HIGH POWER PROTON LINACS, APPLICATIONS AND DESIGN CONCEPTS

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Abstract

Proton linacs with very high beam power constitute the first part in the production chain for different applications. Proton beams of several tens of MW can be used to yield an extremely high flux of neutrons and other secondary particles. Hence, possible applications range from accelerator driven transmutation of nuclear waste and spallation neutron sources to irradiation installations for material testing, radioactive ion beam facilities, neutrino factories and muon colliders. The architecture and beam dynamics of the driver linac are discussed, and the key elements of the accelerator system reviewed. Constraints on the linac performance (H^+/H^-, cw/pulsed, beam intensities, reliability/availability) associated with the different applications are described. The results of the CONCERT (COmbined Neutron Center for European Research and Technology) study, under the leadership of Saclay, using the concept of a single high-power proton linac to serve a multi-application facility are presented.

1 INTRODUCTION

Proton beams of several tens of MW can be used to yield an extremely high flux of neutrons and other secondary particles for research and technology studies in different areas.

2 NEUTRINO AND MUON FACTORIES

Recent measurements of atmospheric muon neutrino fluxes have shown an azimuth dependent depletion that strongly suggests neutrino oscillations of the type $\upsilon_\mu \rightarrow \upsilon_X$. Since the atmospheric υ_e flux is not similarly depleted, υ_X cannot be the same as υ_e, and must therefore be υ_τ or υ_s (a sterile neutrino). Understanding the neutrino-mass hierarchy and the mixing matrix that drives flavor oscillations may help to learn physics at very high-mass scales. High energy neutrino beams are currently produced by creating a beam of charged pions that decay in long channels. This results in a beam of υ_μ and anti-υ_μ only. A muon storage as a source of neutrino beams produces υ_e and anti-υ_μ if μ^+ are stored, and anti-υ_e and υ_μ if μ^- are stored.

This concept to produce neutrinos in a storage ring is linked with the project of circular muon colliders to reach very high center of mass energies (10 TeV). An intense proton accelerator is the first part of the production line (2.2 GeV, 13 mA, 14 % duty cycle, 4 MW pulsed linac for the CERN project).

3 ENERGY AMPLIFIER AND TRANSMUTATION OF NUCLEAR WASTE

The Energy Amplifier proposed by Carlo Rubbia is a subcritical fast neutron system driven by a high power proton accelerator [7]. It is particularly attractive for destroying, through fission, transuranic elements produced inside nuclear reactors. The Energy Amplifier could also transform efficiently long-lived fission fragments using the concept of Adiabatic Resonance Crossing. The main characteristic of the Energy Amplifier is the presence of 10^4 tons of molten lead used as a target for the protons to produce neutrons by spallation, and as neutron moderator and coolant to extract the heat by natural convection and as a radioactivity containment medium. The hybrid reactor and the transmutation of nuclear waste research and development will lead to a new generation of linear proton accelerators capable of meeting extreme beam power requirements of 5 to 50 MW. These power requirements are between 10 and 100 times higher than for the best existing machines like LAMPF at LANL or SINQ at PSI. Higher standards of availability and maintainability are necessary (less than 100 unscheduled beam interruptions per year). The demonstrator stage should include a 1 GeV proton accelerator with a beam power of 5 MW extendable to 20 MW.

4 TECHNOLOGICAL IRRADIATION TOOL

Reactors have been successfully used as irradiation tools for technological purposes. They routinely supply a maximum neutron flux of a few 10^{14} n cm^{-2}s^{-1} in the thermal and in the fast range above 1 MeV. The level of damage is limited to a few displacements per atom per year. The development of new materials, designed for better performance and longer life time, constitutes an issue of major importance. An intense beam of protons of 10 MW on a target of heavy metal should make it possible to produce neutron fluxes of some 10^{15} n cm^{-2}s^{-1} in both the thermal and fast ranges. This will result in an annual damage of a few tens of displacements per atom.

