LINAC ARCHITECTURE FOR HIGH POWER PROTON SOURCES

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Abstract

High-power proton linacs are needed as driver for several applications, namely accelerator based transmutation of nuclear waste, spallation neutron sources, next generation of radioactive ion beam facilities, neutrino factories and muon colliders, irradiation facilities for material testing... The possible architectures for these high power proton linacs are compared with a review of the key elements of the accelerator. The possible synergies will be pointed out. The concept of single high-power proton linac used as driver for a multi-user facility will be also discussed.

1 APPLICATIONS AND BEAM NEEDS

Beams of several tens of MW can be used to produce high flux of neutrons and secondary particles 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. 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 1 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 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 subcritical nuclear reactor with a large degree of liberty in the choice of the fissile core. This constitutes a specific advantage in the transmutation of minor actinides and certain long-lived fission products. The actual design of hybrid systems leads to the use of a new generation of high-power proton accelerators with very high standards of reliability. The demonstrator stage should include a ~1 GeV proton accelerator with an initial power of 5 MW extendable to 20 MW. Operation at 50 Hz with pulses of constant peak intensity and variable length could be advantageous for power adjustment and setting and reactor diagnosis (measurement of k_{eff}). 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 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} for 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 factories - 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. The question of their mass is fundamental but accurate measurements must be done using an indirect method by detection of the oscillation phenomenon between different species of neutrinos. 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. 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). 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. The development work necessary for the high-intensity proton linac could certainly benefit of synergies in the framework of a multipurpose facility.

The following table indicates typical parameters required for the different uses discussed above. The power levels can reach 50 MW for one application, and are far higher than those of existing facilities.

User	Beam Power	Energy	Average Current
Condensed matter	5 MW	1.3 GeV	3.75 mA
Radioactive Ions from protons from neutrons	 ~ 200 kW > 10 MW	 > 200 MeV ~ 1 GeV	 ~ 1 mA ~ 10 mA
Hybrid System 100 MWth demo Industrial system	 ~ 5 MW ~ 50 MW	 ~ 600 MeV ~ 1 GeV	 ~ 10 mA ~ 50 mA
Irradiation tool	10-40 MW	~ 1 GeV	10-40 mA
Tritium production	30-100 MW	~ 1 GeV	...100 mA
Muons - Neutrinos	4 MW	2 GeV	2 mA

- 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. The statistics for linacs in operation give 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.

2- CRITERIA FOR THE CHOICE OF AN ARCHITECTURE

Three fundamental items are usually taken into account to choose a linac architecture :

-1- Minimum cost for both construction and operation

-2- Operation as soon as possible (limited time for construction and commissioning)

-3- Technical risk as low as possible.

The “architect” has to make it work taking into account the 3 items, even if he knows that the technical challenge is difficult. The new generation of short pulse spallation sources will be 10 to 30 time more powerful than ISIS, the most powerful source in operation. A steep of 1 to 2 orders of magnitude is expected with respect to the LANCE linac and SINQ cyclotron for CW machines.

A first type of conflict which must be examined comes from contradictions specific to each item, for example :

- Conflict between construction and operation costs since a reduced operation cost often means an increased construction cost. A typical example is the choice of a low gradient to reduce the power spent in copper cavities (reduced operation cost) leading to a longer linac and an increased construction cost. The optimization of the construction cost is nevertheless often considered as the first priority in order to be funded !

- Conflict between beam dynamics with minimum beam losses and choice of safe parameters and technologies (gradients, accelerating fields…) to reduce the technical risks. As shown below taking the RFQ as example a global view of all the different aspects linked to a choice is needed to reach a good compromise.

- Short construction period means a difficult time sharing with a competition between time for beam dynamics calculations and optimization of the parameters, R&D work, fabrication, installation and commissioning.

