HIGH POWER HADRON ACCELERATORS: APPLICATIONS IN SUPPORT OF NUCLEAR ENERGY

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New generation high power hadron accelerators are more and more required to produce intense fluxes of secondary particles for various fields of science: radioactive ions for nuclear physics, muons and neutrinos for particle physics, and of course neutrons for many applications like condensed matter physics, solid-state physics, or irradiation tools. This paper will focus on the applications of such accelerators in support of nuclear energy, and in particular on the two following cases: the International Fusion Materials Irradiation Facility (IFMIF), which asks for a 10 MW, 40 MeV deuteron beam, and the ADS (Accelerator Driven System) application for transmutation of long-lived radioactive wastes, which typically requires a 600 MeV - 1 GeV proton beam of a few mA for demonstrators, and a few tens of mA for large industrial systems. In this respect, the status of the accelerator proposed for the European MYRRHA project will be detailed and discussed.

I. INTRODUCTION

Following the tracks initiated by the construction and recent starting up of the US Spallation Neutron Source (SNS[1]) and of the Japan Proton Accelerator Research Complex (J-PARC[2]), many projects involving high-power proton – or more generally hadron – accelerators have recently emerged to support various fields of science like particle physics, nuclear physics, or neutron-based physics. Some are presently in construction (LINAC4 at CERN for the LHC upgrade[3], SPIRAL2 in France[4], CSNS in China[5], etc.), and several others are proposed or planned to be built within the next 10 to 20 years (ESS in Sweden[6], SPL for the LHC upgrade[7], Project-X at Fermilab[8], EURISOL project[9], etc.). In opposition to the existing PSI facility[10] and its high-power cyclotron, these new machines are based on MW-class linear accelerators (linacs), most of them using superconducting acceleration technology.

Two of these high-power hadron linac projects are directly supporting the development of nuclear energy: the IFMIF project[11] on the fusion side, and the MYRRHA project[12] on the fission side.

The future IFMIF facility is an irradiation tool, aiming at qualifying advanced candidate materials for the fusion reactors that will succeed to ITER. It will be constituted of two 125 mA deuteron accelerators, delivering in parallel and continuously their 40 MeV beams for a total power of 10 MW on a liquid lithium source, in order to generate an intense flux of neutrons (10^{17} neutrons/s) at 14 MeV. The implementation of this ambitious project requires as a first step the construction of prototypes of the main units. This phase, called IFMIF-EVEDA, includes three themes: prototype accelerator, lithium target and test cells. The activities, planned over a period of six years, are shared between the Team Project located at Rokkasho (Japan) and the System Groups distributed between Europe and Japan.

MYRRHA is planned to be a new multi-purpose hybrid research reactor located at SCK●CEN Mol (Belgium), the construction of which could start in 2015. It is being designed to be able to operate in both sub-critical and critical modes with the following general objectives: first, be an experimental device to serve as a test-bed for transmutation by demonstrating the Accelerator Driven System (ADS) technology and the efficient transmutation of high level waste; second, be operated as a flexible, multi-purpose and high-flux fast spectrum irradiation facility ($\Phi_{>0.75MeV} = 10^{15}$ n.cm^{-2}.s^{-1}); and third, contribute to the demonstration of the Lead Fast Reactor technology, as underlined in the EURATOM SNE-TP roadmap[13], without jeopardizing the two above objectives.

This paper will entirely focus on the design of the accelerator for MYRRHA. Detailed information on the IFMIF-EVEDA project can be found elsewhere in these proceedings[14].

