HIGH POWER CW SUPERCONDUCTING LINACS FOR EURISOL AND XADS

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Abstract

A multi-MW superconducting proton linac is proposed as the baseline solution for the EURISOL and the XADS driver accelerators. In the EURISOL project, which studies the design of the next-generation European ISOL facility, it is used to produce both neutron-deficient and neutron-rich exotic nuclei far from the valley of stability. In the PDS-XADS project, which aims to the demonstration of the feasibility of an ADS system for nuclear waste transmutation, it is used to produce the neutron flux required by the associated sub-critical reactor. In this paper, we report the main results and conclusions reached within these preliminary design studies. A special emphasis is given on the on-going and future R&D to be done to accomplish the demonstration of the full technology. Both of these works have been supported and funded by the EC 5th Framework Program, under contracts n° FIKW-CT-2001-00179 (PDS-XADS) and n° HPRI-1999-CT-50001 (EURISOL).

INTRODUCTION

During the period 2000-2004, the European Commission, within its 5th Framework Program, has been supporting in the field of nuclear physics two distinct projects having between them a high level of synergy due to their rather similar driver accelerators.

The EURISOL Project

The first one is the EURISOL project [1], which looks at the feasibility study of a new European isotope-separation-on-line (ISOL) radioactive ion beam facility, aiming at providing exotic beams which are orders of magnitude higher in intensity than presently available. In the light of this general objective and the inherent limits imposed by practical target considerations, a high power proton driver accelerator has been proposed as the base-line solution for producing both neutron-deficient and neutron-rich exotic nuclei far from the valley of stability.

The EURISOL proton beam main specifications are summarized in Table 1. The beam final energy is 1 GeV, with a 2 GeV upgrade capability, and two main intensity regimes are required: at intensities around a few hundred μA, the driver would be operated as a classical ISOL facility, while the full beam power (5 mA mean current) would be used to generate neutrons from a spallation target, which in turn would be used for producing fission products (converter method). Moreover, because of current interest in some cross section properties of heavy-ion induced reactions, the EURISOL proton accelerator should exhibit a strong heavy-ion capability for low-mass species, with ion beam powers of hundreds of kW.

The PDS-XADS Project

The second project is the PDS-XADS one, which looks at the feasibility study of an experimental Accelerator Driven System (ADS) for nuclear waste transmutation. Consecutive to the work of the European Technical Working Group on ADS [2], this preliminary design study was launched in 2001 within a large European collaboration [3]. Five work packages (WP) cover the relevant issues, and the WP3 is dedicated to the design of the high power proton accelerator providing the neutron flux to the sub-critical reactor via a spallation target.

The XADS accelerator's main specifications are also quite usual for such a machine (see Table 1): 600 MeV final energy, 6 mA maximum mean beam current on target (10 mA for the demonstration of concept), 2 % beam power stability, 10 % beam size stability on target. On the other hand, less than a few (in the order of 5 per year) beam stops longer than one second are allowed for the successful demonstration of the ADS coupling. Given the state-of-the-art in the field of accelerator reliability, this requirement appears to be highly challenging, and could reveal itself as being a "show-stopper" for ADS technology. From this extremely hard requirement, it is clear that suitable design strategies had to be followed early in the conception stage of the XADS accelerator.

Table 1: EURISOL & XADS beams specifications

	EURISOL	**XADS**
Final proton beam energy	1 GeV	600 MeV
Proton beam mean current	• 5 mA (2-step production mode) • 0.2 to 0.5 mA (direct production mode)	• 6 mA max. on target • 10 mA rated
Main additional specifications	Heavy-ion capability for ions with A/q = 2 & 3	Less than 5 beam trips (>1sec) per year
	The machine must be up-gradable to a 2 GeV machine	The concept must stay valid for a 1 GeV, 20 mA industrial machine

Beam Time Structure

In principle, to avoid thermal stresses on the ADS beam window, target and sub-critical assembly, or in the radioactivity-releasing ISOL target, the maximum smoothing-out of the beam structure is favoured: a continuous wave (CW) beam would thus be the best solution. However, a pulsed operation of the beam could also be feasible, under the condition that the time scales of thermal inertia of the different components of the target and the reactor are much longer than that of the beam

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period. The use of a "pulsed beam mode" of the accelerator is anyway needed in both projects. In the EURISOL case, sharp beam interruptions for quite variable periods of time are required for measurements of target release properties. In the XADS case, short and well-defined beam interruptions are mandatory to enable the in-line measurement, during normal operation, of the sub-criticality level through dynamic measurements. The possibility to produce short (a few tens of µs) proton pulses is also needed during operation starting phases.

