Accelerator reference design for the MYRRHA European ADS demonstrator

J.L. Biarrotte*, A.C. Mueller, CNRS-IN2P3 IPN Orsay, France, H. Klein, IAP Frankfurt, Germany
P. Pierini, INFN LASA Milano, Italy, D. Vandeplassche, SCK•CEN Mol, Belgium

Abstract

The goal of the MYRRHA project is to demonstrate the technical feasibility of transmutation in an Accelerator Driven System (ADS) by building a new flexible irradiation complex in Mol (Belgium). The MYRRHA facility requires a 600 MeV accelerator delivering a maximum proton flux of 4 mA CW operation. Such a machine belongs to the category of the high-power proton accelerators, with an additional requirement for exceptional reliability: because of the induced thermal stress to the subcritical core, the number of unwanted beam interruptions should be minimized down to the level of about 10 per 3-month operation cycle, a specification that is far above usual proton accelerators performance. This paper describes the reference solution adopted for such a machine, based on a so-called "fault-tolerant" linear superconducting accelerator, and presents the status of the associated R&D.

INTRODUCTION

SCK•CEN, the Belgian Nuclear Research Centre in Mol, has been working for several years on the design of a multi-purpose irradiation facility in order to replace the ageing BR2 reactor, a multi-functional materials testing reactor (MTR), in operation since 1962. MYRRHA, a flexible fast spectrum research reactor (50-100 MWth) is conceived as an accelerator driven system (ADS), able to operate in sub-critical and critical modes. It contains a proton accelerator of 600 MeV, a spallation target and a multiplying core with MOX fuel, cooled by liquid lead-bismuth (Pb-Bi). MYRRHA is planned to be operational at full power around 2023. The 2010-2014 period will be especially dedicated to the engineering design of the facility and the associated R&D programme. This work will build on the results of the recently achieved EUROTRANS FP6 programme, and be supported by the new EURATOM FP7 projects CDT, FREYA and MAX. Construction and assembly of the components is planned in the period 2015-2019, and three years (2020-2022) are foreseen for the full commissioning of the facility. The total investment cost is currently estimated at 960M€ [1].

To feed its sub-critical core with an external neutron flux source, the MYRRHA facility requires a 2.4 MW proton accelerator (600 MeV, 4 mA max) operating in CW mode, and producing a very limited number of unforeseen beam interruptions per year. This stringent reliability requirement is motivated by the fact that frequently-repeated beam interruptions can induce high thermal stresses and fatigue on the reactor structures, the target or the fuel elements, with possible significant damages especially on the fuel claddings. Moreover these beam interruptions can dramatically decrease the plant availability, possibly implying plant shut-downs of tens of hours in most of the cases. The present tentative limit for the number of allowable beam trips is therefore 10 transients longer than 3 seconds per 3-month operation cycle. This specification has been slightly relaxed compared to the initial requirements inspired from the PHENIX plant operation analysis, because the MYRRHA core exhibit a quite large thermal inertia due to the large LBE pool it offers, and because higher margins seems to exist concerning the fuel and cladding behaviour during these transients.

The conceptual design of the MYRRHA accelerator has been developed during the PDS-XADS and the EUROTRANS projects, following reliability-oriented design practices from the early design stage [2]. It is a superconducting linac-based solution, bringing a high RF-to-beam efficiency thanks to superconductivity (optimized operation cost) and an excellent potential for reliability, both in the highly modular main linac, which is designed to be intrinsically "fault-tolerant", and in the front-end section where a hot stand-by redundant injector, with relatively fast switching capability, can be installed.

THE 17 MEV INJECTOR FOR MYRRHA

The first part of the injector is presently composed of a 50 kV ECR proton source, that is proven to be a very reliable technological choice [3], a short magnetic LEBT line and a 3 MeV 4-vane copper RFQ operating at 352 MHz. This RFQ, slightly overdesigned to handle up to 30 mA CW beams with close to 100% transmission for all currents, is about 4.5 m long, and operates with moderated Kilpatrick factors (~1.7).

