.4 **Equipment suppliers**

Not yet determined.

1.7 Methods of financing

MYRRHA will be financed through direct contributions from the countries who will be members of the MYRRHA consortium through the MYRRHA AISBL/IVZW.

Belgium is the first country to contribute to the MYRRHA ASIBL/IVZW with 558 M€$_{2018}$ as follows:

- 287 M€$_{2018}$ investment (CapEx) for construction, including the commissioning of the MYRRHA Phase 1 infrastructure in the period 2019-2026
- 115 M€$_{2018}$ R&D, design and licensing work to prepare MYRRHA Phase 2 (600 MeV accelerator upgrade) and Phase 3 (sub-critical reactor) for the period 2019-2026, up to the application and obtaining of the Construction authorisation for these phases from the Belgian safety authorities. The exploitation authorisation will follow at a later stage after 2026.
- 156 M€$_{2018}$ coverage of 12 years of operating costs (OpEx) of the Phase 1, for the period 2027-2038.

Belgium advocates more favourable treatment of public investment in the context of budgetary surveillance in the European Union. Consequently, MYRRHA was included in Belgium's list of strategic investments under its National Pact for Strategic Investments. Several options were considered, the first of which would be to revise the investment flexibility clause in Regulation (EC) 1466/97. This revision would entail removing the condition linked to the applicant country's poor economic situation - which currently prevents all Member-States (except Greece) from invoking it - and extending eligible investments to investments directly co-financed by the European Investment Bank. However, only Member-States that have carried out major structural reforms in the last three years could benefit from this revised clause. This option has already been discussed with the Commission and the Member-States in the Economic and Financial Committee. Other options are under consideration. These options could involve changing the formula for calculating the structural balance and/or the expenditure criterion. The objective pursued would in any case be to achieve a better balance between budgetary sustainability and support for Belgian strategic investments. [redacted]

The total CapEx budget of MYRRHA phases 1, 2 and 3 is 1,676 M€$_{2018}$ for period 2019-2033.

The matching funds will be acquired through the means of the specific legal vehicle, the MYRRHA AISBL/IVZW, under the form of an international non-profit organisation in the first years of constructing MYRRHA Phase 1. The MYRRHA AISBL/IVZW structure will welcome international partners and their contributions in-cash and in-kind. International partners that contribute to the realisation of MYRRHA infrastructure become full partners and have representation rights in the Board of Directors and in other MYRRHA AISBL/IVZW Governance bodies.

1.8 Geographical location

The investment project will be built within the SCK•CEN technical site which is located in Belgium, Boeretang 200, BE-2400 Mol. The location of SCK•CEN site is given in Figure 1 and shows MYRRHA on the technical site of SCK•CEN.

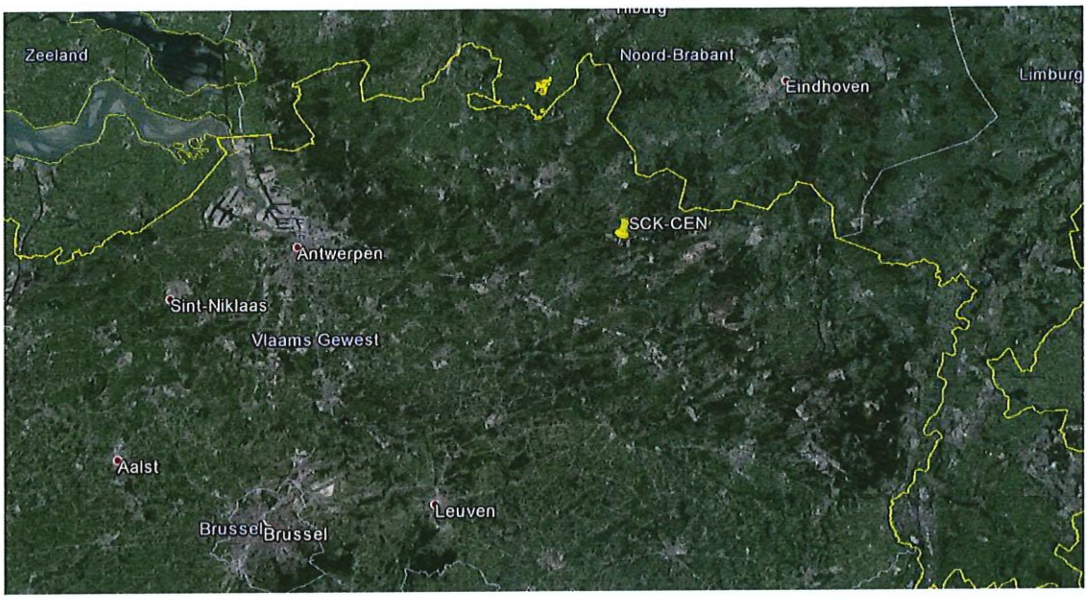


Figure 1: Location of SCK•CEN site

The SCK•CEN site is located northeast of the municipality of Mol (region located in the province of Antwerp). The site covers a surface of 530 ha, of which 100 ha are taken up by its technical site with its nuclear research installations () and by the adjacent residential quarters.

The remaining surface, which outside the technical site, consists mainly of wooded areas and, to a lesser degree, of sports facilities.

The SCK•CEN site is located in a sparsely populated area. Next to the residential quarters north of the site, the nearest accommodations are situated at approximately 1 km from the installation. Table 1 gives an overview of the number of inhabitants in surrounding municipalities.

Table 1: Number of inhabitants in the municipalities in the neighbourhood of the MYRRHA site

Municipality	Distance from SCK•CEN site (km)	Number inhabitants
Mol	3	36034
Dessel	3	9420
Geel	8	39225
Turnhout	15	42965
Herentals	18	27728
Eindhoven (NL)	35	223220
Hasselt	35	76685
Antwerp (incl. districts)	45	517042

The non-nuclear company is the *Vlaamse Instelling voor Technologisch Onderzoek* (VITO) and is located next to the technical site, but clearly separated by state-of-the-art nuclear security systems

Major industrial activities in the immediate vicinity of SCK•CEN technical site are very limited. MYRRHA is located at considerable distance from commercial airports. The nearest airport is in Eindhoven (NL), at approximately 30 km. The most important military airport in the region, the air force base of Kleine Brogel, is located at 26 km from the site.

Access to the technical site takes place via the Boeretang, which is a private road along MYRRHA's site and is exclusively accessible to SCK•CEN, Belgoprocess and VITO staff.

No new road infrastructure will be required for the MYRRHA project.

1.9 Brief description and general plans

MYRRHA is an Accelerator Driven System (ADS) consisting in:

- A linear proton accelerator of 600 MeV x 4 mA operating in CW mode,
- A spallation neutrons source located in the centre of the nuclear sub-critical reactor. The neutron source is created by shooting the proton beam on the LBE coolant of the reactor. The protons are transported until the centre of the core through a guide tube penetrating from the top the reactor lid,
- A subcritical LBE cooled fast reactor with a maximum power of 100 MWth based on the integrated pool design

1.9.1 MYRRHA proton linear accelerator

The MYRRHA proton accelerator will be a high power CW superconducting LINAC based solution with a high Radio Frequency-to-beam efficiency and hence optimised operation costs.

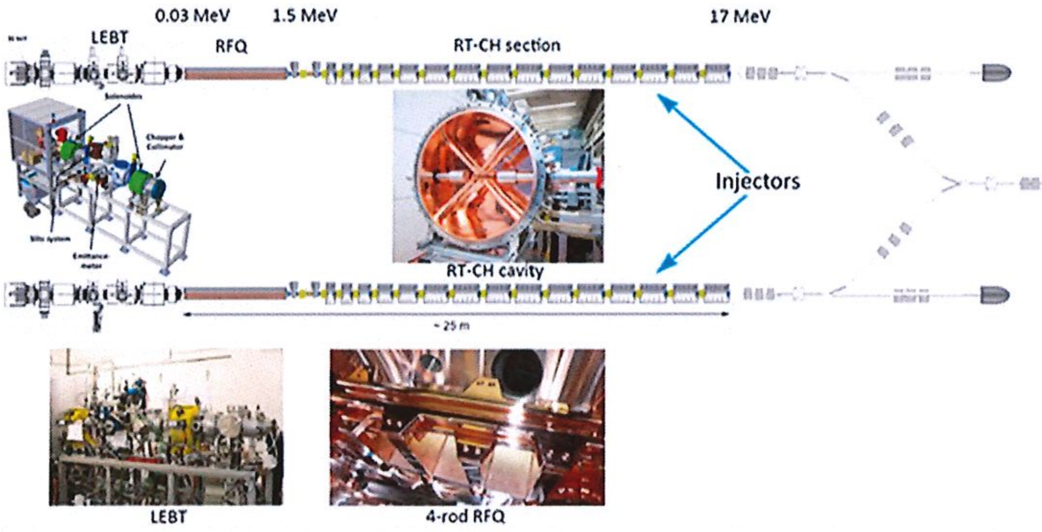
The MYRRHA accelerator system is designed to be intrinsically 'fault-tolerant' to achieve unprecedented reliability. Frequent repetitive beam trips will significantly decrease the ADS infrastructure's availability, and beam trips longer than 3 seconds are expected to require a shutdown of the nuclear system. The reliability requirement in terms of beam trips has been identified as the MYRRHA accelerator's main technological challenge.