5 RADIOACTIVE ION BEAMS

Current nuclear physics focuses on exploring nucleonic matter under extreme conditions, such as those that can be created in modern accelerator laboratories. The opportunities offered by beams of exotic nuclei for research in the areas of nuclear structure physics and nuclear astrophysics are exciting, and world-wide activity in the construction of different types of radioactive beam facilities bears witness to the strong scientific interest in the physics that can be probed with such beams. One basic method to produce radioactive nulear beams is commonly called Isotope Separation On Line (ISOL) and the other is known as in-flight method. In an ISOL-type facility, radioactive nuclei are produced essentially at rest in a thick target, a catcher or a gas cell bombarded with particles from a primary source or driver accelerator. After ionization and selection of a specific mass with electromagnetic devices, these nuclei are accelerated in a post-accelerator. For the in-flight method, an energetic heavy ion beam is fragmented or fissioned while passing through a thin target and the reaction products are subsequently transported to a secondary target, after mass, charge and momentum selection in a fragment separator. Since the reaction products are generated in flight, no post-accelerating is required. The use of a high power proton linac accelerator would provide a flux gain of about two orders of magnitude.

6 STUDY OF CONDENSED MATTER

The scattering of thermal neutrons is a unique technique to study the structure and the dynamics of condensed matter. The recent high-flux neutron sources based on the pulsed spallation technique are: the Spalltion Neutron Source (SNS) being built in Oak Ridge, Tennessee, by the U.S Department of Energy and to be completed in 2006, the JAERI/KEK Joint project for a High Intensity Proton Accelerator will produce 1 MW high power proton beams at 3 GeV and 50 GeV and was already started on April 1, 2001, the European Spallation Source (ESS) is a genuine European project of 18 major research organizations, laboratories and universities from 11 European countries. The ESS accelerator complex features an 1.3 GeV proton linac providing 10 MW beam power and accumulator rings, that compress the 50 Hz, 1 ms linac pulse to 1 μs, in order to supply a 5 MW short pulse target station. A second 5 MW long pulse target station is directly fed by the linac delivering 2 ms pulses at $16^2/_3$ Hz.

High power RFQs are actually the only way to produce drivers for high intensity in H^+ / H^- linacs. Such RFQs are operating or being constructed in many labs. They provide beams with very low duty cycle up to CW application. The RFQ in the low Energy Demonstration Accelerator (LEDA) at Los Alamos produces ~100 mA CW beam. LEDA demonstrated a high output energy at the RFQ of 6.7 MeV with a RF frequency of 350 MHz. This has an important influence on the linac architecture. The RFQ at CERN provides about 200 mA of peak current with a very low duty factor. Such RFQs are four vane-type. Another class are 4-rod RFQs. The University of Frankfurt has been in the forefront of the 4-rod technology. The extracted beam from the RFQ passes through the MEBT to the input of a DTL. This section matches the beam and strongly affects the beam`s performance down the linac. To allow injection into a compressor ring, chopping is required at a frequency close to the ring revolution frequency with beam pulse duty cycles of 0 to 70%, and with rise and fall times of < 3 ns for the chopper deflection fields. R&D is needed to achieve the required rise and fall times, preventing halo growth and to handle deflected beam powers (~10 kW).

Table 1 sums up the typical parameters for the different applications. The demanded power levels can reach 50 to 100 MW, which is far off the capability of existing facilities.

Table 1: Summary of the typical parameters for different applications.

Application	Beam Power	Energy	Average Current
Condensed matter	5 MW	1.3 GeV	3.75 mA
Radioactive Ions from Protons from Neutron	 - 200 kW > 10 MW	 > 200 MeV ~ 1 GeV	 ~ 1 mA ~ 10 mA
Hybrid System 100 MWth demo Industrial System	 ~ 6 MW ~ 50 MW	 ~ 600 MeV ~ 1 GeV	 ~10 mA ~ 50 mA
Irradiation tool	10-40 MW	~ 1 GeV	10-40 mA
Tritium production	10-100 MW	~ 1 GeV	…100 mA
Muons - Neutrinos	4 MW	2 GeV	2 mA

7 KEY-ELEMENTS

All the discussed applications need a high intensity proton source. A 1 to 5 MW proton driver will be the key-element. Based on present accelerator technology and construction experience, it is feasible to build such a proton driver with low technical risk and with minimum cost for construction and operation.

Ion sources are critical elements in terms of beam quality (intensity, emittance, stability) and reliability (sparks, life time). Their achievable performance has a strong influence on the design of the whole linac. High-current proton sources (up to ~200mA) have already been available for several decades for linacs. These sources, developed for low duty cycles (10^{-3}-10^{-2}), lead to life time and reliability problems when increasing duty factors as needed (5%, cw).

Due to recent R&D work done at Chalk River, Los Alamos, Saclay and LNS-Catania, high performance proton sources are available for daily operations. ECR type proton sources [3] with neither filament nor RF antenna are ideal for this high duty factor range (I>100mA, $\Delta I/I < 1\%$, $\varepsilon \sim 0.2\ \pi$ mm mrad normalized rms, duty cycle up to cw, life time > 6 months).