This 3 MeV "classical" injection section is then followed by an innovative and promising energy booster, that is a combination of two normal conducting and four superconducting CH (Crossbar H-mode) DTL structures, as shown in Fig. 1, bringing the beam up to 17 MeV. Focusing is ensured by quadrupole triplets and superconducting solenoids inside the cryomodule containing the superconducting CH cavities, and a couple of re-bunchers is used to perform the longitudinal beam adaptation.

The design of the DTL structures is based on the KONUS beam dynamics concept [4], which allows

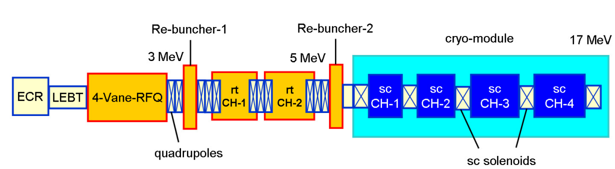

Figure 1: The 17 MeV injector for MYRRHA.

* biarrott@ipno.in2p3.fr

exhibiting excellent accelerating efficiency at these low energies while having very low power consumption in CW operation. Multiparticle beam-dynamics simulations of the whole injector show very good beam behaviour and low sensitivity to errors. The proposed solution can especially cope with various beam currents [5], with very reasonable emittance growth of about 10% at 5 mA. The beam beta-profile is of course frozen by design, so that any accelerating section failure will inevitably lead to a beam interruption. For this reason and in order to enhance the machine reliability, it is proposed to duplicate the injector to provide a hot stand-by injection line able to relieve the main one in case of failure. The detailed design of the corresponding connecting MEBT line is still to be worked out in details.

The actual construction and test of the initial part of the MYRRHA injector, consisting of (at least) the ECR ion source and the RFQ, is foreseen to happen within the 2011-2015 period. To efficiently meet this goal, R&D activities are being actively pursued, building on the EUROTRANS conclusions. In particular, the present 352 MHz injector design will be soon compared to a 176 MHz alternative solution. The use of a lower frequency would indeed allow using a 4-rod RFQ as first accelerating structure instead of a 4-vane-RFQ. This choice could minimize costs for R&D and production, construction time and the overall technical risk, keeping the main linac above 17 MeV unchanged. To feed the comparison, the results from the planned 2-month long-run reliability beam test of the 3 MeV high-current IPHI 352 MHz 4-vane RFQ will be also taken into account as far as possible. This IPHI RFQ, that encountered technological difficulties linked to its brazing procedures, is still presently under final construction at CEA Saclay.

R&D on CH-type cavities is also being actively pursued. A full design of the two MYRRHA room temperature CH-cavities is planned, together with high power RF tests using a relevant prototype. A new optimized superconducting CH-cavity prototype is also presently under construction. It is based on the design of the 19-gap SC CH prototype, first of its kind, which had been successfully built and tested at IAP Frankfurt with excellent measured gradients of 7 MV/m [6]. This new cavity will be tested under realistic conditions in a horizontal cryomodule, fully equipped with high power couplers and tuning systems, and then possibly with beam at the GSI facility.

THE MYRRHA 600 MEV MAIN LINAC

From 17 MeV, a fully modular superconducting linear accelerator accelerates the proton beam up to the final energy, over a total length of about 240 m from the ion source. This CW linac is composed of an array of independently-powered spoke and elliptical cavities with high energy acceptance and moderate energy gain per cavity – low number of cells and very conservative accelerating gradients (around 50 mT and 25 MV/m peak fields nominal operation point) – in order to increase as much as possible the tuning flexibility and provide sufficient margins (about 20 to 30%) for the implementation of the fault-tolerance capability. As a matter of fact, such a scheme should allow to pursue operation despite some major faults in basic RF components: in the case of a loss of any cavity or power loop unit, it should be possible to fairly quickly recover the nominal beam characteristics on target by increasing the accelerating fields and retuning the phases of the RF cavities directly neighboring the failed one [7].