To achieve this reliability, the MYRRHA linear proton accelerator will composed of two injector lines until 17 MeV based on room temperature technology followed by a superconducting unique LINAC until 600 MeV. The primary design characteristics of the accelerator are the particle type and energy, beam current and beam delivery time structure. The beam reliability goal is expressed as a tolerance to beam trip frequencies according to beam trip durations. These tolerances may be translated to values of Mean Time Between Failures (MTBF). The MYRRHA accelerator main beam requirements are presented in Table 2 below:

Table 2: MYRRHA accelerator main beam requirements

Particle		Protons
Beam energy		600 MeV
Peak beam current		2.5–4 mA
Beam duty factor		10^{-4} –1
Time structure	Microstructure	CW
	Nominal macrostructure	[redacted]
Beam power stability		[redacted]
Footprint on target		Circular, ø 85 mm
Footprint stability		±10% (1 s integration time)
Beam trip tolerance	$\tau > 3$ s	10 per 100 day period
	0.1 s $< \tau < 3$ s	100 per day
	$\tau < 0.1$ s	∞
Corresponding MTBF	$\tau > 3$ s	250 hours

Each 17 MeV MYRRHA injector line is designed to provide optimal acceleration efficiency with a minimized number of components. Doubling the whole 17 MeV injector provides a hot stand-by spare one able to quickly resume beam operation in case of any failure in the main one. The fault-recovery procedure is based on the use of a switching dipole magnet connecting the two injectors through a 'double-branch' Medium Energy Beam Transport (MEBT) line (see Figure below).



Each injector line is composed with the following elements:

- 30 kV ECR proton source
- 2 meters long Low Energy Beam Transport (LEBT) magnetic line,
- 4 meters long 176.1 MHz 4-rod RFQ,
- 20 meters long booster composed of 15 room temperature CH cavities interlaced with magnetic quadrupole doublets,
- 15 meters MEBT,

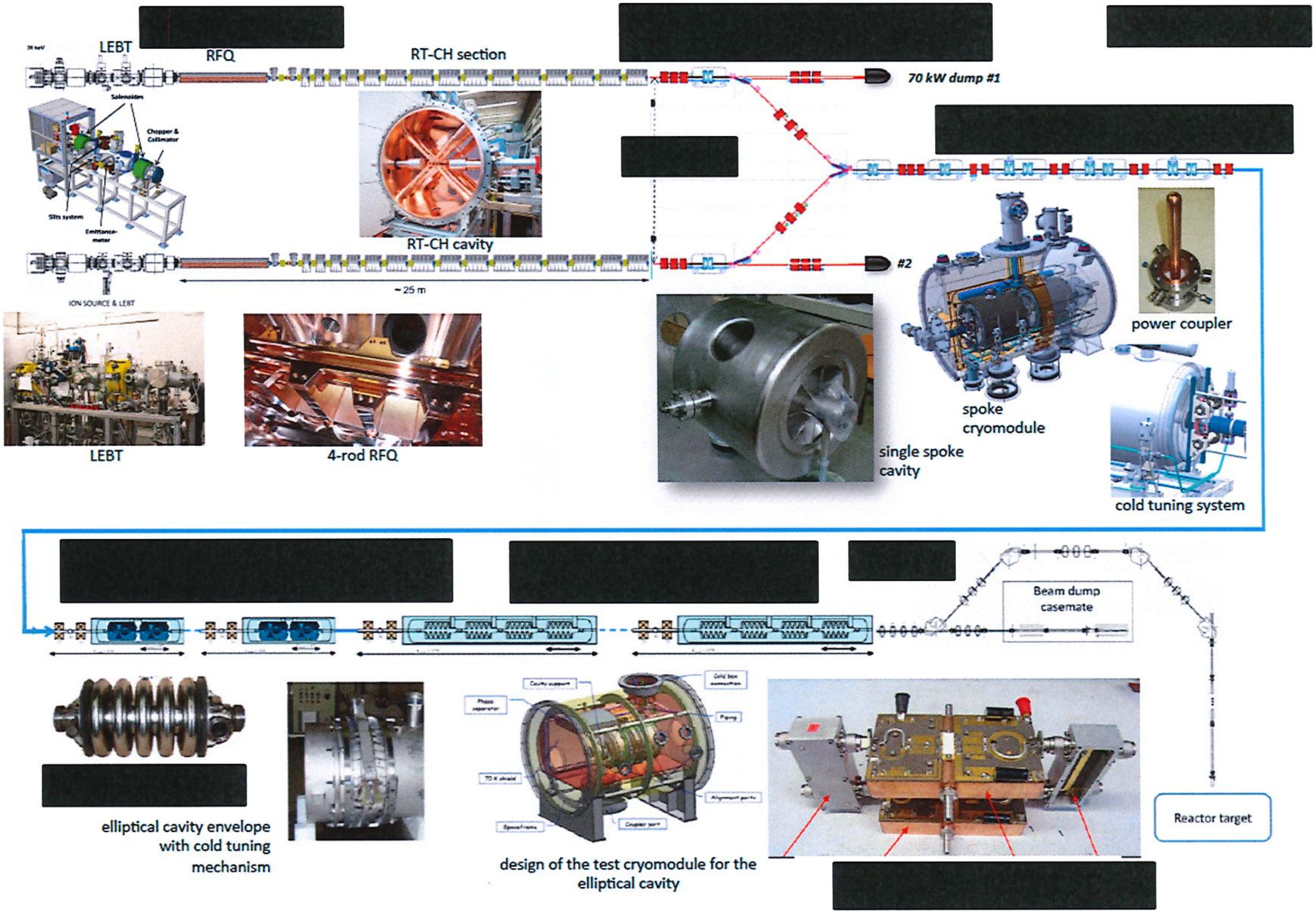
The MYRRHA main superconducting LINAC then brings the beam from 17 MeV to its final energy 600 MeV over about 240 meters (as shown in figure 2 here below). It is composed of a periodic array of independently powered superconducting cavities. Three distinct cavity families are used to cover the full energy range:

- the first section until 100 MeV consist of 30 cryogenic modules containing each a pair of 352.2 MHz single Spoke cavities,
- the next section until 200 MeV consists of 18 interconnected 352.2 MHz Double-spoke cavities
- the final section until 600 MeV consists of 72 interconnected 704.4 MHz Nb-elliptical 5-cells cavities

A final High Energy Beam Transport (HEBT) line finally injects the proton beam onto the spallation target located inside the reactor. This beam line is composed of four 45° bending magnets going up from the LINAC tunnel, and then down through the reactor hall into the sub-critical core located in the nuclear building.

To achieve the reliability goal, each cavity is powered by its dedicated RF amplifier. Highly modular RF amplifiers based on Solid State technology (LDMOS power transistors) and advanced RF power combination techniques are applied in all 3 frequency domains (172.1 MHz, 352.2 MHz, 704.4 MHz). Each transistor typically provides ~1 kW of RF power. This relatively low RP power contributes to a reliable operation, while leaving room for future optimization.

All the superconducting cavities will be operated at 2K in order to minimize perturbations and to obtain the best possible reliability performance. The production of 2K Helium will be local in the cold valve boxes, with one valve box for each of the cryomodules. This redundancy is in accordance with the LINAC fault tolerance goal. The cryogenic plant and distribution system will be a commercially available industrial supply, comparable in size and cooling power to one sector (1/8th) of CERN's LHC.



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[redacted]
[redacted]
[redacted]

Figure 2: The 100 MeV accelerator

1.9.2 MYRRHA Reactor

1.9.2.1 Primary system – general design

The MYRRHA reactor consists of a pool-type Accelerator Driven System (ADS) cooled by liquid lead-bismuth eutectic (LBE) operating in sub-critical mode but with also the ability, for mainly nuclear licensing needs, to operate in critical mode. All the primary systems are housed within the not-pressurized reactor vessel, which is the only component that is not replaceable. The systems comprised in the reactor vessel, connected to the reactor cover, are:

- the core unit with 211 positions which are filled with among others fuel assemblies, control rods, scram rods in the case of a critical configuration, the spallation window in case of a sub-critical configuration, experimental rigs also called In-Pile Sections (IPS), reflector assemblies, instrumentation and surveillance capsules. The fuel assemblies are typical fast reactor MOX fuel assemblies with a maximum Pu-enrichment of approximately 30%. The maximum allowable core thermal power is limited to 100 MWth;
- four primary heat exchangers connected respectively to the four independent water-cooling loops, which produces saturated steam at 16 bar absolute and condensed in aero-condensers. The four cooling loops operate in forced circulations with pumps and are designed for 110 MWth;
- two primary pumps with a combined capacity of 13800 kg/s and a head of 2.9 bar for the circulation of the lead-bismuth eutectic inside the primary system;
- two in-vessel fuel-handling machines (IVFHM), installed permanently in the reactor, handle the loading and the unloading of the fuel assemblies from the core to the in-vessel fuel storages (IVFS) and vice-versa which are integrated inside the diaphragm;
- the diaphragm is the structure separating the cold plenum from the hot plenum and houses the four in-vessel fuel storages[redacted]
- other auxiliary devices needed for the operation of the reactor such as the fuel transfer devices, the failed fuel detection devices and LBE extraction pumps.

