HIGH-POWER PROTON LINAC FOR A MULTI-USER FACILITY

Jean-Michel Lagniel for the CONCERT Project Team, CEA-Saclay, France

Abstract

High-power proton linacs are needed as driver for several applications, namely transmutation of nuclear waste using Accelerator Driven Systems (ADS), spallation neutron sources (ESS in Europe) and other fields of basic and applied research (next generation of radioactive ion beam facilities, neutrino factories, muon colliders, irradiation facilities for material testing...). The possible synergies among these projects will be pointed out and a preliminary concept of high-power proton linac used as driver of a multi-user facility will be presented.

1 FOREWORD

Over the last 70 years, accelerators have become indispensable tools to progress in applied and fundamental research in disciplines as varied as nuclear physics, particle physics, condensed matter, life sciences, radiotherapy, hybrid reactors... Throughout this period fantastic progress has been made in accelerator physics and associated techniques to meet the ever increasing demands. Meanwhile, innovations in the techniques used enabled the emergence of new domains opening up new and unanticipated fields of exploration.

The accelerators used for particle physics are highly specialised. They have also become gigantic and accordingly costly. Their design, construction and operation thus necessitate international collaborations (at European if not intercontinental levels). The same trend is apparent in all the increasingly numerous disciplines where accelerators are used. Large projects have become the rule with costs counted in billions of Euros. In all these disciplines, as in particle physics, international collaboration is a necessity. However, in view of the number of such projects, international collaboration is likely to be no longer sufficient. It is now also necessary to analyse possible synergies between projects and to assess the possibility of sharing installations.

A whole series of applications could now benefit from the performance of a new generation of high-power proton accelerators capable of producing beams of several tens of MW. These applications are reviewed in section 2 which identifies a broad overlap in terms of primary proton beam specifications and point out the possibility of combining a number of these applications on the same site with a single accelerator.

2 HIGH-POWER BEAMS FOR RESEARCH AND TECHNOLOGY

- Spallation Neutron Sources - Due to the characteristics of the neutron (spin, absence of electrical charge, mass, and wavelength to energy relationship) and to its nuclear and magnetic interactions with atoms, the scattering of thermal neutrons is a particularly important technique to study the structure and the dynamics of condensed matter. It concerns both the arrangement and movement of atoms in solids and liquids, as well as the heterogeneity of materials at micrometric and nanometric scales, or microscopic magnetism.

With ILL in Grenoble, SINQ in Switzerland, ISIS at Rutherford and several national reactors, Europe will have the most effective set of neutron sources for several years to come. However, thought must be given to the years 2010 to 2015 in view of the probable decommissioning of a number of research reactors and the appearance of spallation sources offering higher pulsed neutron flux for time of flight measurements and far lower total power and energy dissipation than reactors. The recent international projects are then based on the pulsed spallation technique (SNS in the USA to be commissioned in 2006, Joint project in Japan, ESS in Europe). Proton beam power levels in the 2 to 5 MW range are planned for these new installations.

- Production of radioactive ion beams - Research in the field of nuclear physics associated with the study of these extreme states of the nucleus will be the priority for many years to come. Exotic nuclei firstly constitute an excellent means of studying the fundamental interaction between nucleons, and secondly, beams of radioactive nuclei offer new possibilities for advanced research in astrophysics and particle physics. Rare and highly unstable nuclei (as distant as possible from the valley of stability) can be produced by bombarding heavy metal targets with the primary proton beam (~ 200 kW) or with an intense flux of spallation neutrons. In the ISOL (Isotope Separation On Line) scenario envisaged the neutrons can be produced by a high intensity beam of protons. The use of a MW class proton linear accelerator comparable to that envisaged in other fields of research would provide an additional gain of two orders of magnitude as concerns flux. A time structure with a 50 Hz pulse rate is tolerable.

- Hybrid reactors and transmutation of nuclear waste - Hybrid reactors are based on an accelerator driven source of neutrons used to control the core of a nuclear reactor with a large degree of liberty in the choice of the fissile core. The external neutron source actually allows operation under sub-critical conditions and decreases the neutronic constraints in terms of reactivity control or neutron balance. This constitutes a specific advantage in the transmutation of minor actinides and certain long-lived fission products. In addition, such reactors have advantages such higher burnup and less critical core composition and geometry.

The actual design of hybrid systems lead to the use of a new generation of high-power proton accelerators (5 to 50 MW) with very high standards of reliability ("ADS quality” with probably no more than 100 unscheduled beam interruptions per year). To obtain an industrial system in the longer term, it would be necessary to proceed by stages. The demonstrator stage should include a ~1 GeV proton accelerator with an initial power of 5 MW extendable to 20 MW in a subsequent phase (accelerator designed to evolve from the demonstrator stage to the industrial prototype stage).

