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ACCELERATORS FOR APPLICATIONS IN ENERGY AND NUCLEAR WASTE TRANSMUTATION

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Abstract

SCK CEN is at the forefront of Heavy Liquid Metal (HLM) nuclear technology worldwide with the development of the MYRRHA accelerator driven system (ADS) [1]. An Accelerator Driven System (ADS) is a concept using high power proton accelerators in energy production and nuclear waste transmutation. Amongst typical beam performance requirements, the operational reliability of the accelerator is exceptionally demanding. The advantages and challenges of different driver options, like cyclotrons and linacs, are evaluated and worldwide design studies are summarized. The MYRRHA design is based on a 600 MeV superconducting proton linac. The first stage towards its realization was recently approved to be constructed by SCK CEN in Belgium. The 100 MeV linac will serve as technology demonstrator for MYRRHA as well as driver for two independent target stations, one for radio-isotope research and production of radio-isotopes for medical purposes, the other one for fusion materials research. MYRRHA in its final implementation is envisaged as an international large research infrastructure open for scientific and industrial user-communities.

MOTIVATION FOR ADS

While alternative, renewable energy sources combined with increased efficiencies are being developed, there remains the clear need for complementary large-scale base-load power stations and a strategy for handling the already accumulated nuclear waste. Conventional reactors feature the following two main issues:

- Operation of a critical system: The neutrons emitted during the fission of one atom hit other atoms and trigger their fission. In order to keep the system running, a multiplication factor of K = 1 must be used. This factor is defined by the fission material and reactor configuration. The only control is given by the insertion of additional absorbing elements that limit the exponential increase of activity.
- Radiotoxic waste with >10.000 years half life time. The minor actinides (Np, Am, Cm) are the main concern due to their high radiotoxicity, heat emission and long half-life.

The concept of an ADS [2] is to load the reactor with subcritical mass of fissile material ($k_{eff} < 1$). Left alone, this implies that the chain reaction would naturally shut down exponentially with time (in the order of 10^{-5} to 10^{-6} sec). In order to keep the chain reaction going and hence the power level constant in the reactor, additional neutrons are provided from a spallation target inside the reactor that is driven by a high-power proton particle accelerator. In case of issues, the accelerator is turned off and the chain reaction automatically slows down. This also removes the need for highly enriched fission material.

These kinds of reactor will be loaded with the Plutonium and Minor Actinides "waste" resulting from the reprocessed spent fuel of the nuclear power plants. With help of the subcritical reactor, transmutation can be efficiently achieved. In contrast to conventional reactors, an ADS can safely transmute a large amount of these minor actinides. As shown in Fig. 1, an ADS allows to reduce the time needed to store the nuclear waste to a level that is compatible with the lifetime of human-made buildings.

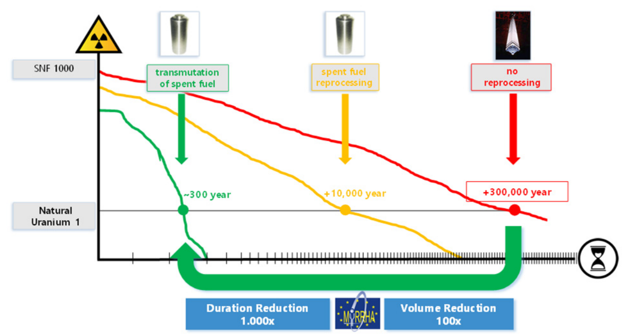

Figure 1: While reprocessing of waste and reuse of Pu in conventional reactors allows to reduce the burden of nuclear waste radiotoxicity by a factor 30, an ADS can reduce the life time by a factor 1000.

REQUIREMENTS ON THE ACCELERATOR

While the exact requirements on the particle accelerator will depend on the design details of the reactor, the following beam requirements can be stated:

- Particle type: protons, readily available and accelerated for neutron production
- Energy: >500 MeV to be in the region of usable neutron production cross-section.
- Beam power: multiple MW, achieving a usable neutron density.
- Reliability: MTBF > multiple weeks. Any beam trips must be resolved within a few seconds as otherwise this would impose severe thermal stress on the reactor materials and components. Furthermore, any longer beam trip requires a time-consuming reactor restart lasting a few days.
- The beam emittances are only important to safely accelerate and transport the beam through the accelerator.

From this list the following additional design choices can be derived:

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- CW operation allows to reduce the space charge and the stress on the spallation target. Furthermore, it allows certain technological choices, in view of reliability, e.g. solid-state amplifiers.
- Need for a fault tolerance scheme: Within a few seconds, a failure is detected, a new configuration is deployed and a fast recommissioning to full power beam operation is performed.

While some groups study also more exotic configurations like an FFAG, the two main options are cyclotrons or superconducting linacs.

DIFFERENT APPROACHES – PAST AND PRESENT

When the first ideas of an ADS were developed, the only available accelerator type that could be envisaged to fulfil the requirements were normal conducting cyclotrons. Based on the successful operation of the 600 MeV, MW-class normal-conducting cyclotron at PSI (with a 72 MeV injector cyclotron), various concepts were proposed e.g. [3]. Since then many ideas have been followed studying e.g. stacked cyclotrons [4] mainly focusing on R&D aspects of super conducting cyclotrons making them more reliable, more compact or make the need for an injector cyclotron obsolete.

