SURVEY OF HIGH-POWER PROTON LINACS

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Abstract

High-power proton linacs are envisaged as drivers for numerous applications, as neutron spallation source for condensed matter study, neutrino factories and muons colliders, hybrid systems for transmutation or energy production, production of rare isotope beams for nuclear physics studies, etc. These new linear accelerators are intended to deliver proton beam of up to several MW and even to several tens of MW power and operate with CW or pulsed high intensity beams. There is a general trend for adopting the superconducting technology, which offers some advantages, like higher gradient capabilities or operational costs reduction, as compared to room-temperatures accelerating structures. The primary concern of building such high-power linacs is the minimisation of beam losses, which could limit their availability and maintainability due to excessive activation of the machine and irradiation of the environment. A careful beam dynamics design is therefore needed to avoid the formation of particle halo that would finally be lost in the linac or in transfer lines. Furthermore, some applications, like accelerator driven systems (ADS) require a very low number of beam interruptions, which could affect the lifetime of key components such as windows, reactor parts and structure, as well as the ADS operation. This paper gives a survey of typical high-power accelerators projects under construction or in planning, compares the beam and linac parameters and points out the choice of the technical options and of the components.

1 INTRODUCTION

The forthcoming generation of High Power Proton Accelerators (HPPA), which have the potential to deliver beams of a few to several tens of MW, are envisaged as drivers for a large variety of applications: condensed matter study with spallation neutrons, hybrid subcritical reactors for nuclear waste transmutation, rare isotope beams for nuclear physics studies, neutrino factories. The superconducting (SC) technology, because of its higher gradient capabilities and lower operational costs with respect to normal-conducting (NC) structures, has been adopted in most of the designs for the major part of the linac. Table 1 gives the main parameters of typical new HPPA projects under construction or in planning. It is worthy mentionning the CONCERT project [1] that proposed to combine the various applications on the same site with a single proton driver.

The pulsed Spallation Neutron Source SNS [2], under construction at Oak Ridge National Laboratory, consists of a full energy injector linac, an accumulator ring and a target station. The facility will deliver a 1 GeV, 1.4 MW proton beam on a liquid mercury target. The operation of the facility will begin in 2006 and incorporates possible future upgrades, as a second target station and an extension of the linac to increase the energy to 1.3 GeV.

The European Spallation Source ESS [3] reference design consists of a full energy 1.334 GeV linac, a 5 MW SP target station fed with protons compressed by a double compressor ring and a 5 MW LP target station fed directly with protons from the linac. The pulse sequence, repeated at 50 Hz, consists of two short chopped beam pulses (0.48 ms), followed by one long unchopped beam pulse (2 ms), occurring once every 3 cycles. Two linac schemes, which are still under consideration, have been studied, a NC version (280/560 MHz) and a SC version (352/704 MHz).

The JAERI/KEK Joint Project [4] combines different applications by making full use of the secondary beams, such as neutrons, muons, kaons and exotic ions, that can be efficiently produced by the proton beams. The phase I of the project, dedicated to condensed matter studies, nuclear and particle physics, comprises a 400 MeV NC linac, a 3 GeV rapid-cycling synchrotron and a 50 GeV synchrotron. In the phase II, the protons will be fast extracted from the synchrotron for neutrino production and the NC linac will be extended by a 200 MeV acceleration SC linac for ADS purpose.

The CERN Proton Driver (SPL) [5] is intended to improve the intensity and quality of the CERN proton beams and thus would benefit the LHC and ISOLDE experiments. It could also provide intense beams of radioactive ions or neutrinos (Superbeam). Ultimately, together with accumulator and compressor rings, it would be a suitable driver for a neutrino factory. The 4 MW 2.2 GeV linac re-uses most of the 352 MHz RF equipment from the LEP machine.

The Korea Multipurpose Accelerator Complex (KOMAC) [6] project has been initiated to develop and build an accelerator capable of delivering 1 GeV 20 mA proton beams in the final stage. It will be used for basic science research, rare isotope beams production and technology development of ADS for transmutation of nuclear waste. The 1st phase consists in the development of a CW 20 MeV high power front end. In parallel, applications using low energy beams are developed

The Rare Isotope Accelerator (RIA) [7] will supply an intense beam of exotic isotopes for nuclear physics research by combining ISOL and in-flight fragmentation techniques. Different types of superconducting cavities accelerate the CW beam of heavy ions to 400 MeV per nucleon, with a beam power of up to 400 kW.