From the accelerator point of view, it is an important design issue to decide between a CW RF machine and a pulsed RF machine, no matter what the beam time structure is. Operation in a CW RF mode is generally preferred to a pulsed one in this kind of high power machine. As a matter of fact, a quantitative analysis has been made for the EURISOL driver machine [4], leading to the conclusion that a CW RF machine solution is recommended: reliability is maximum (lower peak RF power), the Lorentz forces problem vanishes in the superconducting accelerating cavities, the R&D effort is significantly lower, and the machine is simpler and more flexible. With such a solution, the RF remains continuously applied on the RF structures, but the beam intensity can still be arbitrary shaped when needed within a very broad range.

Finally, an accelerator operating in a CW RF mode and accelerating a beam with a CW-based time structure appears to be a natural and simpler choice both for the EURISOL and the XADS projects. Figure 1 shows for example the agreed specifications concerning the XADS nominal beam time structure: additional short and well-defined (sharp edge) beam interruptions of 200 µs are implemented in the CW beam, with a repetition frequency in the order of 1 Hz; these beam holes, shutting down the neutron power source from time to time, should enable continuous and very accurate on-line measurements and monitoring of the reactor sub-criticality.

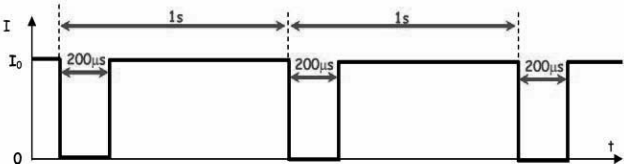

Figure 1: XADS beam time structure (normal operation).

BASIC ACCELERATOR CONCEPT

With the present state-of-the-art in accelerator technology, only two basic concepts of accelerators have shown to be able to deliver proton beams with mean intensities in the mA range. These namely are sector-focused cyclotrons and linear accelerators (linacs). Typical examples, running since a quarter century, are the 590 MeV separated-sector cyclotron of the Paul Scherrer Institute (PSI) at Villigen, Switzerland, and the 800 MeV linear accelerator of the Los Alamos Neutron Science Center (LANSCE) in New Mexico, USA. The PSI cyclotron is a CW-type machine of which the maximum average intensity has been continuously improved: starting initially with 100 µA, steady improvements allow at present to extract up to 2 mA from the machine [5]. The LANSCE's linac [6], designed for (100 Hz) pulsed-beam operation, delivers an average intensity of 1 mA. That means that the instantaneous intensity in the 625 ms lasting beam pulses amounts to 16.5 mA. The high-current capability of linear accelerators, due to the intrinsic strong focusing, is also demonstrated by the 50 MeV CERN injector LINAC-2, which reaches 170 mA during its 150 ms pulses [7]. In principle, strong focusing is also present in a FFAG-synchrotron, and some R&D is presently underway at Kyoto University in Japan [8]. However, this type of accelerator is not sufficiently advanced for assessing the very large extrapolation to the required XADS and EURISOL machines parameters.

Concerning cyclotrons, a final energy of 600 MeV is well established, with the experience of the PSI machine, and it is felt in the cyclotron community that a value of 5 mA should be considered as safely reachable [9]. However, extrapolating up to 10 mA is more questionable, and might require a complex of at least two cyclotrons with the two beams being funneled together. Moreover, for energies reaching the 1 GeV range, the intrinsic limits of the very principle of cyclotrons are reached because the proton is becoming too relativistic. None of all these limitations are present in a linac where intensities can reach more than 100 mA without any intrinsic energy limit. In addition, a cyclotron is basically a CW machine, and the requirement to provide sharp pulses is a major difficulty for a cyclotron of such power.

The minimisation of the number of beam trips, in order to match the XADS specifications, is a very specific and challenging requirement. It was clearly established by the XADS WP3 group that reliability can be implemented into an accelerator by adopting, in a very dedicated manner, the triple concept of over-design, redundancy and fault tolerance [10]. This strategy requires a highly modular system where the individual components are operated substantially below their performance limit. In contrast to circular machines like cyclotrons (and FFAG), a superconducting linac, with its many repetitive accelerating sections, conceptually meets this reliability strategy. It further allows keeping the activation of the structures rather low, which is important for radioprotection and maintenance issues, whereas the extraction channel of high power circular accelerators is in this respect a considerable concern.