This application could benefit greatly from a linear proton accelerator developed for other applications. To provide sufficient compatibility with other applications, a hybrid demonstrator must be able to operate in the pulsed regime. Operation at 50 Hz with pulses of constant peak intensity and variable length is advantageous for power adjustment and setting and reactor diagnosis (measurement of k_{eff}). Nevertheless it remains to be determined whether under certain conditions pulsed operation is not liable to encourage power fluctuations in the sub-critical core.

- Technological irradiation tool - Experimental reactors have been successfully used as irradiation tools for technological purposes. With power ratings of less than 100 MW such installations routinely supply maximum neutron fluxes of a few 10^{14} n $cm^{-2}s^{-1}$ both in thermal and fast range above 1 MeV. The level of damage is limited to a few displacements per atom (dpa) per year. The development of new materials with better performance and longer life time constitutes an issue of major importance. It is necessary to attain neutron fluxes of some 10^{15} n cm^2 s^{-1} in both thermal and fast ranges, as well as an annual damage of a few tens of dpa. Again, high spallation neutron flux should allow to achieve these objectives. A large synergy with the work carried out on hybrid systems is possible since a Pb-Bi target can be used for the irradiation tool. The required proton-beam power is 10 MW.

- Neutrino plants - Neutrinos play a crucial role in particle physics and astrophysics. Being neutral and sensitive to weak interactions only, it is very difficult to study them. On the other hand, these properties make them excellent tools for studying the core of the sun, explosions of supernovas and the outer reaches of the universe. The question of their mass is also fundamental but accurate measurements must be done using an indirect method by detection of the oscillation phenomenon between different species of neutrinos. At present time, the weak flux of neutrinos produced with circular high-energy proton accelerators limits the research goals and the neutrinos produced are mainly of the muon type. Detailed studies require flux greater by several orders of magnitude in the different types of neutrinos. New designs for the production of around 10^{20} neutrino / year are then studied in the major particle physics Laboratories. They are based on an installation comprising a high intensity proton accelerator (2 GeV, 2 mA, 4 MW pulsed linac for the CERN project), an accumulation ring, a production target, a linear accelerator for pre-accelerating the muons resulting from disintegration of pions, a recirculator and a storage ring. Furthermore, the concept of a neutrino plant is linked with the projects of circular muon colliders to reach as yet unattained energies in the centre of mass (10 TeV region) with equipment of a size comparable to that of LEP.

In addition to the development work necessary for the high-intensity proton linac, an important feasibility issue remains to be resolved relating to the collection and cooling of muons. R&D work for these long term neutrino/muon projects could certainly benefit of synergies in the framework of a multipurpose facility.

3 TECHNICAL OPTIONS ANSWERING THE SPECIFICATIONS

The most powerful existing proton accelerators are of either the cyclotron type (SIN - PSI at Zurich) or the linear accelerator type (LAMPF at Los Alamos). Both are limited to 1 MW. The following table indicates typical parameters required for the different uses discussed above. The power levels required can reach 50 MW for one application, and are far higher than those of existing facilities. This factor of 50 justifies the intense R&D work that has been carried out for several years.

User	Beam Power	Energy	Average Current
Condensed matter	5 MW	1.3 GeV	3.75 mA
Radioactive Ions			
from protons	~ 200 kW	> 200 MeV	~ 1 mA
from neutrons	> 10 MW	~ 1 GeV	~ 10 mA
Hybrid System			
100 MWth demo	~ 5 MW	~ 600 MeV	~ 10 mA
Industrial system	~ 50 MW	~ 1 GeV	~ 50 mA
Irradiation tool	10-40 MW	~ 1 GeV	10-40 mA
Muons - Neutrinos	4 MW	2 GeV	2 mA

The linear accelerator is the only type of equipment with which the high intensities required can be reached. Space charge effects set the limit at low energy and the RFQ (Radio Frequency Quadrupole) can accept up to 100 mA CW (i.e. 100 MW after acceleration to 1 GeV) as experimentally demonstrated with LEDA (Low Energy Demonstration Accelerator) at Los Alamos. The IPHI programme (CNRS-CEA) has been started at Saclay on a comparable basis.