1.9.2.2 Reactor building

The reactor building houses primarily the MYRRHA reactor, the support systems to operate the experiments, the radio-isotopes production systems and the end part of the accelerator. The 600 MeV protons are directed to the top of the containment to be bended vertically downwards into the core of the reactor as shown in figure 3.

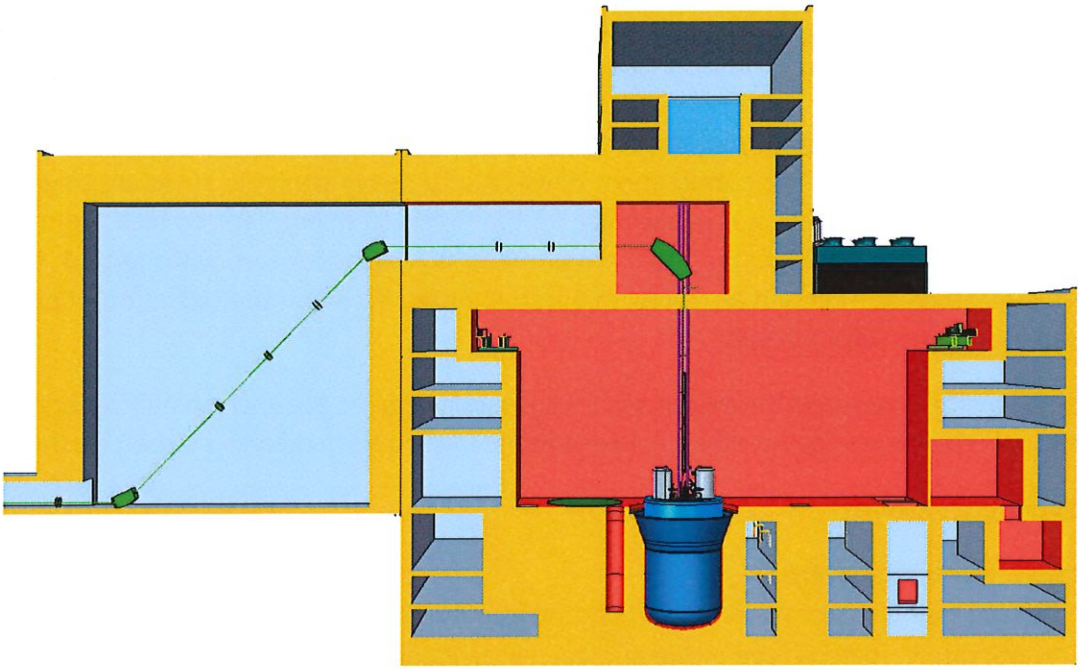


Figure 3: schematic cross-section MYRRHA reactor building

The reactor building is approximately 95 m long, 60 m wide and 75 m high of which 18 m is underground. Next to the reactor building a loading/unloading building for trucks is provided and the full-power 600 MeV beam dump. Within the same security perimeter, the storage building for spent fuel is located (see also the conceptual masterplan in the sub-chapter 'Size of the new construction for the project' below). A 3D view of the reactor building is shown in Figure 4.

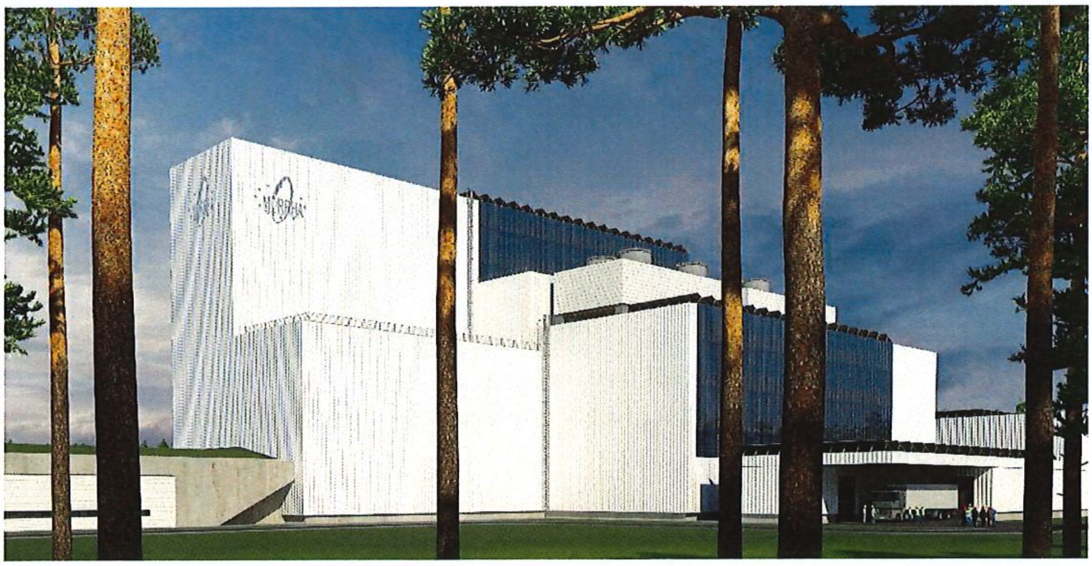


Figure 4: artistic view of the MYRRHA reactor building (accelerator on the left)

Besides the above-mentioned primary systems, the reactor building houses several auxiliary systems for the operation of the research infrastructure. The nuclear part consists of hot-cells for the treatment of activated material, of irradiated samples and of spent fuel; the radioactive LBE- and gas conditioning system; and the storage pools for radio-isotopes. The non-nuclear part consists of several conventional systems such as the electrical power supply, HVAC and depression systems, the secondary and tertiary cooling system and a number of (heavy) cranes.

The systems containing large radiological source terms are located within the containment in the center of the building. The containment consists of a heavy concrete structure to provide biological shielding which has a metallic liner on the inside to guarantee the leak tightness in normal and accident conditions. The containment is depressurized with regard to the surrounding rooms to maintain an inflow of air at all times. To avoid the oxidation of LBE, the containment is filled with nitrogen.

The reactor building protects the systems within naturally against the environmental conditions but also against external hazards like a (large) aircraft crash, a tornado and a strong earthquake.

1.9.2.3 Safety systems

Decay heat removal systems

- Decay Heat Removal system 1 (DHR1): the four independent cooling loops are designed to operate in fully passive mode and each individual loop is able to dissipate the decay heat generated by the core, the irradiated fuel inside the in-vessel fuel storage and the radioactive contaminants inside the coolant.
- Decay Heat Removal system 2 (DHR2): additional to the four redundant cooling systems, the Reactor Vessel Auxiliary Cooling System (RVACS) is a diverse passive cooling system for the hypothetical event of a loss of the four redundant cooling systems.

[redacted]

Containment in case of reactor vessel leak or break

The reactor pit with liner serves as a secondary containment in case of a reactor vessel leakage or break.

Severe accident cooling system (SAC)

In the hypothetical event of an accidental core degradation accident the severe accident cooling system will ensure the cooling of the reactor. The severe accident cooling system consists of the Reactor Vessel Auxiliary System (RVACS) in combination with the Reactor Top Cooling System (RTCS).

- The Reactor Vessel Auxiliary System (RVACS) ensures the cooling of the reactor vessel through the gap between the reactor vessel and the reactor pit as explained in the decay heat removal system 2 (DHR2). The Reactor Top Cooling System (RTCS) consists of water inlet nozzles distributed in the cover in order to evenly cool the floating fuel debris on the LBE free surface inside the reactor. This system protects the cover of the reactor. [redacted]

1.9.2.4 *Storage of new and irradiated fuel*

The intended operation cycle consists of 3 successive irradiation periods of 90 days each, separated by 30 days of short maintenance periods that would mainly be dedicated to core fuel loading and reshuffling adjustments, irradiation devices loading and unloading, systems inspection, management of dedicated irradiation rig instrumentation and minor maintenance. Two short maintenance operations will be followed by a long maintenance, a period of 90 days dedicated to major maintenance activities including fuel unloading and loading to, from and within the reactor.

During the short maintenance period, fuel is handled by the In-Vessel Fuel Handling Machines (IVFHM) from the core to the In-Vessel Storages (IVFS) integrated in the diaphragm [redacted]

In the long maintenance period, cooled spent fuel from the in-vessel fuel storage is transferred to a dedicated fuel hot cell in the reactor building. After inspection, these spent fuel assemblies are inserted into dry storage casks, which are placed in a dedicated dry storage cask building, adjacent to the reactor building. The capacity of this building is dimensioned for the storage of 40 years of operation with the possibility for further extension.