For all these reasons, it was concluded that the reference solution should be a superconducting linac both for the EURISOL and the XADS projects. This assessment is corroborated by the one of OECD/NEA on ADS accelerators [11]: "Cyclotrons of the PSI type should be considered as the natural and cost-effective choice for preliminary low power experiments, where availability and reliability requirements are less stringent. CW linear accelerators must be chosen for demonstrators and full-scale plants, because of their potentiality, once properly designed, in term of availability, reliability and power upgrading capability".

THE EURISOL DRIVER ACCELERATOR

The general layout of the EURISOL proton driver (see Figure 2) is classicaly composed of three main parts: the “low-energy section” (up to 5 MeV), the “intermediate section” (up to around 100 MeV) and the superconducting “high-energy section” (up to 1 GeV).

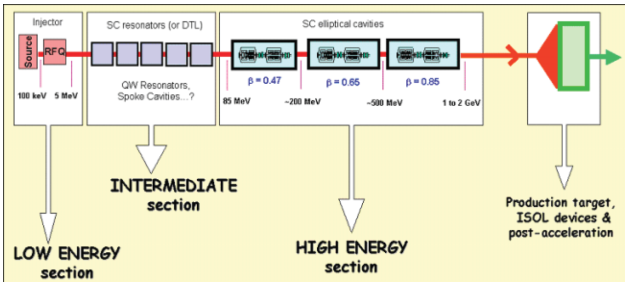

Figure 2: Layout of the EURISOL proton linac.

The Low-Energy Section (Injector)

The injector section is quite straightforward because of the relatively low proton beam current. The source is an Electron Cyclotron Resonance (ECR) ion source, based on the experience accumulated in many laboratories around the world [12,13,14]. It is followed by a room-temperature copper RFQ that has two main functions: it prepares the particles in bunches separated by the RF period and it accelerates the beam to an energy of 5 MeV while maintaining a strong confinement. It operates at a frequency of 352.2 MHz, which is a good compromise between lower sensibility to space charge effects & relaxed fabrication tolerances at lower frequencies, and higher shunt impedance & smaller dimensions at higher frequency. This frequency choice also relies on the existing RF technology at this rather common frequency, traditionally used e.g. at CERN.

The Los Alamos National Laboratory was the first to operate such a 350 MHz injector, LEDA, at intensities of the level of 100 mA CW [15]. In Europe, INFN is building a 30 mA injector in Italy within the TRASCO programme [16], while in France, the IPHI project is composed of an ECR source (SILHI) routinely delivering a 95 keV 100 mA proton beam, followed by a 3 MeV RFQ presently under construction at Saclay [17]. In the three cases, very good performances have been achieved, that fully demonstrates the feasibility of a 5 MeV 5 mA CW proton injector for EURISOL.

The High-Energy Section

There is also a general agreement that the high-energy section should be made of superconducting (SC) multi-cell elliptical cavities. These have been demonstrated to be extremely efficient and cost-effective, and a lot of experience and knowledge has been accumulated. Moreover, large size machines using SC RF Cavities have been constructed (like the TTF injector in DESY, Germany) or are currently under construction (like the SNS at Oak Ridge, USA), giving confidence in the achievable performance for the EURISOL accelerator.

The proposed SC linac for the high-energy section of the EURISOL driver operates at 2K and 704.4 MHz, and has been settled using all the optimisation criteria developed by the French-Italian collaboration [18,19] for the cavities’ design, and the beam dynamics studies. Due to the varying velocity of the moderately relativistic protons, the 85 MeV - 1 GeV high-energy section of the EURISOL linac is divided in three parts, each covering an energy range with a single type of structure. The geometrical β values of these structures are 0.47, 0.65 and 0.85 respectively. The transition energies are set to approximately 200 and 500 MeV, and the last family of cavities, bringing the beam up to 1 GeV, could operate to 2 GeV without great losses of efficiency. The transverse focusing is provided by a periodic array of quadrupole doublets between which the SC cavity “cryomodules” are placed. Comfortable margins on critical values have been chosen in the study to ensure a design as robust as possible. These margins leads especially in limiting, in a reasonable way, the minimum beam apertures, the field in the cavities, the phase advances along the linac, the sensibility to beam mismatch, or the possibility of halo creation, leading to very smooth and safe beam behaviors through the linac. In particular, peak surface magnetic and electric fields of respectively 50 mT and 30 MV/m have been used as upper limits for SC cavity operation.

The Intermediate Section

For this range of energy (5–85 MeV), two solutions with the same frequency (352 MHz) have been discussed: a room-temperature solution, based on a DTL structure, and a cold solution, using superconducting resonators. Comparing the two options, it appears that the investment cost and the overall length for both solutions seem to be of the same order. On the other hand, the AC power difference between the two options is very large (about 7 MW) and makes a huge difference in the operating cost, in the order of 2 M€/year [4]. Moreover, the superconducting option gives higher safety (larger beam tubes), and has great potential in terms of reliability and flexibility thanks to its independently phased structures.