The European Isotope Separation On-Line Radioactive Nuclear Beam project (EURISOL) [8] has two driver options: a 50 MeV electron accelerator to provide photo-fission products and a 1 GeV proton accelerator, operated either at low intensity (a few hundred μA) as a classical ISOL facility or at high intensity (around 5 mA) to generate high neutron fluxes from a spallation target.

Table 1: Main parameters of typical HPPA projects

	SNS	ESS	KEK/JAERI	SPL	KOMAC	RIA	EURISOL
Beam power [MW]	1.6	2 x 5	0.375	4	20	0.4	0.2 - 5
End Energy [GeV]	1.	1.334	0.6	2.2	1.	0.4 / A	1.
HE Frequency [MHz]	805	704	972	352	700	805	704
Rep. rate [Hz]	60	50 - 50/3	25	50	CW	CW	CW
Beam pulse length [ms]	1.04	0.96 - 2	0.5	2.8	∞	∞	∞
duty factor (%)	6.25	4.8 - 10/3	1.25	14	100	100	100
Beam current average in macro pulse [mA]	26	78 - 112.5	50	13	20	-	0.2 - 5

2 BASELINE LAYOUT

A typical ~1 GeV proton linac in MW average power range consists of three main sections:

- A front end (linac injector) is composed of an ion source and a radiofrequency quadrupole (RFQ) accelerator. The ion source has to deliver high brightness beams (intensity, emittance, stability). For applications using accumulator rings, pulsed beams of negative hydrogen ions are required in order to allow for a loss-free injection into the rings. The RFQ, which includes RF electric transverse focusing, bunches and accelerates the beam from about 100 keV to a few MeV. These structures are well suited to keep the beam quality (longitudinal and transverse) at high intensity.
- Intermediate-velocity structures accelerate beam to about 100 MeV in the range $\beta \sim 0.1$ to 0.5. These structures are usually normal-conducting drift-tube linac structures (DTL, SDTL, CCDTL). However, superconducting structures, as spoke type resonators, are being contemplated especially for CW beams.
- High-velocity structures accelerate beam up to GeV energies and consist of normal-conducting coupled-cavity linac structures (CCL) or of superconducting elliptical cavities that offer some advantages such as higher gradient capabilities and lower operation costs.

In addition, some specific components have to be implemented: as a funnel and a chopper. In case of very high intensity (H^-) beams that cannot be achieved by one single source, two independent front ends are funnelled at sufficiently high energy by means of deflecting cavities. To allow injection into a compressor ring, chopping is required at the ring revolution frequency with beam duty cycle of about 70% and with very fast rise times of the deflecting fields, lower than the bunch spacing.

3 ION SOURCE

In the last past years, high power CW proton sources have been developed in different laboratories (LEDA project at LANL and SILHI source at CEA-Saclay) and have demonstrated high current capabilities (> 100 mA) with high availability and reliability. With regard to H^- sources, the simultaneous achievement of the required performances (current, emittance, duty cycle, lifetime) is very challenging. While the 50 mA SNS source is able to meet the required beam current of the SNS project, two 60 mA sources for each of the short and long pulses are needed for the ESS project. Vigorous R&D effort is carried out to explore the possibilities of different source types (Penning surface plasma source, volume source or ECR source).

4 RFQ

RFQs allow adiabatic bunching with high transmission. They are designed to minimize emittance growth during bunching and acceleration process, while keeping a large acceptance. The 350 MHz RFQ in the Low Energy Demonstration Accelerator (LEDA) at Los Alamos has demonstrated the ability to accelerate ~100 mA CW beam up to 6.7 MeV. The output energy is usually chosen as the lowest energy compatible with the technical feasibility of the following Drift Tube Linac (DTL) including electromagnetic quadrupoles. The energy is then set in the 5-7 MeV range and in the 2-3 MeV range in case of insertion of a chopper system, for which a lower energy is preferred. The choice of the technology, four-vane or four-rod type, is mainly driven by the operation frequency. Though most of the RFQs are of the first type, large experience has now been gained by the University of Frankfurt in the design and operation of four-rod RFQs, which provides easier tolerance fabrication and cooling at lower cost. In order to minimize the risk of RF breakdowns and then to increase the reliability and availability, the peak surface electric field is chosen lower than 1.8 Kilpatrick.