1.9.2.5 *Electrical installations*

The electrical distribution comprises the connection from the high voltage external substation, to the final MYRRHA consumers, most of them at 6,6 kV and 400 V.

Two independent lines arrive from the external grid in a high voltage level of 150 kV, which are connected to the main redundant transformers of MYRRHA. The transformer's secondary windings are connected to redundant medium voltage switchgears, constituting the main distribution in a voltage level of 15 kV. The different medium (6,6 kV) and low voltage (400 V) transformers, supplying power to the consumers of MYRRHA, are connected to this main distribution grid. The main consumers of MYRRHA, adding up to an estimated total power of [redacted]

[redacted]

The main distribution is connected to a standby power supply including a UPS and diesel generators. All consumers to be powered in the event of a loss of off-site power are connected to this emergency power supply.

1.9.2.6 Cooling water systems

Two diverse residual heat removal systems with an independent ultimate heat sink exist that will remove the residual heat in case of loss of off-site power without the need for diesel generators

The secondary cooling system - that removes the core heat of the reactor – is cooled by aero-condensers. As such, the air acts as ultimate heat sink. [redacted]

The auxiliary cooling water systems provide cooling for:

- Nuclear applications except removal of the core heat
- Non-nuclear applications, e.g.:
    - The accelerator and its subsystems
    - HVAC- and other chilled water applications

The core equipment of the auxiliary cooling water systems consists out of:

- Cooling towers
- Chillers

[redacted]

1.9.3 Proton Target Facility

The Proton Target Facility (PTF) will receive up to 0.5 mA of the 100-MeV proton beam, which will be further transported towards an Isotope Separation On-Line (ISOL) system for the production of radioisotopes and fundamental nuclear physics research in ISOL@MYRRHA facility. The operation limits will be set at 0.5 mA on non-actinide targets and 0.2 mA on actinide targets (ThCx and UCx target materials). Details on this system and its applications are given in the following section. The PTF will also contain a.o. the necessary laboratories for the manufacturing and testing of the ISOL target assemblies used for the production of radio-isotopes, a facility for handling the targets, a temporary storage for irradiated targets prior to final disposal, hot-cells for target exchange and waste sorting / treatment, a dedicated isotopes collection station that is directly connected to a radiochemistry laboratory and a special laboratory where the various experimental setups for fundamental research studies can be installed. A second irradiation pit is foreseen to enable, at a later stage, advanced nuclear research such as testing of electronic components at low beam intensity, next generation medical radioisotopes production, testing of high-power target materials or innovative target assemblies, etc.).

1.9.4 Isotope Separation On-Line (ISOL) at the ISOL@MYRRHA Facility

Radioisotopes are used every day in several fields including medical research, condensed-matter physics and nuclear physics. This technique relies on a series of subsequent steps starting with target material irradiation by a particle beam. The particles induce nuclear reactions through which the radioisotopes are produced. At the ISOL@MYRRHA facility, 100-MeV protons will impinge on a variety of targets, out of which the most frequently used will be based on a ceramic material containing natural uranium or thorium. This results in the combined fragmentation, spallation and fission of uranium or thorium, producing radioisotopes from nearly the entire nuclear landscape. One of the ISOL technique's strengths is the versatility/flexibility to produce a wide catalogue of radioisotope samples with the same infrastructure.

Under influence of high temperatures (~2,000 °C) many of the produced isotopes will evaporate from the target and will find their way towards the ion source, where some of them are ionised and extracted over a 60 kV potential difference (see the schematic representation in Figure 3). By carefully selecting the proper target configuration, target material and ionisation mechanism one can stimulate the production of a specific isotope. Ionisation is one of the steps that can have a great influence here, since the ionisation mechanism can be selected in order to facilitate the desired isotope's ionisation. MYRRHA uses a Resonant Ionisation Laser Ion Source (RILIS) that is internationally recognised as the most selective ionisation form at ISOL facilities. It consists of exciting a valence electron from the atom via resonant transitions using laser light tuned to appropriate frequencies, through intermediate states until the electron is brought beyond the ionisation threshold, leaving the atom in an ionised condition.

Once the radioisotopes have been ionised and extracted, they form a so-called Radioactive Ion Beam (RIB), which is manipulated to provide further purification via mass separation. This is achieved by flying the mono-energetic ion beam through a uniform magnetic field from a dipole magnet. Because each ion's trajectory will be determined by its mass-to-charge ratio, the magnetic field strength is tuned to select the desired mass. This results in an isotopically pure beam of radioactive ions, which can be collected to produce radioisotopes for medical applications or for fundamental physics experiments. The ISOL system parameters will be optimised for each type of radioactive ion beam to be produced.

1.9.5 Medical Isotopes production at the ISOL@MYRRHA facility

The ISOL system nature makes it an ideal tool in the search towards innovative medical isotopes. Indeed, not only does the ISOL technique offer a vast catalogue of producible isotopes, it intrinsically produces them with unmatched purity. This purity eliminates the need of complex chemical purification steps. Moreover, thanks to the on-line isotope extraction, the time between their production and the actual use can be reduced significantly, which open the way to the use of shorter-lived isotopes for patients treatment.

1.9.6 **Physics Cases for the ISOL@MYRRHA facility**

The expected ISOL@MYRRHA system merits in fundamental science should also be underlined. The facility will provide long uninterrupted periods of intense beams of long- and short-lived radioisotopes allowing research in several fields of science. The focus will therefore be on experimental programs in need of extended beam-times, which enables the implementation of an experiment class that cannot be accommodated at currently operating ISOL facilities. These are experiments hunting for very rare events, high-precision studies that need many time-consuming measurements to reduce statistical uncertainties, experiments using very accurate detection systems which intrinsically suffer from low-detection efficiency (e.g. measurements with a gamma spectrometer), experiments in need of high statistics or experimental programs which require many repeated measurements for scanning a large set of samples and beam parameters (e.g. studies in condensed-matter physics and biology).

1.9.7 **Target station for fusion material research**

For decades, SCK•CEN has been working on the development of sample miniaturisation testing techniques (SSTT) for the qualification of materials to be used in nuclear power reactors, and has successfully developed the SSTT program for reactor pressure vessel steel to extend the confidence in the database on steel used in Belgian power plants, contributing to the continuous improvement of their nuclear safety.

The extensive knowledge of SCK•CEN in the qualification of material for fission materials, its BR2 material testing reactor and the dedicated hot cells were also part of the voluntary contribution of Belgium to the Broader Approach agreement, concluded between the European Atomic Energy Community (Euratom) and Japan, aiming to complement the ITER project and to accelerate the realisation of fusion energy through R&D and advanced technologies for future demonstration fusion power reactors (DEMO).

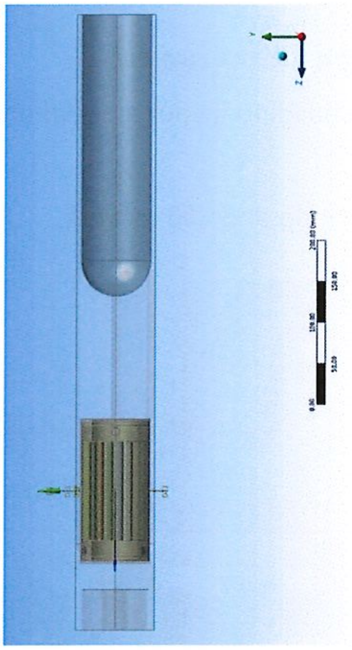
The future challenges in the qualification of materials for the demonstration of the safety roles of key components of the future commercial fusion power plants. It will require testing candidate material in representative 14 MeV neutron fluxes that cannot be obtained in existing material testing reactors, driving the design of dedicated 14 MeV neutron sources. The key to the success of these future qualification programs is the development and the validation of sample miniaturisation testing techniques for fusion materials due to the limited irradiation volumes available in the proposed 14 MeV neutron sources like IFMIF in Japan or IFMIF-DONES in Spain.

From 2015, SCK•CEN has been contributing to the development of SSTT for fusion materials using high temperature high flux (HTHF) experimental rig of the BR2 and its hot cells

MYRRHA Phase I implementation stage will play an important role in the fusion roadmap materials. The target station for fusion material research will be used to prove whether SSTT may be applied for baseline fusion materials as well as to down select advanced materials that are being developed by the fusion research community to mitigate potential accelerated degradation mechanisms found in baseline fusion materials.

