THE MYRRHA LINEAR ACCELERATOR

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For the Myrrha Accelerator Collaboration

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Accelerator Driven Systems are promising tools for the efficient transmutation of nuclear waste products in dedicated industrial installations (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 PbBi (LBE) cooled fast reactor (80 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 CW superconducting linac which is laid out for the highest achievable reliability. The combination of a 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 mainly focused on the reliability aspects.

I. 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 would 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 approximately 80 MW_{th}. The core geometry is optimized for an impinging proton beam energy of 600 MeV, where the Pb-Bi coolant is also used as the heavy target for the spallation reaction. At this energy the neutron yield is around 15 per incoming proton.

Combining these data it is found that the required beam current varies between 2.5 and 4 mA, depending on the burnup of the nuclear fuel. This up to 2.4 MW beam is delivered to the core in Continuous Wave mode, from above and through a beam window. The most significant characteristics of the beam are summarized in table I.

TABLE I. Myrrha beam characteristics

Accelerated particle	protons
Beam energy	600 MeV
Beam current	4 mA
Time structure	CW, with 200 µs holes at 1 Hz repetition for sub-criticality monitoring
Beam delivery to the reactor	Vertically from above through an achromatic beam line
Beam stability	Energy ±1% Current ±2% Position and size ±10%
Beam shape on target	Circular r=40 mm, flat or donut shaped power density, by AC scanning magnets
MTBF	> 250 h

The figures definitely label the Myrrha accelerator as a high power machine, but due to its CW operation the current requirement may be considered as moderate, especially with respect to peak current requirements in pulsed beam facilities. This is fortunate, because it leaves the necessary margin for another, ADS specific, requirement imposed to the accelerator: its reliability should be such that the number of beam trips lasting for more than 3 s remains under 10 during an operational period of the Myrrha reactor, i.e. 3 months. It is worthwhile noting that shorter beam trips are tolerated without limitation. This beam trip frequency is very significantly lower than today's reported achievements on comparable accelerators,[2] and therefore the issue of reliability is considered as the main challenge and as the permanent consideration in all the R&D activities pertaining to this accelerator.

II. CHOICES AROUND RELIABILITY

The reliability constraint may be reformulated in the following way: the Mean Time Between Failures of the beam delivery must be > 250 h. Obviously, a failure is defined as a beam trip > 3 s. In the accelerator context the beam MTBF is a combination of many subsystems and sub-subsystems, all contributing fundamentally to a successful beam generation. It has been shown that in such a configuration an important increase of the "natural" MTBF may only be obtained if a single failing element does not automatically imply a global failure.[3] Moreover, such a fault tolerance can only be effective if it is accompanied by 2 more constraints:

1. A realistic switching time.
2. A Mean Time To Repair that is much shorter than the MTBF of the failing element.

In the Myrrha case the switching time (which is the sum of the fault detection time and the reconfiguration time) is clearly 3 s. This is definitely short, but is felt as a realistic goal in view of the performances of present day digital electronics. The MTTR is an engineering issue which will deserve continuous attention during the whole design phase.

The key for implementing the fault tolerance concept is redundancy. Parellel redundancy is common, and 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:

1. Use of components far from their limits
2. Fault tolerance, hence redundancy, with a maximum of the serial version
3. Repairability

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

1. The beam current handling capability is much higher than 4 mA: fundamental current limitation is far away. On the other hand present day superconducting RF cavity performances are high enough for adopting comfortable margins to be a viable option.
2. The architecture of a superconducting linac, consisting of a sequence of nearly identical, modular RF cavities, is in excellent agreement with the concept of the serial redundancy scheme. Further conditions are (i) an independent amplitude and phase control of each individual cavity, and (ii) tolerant beam dynamics, permitting the presence of an inactive cavity and a subsequent retuning of adjacent cavities without loss of the nominal beam properties. The former condition is a mere question of layout of the RF system and of its low level control – the switching time of 3 s will be the critical issue. The latter condition is of a fundamental nature. Several beam dynamics studies have already been performed,[7] yielding the certainty of the theoretical feasibility of the fault tolerant scheme. Furthermore the scheme was verified experimentally in the SNS.[8] The remaining issue is the error analysis in the presence of faulty cavities – this is an outstanding R&D item.
3. The repairability is an engineering design issue. It 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 reliability scheme (or, equivalently, the redundancy scheme) will be as follows. The linac will consist of 2 clearly distinct sections:

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 (or injector), in which the modularity and fault tolerance are not applicable: this section is mainly based on multicell cavities. Here redundancy has to be applied in its parallel form, and so 2 complete injectors are foreseen. The transition energy between the 2 sections is put to 17 MeV. At this energy a fast dual input switching magnet will be installed for merging the 2 injector lines.