Table 2: RFQ parameters for a few projects

	SNS	nc ESS sc		SPL	KOMAC
Ener.[MeV]	2.5	2.5	2	3	3
Freq.[MHz]	402.5	280	352	352	350
Type	vane	rod	vane	vane	vane
Ep [MV/m]	36	22	33	34	?
Transm.[%]	> 90	> 97	> 98	95	?

Table 2 shows some relevant parameters for a few projects, including the two versions of ESS (280 MHz for the NC scheme and 352 MHz for the SC scheme).

5 INTERMEDIATE-VELOCITY STRUCTURES

As the efficiency of RFQs drops rapidly with energy, more attractive accelerating structures have to replace them above a few MeV.

Alvarez type Drift Tube Linac (DTL) structures are usually selected just downstream the RFQ. Post-couplers are used for stabilisation of the fields in the tanks. They have a relatively high shunt-impedance at low energy and as they integrate a quadrupole at each drift tube, they provide a frequent focusing, which is essential for the high intensity beam at low energy. In addition, the continuity of the focusing forces with the upstream RFQ can be ensured. On the one hand, the input energy is chosen sufficiently high to allow for the use of electromagnetic quadrupoles, such that the focusing parameters can be finely tuned to avoid any halo formation. Some effort has been put on the development of high field gradient and small electro-magnets: hollow coils were fabricated by using the electroforming method and the wire cutting for the JAERI/KEK project [4]; efficient cooling outside the conductor and inside the drift tube has been developed for the IPHI project [9]. On the other hand, when a chopping system - easier to build at low energy, less than 3 MeV - is used, the input energy must not be to high if one wants to avoid a second costly RFQ. This solution is being contemplated for the SPL project. Table 3 shows the chosen energy of DTL structures for a few projects. In order to compensate the missing focusing gap and the associated transverse defocusing lens between two tanks, a careful matching is necessary in order to prevent any halo development. This is done by adjusting the length of a few adjacent cells in the SNS linac [10], while a common vacuum vessel is used to avoid this break in the focusing pattern in the 280 MHz normal-conducting ESS linac [3].

Again, the shunt impedance of Alvarez-type DTL is strongly decreasing with energy and more efficient DTL structures have to be used. At sufficiently high energy (a few tens of MeV) the focusing period can be made longer and the quadrupoles can be moved outside the tanks. The so-called Separated-function DTL (SDTL) structures offer the double advantage of a higher shunt-impedance and an easier alignment of quadrupoles, thus relaxing the alignment of the drift tubes. However, in order to reduce the lattice period, a quadrupole-doublet focusing will be preferred. The drawback is the RF feeding system: the tanks are fed by individual RF power sources or by fewer sources but with a complex waveguide distribution. SDTL structures have been selected in the 704 MHz ESS linac and in the 324 MHz Joint Project linac.

The Cell-Coupled DTL (CCDTL) is a hybrid structure combining the advantages of a Coupled Cavity Linac (CCL) with the features of a DTL. It is made of chains of small 2-gap DTL structures connected by bridge couplers with the quadrupoles located outside the cavities. The advantages are easy access and alignment of the quadrupoles, low construction cost and simple RF distribution. The quadrupole spacing is shorter than for the SDTL and allows keeping the FODO lattice. This is very convenient for matching the upstream Alvarez-type DTL, as well as a downstream CCL.