As a consequence, the EURISOL intermediate section will use, a priori, superconducting cavities. Two different preliminary designs have been proposed by INFN Legnaro [20] and IPN Orsay [21], the first using half-wave and 4-gap ladder resonators, the second using 2-gap spoke cavities. The “warm” DTL-like solution, while less attractive from the point of view of efficiency, cost and flexibility, still exists as a back-up solution.

Heavy-Ion Capability

The development of a superconducting version for the intermediate section of the EURISOL driver is crucial if one wants to fullfill the heavy-ion capability requirement. As a matter of fact, in order to be able to accelerate both protons and heavy-ions in the linac, the number of gaps per accelerating structure has to be kept small, and the phase in the successive accelerating structures has to be independently controlled so as to provide a large velocity acceptance. Different heavy ion capability scenarios have been identified within the EURISOL study [4]. The conclusion is that, owing to the principle of independent phasing and some margin in the maximum surface fields, acceleration of A/q=2 ions is potentially feasible up to 500 MeV/u, under the condition that a second dedicated 5 MeV injector is constructed. Acceleration of A/q=3 ions can also be envisaged, but it would need significant modifications in the linac architecture.

THE XADS DRIVER ACCELERATOR

The layout of the XADS driver accelerator is of course very similar to the EURISOL one, with the only difference that reliability is here a major issue. In particular, the design should look at the ability to either maintain the beam under safe conditions, or to recover the beam through, in less than one second, to avoid any core shutdown. This is a new feature, not required for any other accelerator application, which is quite specific to ADS linacs. Thus, the philosophy prevailing on current machines to cope with component failures should be reconsidered, taking into account this requirement. The main guidelines that have been highlighted to drive the study are a strong design (which makes extensive use of component derating and redundancy) and a high degree of fault tolerance (i.e. the capability to maintain beam operation within nominal conditions under a wide variety of accelerator component faults). A reference solution based on a linear superconducting accelerator with its associated doubly achromatic final beam line has been worked out up to some detail by the XADS WP3 group [22], including studies on radioprotection and maintenance aspects. It is shown on Figure 3.

The XADS Reference Accelerator

The XADS reference design is optimized for reliability, and all selected components have the capability to accelerate higher beam currents (~ 40 mA) without major changes. It uses a “classical”proton injector (ECR source + normal conducting RFQ), followed by additional warm IH-DTL, developed by IBA (Belgium), or/and superconducting CH-DTL structures, developed by Frankfurt University [23], up to a transition energy still to be defined between 5 and 50 MeV. At this point, a fully modular independently-phased superconducting linac accelerates the beam up to the final energy.

Up to the transition energy (linac front end), fault-tolerance is guaranteed by means of a "hot stand-by" spare, keeping the possibility to switch the second injector on if the first one fails or have any long beam trip. Above this energy, spoke and, from 90 MeV on, elliptical cavities are used. An individual cavity failure in this part can be handled at all stages without loss of the beam. This characteristic relies on the use of highly “de-rated” and independently powered accelerating components, associated to a fast digital feedback system and adequate diagnostics. Note that these SC cavities (spoke and elliptical) are subject of important R&D programmes presently underway, e.g. at CEA Saclay, IPN Orsay and INFN Milano. The performance of the prototypes has been measured to exceed the operational characteristics by a very comfortable safety margin [24,25,26], that ensures the overdesign criteria imposed by the reliability strategy.

Besides this fault-tolerance, another remarkable feature of the concept is its validity for a very different output energy range: 350 MeV for the smaller-scale XADS require for example nine β=0.65 elliptical cavities cryomodules; in order to obtain 600 MeV, simply ten more cryomodules have to be added (7 with β=0.65 and 3 with β=0.85) and 12 additional (β=0.85) boost the energy to 1 GeV. Therefore, already the small-scale XADS accelerator is fully demonstrative not only of the 600 MeV XADS, but even for an industrial machine.

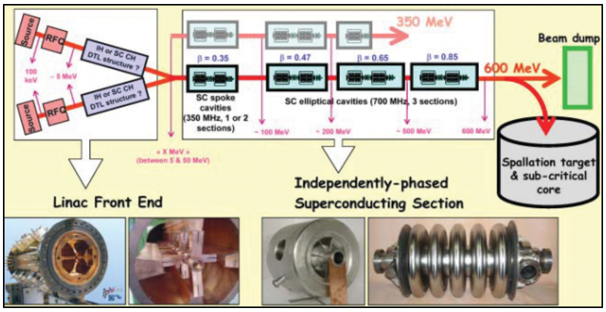

Figure 3: XADS reference accelerator layout (Photos, from left to right: RFQ, CH-DTL, spoke and 5-cell elliptical cavity).