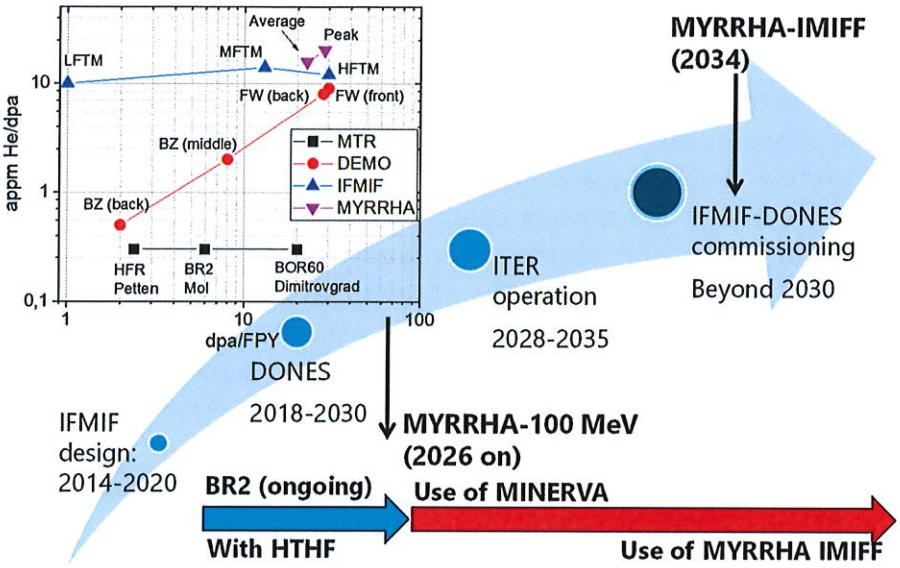
The design of the fusion target station is currently under active development at SCK•CEN. Two main irradiation concepts are being considered to produce fusion-relevant neutrons: direct irradiation by protons and/or by a dedicated spallation neutron irradiation. An irradiation position will be created in the flowing cooling water but separated from the accelerator vacuum by means of a thin metal window. The proton beam is expected to spread on a surface of about 400 cm^2 to allow sufficient cooling of the irradiation position and the window. The irradiation samples will act as a proton energy degrader, which in turn allow different irradiation conditions in function of their position in the irradiation volume. The samples are inserted in the water volume via a dedicated hot cell with a transfer tube.

Under the MYRRHA sub-critical core, a dedicated fusion material irradiation facility will be constructed under the spallation target as shown in the figure below.



The facility, named **I**nnovative **M**aterial **I**rradiation **F**acility for **F**usion (IMIFF), will offer an irradiation volume up to 3 litres and produce a fusion-relevant neutron fluence ranging between 12 to 50 dpa/year and 5-20 appm He/dpa. The IMIFF specifications are in line with the expected irradiation conditions at the first wall of DEMO, being 20-30 dpa/year and a 10 ppmHe/dpa.

The target station for fusion material research of the phase 1 of MYRRHA, first, and IMIFF will bring to the European fusion community and industry new powerful versatile irradiation facilities. The fusion research community and industry will also be able to use the services of the fully equipped material research laboratory operated by SCK•CEN in its Low-Medium High Activity lab and benefit from the irradiation services of the BR2 material testing reactor. This will create a centre of excellence on fusion material qualification to support the European Fusion Electricity Roadmap until 2050 and well beyond, as illustrated in the figure below:



1.9.8 Size of the new construction for the project

Figure 5 is a general scheme of the building layout and dimensions of the complete MYRRHA infrastructure.

The infrastructure will be +/- 500 m long and 200 m wide.

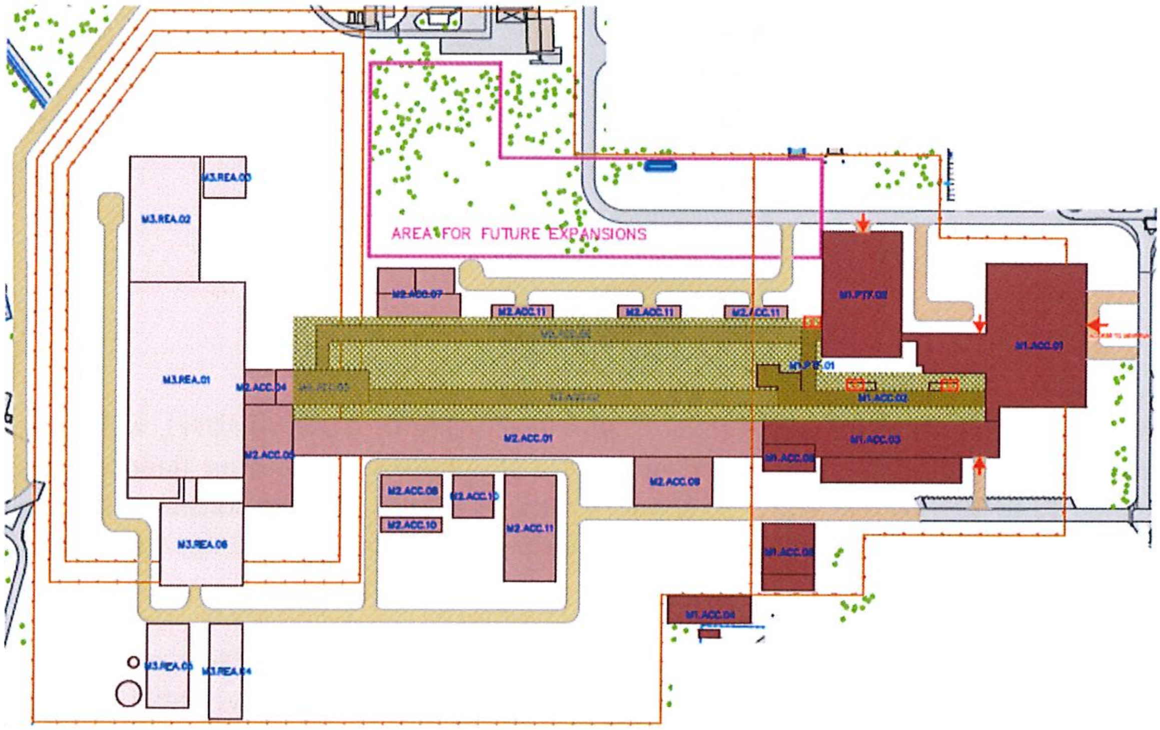


Figure 5: Masterplan full MYRRHA project (MINERVA in dark red on the right; 600 MeV accelerator in red in the middle; MYRRHA reactor in light red on the left; the green-brown part are the buried accelerator beam tunnels)

The first phase of the MYRRHA project is called **MINERVA** and shall be ready for operation in 2026.

The **MINERVA** facilities consists of the 100 MeV accelerator, the PTF building and the Fusion Target Station (FTS), being linked to each other via beam transfer tunnels. The accelerator buildings consist of a front-end building, the LINAC tunnel, the utilities building and a cryogenic plant. A schematic overview of MINERVA is given in figure 6. The facility's total length is approximately 160 m and the width is 120 m. The highest building is about 15 m high. The LINAC tunnel and target pits are a few meters underground to ease the biological shielding.

The front-end building contains offices, the control room, laboratories, storage rooms for components and waste, workshops and the injector. The building is the main entrance to the facility.

The LINAC tunnel houses the beam line from 17 MeV up to 100 MeV and a fine-tuning beam dump at the end of the line. To avoid neutron back scattering, the full-power beam dump is located adjacent to the LINAC.

Figure 6: 3D-model MINERVA looked at from the MYRRHA reactor building. PTF building on the left, utilities building on the right and Front-End building in the back

The utilities building houses the RF-amplifiers to accelerate the beam, the electrical systems and parts of the process, HVAC and I&C systems. The building is connected to the LINAC tunnel through a number of chicanes for the systems distribution.

The compressors, liquefier, cold box and a certain volume of stored helium for the cryogenic system are located in the cryogenic plant. The compressors are at a few dozen meters' distance from the LINAC tunnel in order to avoid vibrations.

The PTF building contains two target pits, a target hall for the targets transfer, hot-cells for irradiated targets and waste handling, a shipping bay for the removal of (radioactive) waste, laboratories for common and radioactive materials, an experimental hall, workshops and technical rooms for process, HVAC and dynamic confinement, electrical and I&C systems. The PTF building is 45 m by 70 m and is 15 m high.