A typical illustration of dilemma for the item “low technical risk” is the choice of the RFQ vane voltage and maximum electric field to reach a high availability. A low vane voltage and peak electric field is a priori the good choice for a low sparking rate, it nevertheless leads to serious difficulties with the length of the cavity, the final energy of the RFQ and the level of beam losses. All these parameters are linked. Low vane voltage means lower transmission and increased beam losses that can be partly compensated from the beam dynamics design point of view if the cavity length is increased or if the final energy is decreased. A longer cavity is nevertheless more difficult to tune and more sensitive to mechanical fault which can induce halo formation and again increase the beam losses. The consequences can be an activation of the RFQ with severe sputtering and vacuum problems leading to a high sparking rate, just at the opposite of the primary goal. The final energy of the RFQ can be lowered to improve the situation but the difficulties are then pushed on the front end of the DTL which becomes more difficult to build.

The second type of conflict comes from obvious contradictions between the 3 items.

- Low construction and operation cost push to technical options such as higher field for a shorter linac..., reduced R&D programe, use of lower quality components, minimum redundancy... leading to higher technical risks.

- A too short construction period impose the availability of extended production tools with more people at work, often leading to a higher construction cost and increased technical risk. A reduced optimization period and a limited R&D programe on key subjects due to a lake of time obviously also leads to increased technical risks.

A possible way to reduce the costs (competition), go faster and reduce the technical risks is to work with several companies on key elements such as RF systems and RF cavities.

The choice of the linac architecture is sometime also dependent on less scientific and technical reasons ! The “architect” background and the experience of the Project Team are also determinant. Political considerations such as the choice of a technology to save a know-how, to select the construction Team, to favor a company, to develop a technology in view of future other projects... must also be taken into account.

The choice of HPPA architectures is then a difficult “Optimization Problem” with strong nonlinear dependencies over a large number of parameters. Some basic rules could nevertheless be used :

① As far as possible, the architect has to try to analyze all the consequences of a technical choice. The example of the choice of the RFQ vane voltage has been discussed above. It is a good example of strong non-linearity since no acceleration is possible with a maximum electric field limited to 1.3 Kp when the current limit is greater than 200 mA for 1.7 Kp. Another example is the choice of the length of the cryostats for the superconducting part of a linac. Several designs are based on long cryostats to try to reduce the costs without a detailed analysis of the beam dynamics including errors showing that the beam losses can remain acceptable. Good and bad sides of a choice could be analyzed and presented to justify it.

② Performances, costs AND technical risks must be taken into account when 2 linac “architectures” are compared.

③ A hierarchy must be established to focus the discussions on major topics avoiding a waste of time on second order subjects.

Beam loss control is the HPPA main issue. The design must be done with an optimum working point with space charge to ovoid the resonances, with smooth transitions (RF frequencies, focusing period length ...), for good beam matchings using an efficient tuning procedure and powerful diagnostics. Particular care must be devoted to the linac front end which must deliver a high quality beam for low beam losses at higher energy.

Availability and limited number of beam trips are also two key constraints to chose the linac architecture for the accelerator driven systems using sub-critical reactors. Options such as working point well below the nominal performances and large redundancies must be taken to fulfill the specifications, even if these options are costly.

The optimization of the construction cost must be also focused on major items. For example, the ESS reference design total construction cost can be decomposed in :
- 44% for the accelerators (27% for the linac + 17% for the accumulators and beam transport lines),
- 16% for the spallation targets,
- 40% for the “general site” including the “buildings and services” for 22% of the total construction cost.

The total manpower is 2626 staff.year (525 staff.year/year over a 5 years construction period), representing around 22% of the total construction cost. The US-SNS construction cost breakdown shows similar numbers clearly indicating that the construction cost is dominated by 3 items (linac ~ 30%, buildings and services ~ 25%, manpower ~ 25%). The construction cost breakdown of the US-SNS linac given on figure 1 (March 2000 data) shows the very high importance of the RF system.