II. MYRRHA BEAM SPECIFICATIONS

MYRRHA ("Multi-purpose Hybrid Research reactor for High-tech Applications") is composed of a proton accelerator, a spallation target and a ~70 MW_{th} core cooled by liquid lead-bismuth (LBE). To feed its sub-critical core with an external neutron source, the MYRRHA facility requires a powerful proton accelerator (up to 2.4 MW beam) operating in continuous mode, and above all featuring a very limited number of unforeseen beam interruptions. The up-to-date proton beam general specifications are the following:

- beam energy: 600 MeV;
- beam energy stability: better than ±1%;
- beam pulse current: 2.5 mA, and up to 4 mA for core burn-up compensation;
- beam current stability: better than ±2%;
- beam time structure: CW, with low frequency 200 μs zero-current interruptions for on-line sub-criticality monitoring of the core;
- beam footprint on the spallation target window: "donut-shape", 85 mm diameter;
- beam footprint stability: better than ±10%;
- beam reliability: less than 10 beam interruptions longer than 3 seconds during a 3-month operation period.

The 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, 10 transients longer than 3 seconds per 3-month operation cycle, comes from the EUROTRANS project conclusions[15]. 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 seem to exist concerning the fuel and cladding behaviour during these transients.

This beam trip frequency remains anyway very significantly lower than today's reported achievements on comparable accelerators (cf. Figure 1), and therefore the issue of reliability is considered as the main challenge and as the permanent consideration in all the design and R&D activities pertaining to the MYRRHA accelerator.

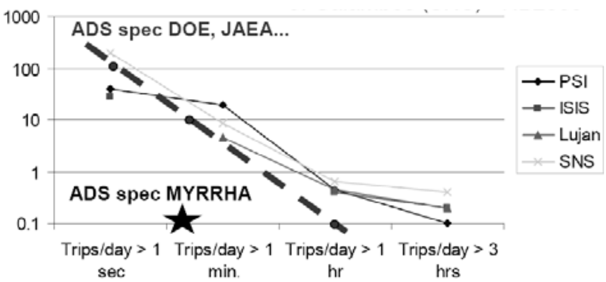

Fig. 1. Trip frequency vs. trip duration for high power proton accelerators[16] & ADS specifications.

Nevertheless, it is worth noting that several other ADS studies in Japan or in the US claim beam trip limits two orders of magnitude less stringent than the MYRRHA requirements, as illustrated in Figure 1. This is especially written in the recent DOE white paper on ADS technology[17] that: *"Finding #6: Recent detailed analyses of thermal transients in the subcritical core lead to beam trip requirements that are much less stringent than previously thought; while allowed trip rates for commercial power production remain at a few long interruptions per year, relevant permissible trip rates for the transmutation mission lie in the range of many thousands of trips per year with duration greater than one second."*

III. ADS ACCELERATOR RELIABILITY-ORIENTED CONCEPTUAL DESIGN

The MYRRHA reliability constraint may be reformulated in the following way: the Mean Time Between Failures (MTBF) of the beam delivery must be longer than ~250 hours, a failure being defined as a beam trip longer than 3 seconds.

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[18].

Moreover, such a fault tolerance can only be effective if it is accompanied by 2 more constraints: a realistic switching time, and a Mean Time To Repair (MTTR) 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. Parallel 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 therefore adopted regarding the reliability goal:

- use of components far from their limits;
- fault tolerance, hence redundancy, with a maximum of the serial version;
- repairability.

Thus, basically the MYRRHA accelerator is a high power proton accelerator with strongly enhanced reliability. The adopted technical solution is that of a superconducting (SC) linac, in agreement, as already mentioned, with most of the high-power accelerator projects, in operation or to be built. The CW operation of this accelerator strengthens this choice, and its compatibility with the 3 reliability principles has to be highlighted.

- 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.
- 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[19,20] yielding the certainty of the theoretical feasibility of the fault tolerant scheme. Furthermore the scheme was verified experimentally in the SNS[21].
- The reparability 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. The aspects of early fault detection and fault diagnostic are also to be carefully considered at the engineering design level.

