THE MYRRHA LINEAR ACCELERATOR*

D. Vandeplassche, SCK•CEN, Mol, Belgium
J.-L. Biarrotte, Institut de Physique Nucléaire, Orsay, France
H. Klein, H. Podlech, Institut für Angewandte Physik, Frankfurt am Main, Germany

Abstract

Accelerator Driven Systems (ADS) are promising tools for the efficient transmutation of nuclear waste products in dedicated industrial installations, called transmuters. The Myrrha project at Mol, Belgium, placed itself on the path towards these applications with a multipurpose and versatile system based on a liquid Pb-Bi (LBE) cooled fast reactor (70 MWth) which may be operated in both critical and subcritical modes. In the latter case the core is fed by spallation neutrons obtained from a 600 MeV proton beam hitting the LBE coolant/target. The accelerator providing this beam is a high intensity CW superconducting linac which is laid out for the highest achievable reliability. The combination of a parallel redundant and of a fault tolerant scheme should allow obtaining an MTBF value in excess of 250 hours that is required for optimal integrity and successful operation of the ADS. Myrrha is expected to be operational in 2023. The forthcoming 4-year period is fully dedicated to R&D activities, and in the field of the accelerator they are strongly focused on the reliability aspects and on the proper shaping of the beam trip spectrum.

INTRODUCTION

Accelerator Driven Systems are presently considered worldwide as potential and promising candidates for the industrial transmutation of very long living nuclear waste into isotopes with much shorter life times. This method can significantly alleviate the burden upon geological disposal. However, the road towards the industrial transmuter still features many R&D steps. SCK•CEN's Myrrha project [1] is one of these steps, aiming at demonstrating the feasibility and operability of a subcritical core fed by an external neutron source obtained by a high power proton accelerator.

The object of this contribution is the accelerator that may be used for the Myrrha project in its ADS configuration. The Myrrha reactor will be cooled by liquid Pb-Bi eutectic. In the ADS mode this reactor will have a thermal power of $\sim$ 70 MW$_{\text{th}}$. The core geometry is optimized for a proton energy of 600 MeV, where the Pb-Bi coolant is also used as spallation target.

The required beam current varies between 1 and 4 mA, depending on the burnup of the nuclear fuel and on its reshuffling scheme. This beam is delivered in Continuous Wave mode, from above and through a beam window. The most significant characteristics of the beam are summarized in Table 1.

Table 1: Myrrha Beam Characteristics

particle	protons
energy	600 MeV
current	4 mA
time structure	CW, with 200 μs holes, $\geq$ 1 Hz repetition, for subcriticality monitoring
beam delivery to the reactor	vertically from above through an achromatic beam line and window
beam stability	energy $\pm$1%, current $\pm$2%, position and size $\pm$10%
beam shape on target	circular r = 40 mm, flat power density, by AC scanning magnets
MTBF	$>$ 250 h

The CW operation makes the current requirement moderate with respect to peak current requirements in pulsed beam facilities. This is fortunate, because it leaves the necessary margin for an ADS specific requirement imposed to the accelerator: its reliability should be such that the number of beam trips longer than 3 s remains under 10 during a 3-months operational period of the Myrrha reactor. Shorter beam trips are tolerated without limitation. This beam trip frequency is very significantly lower than today's reported achievements on comparable accelerators [2]. Therefore the reliability is the main challenge and the permanent R&D consideration.

CHOICES AROUND RELIABILITY

The reliability constraint implies that the Mean Time Between Failures of the beam delivery must be $>$ 250 h. Obviously, a failure is defined as a beam trip $>$ 3 s. It has been shown that an important increase of the "natural" MTBF may only be obtained if a single failing element does not automatically imply a global failure [3], which means fault tolerance. The key for implementing the fault tolerance concept is redundancy. Parellel redundancy uses 2 elements for 1 function. For clear economical reasons this parallel scenario has to be minimized. Serial redundancy, on the contrary, replaces a missing element's functionality by retuning adjacent elements with nearly identical functionalities. It is closely linked to a modular structure.