Fault-Tolerance Capability

The fault-tolerance concept is a crucial point in the design of the overall XADS accelerator. The state of the art in RF system technology is indeed not reliable enough to envisage an operation of the XADS accelerator during several months without any beam trip. We can actually foresee at least a few tens of failures per year, only due to these RF systems, based on parts count reliability estimates. Therefore, even if a great effort can be directed at improving the MTBF of RF systems, it seems difficult to reach the reliability requirement without implementing any fault-tolerance philosophy for the linac design.

The fault-tolerance principle of the independently-phased superconducting section has been thoroughly analysed by means of beam dynamics multiparticle simulations. The calculations have been performed on the basis of a 5 MeV - 600 MeV superconducting linac (see Table 2) using the “local compensation” method (see Figure 4): if a cavity (or quadrupole) fails, the nominal beam is recovered by retuning as fast as possible a few accelerating cavities and/or quadrupoles neighbouring the failing element.

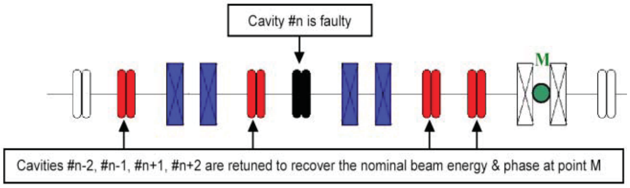

Figure 4: The “local compensation” method.

Table 2: Layout of the SC linac used for the fault-tolerance simulations; focusing is ensured by warm quadrupole doublets

SC linac sections	Energy range	Nb of cavities
Spoke 2-gap, 352.2 MHz, β=0.15 (~30 metres)	5 - 17 MeV	36 (2 per lattice)
Spoke 2-gap 352.2 MHz, β=0.35 (~50 meters)	17 - 91 MeV	63 (3 per lattice)
Elliptical 5-gap, 704.4 MHz, β=0.47 (~60 meters)	91 - 192 MeV	28 (2 per lattice)
Elliptical 5-gap, 704.4 MHz, β=0.65 (~100 meters)	192 - 498 MeV	51 (3 per lattice)
Elliptical 6-gap, 704.4 MHz, β=0.85 (~25 meters)	498 - 615 MeV	12 (4 per lattice)

A systematic study of the XADS linac fault-tolerance capability has been performed, optimizing the retuned values to be applied for local compensation in the case of the failure of most of the linac cavities and quadrupoles. The conclusion of the study [27] is that in every case, with an appropriate retuning, the beam can be transported up to the high energy end without any beam loss (100 % transmission, reasonable emittance growth), and within the nominal target parameters. It is also recommended to switch off the whole quadrupole doublet if one quadrupole fails.

PERSPECTIVES

The 6th European Framework Program is now running. The EURISOL and XADS preliminary design studies will be pursued within, respectively, the EURISOL Design Study, and the EUROTRANS Integrated Project. The final goal is to be ready to launch an eventual construction of these machines at the end of 2008. In the meanwhile (2004-2008), a huge R&D program will be undertaken, focusing on two main items.

The first one concerns basic R&D and prototyping for the intermediate energy section (5 MeV – 100 MeV) of such linacs. The construction and test of HWR and ladder resonators at Legnaro [28], of spoke cavities at Orsay, of a SC CH-DTL at Frankfurt, of a normal conducting IH-DTL by IBA, and of their associated equipments (coupler, tuner, cryostat, LLRF system...) should allow to choose the best technical option in this energy range. This R&D should also enable to qualify the reliability of these different components. The second item concerns indeed the accelerator reliability, which is a crucial issue in the XADS case. The reliability of the injector section will be experimentally determined by means of a long test run of the 3 MeV, 100 mA accelerator IPHI, presently in construction by CEA Saclay and IPN Orsay. Concerning the high-energy section, a complete elliptical cryomodule with all subsystems running at rated power and nominal temperature will be built, tested and qualified by INFN Milano and IPN Orsay. Finally, studies on fault-tolerance will be pursued with the development of more adapted beam dynamics simulation code, and the development by CEA Saclay of an adequate LLRF system, able to handle beam trips as quickly as possible using the local compensation method.

This R&D program should finally lead to a frozen design of the XADS and EURISOL linacs, with assessed reliability and costing.

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