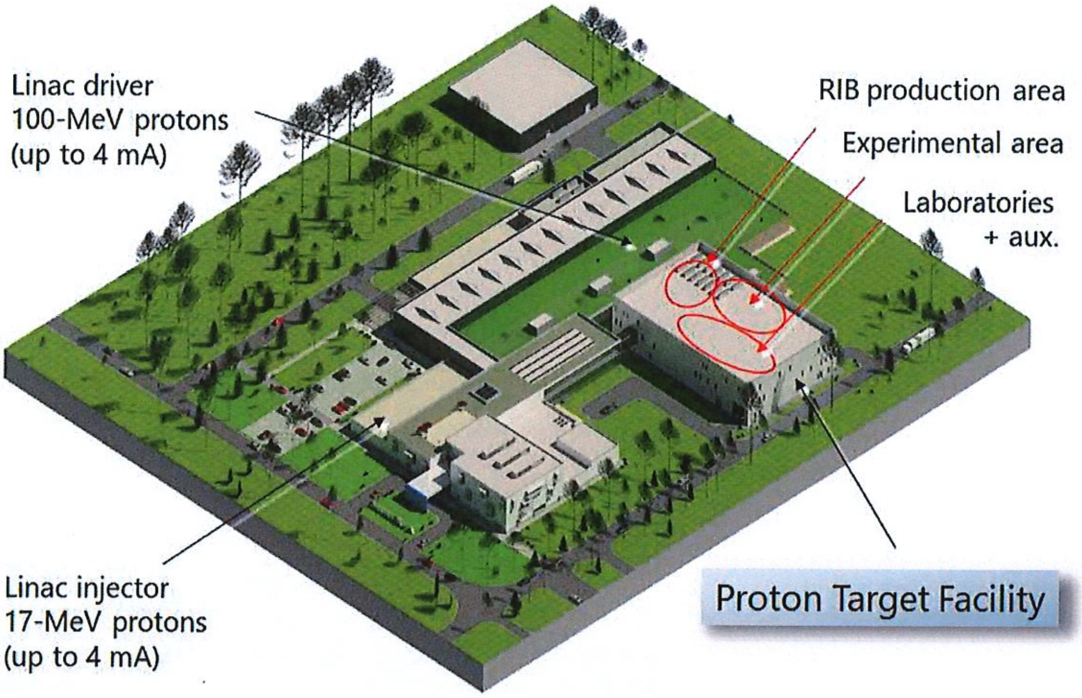


Figure 7: overview MINERVA facility

1.9.9 **Building technologies**

The conventional systems and utilities of the MYRRHA Phase 1 accelerator and Proton Target Facility are grouped under the term 'Balance of Plant (BOP)'. Besides the strictly technical requirements, the BOP follows design guidelines in order to achieve additional goals such as sustainability and life-cycle management, creating a safe and stimulating working environment, saving and recycling energy to the maximum extent possible, and to include nuclear safety and security requirements by design.

The conceptual design of the MYRRHA Phase 1, which focuses on the systems functions and requirements is now been completed.

The basic design, which includes a complete facility configuration as a whole and all buildings and systems individually, sets the framework to build the next phases. It will be allowing for separating the installation in clearly distinct work-packages, will be subcontracted during the second half of 2019 to a specialised engineering company, called the Design Engineer. The various Work-packages shall be contracted. Once the basic design is finalised, specialized contractors shall be appointed for the manufacturing and construction.

The building technologies for MYRRHA phase 2 and 3 are yet to be determined.

1.10 Costs of initial installation (in Euro) and breakdown for the main components of the costs.

The future CapEx budget for MYRRHA is 1 676 MEUR (value 2018) for the period 2019-2033 as:

MYRRHA Budget	**M€**2018
[redacted]	[redacted]
Total	**1 676**

This amount includes the future capex needed to MYRRHA including Project management, licensing, R&D, engineering, commissioning of phase 1 and the initial nuclear fuel assembly needed for the first 2 years of the MYRRHA reactor operation.

1.11 Proposed time-scale for the placing of main orders, installations and start-up, particularly the conclusion of initial contracts with suppliers of the commencement of construction work, and the planned commissioning date

In simplified terms, the full MYRRHA infrastructure consists of:

- A 600 MeV (Mega Electron Volt) accelerator ("the 600 MeV accelerator"); coupled with
- A Lead-Bismuth Eutectic (LBE) cooled reactor ("the reactor").

The timeline of MYRRHA with its phased construction consisting of **3 phases,** is as follows:

- In the **first phase (2018-2026)**, a first part of the accelerator is constructed, the so-called 100 MeV accelerator, together with a Target Station. Also during the first Phase, preparations and R&D are performed to prepare Phases 2 & 3;
- In **Phase 2 (2027-2033)** the 100 MeV accelerator is extended into the 600 MeV;
- In **Phase 3**, the reactor is constructed.

At the end of Phase 1 in 2026, a stage-gate decision is taken whether to execute Phases 2 and 3 either sequentially, or in parallel. **Figure 8** summarises MYRRHA's global planning until 2040 for the scenario where Phases 2 and 3 are executed in parallel, SCK•CEN's current working hypothesis. The planning given here is limited to 2040 whereas the facility operation is foreseen till 2065.

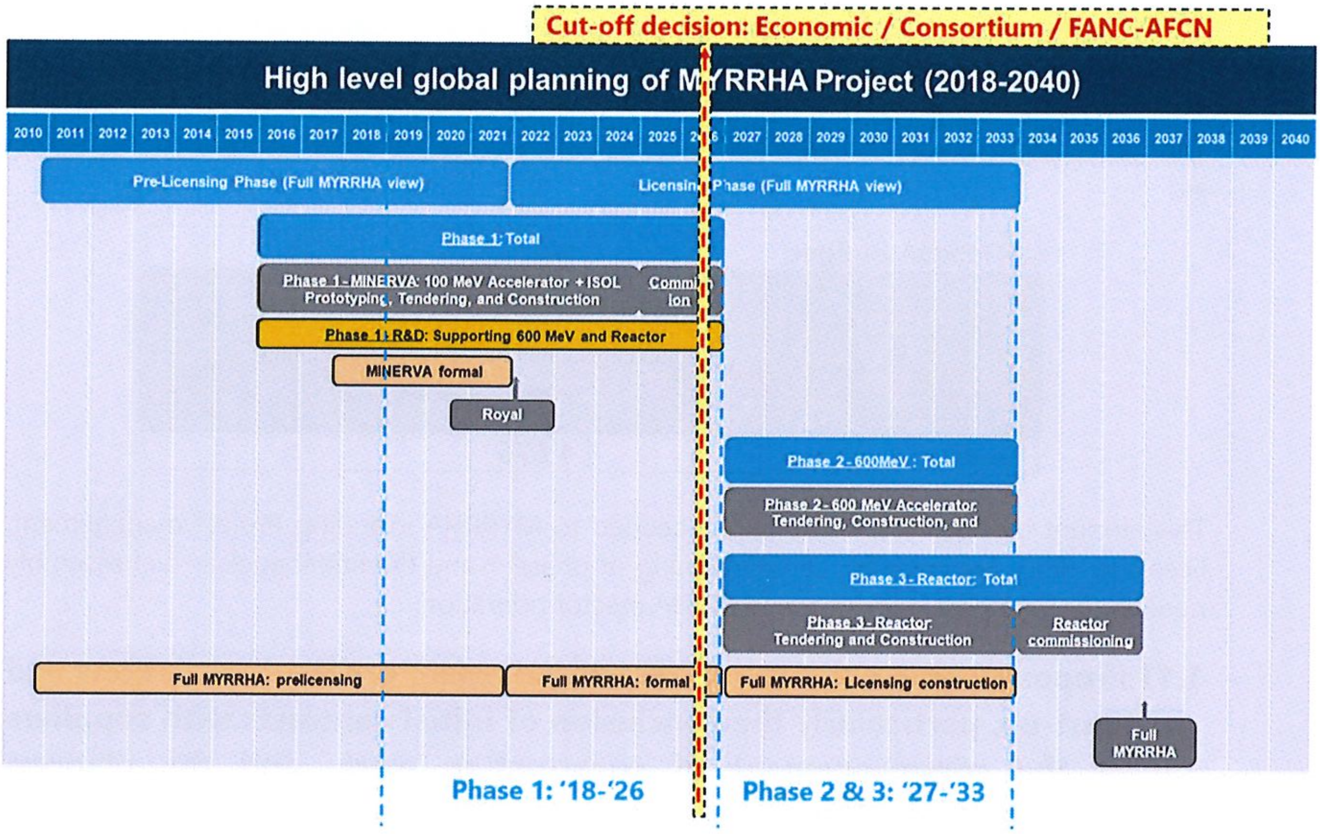


Figure 8: Phased construction and implementation plan

The detailed time-scale for the placing of main orders, installations and start-up, the awarding of initial contracts with suppliers of the commencement of construction work and the planned commissioning date are in preparation.

1.12 Description of the installation's decommissioning plans

Together with the license application, a preliminary initial decommissioning plan will be provided to FANC/AFCN as requested by Belgian law.

Already during the licensing process, an analysis will be performed on the future dismantling of the installation that will be reviewed by ONDRAF-NIRAS. The design of the installation will take into account elements that will allow facilitate the future dismantling.

During installation and commissioning, the initial dismantling plan will be established based on the as-built drawings as required by the Belgian law [1]. The initial decommissioning plan will be reviewed every 5 years by ONDRAF-NIRAS and decommissioning costs will be re-evaluated. The decommissioning provisions will be adapted accordingly, in accordance with the Belgian legislation.

The decommissioning and the management of the resulting nuclear waste will be financed using nuclear provisions setup by MYRRHA AISBL/IVZW in accordance with standard accounting principles in Belgium.