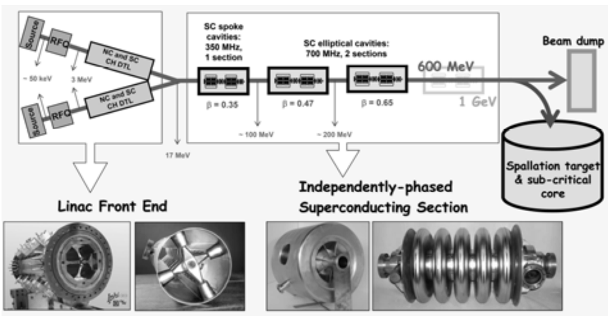

Fig. 2. Conceptual scheme of the MYRRHA accelerator.

In practice the reliability scheme (or, equivalently, the redundancy scheme) will be as follows. The linac will consist of 2 clearly distinct sections (see Figure 2).

1. A medium and high energy section (main linac or independently-phased SC 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 or linac front end), in which the modularity and fault tolerance are not applicable since this section is mainly based on multicell cavities. Here redundancy has to be applied in its parallel form, and so 2 complete injectors with fast switching capabilities are foreseen. The transition energy between the 2 sections is put to 17 MeV.

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 favorable 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.

IV. MYRRHA LINAC IMPLEMENTATION PLAN

IV.A. 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 the injector is the Institute for Applied Physics (IAP) in Frankfurt, Germany.

A 352 MHz version of the injector has been already described[22]. It is based on a sequence of 3 subsections:

- a particularly flexible and versatile 4-vane RFQ, accelerating the beam to 3 MeV;
- 2 copper multicell CH-DTL structures for acceleration to 5 MeV;
- 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[23] and the test of a fully functional single cavity cryomodule with beam is under preparation[24].

This 352 MHz layout was developed in the framework of the FP6 EUROTRANS project[15,22] in which a common accelerator layout was envisaged for the ADS demonstrator (XT-ADS 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 Figure 3.

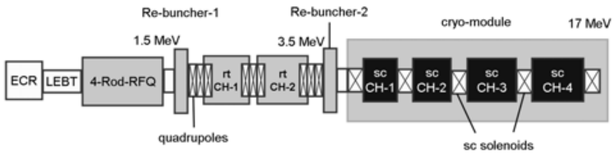

Fig. 3. Schematic overview of the 176 MHz injector (courtesy of H. Podlech and C. Zhang).

The 176 MHz scheme is now considered as the preferred one for the MYRRHA injector, and it will be the object of a dedicated R&D program, heavily supported by the EURATOM FP7 MAX project[25]. In a first time period this R&D program will focus on the 4-rod RFQ, with the design and construction of a short test section for thermal behaviour investigation, and then (outside MAX) with the 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.

IV.B. Independently-phased 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 source (see Figure 4).

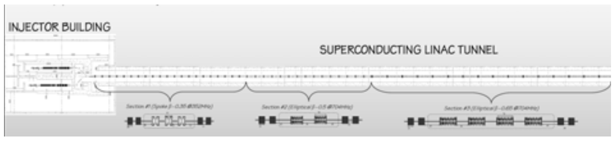

Fig. 4. Schematic overview of the full linac (to scale).

This CW main linac is composed of an array of independently-powered superconducting 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). The goal is to increase as much as possible the tuning flexibility and to provide sufficient margins (about 20 to 30%) for the implementation of the fault-tolerance capability by serial redundancy.

As stated below, the fault-tolerance capability is inescapable to achieve the required level of reliability, the allowed switching time in case of a fault being 3 seconds. A reference "fast failure recovery scenario" has been defined in the case of an RF loop failure, that consists in stopping the beam while achieving the appropriate retuning, and a novel fully digital Low Level RF is being prototyped in view of this particular application[26]. During the upcoming R&D activity period, it is planned to test it experimentally 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 MYRRHA-like 5-cell β 0.47 elliptical superconducting cavity and will be fed with a 80 kW CW RF source; it is presently under final commissioning phase[27].

Table I. Characteristics of the MYRRHA main linac.