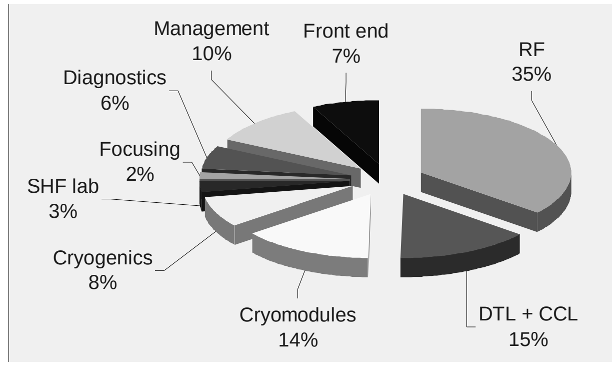

Fig. 1 : US-SNS linac construction costs

Each part of the linac can be analysed to focus the efforts on the major topics giving priorities which are far to be obvious to define without such analysis. Figure 2 gives the example of the US-SNS cryomodules. Efforts to reduce the construction cost on that part of the linac must be focussed on the choice of an architecture for easy assembly & installation since trying to save some niobium to reduce the construction cost is clearly a waste of time.

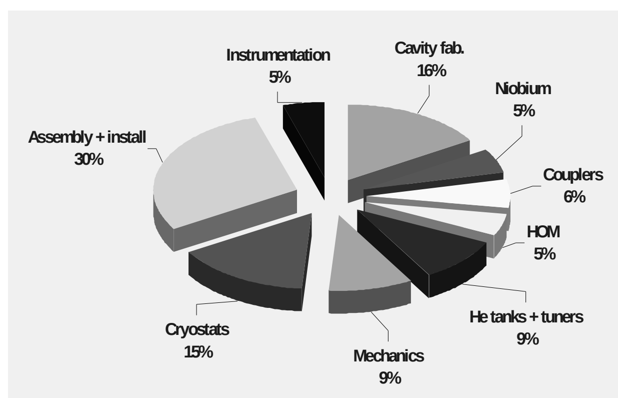

Fig. 2 : US-SNS cryomodule construction costs

Similar analysis must be done for a real optimisation of the operation cost dominated by the costs of manpower and electricity. For the ESS reference design based on a room temperature linac, ~ 40% of the total operation cost comes from manpower (570 Staff.year/year) with another ~ 40 % for electricity (16% of total operation cost for the RT linac electricity).
Attention must then be put on technical choices leading to an increase of manpower. Superconducting cavities must be used for CW operation. The cost of electricity can have variations as large as 50% (from .04 to .08 Euro/kWh depending on the type of contract and geographic position). This data is important since this cost apply to the total electricity consumption. It is also interesting to note that an effort to gain 20% of efficiency on the ESS RT linac is only “paid” by a 3% gain on the operation cost.

3- **KEY COMPONENTS & LINAC ARCHITECTURES**

- Sources & LEBT – Great progress have been achieved on ECR CW proton sources thanks to strong R&D programs at Chalk River, Los Alamos, Saclay, LNS-Catania... High performance sources (100 mA CW with 0.2 π mm mrad rms norm emittances) are now available for daily operations. ECR sources with no filament nor RF antenna have demonstrated high reliability capabilities (99.98% with only one beam trip during a 100 hour continuous test for the SILHI source at Saclay). Recent progress on H- sources have been done at Berkeley for the US-SNS project. The 2 MHz RF Driven Multi-cusp "startup" source can deliver 35 mA with 6% duty cycle for 1MW operation. A 65 mA "production system" is in progress. A 120 mA H- beam has been obtained at Frankfurt University with further developments needed to use such high current in operation. The JAERI H- source developed for the Japanese joint project can be operated at 40 mA with a 5% duty cycle. Reliability and long life time could come from ECR H- sources. R&D programs are in progress at Argone, KEK and Saclay where an international collaboration is started.

The two major technical choices concern the architectures of the spallation neutron sources (SNSs).

-①- Choice between electrostatic and magnetic LEBT lines. This choice is related to one of the most difficult problem in the HPPA field, namely the space charge compensation by electrons or ions from the residual gas. An electrostatic solution, forbidding space-charge compensation and often associated with strong aberrations, leads to emittance growth and serious difficulties to match the beam to the RFQ at beam currents higher than 50 mA.. On the other hand a magnetic solution allows a space–charge compensation with ~ 10 µs time constant. This choice is then the best choice for long pulse and CW operations. Transient problems and high sensitivity to the residual gas pressure can lead to choose an electrostatic LEBT for short pulse operation (US-SNS choice).