A key-element in the design of the ESS is the negative ion source. The short pulse option requires an H^- ion source with a duty cycle and intensity determined by the injection requirements into the compressor rings. The H^- sources have limited performance when high intensity, low beam noise, low emittance, long life time and high duty factor are required simultaneously.

To meet the ESS requirements, the demands on the ion source can be reduced by funneling two beams into the input of the linac. Two identical H^- ion sources are required, each delivering 65 mA in 1.0 ms, pulsed at a repetition rate of 50 Hz (5% duty cycle) and with 0.1 π mm mrad normalized rms emittance. In addition, the source must operate with high availability and reliability. Two types, the Penning source and the volume source are suitable candidates. The SNS H^- source program and the Negative Ion Source (NIS) network [4] supported by the European Community have identified the need for the improvement of H^- ion sources for all future accelerators projects.

The function of the Low Energy Beam Transport (LEBT) is to match the beam from the ion source into the RFQ accelerator with minimum emittance growth and minimum loss of beam current. The LEBT includes diagnostics for the beam from the ion sources. Experiments at the ISIS spallation neutron source at RAL show that this information is very useful operationally [10].

Two types of LEBT are in use: Magnetic and Electrostatic. It is thought unlikely that in practice an electrostatic LEBT (assuming no space charge compensation of the beam) would perform as well as a magnetic LEBT (assuming the beam to be space charged compensated). To accommodate the unequal horizontal and vertical transverse emittance from the Penning source, a LEBT for H^- ion sources has been designed with three solenoids [5] for the ESS.

An alternative design has recently been proposed in the form of a five quadrupole arrangement [2]. Suitable two solenoid LEBT designs for H^+ sources are already available and have been demonstrated within the Los Alamos LEDA [9] and Saclay IPHI [1] projects. At SNS an H^- ion source and an electrostatic LEBT is being designed to produce a 65 mA beam of 65 keV energy at 6% duty factor with a narrow transverse normalized rms emittance of 0.2 π mm mrad.

Several high-power designs are based on funneling. The beams are produced by two independent sources and funneled to double the beam current. R&D and experiments are needed to demonstrate the doubled intensity, and the hopefully unchanged emittance of the funneled beam compared to the emittances of the separate beams. In addition to the RF-deflector work at Los Alamos, new funneling designs have been developed for the ESS study [6] and the CONCERT project [8].

A typical 1-2 GeV proton linac is a pulsed accelerator with a pulse length of about 1 ms and a repetition rate of 50 to 100 Hz. The linac consists of three main sections: an RFQ, intermediate-velocity accelerating structures and high-velocity structures. The intermediate-velocity structures accelerate the beam in the velocity range from $\beta = 0.1$ to $\beta = 0.5$.

These structures can be built either as normal-conduction drift-tube linac structures (e.g. DTL, SDTL or CCDTL) or superconducting structures (HWR or spoke type resonators). The frequency of the low energy part, up to about 150 MeV, ranges from about 200 to 400 MHz. The high-velocity structures consist of normal-conducting coupled-cavity structures or of superconducting multicell elliptical cavities. The RF frequency of the high-velocity structures is a multiple of the frequency of the low-beta structures. The superconducting linacs for both the intermediate and high velocities are built of individual sections.

The sections consist of cryomodules, the vessels for the cavities and transverse focusing elements. Either quadrupoles or solenoids provide the transverse focusing. Normal-conducting magnets are located outside the cryomodules or superconducting magnets within the cryomodules. The choice between normal conducting and superconducting linacs is dominated by the pulse scheme of the beam. For cw operation the superconducting cavities will save a large amount of electric power.

For pulsed-beam operation the cost saving has to be balanced over the operational life time of the machine against the capital costs. Superconducting linacs provide several advantages over normal-conducting linacs such as reduction in RF power dissipation, higher accelerating gradients, larger bore radii and stability.

Higher accelerating gradients reduce the linac length. Larger bore radii relax the alignment and beam steering. The drawbacks of the superconducting cavities are the problems of Lorentz forces and microphonics. Higher investments in RF control systems and tuning systems are also necessary.