- Reliability - As concerns reliability, the hybrid reactor application is by far the most demanding as it requires a very limited number of unscheduled beam interruptions, of the order of 100 per year at maximum provided the target and reactor designs are optimised for this. In comparison, the specification for the study of condensed matter by neutron scattering is relaxed with several hundreds. The statistics for linacs and cyclotrons in operation give similar results, amounting to some 10,000 interruptions per year, i.e. some two orders of magnitude higher than the specifications. It is evident that the equipment involved was not designed according to severe reliability criteria. More recently, high reliability levels have been demanded and achieved on synchrotron light rings of the third generation with mean times between failures of around 20 hours (300 unscheduled interruptions per year). Means are available of doing substantially better and thus meeting the objective of one hundred. Efforts could also be pursued in parallel to achieve greater tolerance on the reactors and targets side.

- Beam time structure - The time structure of the proton beam from a linear accelerator can be adjusted according to user demand. This can be illustrated by the example of a beam power of 5 MW, supplied at an energy level of 1 GeV, in the form of a 1 ms pulse, with a repetition period of 20 ms (frequency of 50 Hz).

4 MULTIPURPOSE FACILITY

As all the foreseen applications (probably including the hybrid demonstrator) can operate in a pulsed regime, it is possible to meet the requirements with a single accelerator saving both construction and operation costs. For example, series of 50 Hz pulses can be distributed over a 20 ms period, each pulse being formed to satisfy the needs of a given application at the required power level by adjusting the pulse duration (fig. 1). With a 1 GeV linac supplying 100 mA peak current (i.e. 5 MW/ms of beam), it is possible to provide the following pulse sequence :

- 1 ms of H^- (5 MW) for the two compression rings of a spallation neutrons source,
- 0.2 ms of protons (1 MW) for the production of radioactive nuclei,
- 1 ms of protons (5 MW) for the hybrid demonstrator,
- 2 ms of protons (10 MW) for the irradiation tool,
- 0.8 ms of H^- (4 MW) for R&D on a neutrino plant.

In this example the accelerator total beam power is 25 MW with a duty cycle of 25%. The interval between successive pulses must be sufficient to operate fast switching magnets without particle losses.

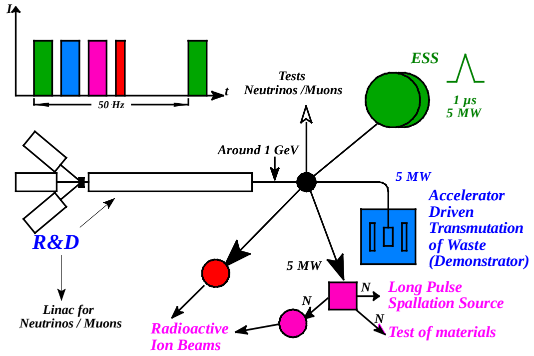

Figure 1 : Basic layout of a multi-user facility

The accelerator would include:

- the low energy linac with
    - a proton and one or two H- sources,
    - low-energy beam transport lines and RFQ accelerators with fast chopper systems to form the pulsed beams up to around 5 MeV,
    - a succession of copper (DTL, SDTL ...) and/or very low beta superconducting cavities up to 100 or 200 MeV,
- the high energy linac made up of a succession of superconducting elliptical cavities to raise the linac final energy (0.8 to 1.3 GeV) with high accelerating gradients,
- two accumulator rings or a rapid cycling synchrotron to meet the short pulse spallation neutron source requirements,
- high-energy transport lines and distribution systems used to direct the beam to the different targets of the users.

To share the accelerator in a multi-user facility certainly leads to substantial savings on both construction and operation costs. Other important savings are also expected from common R&D programs for the different applications, studies and designs of the spallation targets, infrastructures (buildings, power lines, utilities etc.), safety aspects...

5 CONCLUSION

There are excellent scientific, technical and economic reasons to start the feasibility study of a COmbined Neutron Center for European Research and Technology (CONCERT) based on a high-power proton accelerator. Such an installation could be operational around 2010-2015 and serve for a number of decades : an hybrid reactor demonstrator, condensed matter studies by spallation neutron scattering, a technological irradiation tool, a radioactive ion beam facility for nuclear physics, R&D developments for a muon/neutrino facility. The installation could constitute a European centre of excellence in the field of neutronics where a large number of scientific and technical executives could be trained.

The organisation of a well structured European Project Team in charge of the feasibility study and conception phase of such a multi-user facility is started. During this two year phase, the Team will :

- review the beam needs of the different applications,
- analyse their compatibility,
- define the scope of a site-independent project,
- select the most appropriate options regarding scientific, technical, financial, organisational and administrative aspects,
- estimate the costs for construction, operation and the needs in manpower,
- draw up the specifications for the site ...

The study finalised by a conceptual design report will be sufficiently detailed to minimise contingencies on those parts of the project having a large potential impact in terms of performances, costs or delays.

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