Since the advent of superconducting RF-technology, the option of linacs was also studied. The first example is the MYRRHA project that has been studied since 1999 [5, 6] and is explained in more detail in the following section. This approach was then also chosen by the Chinese ADS-project C-ADS [7] which was launched in 2011 and operates a test-injector since 2014. The target of the current extension phase is 500 MeV at 5 mA, with the final configuration aiming for 1 GeV at 15 mA. The reliability target is to have less than 25.000 beam trips/year with $1\ s < t < 10\ s$. The second example, the MYRRHA project is detailed in the following chapters.

MYRRHA AND ITS FIRST IMPLEMENTATION PHASE (MINERVA)

Overview

The concept of an ADS has been studied at SCK CEN in Mol (Belgium) since a long time [5] which lead to the inception of the MYRRHA project in 1998 [8]. MYRRHA (Multi-purpose hYbrid Research Reactor for High-tech Applications) aims to demonstrate the ADS concept at pre-industrial scale, demonstrate transmutation and being a multipurpose and flexible irradiation facility. The project follows a staged implementation plan:

- Phase 1, also referred to as MINERVA: SC linac to 100 MeV, 4 mA CW
- Phase 2: extending linac to 600 MeV
- Phase 3: sub-critical reactor connected to the linac

The funding for the initial 100 MeV stage was approved by the Belgian government in 2018 and implementation has started at SCK CEN, the Belgium nuclear research center, which currently operates three nuclear reactors for research, education and industry, e.g. production of radio-pharmaceuticals.

The MINERVA ground breaking is planned for summer 2022, and first accelerator operation in 2026. The project is setup to only have a relatively small core team at SCK CEN leveraging many international collaborations and aims to outsource significant parts to our industrial partners.

The 2nd and 3rd phases of MYRRHA are envisaged to be implemented until 2035, within an international consortium.

Accelerator Configuration

While in the final configuration the accelerator will feature two injectors and accelerate a 4 mA CW beam to 600 MeV, the first implementation stage, will be limited to 100 MeV with a single injector (see Fig. 2).

The injector consists of an ECR ion source, a LEBT with space charge compensation and two solenoids, a 4-rod RFQ (IAP Frankfurt) [9] and a normal conducting 176.1 MHz CH-cavity section including several rebunching cavities accelerating to 17 MeV (Fig. 3).

After the injector switchyard, the protons will be accelerated in superconducting single 352.2 MHz spoke cavities to 100 MeV. The design of the Single Spoke cavity has been developed by IPNO and first prototypes have been successfully tested [9]. There are 30 cryo-modules each housing 2 cavities. Each cavity is powered by a dedicated solid-state amplifier.

In the later extension stage, it is envisaged to switch at 100 MeV to switch to medium beta cavities, where it is not yet finally decided which type, spoke at 352.2 MHz or elliptical at 704.4 MHz, they are going to be. At around 200 MeV it is then foreseen to switch to 704.4 MHz elliptical cavities with a matched beta of 0.7.

As the RF-cavities in the injector must be individually matched to the beam energy, no serial redundancy is possible and thus two injectors are envisaged for MYRRHA. On the other hand, serial redundancy with approx. 30% overhead is applied in the single spoke section. Local compensation schemes have already been established, where the loss of one RF-cavity is compensated by the next neighbours. In the future, a global compensation scheme will be studied to distribute the compensation over the whole machine. While this will increase the requirements on the control system to reconfigure many elements, it will allow to use the cavities more effectively. More detailed studies e.g. on the orbit correction as part of the fast recommissioning are under investigation.

Operational Injector Test Stand

Since March 2019 an injector test stand is available and accelerating protons (Fig. 4). It is used to test critical components like the RFQ or the CH cavities along with the solid-state amplifiers as well as e.g. the space charge compensation in the LEBT.

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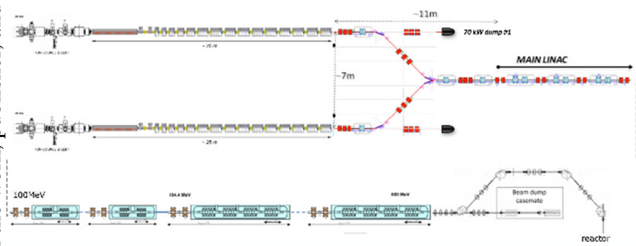

Figure 2: The final MYRRHA accelerator layout. In the first implementation phase, called MINERVA, only a single injector and up to 100 MeV (the single spoke section) will be constructed.

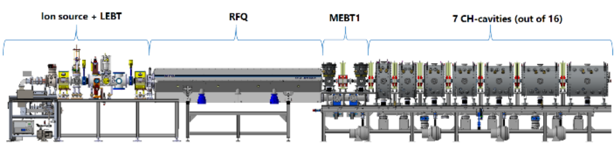

Figure 3: Sketch of the injector test stand as foreseen to be installed. The elements up (including) the RFQ are already available.