8 MULTI-APPLICATION FACIILITY

There is a broad overlap between these different applications in terms of proton beam specifications, so that one can think of combining a number of these applications on the same site with a single accelerator. The CONCERT project aims at exploiting this concept. The feasibility study for CONCERT was finished in June 2001 and can be summed up as follows. For the accelerator part and all related conventional facilities, including safety aspects, the activities have focused on :

-Selection of all key technical options and parameters
-Optimization of a pulsed linac architecture for one high power unit
-Preliminary considerations on costing

It should be pointed out that the proposed pulsed operation is very robust, having the same beam parameters at all times. Peak current, space charge, focusing, beam loading, etc. are all fixed. The average beam power delivered to a certain application is adjusted by the pulse width. The repetition frequency at the target could be 50 Hz or less (by delivering one pulse every second or third period).

The linac parameters are defined to match the user requirements. The accelerator has to perform excellent also in terms of reliability, availability and flexibility. The accelerator has to be robust and is based on the most well proven technologies.

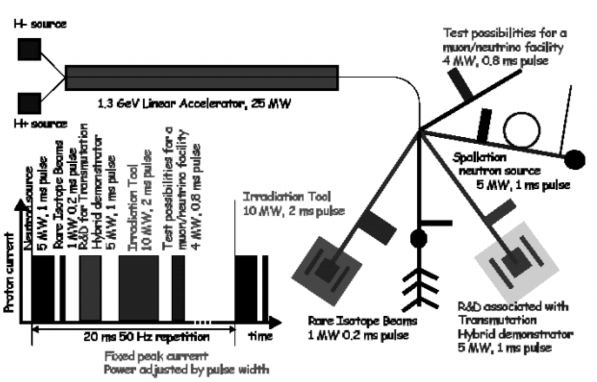

Fig. 1 Schematic of Multi-Application Facility

A major concern in the design of the linac is the minimization of beam losses, in order to avoid activation of the machine and irradiation of the environment. The main constraint is to maintain losses below the commonly agreed limit for hands-on maintenance of 1 W/m or 1 nA/m.

The shielding is dimensioned to keep radiation at the surface below the limit for public areas, assuming 1 W/m loss in the machine. A careful beam dynamics design is needed to avoid the formation of a particle halo that would finally be lost along the linac or the transfer lines. Losses caused by collisions with the residual gas and by H^- stripping in the magnetic field can be maintained below the activation limit.

The basic principle in the design of the linac is to vary smoothly the focusing parameters, to provide matching capabilities at the transitions between different structures and to avoid the crossing of resonances. The design also takes into account the following points: The same space charge level and emittances for H^- and protons in the common part of the linac, independent proton and H^- tuning upstream the funnel, minimize the risks (choppers, funnel).

Concerning the H^- source performances, the required maximum current, beam emittances, duty cycle or repetition rates have been achieved or approached (once at the time) on different sources. With a view to serve the condensed matter study application, all these achieved best performances are simultaneously required. This is considered to be very challenging.

It was already pointed out that availability and reliability are essential elements of the overall CONCERT project. From this point of view, the short lifetime of classical surface and volume H^- sources (of the order of a few hundreds hours) is a major concern. It is expected that the developments of H^- sources needed for SNS and other parallel projects will be successful and allow reaching 55 mA with high stability and long lifetime at high repetition rate.

For the proton source, the project specification of 100 mA with a 20% duty cycle makes it very close to a cw design. In the past years, a considerable effort was invested in the development of high current cw proton sources. The ECR SILHI source is a good choice for stability, reliability and maintenance, and thus the reference option for the CONCERT project. The RFQs bunch and accelerate the H^+ and H^- beam extracted from the sources up to 5 MeV. This energy is chosen as the lowest energy compatible with the technical feasibility of the first electromagnetic quadrupoles in the following Drift Tube Linac (DTL) structure.

An intense R&D effort is done within the IPHI project to demonstrate the feasibility of the first electromagnetic quadrupoles in the first drift tubes. The RFQs of the H^+ and H^- branch are necessarily different. The proton line has to operate with a higher duty cycle (~20 %), while the RFQs of H^- lines have to be split into two parts (RFQ1 and RFQ2) to allow the insertion of the chopper line. A time structure is required in the H^- lines to feed the accumulator rings (condensed matter studies with extremely short pulses of neutrons). The purpose of these rings is to multiply the linac peak current by a factor of about 1000. The 1 ms long pulse from the linac is therefore wound around the 1 μs long circumference (1000 turns) and then extracted in one turn by means of a fast kicker magnet.