In the end, the aimed at reliability of the Myrrha accelerator will only be realized if, besides the accelerator layout itself, all ancillary equipment is compatible with this goal. It is extremely probable (but to be further analyzed) that redundancy will be a key issue in many of these systems as well. And also there serial redundancy will be economically much more favourable than the classical duplication. Domains in which very promising progress is being made in this perspective are: (i) solid state (SS) based RF amplifiers, (ii) modular DC power supplies. They deserve all our attention and a supported R&D effort. Note that the CW nature of the Myrrha beam, hence without peak power demand, is well adapted to a SS solution of the RF amplifier.

As stated before, the allowed switching time in case of a fault is 3 s. In the medium and high energy section 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, in which accelerator reliability will be the actual hot issue through topics like

- Advanced beam dynamics and error studies
- Reliability modeling studies
- Optimized injector design
- Prototype cryomodule operation

As a conclusion on the accelerator reliability issue a few keypoints may be highlighted. The MTBF goal of 250 h is considered as realistic, but if and only if

1. A redundancy scheme is implemented all along the linac. The maximum switching time of 3 s is challenging but appears as feasible.
2. The intrinsic reliability of every component (of the linac itself, but also of all the auxiliaries) conforms to the global MTBF goal. A quantification of this needs a detailed reliability modeling.
3. The aspects of early fault detection, fault diagnostics and repairability are carefully considered at the engineering design level.

III. SPECIFIC LINAC IMPLEMENTATION

III.A. Intermediate and high energy

For the high energy part of the Myrrha linac the technological choice of the superconducting cavities is conventional for a high power proton linac: elliptical cavities at a frequency of 704 MHz will be used from 90 MeV up to the final 600 MeV. This elliptical section is realized with 2 geometrical families – see table II.

TABLE II. 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 configuration	3 cav. /cryom.	2 cav. /cryom.	4 cav. /cryom.
# cryomodules	21	15	16
Section length [m]	63.2	52.5	101.0
Energy range [MeV]	17-86.4	→186	→605

For the intermediate energy part, 17 MeV to 90 MeV, the technology of the spoke cavities is retained.[10] The principal architect is the Institute for Nuclear Physics (IPN) in Orsay, France. The operating frequency is 352 MHz. For maximal compatibility with the fault tolerance scheme, a 2-cell cavity is chosen. Table II shows further characteristics.

The intermediate and high energy sections together (total length of 216.5 m) are called 'the independently phased linac'. Throughout this linac the focusing elements (quadrupole doublets) and the diagnostics are installed in short warm sections between the cryomodules.

III.B. Injector

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

The principal architect of this section is the Institute for Applied Physics (IAP) in Frankfurt, Germany. A 352 MHz version of the injector has been described.[11] It is based on a sequence of 3 subsections:

1. A particularly flexible and versatile 4-vane RFQ, accelerating to 3 MeV
2. 2 copper multicell CH-DTL structures for acceleration to 5 MeV
3. 4 superconducting multicell CH-DTL structures, combined in 1 single cryomodule, for the acceleration till 17 MeV. The rationale of this solution is of course to extend the advantages of the superconducting RF to the lowest possible energy. Today a superconducting multicell CH structure has been very successfully tested in a vertical cryostat.[12] The test of a fully functional single cavity cryomodule with beam is under preparation.[13]

The 352 MHz layout was developed in the framework of the FP6 EUROTRANS project,[14] in which a common accelerator layout was envisaged for the ADS demonstrator (i.e. Myrrha) and for the industrial transmuter prototype (called EFIT). This requirement being dropped for the upcoming R&D program, now focused on the Myrrha case, it was decided to investigate the potential benefits of a 176 MHz injector, mainly in view of an optimized reliability but at the cost of a reduced maximum beam current capability. The expected benefits are:

- A lower input energy of the copper CH-DTL, and therefore a shorter RFQ

- 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

The pre-study of this 176 MHz scheme confirms all these benefits, and adds 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. This scheme is now considered as the preferred one for the Myrrha injector, and it will be the object of a dedicated R&D program.

In a first time period this R&D program 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. A commercial 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.

At a later stage long term reliability runs may be envisaged, and a copper CH-DTL structure might be added.

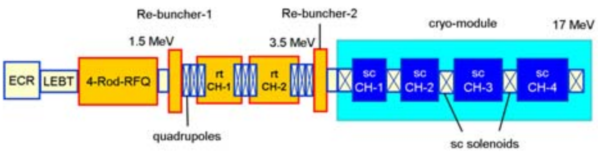

Fig. 1. Schematic overview of the 176 MHz injector

III.C. Further R&D activities

In parallel with the injector R&D activities it is foreseen to initiate another collaborative R&D program aiming at the detailed engineering design of each of the different cryomodules which will constitute the Myrrha linac:

- The CH-DTL cryomodule (4 CH cavities and 5 solenoids)
- The spoke cryomodule (3 single spoke cavities)
- The large elliptical cryomodule (4 5-cell elliptical cavities)

These design activities should be terminated by the end of 2014 (this date corresponding to the Myrrha Project International Review), then followed by construction and extensive testing in view of design feedback. These R&D activities will be conducted by the principal architects of the respective assemblies, as they were defined earlier.

IV. 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 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.

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