-②- Choice of the H- beam current for reliable operation. SNS designs must be done using peak and mean beam currents such that the source and LEBT can operate with the requested availability. This is a major choice since its determine the final energy and duty cycle of the facility to reach the nominal beam power. Relatively low beam currents mean higher energies, for example using rapid cycling synchrotrons (RCS). The duty Cycle can be also increased increasing the number of compressor rings (constant space-charge tune shift and stripping foil temperature for the rings). The optimization is complex and the 3 major SNS projects in the world have different designs :

- 2 MW US SNS

LINAC : 1 GeV - 52 mA peak
6% duty - 68% chopping - 60 Hz
1 Compressor Ring : 1060 injected turns / 1.0 ms

- 1 MW Japanese Joint Project (upgradable to 5 MW)

LINAC : 400 - 600 MeV - 50 mA peak
2.5% duty - 56% chopping - 50 Hz
0.4 - 3 GeV 25 Hz RCS (500 µs injection) as injector for the 50 GeV main synchrotron

- 5 MW ESS

Funneling with 2 x 70 mA peak H- ion sources
LINAC : 1.3 GeV - 107 mA peak
6.0% Duty - 60% chopping - 50 Hz
2 x 50 Hz Compressor Rings (1000 injected turns / 0.6 ms in each ring)

Two different designs studied for ESS can be given to illustrate the complexity of the choice. The first one based on a 800 MeV linac and three 50 Hz compressors (same current 10% duty cycle) was cheaper but has been considered as more complex than the reference design. The second one based on a 800 MeV 50 Hz Linac and two 3 GeV 25 Hz RCSs (1.334 MW Linac) has been also considered as more complex. The ESS design is nevertheless based on a funneling system which is also "complex" !

- RFQ, Chopping Line & DTL (up to 40–50 MeV) - HPPAs can work only because RFQ exists ! The RFQ is actually the only way to start with the continuous beam of the source and produce high quality bunched beam. In this domain, the Low Energy Demonstration Accelerator (LEDA) at Los Alamos is the reference. The operation of the 6.7 MeV LEDA RFQ at 100 mA CW (670 kW) is actually a decisive step with several consequences on the architecture of the new generation of HPPAs :

- LEDA demonstrated the acceleration up to 6.7 MeV of a high beam current with high duty cycle up to cw in the most difficult part of the linac (maximum space-charge forces and peak fields which can seriously penalize the reliability).

- LEDA has successfully tested several new techniques : evolution of the parameters to optimize the beam dynamics, new cavity design, manufacturing procedure, segmented cavity, RF stabilization with respect to parasitic modes, RF tuning procedures... RF coupling with ridged guides and coupling slits, beam tuning procedures… These original solutions can now be used as solid references for the new designs.

- LEDA gives the knowledge of the beam parameters at low energy allowing a validation of the beam dynamics codes and the choice of optimum cavity beam apertures for limited beam losses.

- LEDA demonstrated the feasibility of a high output energy RFQ (6.7 MeV) using a quite high RF frequency (350 MHz).

The last point has important consequences on the linac architecture choices bringing much more possibilities to optimize HPPAs "from the source to the final energy". A

DTL using a FODO focusing lattice and electromagnetic quadrupoles can be used directly after the RFQ. The focusing period is as short as possible with a smooth transition with the RFQ. Source of emittance growth and halo formation resulting from FFDD focusing schemes or 2 or 3 $\beta\lambda$ operation mode (longer focusing period) can then been avoided. It also allows to design a chopping line at 2 MeV (below the copper activation threshold) between 2 RFQs for a smooth transition and an adiabatic re-capture of the beam after the chopping line. The LINAC can now be designed with a RF frequency jump reduced to a factor 2 for a better beam dynamics using frequencies leading to optimal cavity sizes at low energy (f < 400 MHz) and high energy (f ≥ 700 MHz). All this leads to a reduction of the technical risk at a minimum cost.