A fast chopper has to be inserted in the front end between RFQ1 and RFQ2 with a view to inject all particles in the rf bucket to achieve a no-loss injection and extraction processes. Accordingly, the chopper repetition is 1 MHz and the gap in the beam is of the order of 100 ns (1/10 of the ring circumference). The transition energy between RFQ1 and RFQ2 should be not too low to limit the debunching in the interval of the chopper insertion, but also not too high to limit the chopper voltage. A lower limit of 2 MeV was chosen. This choice will therefore avoid unnecessary beam loss and induced activation in the succeeding structures (up to only 2 MeV) and problems in the chopper line.

As already stated, it is proposed to switch from 176 to 352 MHz in the chopper line. In order to avoid large differences in space charge detuning linked with partially filled buckets and beam losses in the following structures, the chopper field has to be raised during the interval between 2 bunches. The choice of 176 MHz and 2 MeV for RFQ1 will then relax constraints on the chopper (no need for an anti-chopper). For a maximum phase width of ± 45° at 176 MHz, the chopper rise time has to be shorter than 4.3 ns.

Such rise times can be obtained using traveling-wave strip line structures, in which the strip lines are meander-folded in order to match the traveling-wave velocity with the beam velocity. The chopper line will have to be kept as short as possible to avoid too much emittance growth. A careful dynamics design should allow for a 10% emittance growth. However, the actual blow up during daily operation could be much worse.

Error studies of such a line will certainly help to optimize the robustness of the chopper line. However, at this stage and with a view to remain on the safe side, the second RFQ will be designed to have an acceptance sufficiently larger than the blown up emittance. A 5 MeV input energy into a 352 MHz DTL allows for the use of conventional electro-magnets, instead of the permanent magnets used in the SNS design. The need to be able to tune the DTL is required to avoid halo development and therefore losses at higher energy.

The IPHI project shows the feasibility of the quadrupoles in the first drift tubes at such a low energy and strong focusing. Fine-tuning of the individual quadrupoles could be difficult to optimize. It is hoped that a beam-based procedure with clever use of a minimum set of diagnostics will display all the advantages of this option. Due to the large apertures needed to achieve a loss free beam transport through the structures, a 704 MHz DTL or SDTL immediately downstream the funnel would have the disadvantage of a lower shunt impedance than 352 MHz structures. That is why 352 MHz structures are preferred.

The energy at which the funnel line operates is a compromise between lower beam rigidity at low energy and lower space-charge effects along the beam transport at high energy. The proposed compromise for CONCERT sets the funnel energy between 20 and 25 MeV. The final energy of the structure downstream the funnel depends on the variation of the effective shunt impedance along the structure. 90 MeV appears to be a suitable energy for the transition to a CCL structure.

The CONCERT linac is required to deliver 1.3 GeV H^- and H^+ beams in a sequence of current pulses of about 100 mA at peak with a 20 ms repetition period. The average beam power is as high as 25 MW. The peak current is made identical for all pulses to keep space charge forces constant, apart from a slight emittance change between H^+ and H^- bunches. The beam power required for a given application is then obtained by adjusting individual pulse duration. Because of their high acceleration efficiency, superconducting cavities of elliptical shape and working at 700 MHz have been selected.

The overall architecture - transition energy warm-cold and between families, number of cavities per module, cavity design and number of families - results from linac length/cost optimization and does not depend on the duty cycle, which can vary from 5% to 25%, typical values for stand-alone and multi-user facilities. RF power generation is based on individual klystrons and pulsed IGBT high voltage power supplies. Each cavity is fed by two symmetrical couplers to achieve the required peak power and to reduce the rf kicks. With adequate beam matching between the different sections, 3D simulations of beam dynamics (in the absence of errors and with various realistic errors) show stable beam behavior, as well as moderate halo enhancement and emittance growth.

Due to the large range of ion velocities and the limited velocity acceptance of the accelerating cavities, different families of cavities have to be used which are characterized by their “beta-value”. The linac is then divided into sections, and each section consists of a chain of identical cryomodules housing a given number of cavities of the same family. Focusing magnets ensure the transport of the beam and two successive sections have to be matched in transverse and longitudinal planes. Once the input energy has been chosen, the linac can be optimized in terms of number of cavity families, number of cells per cavity and number of cavities per cryomodule. The choice of the transition energy between nc and sc structures is governed by several considerations. Below 200 MeV, the energy gain per real-estate of sc cavities is lower than 2 MeV/m, which also can be obtained by warm Coupled Cavity Linac (CCL) structures. The design of sc cavities for beta values lower than 0.6 is complicated by stiffness and microphonics issues. Therefore, the transition energy has been fixed at 185 MeV.

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