Table 3: Energy of DTL structures for a few projects

	SNS	nc ESS	sc	SPL	JP
Alvarez DTL					
Frequency [MHz]	402.5	280	352	352	324
Ein DTL [MeV]	2.5	2.5	5	3	3
Eout DTL [MeV]	87	20	20	40	50
X-DTL					
Frequency [MHz]	-	560	704	352	324
X- Type	-	CC-	S-	CC-	S-
Eout X-DTL [MeV]	-	100	100	120	190

The SNS design, which originally integrated a CCDTL operating at two times the DTL frequency, extends the DTL to higher energy on account of the abandon of the funnel upgrade option and of the design simplification.

Alternatively, low-velocity Superconducting (SC) structures, which have been primarily developed for heavy-ion linacs (half-wave, quarter-wave, spoke resonators, etc) can be envisaged owing to their high accelerating field capability. Elliptical SC cavities, foreshortened versions of the multi-cell cavities used for electrons, cannot be used for $\beta < 0.5$ because of their poor mechanical stability and their high peak surface field over accelerating field ratio. A more promising geometry resonator is the spoke resonator [11] because of its simplicity, high mechanical stability and compact size. Quite high accelerating gradients have been recently obtained [12] corresponding to peak surface fields of about 40 MV/m and 100 mT. Using 2-gap or 3-gap spoke resonators, only two or three families of different β-values are necessary to accelerate a beam from 5 to 100 MeV [8] due to the very large energy acceptance. This independently-phased cavities linac provides not only for high transmission but also for great operational flexibility and fault-tolerance. However, since an excessive longitudinal phase advance must be avoided, full advantage of the high gradient available with SC cavities cannot be taken at low energy. As a result, the energy gain per real estate meter in a SC linac (~0.8 MeV/m) is about two times lower than in a normal-conducting DTL linac in this energy range. Consequently, intermediate velocity SC structures will be better favoured when the application requires the acceleration of CW beams and/or of species with a broad mass-to-charge ratio. In fact, the velocity profile in a normal-conducting linac is fixed in order to maximise the shunt impedance and a light-ion linac would have then to be operated at significantly lower gradient for lighter ions, particularly for protons. The low-velocity SC cavities technology, essential to multi-beam drivers as the US rare isotope facility (RIA) [13], is also being contemplated for proton drivers, as the European ISOL facility (EURISOL) or Accelerator Driven Systems (ADS) for waste transmutation [8,14].

6 HIGH-VELOCITY STRUCTURES

The high energy part of the proton linac is by far the most expensive one of the whole linac for both capital and operating costs. For room-temperature linacs, more efficient CCL structures usually replace the DTL like structures above about 100 MeV due to the their continuously decreasing shunt-impedance with energy. As higher gradients lead to shorter tunnels but to higher RF power demands, cost optimisation leads to an accelerating gradient EoT of about 1.3 MV/m for cw operation and about 2.8 MV/m for pulsed operation (with a very flat optimum between 2 and 4 MV/m) corresponding to an energy gain per real estate meter of about 1 MeV/m and 2 MeV/m, respectively. To simplify the mechanical design, each cavity (segment) contains usually cells of equal length, reasonable compromise between exact phase match and easier fabrication. The tanks are coupled together via a bridge coupler to form a continuous RF resonator and tuning posts are added to prevent field instability by moving the TE parasitic modes from the TM010 passband.

Alternatively, high gradient elliptical SC cavities can be used in the high energy part because they offer some advantages as operation cost saving and reduction of linac length and peak power installation.

A SRF linac using a minimum number of cavities and making maximum use of the available surface field leads to a capital cost similar to the one of a normal-conducting linac. Two types of cavities are sufficient to efficiently accelerate the beam from 185 MeV to top energy (SNS and ESS). Starting at a lower energy requires another lower β cavity. Table 4: β values of the SC cavities for some projects shows the β values of the SC cavities for some projects.