1.13 Official state authority supplying the licenses for construction and operation: duration of license for operation

The federal operating license for a nuclear research infrastructure in Belgium is granted by royal decree, after approval of the application file by the FANC/AFCN. The federal operating license is granted for an unlimited period but imposes periodic safety reviews (PSR) every ten years.

The regional authorities are responsible for non-radiological aspects of environmental protection as well as for urbanisation. Hence, the regions are authorised for granting licenses regarding non-radiological (i.e. industrial) impact on the environment and construction permits.

1.13.1 Status of the Licensing process and major milestones in the foreseen timeline

The formal licensing process of the phase 1 of MYRRHA has not yet started but informal exchange of information started already in 2016. Since beginning of 2018, SCK•CEN is having close contacts and exchanges of information with FANC/AFCN in the frame of a so-called pre-consultation phase for MYRRHA phase 1. During this phase available information on safety related subjects are discussed with the authorities. The discussion is based on deliverables demonstrating the safety of the installation (safety studies). The discussion and pre-consultation will eventually lead to the PSAR that is the basis for the licence application. This pre-consultation phase is intended to facilitate the licensing process afterwards.

This licensing process will start at the moment the License application containing the PSAR (Preliminary Safety Assessment Report) will be handed over to the nuclear safety authorities (FANC/AFCN and BelV) in September 2020 for the phase 1 of MYRRHA. MYRRHA IVZW/AISBL and SCK•CEN will provide Euratom with the Basic Technical Characteristics (BTC) of the MYRRHA phase 1 (MINERVA) in the second half of 2020. Following this transfer, the Licensing process will start and finally lead to the publication of a royal decree allowing the start of the facility construction. This royal decree is foreseen in the beginning of 2022. During the construction period, the PSAR will be upgraded into a SAR (Safety Analysis Report). This SAR will contain all the final information on the safety related subjects discussed in PSAR. The SAR will also have to be approved by the authorities before the actual start-up of the facility, meaning the accelerator commissioning, and will result in the publication of a second royal decree, the confirmation royal decree. The first accelerator commissioning tests are expected to start in 2026.

For the entire MYRRHA facility, the planning consists of three steps:

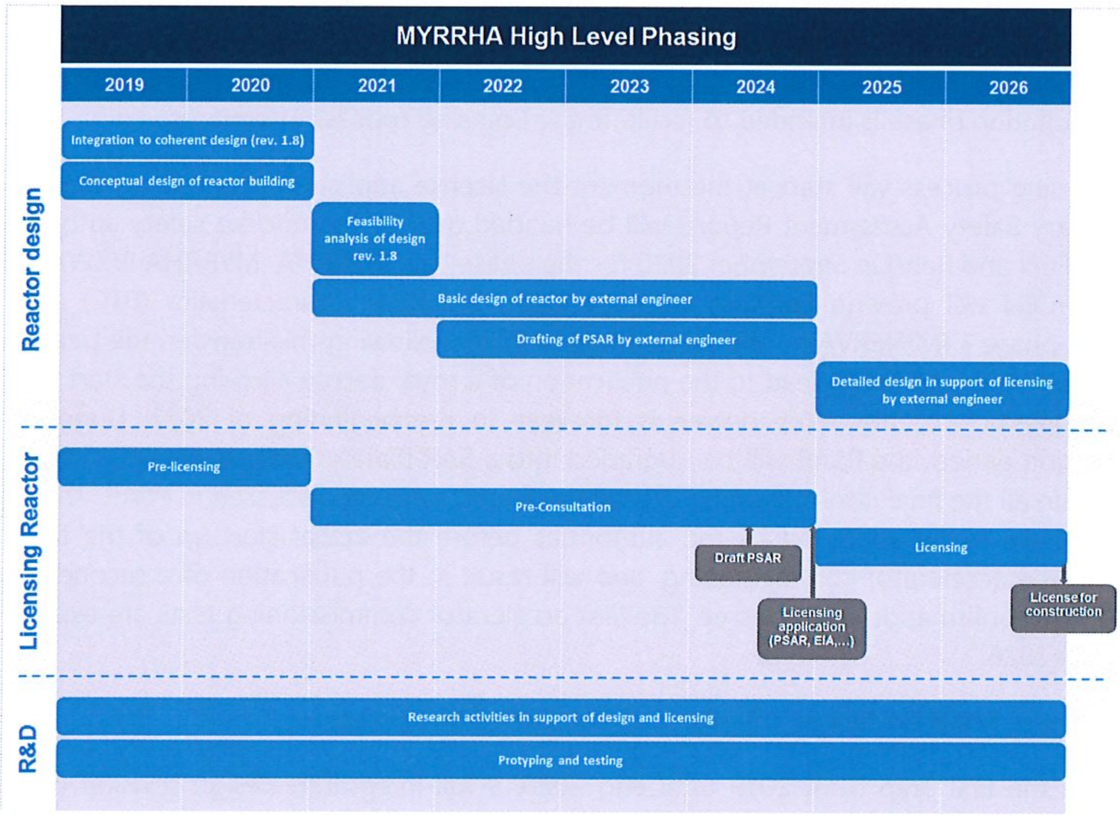
1. In the first step from 2019 until end 2020, a full-integrated design revision will be completed. This coherent conceptual design serves as input for the external engineer in step 2. This first step closes the so-called pre-licensing phase of MYRRHA.

   The MYRRHA pre-licensing phase was established specifically for such an innovative project to deal with the different innovative safety-related items. The pre-licensing phase contains a set of so-called focus points and the Design Option and Provision File (DOPF). Focus points are items that deserve special attention since they are significantly different from known technologies/methodologies and are directly safety related.

2. In this second step, starting in 2021, an industrial engineering partner or consortium experienced in reactor design and licensing will further develop the conceptual design up to a basic design necessary to establish, amongst other, the PSAR to request a license. The basic design includes a complete facility configuration as a whole and all buildings and systems individually. It sets the framework to build the next phases, allowing for separating the installation in clearly distinct work-packages. In parallel with the basic design, the required safety studies are performed and reported to the federal safety authority in the pre-consultation process. At the end of this process in 2024 the final report consisting of among others the PSAR will be delivered to the safety authority and the licensing is then formally started.

3. In the final step, starting in 2025 the safety authority will finalise the document review. During this period, some design features could be changed upon request of safety authority. It is expected that the construction permit be obtained at the end of 2026.

During the three steps SCK•CEN will contribute with licensing studies and R&D support required for design and licensing. The role of SCK•CEN evolves from an active development of the reactor design in phase 1 to a management and review role in the next phases.



1.14 Description of the supporting research and development programs

The MYRRHA R&D and Demonstration programme in support of the MYRRHA engineering and licensing includes the following domains:

- ***R&D, Prototyping, testing and assembly of accelerator components***

The reliability requirement in terms of beam trips has been identified as the MYRRHA accelerator's main technological challenge. A dedicated accelerator laboratory aiming to test the injector components of the MYRRHA LINAC up to 5,9 MeV is already in operation in the CRC of the University of Louvain-la-Neuve. First components are commissioned and tests campaigns are launched. Once the Phase 1 accelerator buildings are constructed, the accelerator's assembly and the reliability tests will be continued. In parallel, the necessary R&D will be conducted for the component development of the 600 MeV accelerator as planned in phase 2, specifically qualification of double-spoke cavities for the accelerator stage between 100 and 200 MeV.

- ***ISOL system***

The R&D activities in this domain are focused on development of targets and several main components of the ISOL@MYRRHA.

- ***Fusion material testing facility***

The fusion target station concept consists of a flowing water volume separated from the vacuum by means of a thin metal window. In such design, the proton beam should be spread on a surface of about 400 cm^2 this to allow sufficient cooling. The water fulfils the cooling needs of the window and samples and acts as a proton degrader. This latter is especially interesting since the incident proton energy on the samples simply depends on the position in the water volume, which make it simple to tune the irradiation conditions. The samples are inserted in the water volume via a dedicated hot cell with a transfer tube. Two main irradiation concepts are considered in this design: direct irradiation by protons and/or by spallation neutron irradiation. Prototyping of the target concept and its cooling system are the main topics of research

- ***Instrumentation and control***

The activities in this domain are dedicated to the development of technologies for the instrumentation and the control of the MYRRHA accelerator (beam diagnostic, beam focussing, ...) and reactor including inspection and repair (ultrasonic visualisation, oxygen-meters, HLM flow meters,...). An important part of the works is focused on the development and implementation of control strategies able to fulfil the reliability requirements of the MYRRHA accelerator.

- ***Materials selection and qualification***

The main goal of the materials R&D selection and qualification programme is to provide reliable material property data to support the design and licensing of MYRRHA reactor. LBE and irradiation effects on the mechanical properties are assessed on bulk as well as on welded material samples. To achieve this goal set-ups and testing methodologies developed by SCK•CEN are adapted in order to perform tensile, fracture toughness and fatigue tests of stainless steel in LBE environment.