Section #	**#1**	**#2**	**#3**
Input energy	17.0 MeV	86.4 MeV	186.2 MeV
Output energy	86.4 MeV	186.2 MeV	600.0 MeV
Cav. techno.	Spoke	Elliptical	
Cav. frequency	352.2 MHz	704.4 MHz	
Cav. geom. β	0.35	0.47	0.65
Cells /cav.	2	5	5
Focusing type	NC quadrupole doublets		
Cav /cryom.	3	2	4
Total nb of cav.	63	30	64
Nom. E_{acc}	5.3 MV/m	8.5 MV/m	10.3 MV/m
Synch. phase	-40° to -18°	-36° to -15°	
Beam load /cav	1 to 7 kW	3 to 18 kW	14 to 31 kW
Section length	63.2 m	52.5 m	100.8 m

The detailed architecture of the 600 MeV MYRRHA linac is summarized in Table I. 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).

For the high energy part of the linac, the technological choice of the superconducting cavities is rather 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.

For the intermediate energy part, 17 MeV to 90 MeV, the technology of the spoke cavities is retained. The principal architect is the Institute for Nuclear Physics (IPN) in Orsay, France. The operating frequency is 352 MHz, and for maximal compatibility with the fault tolerance scheme, a 2-cell cavity is a chosen. A first spoke cavity has been successfully tested at 4K and 2K in an "accelerator-like" horizontal cryostat configuration[28], fully equipped with its tuning system, magnetic shield, RF power coupler, and fed by a 10 kW solid-state amplifier. Nevertheless, this technology is still rather young and R&D effort has to be intensively continued.

IV.C. Connection to reactor

The objective of the MYRRHA final high-energy beam line is to safely inject the proton beam onto the spallation target located inside the reactor. This beam line is composed of two 45° bending magnets going up from the linac tunnel, and a last 90° dipole bending the beam 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.

This line, presently under detailed design phase within the EURATOM FP7 CDT project[12], is shown on Figure 5. Preliminary statistical error studies show that the very long "naked" final drift (27 m) makes the line quite sensitive to errors, inducing tight specifications for the magnets alignment or the beam stability. 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[29] developed at PSI. Finaly, a full power beam dump is foreseen, allowing the commissioning of the MYRRHA accelerator fully independently from the reactor.

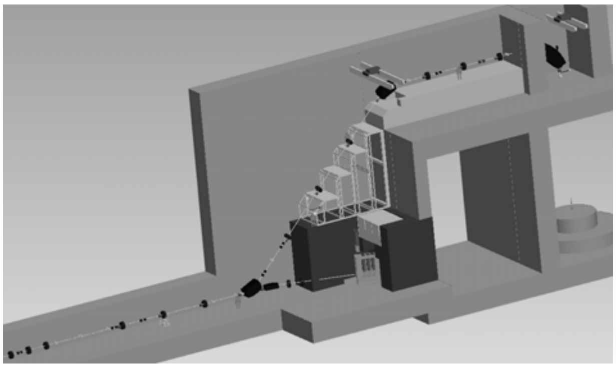

Fig. 5. Layout of the MYRRHA beam lines to reactor and dump (courtesy of H. Saugnac).

V. CONCLUSIONS

The use of RF superconductivity has become a recurrent choice in present day or future high power accelerators, and the global layouts of the IFMIF and MYRRHA linacs, dedicated to the development of nuclear energy, are in line with several other hadron beam projects and facilities.

While the beam current level (125 mA CW) is the main issue of the IFMIF linac design, the reliability of the MYRRHA 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 MYRRHA R&D program is therefore mainly focused on this reliability issue, both from a fundamental point of view and from that of the practical and technological implementation, through topics like advanced beam dynamics and error studies, reliability modeling studies, optimized injector design, or prototype cryomodule operation.

This work programme is meant to reach in 2015 an updated coherent and consolidated design of the 600 MeV accelerator before a possible MYRRHA construction start. Intensive efforts will especially be made to increase the level of confidence that the required reliability level will be reached, at least after a few years of commissioning and practice of the MYRRHA machine.

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