Table 4: β values of the SC cavities for some projects

	SNS	ESS	JP	SPL	KOMAC	RIA
Ein [MeV]	186	185	400	120	100	-
Eout [GeV]	1	1.3	0.6	2.2	1	0.4/u
Cavity β	 0.61 0.81	 0.68 0.86	 0.72 0.79	0.52 0.7 0.8	0.45 0.52 0.71	0.49 0.61 0.81

The achievable gradient in SC cavities is determined by the maximum peak surface field that we can expect at the niobium cavity walls in a reproducible way. From the current superconducting RF state-of-the-art, a peak magnetic surface field of Bp = 50 mT (corresponding to an electric field Ep slightly lower than 30 MV/m) can be considered as a conservative value. This value is lower by a factor of two than the surface field aimed at for the TESLA project. In addition, further improvement of the RF superconductivity state-of-the-art is going on, thanks to the surface electropolishing technique. For example, the surface field was increased from 27 MV/m to 35 MV/m in the SNS high-β cavities, which reduced the number of cryomodules to achieve 1 GeV. As the acceleration efficiency for a given geometric β varies with the beam energy, the SRF linac is composed of different cavity families. There is no great interest to choose an energy transition between NC and elliptical SC structures much lower than 200 MeV because the average energy gain is actually lower than 2 MeV/m, a gradient which is easily reached in NC structures. Furthermore, the cavity design for beta values lower than 0.6 is complicated by mechanical stiffness, Lorentz forces detuning and microphonics issues. Table 5 shows the selected input energy of the SC section made of elliptical cavities for a few projects.

Table 5: Input energy of the SC section (MeV)

SNS	ESS	SPL	JP	EURISOL	ADTF
186	185	120	400	85	109

Once the input energy and the maximum peak surface fields are given, the SRF linac architecture (cavity “beta”, number of cavities per cryomodule, transition energies) can be optimised from length and cost considerations with two additional constraints: i) longitudinal phase advance below 90° to avoid structure resonance and ii) maximum power coupler capability.

The highest RF peak power are required for the pulsed high intensity linacs (SNS, ESS). Up to now, the KEK-B coupler has delivered to the beam the highest power (~380 kW CW). First power tests of the SNS coupler, a derived version of the KEK-B coupler, showed very promising results on test stand at room temperature (750 kW with 1.3 ms and 2 MW with 0.65 ms) and on a prototype cryomodule [15]. For very high beam current, as required for ESS (> 100 mA), one has to rely on the 2-coupler scheme. This scheme has been extensively studied for ESS and is based on a pair of 800 kW couplers mounted on the beam tube of each SC cavity.

The non-relativistic nature of proton beam, with respect to relativistic electron beam, results in a larger sensitivity to cavity field fluctuations due to phase slippage along the linac (inside the cavities and from cavity to cavity). As a result, the requirements on the stability of the individual cavity fields among the different applications are very similar, of the order of 0.5% in amplitude and 0.5° in phase. Furthermore, the great sensitivity of SC cavities to mechanical vibrations and gradient dependent Lorentz force stems from both the inclination of their walls to deform easily and the narrow cavity bandwidth. While CW linacs are mainly upset by microphonics, a major concern for pulsed operation in high power proton linacs is the effect of cavity detuning by mechanical vibrations excited by dynamic Lorentz forces. However, provided that the cavity boundary conditions are not too loose (stiffness of the external structure including helium vessel and tuning system ~100 kN/mm), it has been shown [16] that there should be no dramatic increase of the oscillations due to cumulative effect from pulse to pulse, because the low frequency modes, those that could be excited by the RF field pulsing, have small K_m values and hence little impact on the cavity detuning. Furthermore, would the Lorentz force detuning be too large, it could be efficiently counteracted by a fast piezo-element, implemented onto the tuning system. Such an active compensation, whose efficiency has been demonstrated on pulsed mode experiments made on a TESLA 1300 MHz cavity at DESY [17], has been adopted for the SNS project. The "one cavity per klystron" scheme, where each cavity has its own feedback/feedforward RF control system, is generally favoured because it provides the best RF stability, the simplest operation procedure and the greatest flexibility in the event of a sudden RF failure. However, driving multiple cavities by a common klystron can be envisaged at sufficient high energy, where the dynamic properties of the cavities are closer and the phase slippages are smaller ("multiple cavities per klystron" scheme for SPL at CERN and JAERI/KEK above ~400 MeV).