The architecture of the 600 MeV MYRRHA linac is summarized in Table 1. This design has been optimized in terms of total length using the CEA Saclay codes' package [8]. It is based on the use of regular focusing lattices, with not-too-long cryostats and room-temperature quadrupole doublets in between. Such a scheme provides several advantages: easy maintenance and fast replacement if required, easier magnet alignment at room-temperature and no fringe field issues, possibility to provide easily reachable diagnostic ports at each lattice location, and last but not least, nearly perfect optical lattice regularity (no specific beam matching required from cryostat to cryostat). The beam tuning has been performed with great care: phase advances are limited below 90° per lattice and parametric resonances are avoided, phase advances per meter are tuned as continuous as possible so as to ease the beam matching, and a very safe and constant longitudinal acceptance is kept all along the accelerator, especially at the 350 to 700 MHz frequency jump transition, as recommended in [9]. This "conservative" optical design leads to very safe beam behaviours, with low sensitivity to mismatched conditions or current fluctuations, and producing very low emittance growths (about 5%). No beam loss is observed in the multi-particle simulations that have been performed using a 100 000 particles input distribution, coming from the simulation of the 17 MeV full injector.

Several R&D activities are on-going, both on the design of the different MYRRHA cryomodules, and on the study of the fault-tolerance implementation. In particular, a reference "fast failure recovery scenario" has

Table 1: Architecture of the MYRRHA Main SC Linac

Section #	**#1**	**#2**	**#3**
E_{input} (MeV)	17.0	86.4	186.2
E_{output} (MeV)	86.4	186.2	605.3
Cav. technology	Spoke	Elliptical	
Cav. freq. (MHz)	352.2	704.4	
Cavity geom. β	0.35	0.47	0.65
Nb of cells / cav.	2	5	5
Focusing type	NC quadrupole doublets		
Nb cav / cryom.	3	2	4
Total nb of cav.	63	30	64
Nominal E_{acc}* (MV/m)	5.3	8.5	10.3
Synch. phase (deg)	-40 to -18	-36 to -15	
5mA beam load / cav (kW)	1 to 8	3 to 22	17 to 38
Section length (m)	63.2	52.5	100.8

*E_{acc} is normalized to $L_{acc}=N_{cell}\beta_{opt}\lambda/2$, & given at β_{opt}

been defined in the case of an RF loop failure, that consists in stopping the beam for one to a few seconds while achieving the appropriate retuning using the following sequence: 1. the RF fault is detected (or anticipated) via suited dedicated diagnostics and interlocks, and a fast beam shut-down is triggered; 2. the new correcting field and phase set-points (previously stored in the low level RF cards' memory during the commissioning phase) are updated; 3. the failed cavity is quickly detuned (using piezoactuators) to avoid the beam loading effect, and the associated failed RF loop is cut off; 4. once steady-state is reached, beam re-injection is triggered. Simulations made with MATLAB Simulink show that such a procedure should be achieved in a few hundreds of milliseconds at maximum. A suitable digital LLRF system is currently being developed [10].

It is planned to experimentally test specific sequences of this fast fault-recovery scenario using a prototypical 700 MHz cryomodule, funded by the EUROTRANS project, that has been designed from scratch, built and installed in a former cyclotron pit at IPN Orsay. This module contains a 5-cell β 0.47 elliptical SC cavity and will be fed with a 80 kW CW IOT; it is presently being commissioned [11]. R&D on Spoke cavities is also on-going. A 352 MHz spoke cavity had been successfully tested at 4K and 2K in an "accelerator-like" horizontal cryostat configuration, fully equipped with its tuning system, magnetic shield, RF power coupler, and fed by a 10 kW solid-state amplifier [12]. These activities will be pursued, focusing on the detailed design of a MYRRHA-like spoke cryomodule.