For the Myrrha accelerator the following 3 principles have been adopted regarding the reliability goal:

---

* Work supported by the European Atomic Energy Community's Seventh Framework Programme under grant agreement nr. 269565 (MAX project)

1. use of components far from their limits
2. redundancy, maximally serial
3. repairability

In agreement with several high power accelerator projects, in operation or to be built, the adopted technical solution for Myrrha is that of a superconducting linac [4, 5, 6]. The CW operation strengthens this choice. Its compatibility with the 3 reliability principles is shown.

1. The fundamental current limitation is much higher than 4 mA, and present day superconducting RF cavity performances allow adopting comfortable margins.
2. The modular architecture of a superconducting linac is in excellent agreement with the serial redundancy scheme. Further conditions are (i) an independent amplitude and phase control of each individual cavity, and (ii) tolerant beam dynamics, permitting an inactive cavity and a subsequent retuning of adjacent cavities without loss of the nominal beam properties. The critical issue of the former condition is the switching time of 3 s. Regarding the latter condition beam dynamics studies have been performed [7], yielding the certainty of the theoretical feasibility of the fault tolerant scheme. The scheme was also verified experimentally in the SNS [8]. The issue of the error analysis in the presence of faulty cavities is an outstanding R&D item.
3. The repairability is required in combination with the redundancy schemes for guaranteeing continued availability. The modularity of the SC linac is an asset for this aspect as well.

In practice the redundancy scheme will be:

1. A medium and high energy section, highly modular, based on individual, independently controlled cavities. In this section the serial redundancy may be applied successfully so as to yield a strong fault tolerance. The function of a faulty cavity may typically be taken over by 4 adjacent cavities.
2. A low energy section (injector), in which the modularity and fault tolerance are not applicable since it is based on multicell cavities. Here parallel redundancy has to be applied, and so 2 complete injectors are foreseen. The transition energy between the 2 sections is 17 MeV.

On the reliability of ancillary equipment very promising progress is being made in (i) solid state (SS) based RF amplifiers, (ii) modular DC power supplies.

In the medium and high energy sections the fault tolerance has to be realized via the Low Level RF control. A novel fully digital LLRF has been prototyped in view of this particular application [9]. It will be tested on a prototype single cavity cryomodule during the upcoming R&D activity period.

It is considered that the combination of a fault tolerant linac, of intrinsically reliable auxiliaries, of powerful early fault detection techniques and of adequate repairability, the beam MTBF goal of 250 h is realistic.

Table 2: Independently Phased Linac Data

	spoke	**elliptical**	
geometrical β	0.35	0.47	0.66
frequency [MHz]	352	704	704
# cells/cavity	2	5	5
cavity length [mm]	570	830	1050
cryomodule config.	3 cav.	2 cav.	4 cav.
# cryomodules	21	15	16
section length [m]	63.2	52.5	101.0
energy range [MeV]	17-86.4	→ 186	→ 605

SPECIFIC LINAC IMPLEMENTATION

Intermediate and High Energy

For the high energy part of the Myrrha superconducting linac the technological choice is conventional: elliptical cavities at 704 MHz will be used from 90 MeV up to 600 MeV. This elliptical section is realized with 2 geometrical families — see Table 2.

For the intermediate energy part, 17 to 90 MeV, spoke cavities at 352 MHz are retained [10]. For maximal compatibility with the fault tolerance scheme, a 2-cell cavity is chosen. Table 2 shows further characteristics.

Throughout the intermediate and high energy sections the quadrupole doublets and the diagnostics are installed in short warm sections between the cryomodules.

Injector

The injector part (0 – 17 MeV) is based on unconventional solutions, chosen in view of optimal efficiency, considering that this section has to be doubled for reliability.

A 352 MHz version of the injector, developed in the EUROTRANS framework [11], has been described [12]. With a focus on Myrrha, the benefits of a 176 MHz injector have been investigated in view of optimized efficiency and reliability but at the cost of a reduced maximum beam current capability. The benefits are:

- a lower input energy of the copper CH-DTL
- reduced power densities in the copper structures
- a lower input energy of the RFQ, thus a reduced electrostatic potential on the ion source
- the possibility to consider a 4-rod RFQ instead of a 4-vane version, yielding relaxed tolerances, easier adjustments and significant savings.