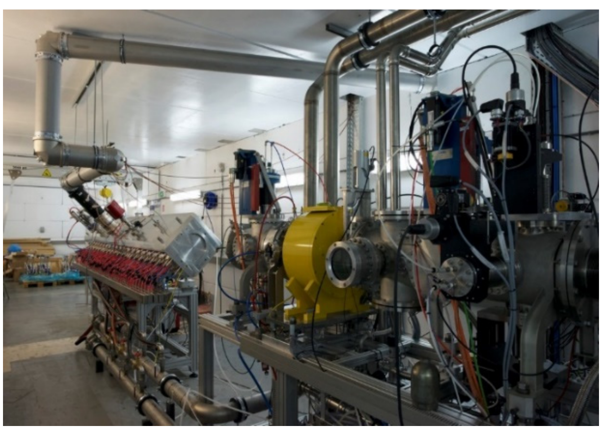
Figure 4: Photo of the injector test stand just before the connection of the RFQ to the LEBT.

Proton Target Facility

While MINERVA will at the start be used to develop and prove to meet the stringent reliability requirements, it will in parallel be able to deliver beam to a Proton Target Facility (PTF). It is envisaged to be able to kick up to 0.5 ms beam pulses with up 250 Hz to the PTF facility, allowing up to 0.2 mA on fissile material targets or up to 0.5 mA on non-fissile material targets [10].

The generated high-purity Radioactive Ion Beams (RIB) will be used for physics experiments and as well as radioisotopes collection for medical research and use purpose [10].

The layout of this Isotope Separation OnLine (ISOL) system is strongly inspired by the proton target irradiation facility ARIEL at TRIUMF. The chosen modular facility providing required shielding whilst allowing ISOL components maintenance and target replacement. The envisaged conceptual target configuration is shown in Fig. 5.

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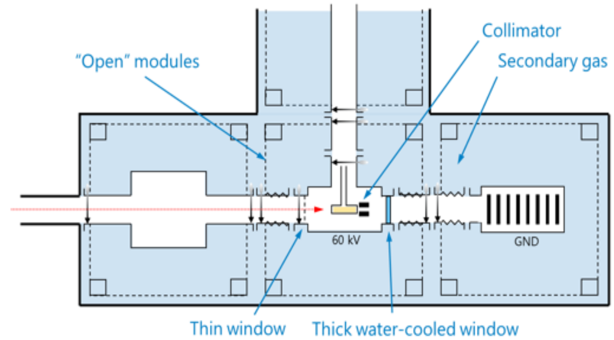

Figure 5: Envisaged ISOL target concept where up to 0.5 mA beam current is available in parallel to the other user stations.

REFERENCES

[1] H. Aït Abderrahim and P. D'hondt, "MYRRHA: A European Experimental ADS for R&D Applications, Status ad Mid-2005 and Prospective towards Implementation, *Journal of Nuclear Science and Technology*, Vol. 44, No. 3, pp.491-498, 2007. doi:10.1080/18811248.2007.9711313

[2] C. Rubbia *et al.*, "An energy amplifier for cleaner and inexhaustible nuclear energy production driven by a particle beam accelerator", 1993, CERN/AT/93-47.

[3] C. Rubbia *et al.*, "Conceptual design of a fast neutron operated high power energy amplifier", 1995, CERN/AT/95-44.

[4] P. McIntyre *et al.*, "Superconducting Sector Magnets for a Flux-Coupled Isochronous Cyclotron Stack." *IEEE Trans. on Appl. Superconductivity*, vol. 13, No. 2, Jun. 2003. doi:10.1109/TASC.2003.812669

[5] H. Aït Abderrahim and Y. Jongen, "ADONIS: the proton-driven neutron source for radioisotope production", 1999, *in IAEA-TECDOC-1065.*

[6] H. Saugnac *et al.*, "The MYRRHA Spoke Cryomodule Design", in *Proc. LINAC'14*, Geneva, Switzerland, Aug.-Sep. 2014, paper TUPP082, pp. 613-615.

[7] Shuhui Liu *et al.*, "Commissioning of China ADS demo Linac and baseline design of CiADS project", *2020 J. Phys.: Conf. Ser.,* vol. 1401, p. 012009. doi:10.1088/1742-6596/1401/1/012009

[8] MYRRHA, https://myrrha.be/

[9] S. Lamprecht *et al.*, "Conditioning of the Frontline Cavities of the MYRRHA Injector", in *Proc. 10th Int. Particle Accelerator Conf. (IPAC'19)*, Melbourne, Australia, May 2019, pp. 895-897. doi:10.18429/JACoW-IPAC2019-MOPTS023

[10] L. Popescu *et al.*, "High-power target development for the next-generation ISOL facilities", *Nucl. Instr. Meth. Phys. Res. B*, vol. 463, pp. 262-268, 2020. doi.org/10.1016/j.nimb.2019.05.023