7 BEAM DYNAMICS AND SPACE CHARGE EFFECTS

The primary concern of high-intensity proton linac is to restrict the average uncontrolled beam loss to a very low level (1-2 Watts of beam power per tunnel-meter) to allow hands-on maintenance. Simulation studies in SNS showed of course that localized losses most likely occur at matching sections (DTL-CCL or CCL-SCL), where special shielding can be easily installed. In addition to the risk of halo formation, the main source of distributed beam loss, care must be paid to emittance preservation in all directions, particularly for the applications requiring an accumulator ring, for which a loss-free injection is essential. The designs have adopted a low-loss design philosophy to eliminate the main sources of potential halo and emittance growth:

- Structure instability: zero-current phase advance per period length below 90°.
- Potential mismatches: phase advance per meter as smooth as possible and continuous across all transitions.
- Space-charge coupling resonances: tunes adjusted in the stable region, especially far away from the leading 4th order resonance (tune ratio 1) to minimize energy exchange between longitudinal and transverse planes and possible diffused halo [18].
- Space-charge parametric resonances: careful beam matching and removal of the excited eigenmodes frequency from the beam tune range to limit the extent of particle oscillations, which are resonantly driven by bunch core oscillations, induced by mismatch in the linac [19].

For the last phenomenon, a bore radius aperture much larger than the nominal beam size will definitely help in reducing the beam loss along the linac. The large aperture of SC linacs is undoubtedly a large advantage as compared to NC linacs. Figure 1 gives for example the beam radii compared to the bore radius along the SC version of the ESS linac.

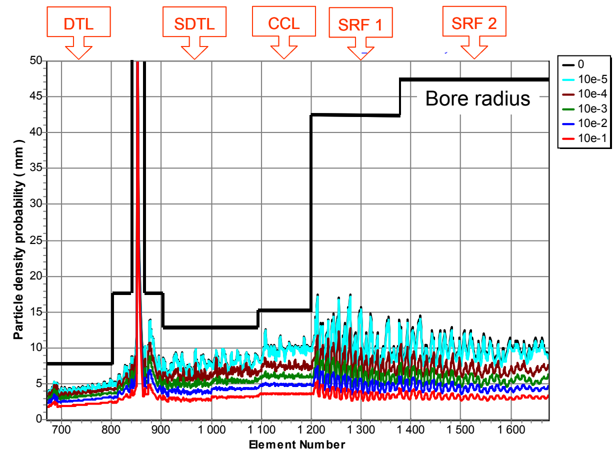

Figure 1: Beam radii containing 90% to 100% of particles and bore radius along the SC version of the ESS linac.

8 REFERENCES

[1] J.L. Laclare, http://web.concert.free.fr
[2] N. Holtkamp, European Part. Acc. Conf. 2002, Paris, p. 164.
[3] The ESS project, Vol. III, 2002, www.ess-europe.de
[4] Y. Yamazaki, European Part. Acc. Conf. 2002, Paris, p. 169.
[5] Conceptual Design of the SPL, CERN 2000-012.
[6] B.C. Choi, 3rd Int. Conf. ADTTA, Prague, 1999.
[7] G. Savard, Part. Acc. Conf. 2001, Chicago, p. 565.
[8] J.L. Biarotte, European Part. Acc. Conf. 2002, Paris, p. 1007.
[9] J.M. Lagniel et al, Part. Acc. Conf. 1997, p. 1120.
[10] J. Stovall et al, Part. Acc. Conf. 2001, Chicago, p. 446.
[11] J. Delayen et al, Int. Linac Conf. 1992, Ottawa, p. 695.
[12] T. Tajima et al, Part. Acc. Conf. 2001, Chicago, p. 903.
[13] K.W. Shepard et al, 9th Workshop on RF Superconductivity 1999, Santa Fe, WEA002.
[14] R.W. Garnett et al, Part. Acc. Conf. 2001, Chicago, p. 3295.
[15] M. Stirbet et al, European Part. Acc. Conf. 2002, Paris, p. 2283.
[16] A. Mosnier, European Part. Acc. Conf. 2002, Paris, THXLA001.
[17] M. Liepe et al, Part. Acc. Conf. 2001, Chicago, p. 1074.
[18] I. Hofmann et al, Part. Acc. Conf. 2001, Chicago, p. 2902.
[19] R.L. Gluckstern, Part. Acc. Conf. 1999, New York, p. 606.