Additionally, the study of this 176 MHz scheme shows the possibility of reducing the inter-electrode voltage in the 4-rod RFQ for a Kilpatrick factor of 1.2. The schematic layout of the 176 MHz injector is shown in Fig. 1. It is based on a sequence of 3 subsections:

1. a 4-rod RFQ, accelerating to 1.5 MeV
2. 2 copper multicell CH-DTL structures with KONUS focusing scheme for acceleration to 3.5 MeV
3. 4 superconducting multicell CH-DTL structures, combined in 1 single cryomodule, for acceleration to 17 MeV. This solution extends the advantages of the superconducting RF to the lowest possible energy. A superconducting multicell CH structure has been very successfully tested in a vertical cryostat [13]. The test with beam of a fully functional single cavity cryomodule is under preparation [14].

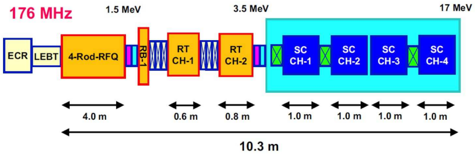

Figure 1: Schematic overview of the 176 MHz injector.

This scheme will be the object of a dedicated R&D program, which at first will focus on the 4-rod RFQ:

- construction of a short test section for thermal behaviour investigation
- construction of the full-size RFQ and its installation for beam tests. An ECR ion source and a dedicated LEBT section will be installed in front of the RFQ, a diagnostic section and a beam dump after it.

Further R&D Activities

It is also foreseen to launch a collaborative R&D program aiming at the detailed engineering design of each of the different cryomodules of the Myrrha linac. These design activities should be terminated by the end of 2014, then followed by construction and extensive testing in view of design feedback.

CONCLUSION

The use of RF superconductivity has become a recurrent choice in present day or future high power accelerators, and the global layout of the Myrrha linac is in line with several other proton beam projects, like e.g. ESS, EURISOL, ProjectX.

The fact that the Myrrha accelerator has, after all, relatively modest performance requirements in terms of instantaneous beam current gives the possibility of using an alternate and simplified injector design.

The reliability of the accelerator, expressed as a very reduced number of allowable beam trips longer than 3 s, is the outstanding challenge and calls for a high level of intrinsic and fundamental fault tolerance besides a particular care for the reliability of every subsystem.

The R&D program is strongly focused on this reliability issue, both from a fundamental and theoretical point of view, and from that of the practical and technological implementation.

REFERENCES

[1] A. Aït Abderrahim, AccApp'11, Knoxville, April 2011, to be published.

[2] J. Galambos, T. Koseki and M. Seidel, Hadron Beams 2008, Nashville, Tennessee, CPL04, p. 489 (2008).

[3] L. Burgazzi and P. Pierini, Reliability Engineering and Systems Safety 92,4 (2007) 449.

[4] `http://neutrons.ornl.gov/APGroup/Papers/SC_LinacCDR.pdf`.

[5] M. Lindroos, C. Oyon and S. Peggs, SRF2009, Berlin, FROBAU02, p. 918 (2009).

[6] "Final Report of the EURISOL Design Study", J.C. Cornell, ed., published by GANIL, Caen (2009).

[7] J.L. Biarrotte and D. Uriot, Phys. Rev. ST – Accel. and Beams 11 (2008) 072803.

[8] J. Galambos, S. Hendersen, A. Shishlo and Y. Zhang, HPPA5, Mol, Belgium, May 2007, edited by Nuclear Energy Agency (2008) p. 161.

[9] F. Bouly, J.L. Biarrotte and C. Joly, LINAC'10, Tsukuba, September 2010, MOP082, to be published.

[10] F. Bouly, S. Bousson, J.L. Biarrotte, P. Blache, F. Chatelet, C. Commeaux, P. Duthil, C. Joly, J. Lesrel, G. Olry, E. Rampnoux, H. Saugnac, S. Barbanotti and P. Pierini, OECD/NEA Workshop on Technology and Components of Accelerator driven Systems, Karlsruhe, March 2010, to be published.

[11] J.L. Biarrotte, A.C. Mueller, H. Klein, P. Pierini and D. Vandeplassche, LINAC'10, Tsukuba, September 2010, TUP020, to be published.

[12] C. Zhang, M. Busch, H. Klein, H. Podlech, U. Ratzinger, R. Tiede and J.L. Biarrotte, Phys. Rev. ST – Accel. and Beams 13 (2010) 080101.

[13] H. Podlech, Habilitationsschrift (Frankfurt University, 2008)

[14] H. Klein, private communication