- ***Nuclear fuel research and qualification for MYRRHA***

The fuel system design on the whole must be known and its behaviour must be analysed in normal operation (including transportation and/or handling), anticipated operational occurrences and accidental conditions: irradiation of mock-up fuels in normal and transient conditions of MYRRHA in existing facilities (BR2 in Belgium, BOR-60 in Russia, ACPR TRIGA in Pitesti Romania).

- ***Development and qualification of lead-bismuth technology***

LBE Technology development are carried out to demonstrate the feasibility of key components in LBE environment representative of MYRRHA as well as to develop the technology for coolant chemistry control and to study the release and capture of hazardous volatile impurities. In this frame SCK•CEN has constructed and commissioned various LBE test facilities. These facilities are used for research on liquid metal thermal hydraulics, coolant chemistry control and for the qualification of the key materials, components and procedures of the MYRRHA reactor.

- ***Verification and validation of computational codes***

The process of verification and validation of computer codes entails the justification that a computer code and its models can capture and predict a real life system. The verification part checks whether physical data and correlations are accurately implemented. The validation process aims to obtain confidence in the predictive nature of the codes and the models used therein within certain boundaries of applicability. The validation part relies heavily on experiments, ranging from single parameter experiments to complex installations as developed in the frame of the MYRRHA R&D programme (LBE loops such as E-SCAPE, COMPLOT, MEXICO, CRAFT, HELIOS, LIMETS-1-2-3 and GUINEVERE zero-power reactor).

2 Technical information (not applicable)

3 Nuclear reactors of all types and for all purposes

3.1 Name of planned reactor types and principal use(s)

MYRRHA is an Accelerator Driven System (ADS) consisting in:

- A linear proton accelerator of 600 MeV x 4 mA operation CW mode,
- A spallation neutrons source located in the centre of the nuclear sub-critical reactor,
- A subcritical LBE cooled fast reactor with a maximum power of 100 MWth

3.2 Main features of the installation

3.2.1 Accelerator

Type	superconducting linear accelerator
Beam energy	600 MeV
Nominal beam intensity	4 mA
Nominal beam delivery mode	Continuous Wave (CW)
Beam power	[redacted]
Accelerating RF cavities (NC = Normal Conducting, SC = SuperConducting) :	
Radio Frequency Quadrupole (RFQ) (1)	NC, 4-rod type, [redacted]
Drift tube cavities [redacted]	NC, CH-type, [redacted]
Main LINAC cavities [redacted]	SC, Single Spoke type, [redacted]
Main LINAC cavities II [redacted]	SC, Double Spoke type [redacted]
Main LINAC cavities III [redacted]	SC, 5-cell elliptical, [redacted]
Transverse focusing elements	magnetic quadrupoles, NC
Cryogenic power requirement [redacted]	[redacted]
Overall LINAC length	[redacted]

3.2.2 Reactor

Maximum core power:	100 MWth
Reactor power:	110 MWth
Design life:	40 years
Spallation target	
Type:	Loopless spallation window
Number of core positions:	One core position
Reactor vessel	
Type:	Cylindrical with a tori spherical head
Internal diameter:	10200 mm
Length:	15960 mm
Thickness:	110 mm
Material:	AISI 316L
Primary heat exchangers	
Type:	Tube-and-shell
Material:	AISI 316L
Number of exchangers:	4
Rated power:	27.5MW
Primary coolant fluid:	Liquid LBE

- [redacted]
- Maximum primary fluid inlet temperature: 325 °C
- Maximum primary fluid outlet temperature: 270 °C
- Secondary coolant fluid: Saturated water/steam
- [redacted]
- Secondary coolant fluid pressure: 16 bar
- Secondary coolant fluid temperature: 200 °C

Primary pumps

- Type: Axial flow pump
- Material: AISI 316L
- Number of pumps: 2
- [redacted]

3.3 Main features of the fuel elements to be used

Core

- Number of positions: 211
- [redacted]

Fuel assembly

- Assembly type: Hexagonal fuel bundle with wrapper
- Number of pins: 127
- Wrapper material: 15-15Ti
- Spacer type: Wire spacer in 15-15Ti
- Assembly length: [redacted]

Fuel pin

- Fuel type: MOX, max. 30wt.% PuO_2, natural UO_2
- Fuel pin clad: 15-15Ti
- Fuel pin dimension: [redacted]

3.4 Characteristics of the moderator and reflector

As MYRRHA is a fast spectrum reactor, there is no moderator.

Reflector: Yttria stabilised Zirconia (ZrO_2-Y_2O_3 ≈ 5%)
LBE filled assemblies

3.5 Characteristics of the primary and the secondary coolant

Primary coolant

- Composition: Lead Bismuth Eutectic
- Coolant inventory: 7800 ton
- Nominal pressure: Not pressurized
- [redacted]
- Temperatures
  - Shutdown state: 200 °C
  - Maximum core inlet temperature: 270 °C
  - Average core outlet temperature: 360 °C
  - Maximum hot plenum temperature: 325 °C

Secondary coolant

Composition: Saturated water/steam
[redacted]
Coolant fluid pressure: 16 bara
Coolant fluid temperature: 200 °C

4 References

- Royal Decree of 30 November 2011 on the safety regulations of nuclear installations[7];
- The Law of 15 April 1994 on the protection of the population and the environment against the dangers of ionizing radiation and regarding the Federal Agency for Nuclear Control (FANC/AFCN)[8] and the Royal Decree of 20 July 2001 with regard to the general regulation on the protection of the population, the workers and the environment against the dangers of ionising radiation[9];
- The 4 Royal Decrees of 17 October 2011 on Trustworthiness, Categorisation of facilities (Security areas) and transports, Physical Protection measures and Information Protection[10].
- MYRRHA business plan 2017 (SCK•CEN/22239376)

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[7] Royal Decree of 30 November 2011 on the safety regulations of nuclear installations, *Belgian State Gazette* 21 December 2011.

[8] The Law of 15 April 1994 on the protection of the population and the environment against the dangers of ionizing radiation and regarding the Federal Agency for Nuclear Control (FANC/AFCN), *Belgian State Gazette* 29 July 1994.

[9] Royal Decree of 20 July 2001, with regard to the general regulation on the protection of the population, the workers and the environment against the dangers of ionizing radiation, *Belgian State Gazette* 20 July 2001.

[10] The 4 royal decrees of 17 October 2011 on Trustworthiness, Categorization of facilities (Security areas) and transports, Physical Protection measures and Information Protection, *Belgian State Gazette* 8 and 25 November 2011.

5 List of acronyms

ADS	Accelerator Driven System
AISBL	Association Internationale Sans But Lucratif
BOP	Balance of Plant
CAGR	Compound Annual Growth Rate
CAPEX	Capital Expenditures
CDT	Central Design Team
CRC	Cyclotron Resources Centre at Louvain-La-Neuve
DEMO	DEMOnstration Power Station for Fusion
DHR	Decay Heat Removal system
DOPF	Design Option and Provision File
EIB	European Investment Bank
ESFRI	European Strategy Forum on Research Infrastructures
ESNII	European Sustainable Nuclear Industrial Initiative
F4E	Fusion for Energy
FANC/AFCN	Federaal Agentschap voor Nucleaire Controle/Agence Fédéral pour le Contrôle Nucléaire
FEED	Front-end Engineering Design
FTS	Fusion Target Station
HEBT	High Energy Beam Transport
HVAC	Heating, Ventilation & Air Conditioning
IFMIF	International Fusion Materials Irradiation Facility
ISOL	Isotope Separation On-Line
IVFHM	In-Vessel Fuel Handling Machine
IVFS	In-Vessel Fuel Storages
IVZW	Internationale Vereniging Zonder Winstoogmerk
LBE	Lead Bismuth Eutectic
LEBT	Low-Energy Beam Transport line

LINAC	Linear Accelerator
MAHG	MYRRHA Ad-Hoc Group
MEBT	Medium Energy Beam Transport
MeV	Mega Electron Volt
MFC	Multi-Functional Channels
MINERVA	MYRRHA Isotopes productioN coupling the linEar acceleRator to the Versatile proton target fAcility
MYRRHA	Multi-purpose Hybrid Research Reactor for High-tech Applications
NEA	Nuclear Energy Agency
NuPECC	Nuclear Physics European Collaboration Committee
OECD	Organisation for Economic Cooperation and Development
ONDRAF-NIRAS	Belgian waste management agency
OPEX	Operating Expenses
PRS	Pressure Relief System
PSAR	Preliminary Safety Analysis Report
PSR	Periodic Safety Reviews
PTF	Proton Target Facility
RFQ	RadioFrequency Quadrupole
RIB	Radioactive Ion Beam
RIs	Radio-Isotopes
RILIS	Resonant Ionization Laser Ion Source
RTCS	Reactor Top Cooling System
RVACS	Reactor Vessel Auxiliary Cooling
SAC	Severe accident cooling system
SAR	Safety Analysis Report
SET-Plan	European Strategic Energy Technology Plan
VITO	Vlaamse Instelling voor Technologisch Onderzoek