INTERFACE WITH THE REACTOR

The objective of the final HEBT line is to safely inject the proton beam onto the spallation target located inside the reactor. This beam line is about 120 m in total from the last cryomodule, and composed of four 45° bending magnets going up from the linac tunnel, and then down through the reactor hall to the sub-critical core. It has achromatic and telescopic optics in order to guarantee the beam stability on target and to ease the tuning, and it houses the AC magnets which allow scanning the beam on target with the specified donut shape. The line is presently under detailed design phase. Preliminary statistical error studies show that the very long "naked" final drift (27m) makes the line quite sensitive to errors, inducing tight specifications for the magnets alignment (<±100 μm) or for the beam energy stability (<±1 MeV). In the dispersive region, position monitors will be able to provide information on proton energy variations and to trigger a fast safety shutdown system. The monitoring of the target will be performed using an optical beam diagnostic inspired from the VIMOS apparatus developed at PSI [13]. A full power beam dump is foreseen in the alignment of the linac, allowing for the commissioning of the MYRRHA accelerator fully independently from the reactor. The design of this beam dump will be based on the 1 MW PSI one. Finally note that it is also planned to look at the possibility to send a small part of the MYRRRHA beam to an ISOL facility by using a deflecting RF cavity located in the first part of the HEBT line, taking advantage of the 200 μs beam interruptions to be regularly produced for the on-line monitoring of the core sub-criticality.

CONCLUSION

A reliability-oriented CW superconducting linac has been identified as the reference solution for the MYRRHA ADS project, composed by a 17 MeV redundant injector followed by independently-phased modular SC cavities with fault tolerance capability. Huge R&D have been already performed in the past years, with very successful results and conclusions. These activities are being pursued, focusing on several main aspects: linac design consolidation, investigations on a 176 MHz injector alternative, experiments focused on fast fault-recovery scenarios, buildings definition, and several activities on system optimization (RF system, with special focus on solid-state amplifiers at 700 MHz, detailed reliability analyses, etc.). The goal would be to be ready for a possible MYRRHA construction phase by 2015.

REFERENCES

[1] See e.g. http://myrrha.sckcen.be/
[2] J-L. Biarrotte et al, "Accelerator reference design for the European ADS demonstrator", TC-ADS workshop, March 2010, Karlsruhe, Germany.
[3] R. Gobin et al, "Saclay High Intensity Light Ion Source status", Proc. EPAC 2001, Paris, France.
[4] U. Ratzinger and R. Tiede, "Status of the HIIF RF linac study based on H-mode cavities", Nucl. Instr and Meth. in Phys. Res. A 415 (1998), pp. 229-235.
[5] C. Zhang et al, "Reliability and current-adaptability studies of a 352 MHz, 17 MeV, continuous-wave injector for an accelerator-driven system", Phys. Rev. ST – Accel. & Beams, Vol. 13, 080101 (2010).
[6] H. Podlech et al, "Recent developments on superconducting CH-structures and future perspectives", Proc. LINAC 2008, Victoria, Canada.
[7] J-L. Biarrotte, D. Uriot, "Dynamic compensation of an rf cavity failure in a superconducting linac", Phys. Rev. ST – Accel. & Beams, Vol. 11, 072803 (2008).
[8] See http://irfu.cea.fr/Sacm/logiciels/index.php
[9] R. Duperrier et al., "Frequency jump in an ion linac", Phys. Rev. ST Accel. Beams 10, 084201 (2007).
[10] F. Bouly et al, "LLRF developments toward a fault tolerant Linac scheme for ADS", these proceedings.
[11] F. Bouly et al, "Developments and test of a 700 MHz prototypical Cryomodule for the MYRRHA ADS proton linear accelerator", these proceedings.
[12] F. Bouly, S. Bousson et al, "Developments of 350 MHz and 700 MHz prototypical cryomodules for the EUROTRANS ADS proton linear accelerator", TC-ADS workshop, March 2010, Karlsruhe, Germany.
[13] K. Thomsen, "VIMOS, near-target beam diagnostics for MEGAPIE", Nuclear Instr. & Methods in Phys. Research A 575 (2007) 347-352.