- Medium Energy Linac (40 – 50 to 100 – 400 MeV) – This part of the linac offers a large open choice between different types of copper cavities (DTL, SDTL, CCDTL, Quasi-Alvarez, IH.. and super-conducting cavities (spokes, quarter-wave…). SDTL room temperature cavities seems to be a good choice since super-conducting cavities have to be considered for CW machines. The design must be done with a progressive transition from the end of the DTL up to the high energy structures. It seems interesting to consider the RF frequency jump (x2) in this part of the linac (Medium Energy Linac) instead of systematically making it at the end. The choice of the architecture must result from beam dynamics studies including errors showing that the linac is as “fault tolerant” as possible. The design must also be done thinking to the tuning procedure with diagnostics and correctors.

- High Energy Linac (W > 100 – 400 MeV) – Super-conducting cavities must be used to save a large amount of operation cost in the case of CW operation. Actually, an optimized room temperature 1 GeV CW linac operates with an accelerating field around 1.5 MeV and a mean shunt impedance around 35 MΩ/m. The cavity length is ~670 m and the 43 MW RF power lost in the copper cost around 30 MEuro per year. The advantage of superconducting cavities is more questionable for the spallation neutron sources. It seems that this remains an open question which needs more developments to demonstrate the real technical advantages of this technology. Typical questions to discuss are :

- Larger bore for less beam loss ? Not true for particles lost in the longitudinal phase plane. The focusing period is usually longer using super-conducting cavities, often leading to larger beams and more sensitivities to errors. Larger bore means less efficient and more expensive also for super-conducting cavities.
- Energy stability is better ? Added problems of Lorenz forces & microphonics.
- Substantial reserve capability for availability and “upgradability” ? A reserve capability means an increased cost of the project. Reserve capabilities are possible with copper cavities as well.
- Construction and Operation cost advantages ? It seems that there are no significant differences between both options. The need of small RF systems strongly penalize the cost of the super-conducting linac (RF cost scale as the square root of the number of RF units).

4- MULTI-USER FACILITIES

Several applications can be based on HPPAs with similar architectures and the concept of single high-power proton linac used by several user seems attractive. It is not a new idea. The “Intense Neutron Generator” proposed by Chalk River in the late 60’s was designed with a 65 mA 1 GeV CW (65 MW) linac. The scientific motivations were expressed as follow : “Many features of the ING arise because it is multipurpose. An intense thermal-neutron flux (10^{16} neutrons/cm^2.sec) at the main target would be used for research in solid state, nuclear, and reactor science and for production of radioactive isotopes of both research and commercial value”. A CW meson factory and pulsed beams for time of flight measurements were also foreseen.

The recent progress done in the HPPA field allow to think again to such “multipurpose facilities”. The Japanese JAERI-KEK joint project is a good example of facility devoted to both basic and applied research. The 20 MW KOrean Multipurpose Accelerator Complex (KOMAC, 1 GeV – 20 mA CW) follow the same logic. The study of a COmbined Neutron Center for European Research and Technology (CONCERT) is now undertaken by several European Institutions. 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. 3). The CONCERT project is now in a 2 year phase of feasibility study including the optimisation of the linac architecture and a detailed cost analysis.

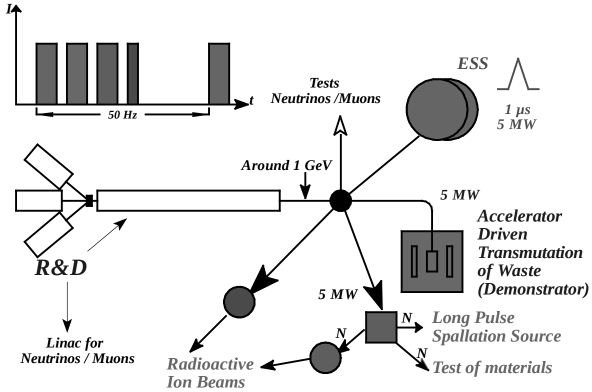

Fig. 3 : Basic layout of a multi-user facility