A REVIEW OF LINACS AND BEAM TRANSPORT SYSTEMS FOR TRANSMUTATION

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Abstract
A review of the proposed designs for high-power linacs and the special beam transport lines needed to enlarge the beam on targets is given. Both normal conducting and superconducting accelerator designs are presented and compared. RF power sources are also discussed.

1 INTRODUCTION

High-power proton or deuteron accelerators (average beam power > 1 MW) are studied for numerous applications (see [1-2] for reviews), mainly because they are increasingly considered as ideal sources of neutrons (high flux, broad energy spectra, CW or pulsed mode). These applications include nuclear waste transmutation and tritium production as discussed in this paper. In both the cases, high-intensity CW proton beams are used to produce high neutron flux through spallation process in heavy metal targets. For accelerator driven transmutation of waste (ADTW), the aim is to use these neutrons to transmute long lived nuclei with high radio-toxicity into short lived or stable nuclei. The accelerator is coupled with a sub-critical target (k_{eff} ~ .95) where minor actinides (Np, Am, Cm ...) and/or fission products (^{99}Tc, ^{129}I ...) are located for transmutation [3]. For tritium production, the neutron flux is used to transmute either ^{3}He in the US APT project [4] or ^{6}Li in the TRISPAL project [5] in France.

The choice of the beam intensity and energy must result of complex optimisation of the whole system. The number of neutrons produced per incident proton (n/p) is obviously an important ingredient in this optimization ; it is a function of both proton energy, and spallation target composition and geometry. Fig.1 shows that the efficiency in term of neutrons produced per GeV of incident proton in a 40 cm long ϕ 20 cm solid lead target has a broad maximum between 800 MeV and 2 GeV [6]. However, this maximum efficiency shifts above 1.4 GeV when the target geometry is optimised for incident beam energy (results to be published).

The neutron flux needed for the ADTW system is mainly determined by the choice of k_{eff} through the factor $(1 - k_{eff}) / k_{eff}$ and is proportional to the thermal power (P_{th}) of the sub-critical reactor. The beam power must then be adjusted to track the change in k_{eff} which evolves with the changing core composition in order to keep P_{th} constant (fig.2). The beam power needed for a 1000 MWth ADTW system is of the order of 20 to 40 MW. Some more ambitious projects require up to 200 MW.

Accelerator parameters for tritium production are obviously based on the number of neutrons needed to produce the required quantity of tritium per year. The optimization must also take into account the fluctuations in the cost of electricity during the year to time the production period. These considerations lead to a beam power of 170 MW for the 3-kg/yr production rate in the APT project and 24 MW for the TRISPAL project.

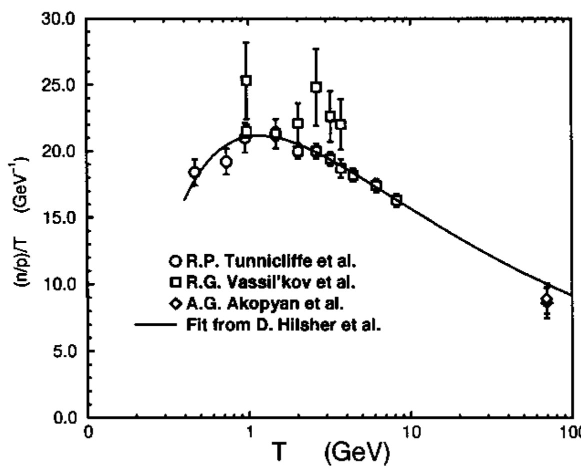

Figure 1 : Spallation efficiency (n/p) / GeV vs energy [6]

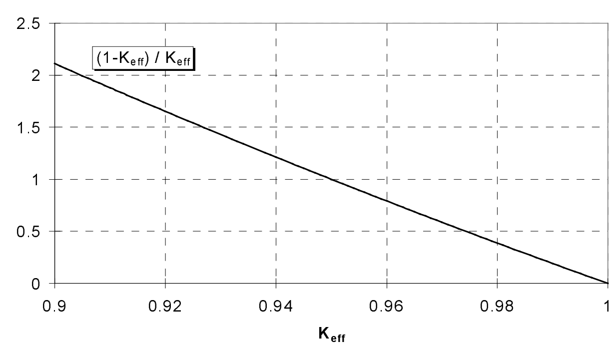

Figure 2 : Beam power evolution with k_{eff}
(normalized to 1 for k_{eff} = .95)

Therefore, CW proton accelerators with beam powers greater than 20 MW are needed for both the ADTW and tritium production systems. A workshop was organized in 1995 to examine the feasibility of using cyclotrons in this high-power range [7]. World experts attended. The conclusion was clear : "- 2 MW is a good choice for cyclotrons, - 5 MW requires some R&D and engineering development but seems possible, -10 MW will require significant investments, research and development". Since then, all the laboratories have directed their efforts towards high-intensity linear accelerators. For the above noted applications, these linacs must be built as an integral part of an industrial facilities. The major points to be taken into account are :

-1- The required beam power is one to two order of magnitude higher than that available today and beam losses must be limited to an extremely low level to allow hands-on maintenance [8-9].

-2- The accelerator must achieve higher reliability /availability than usually requested in research facilities. Availability greater than 90% is needed along with additional constraints on the number of abrupt beam interruptions in order to limit the stress on the target.

-3- The total cost of the machine (construction and operation) must be as low as possible.

It should be emphasized here that the points noted above are closely interrelated. For example, to increase availability, one needs quick access to the accelerator areas. This is not practical because of radio-activation if high beam losses are allowed by design. The alternative is to provide extensive remote-handling and heavy shielding, both of which involve substantial increase in cost.

To illustrate the second point, reactor engineers point out that the PWR can accept only three abrupt stops per year. The constraint is not so severe for cold targets ; Preliminary studies done for TRISPAL show that the target (including the window) can accept up to 10000 beam interruptions (longer than 100 ms) per year. This approximately corresponds to a mean value of one stop per hour which seems feasible. However, the situation is more difficult with ADTW systems which operate at much higher temperatures. This is a very important issue and we can only hope that more than 3 abrupt stops per year is permitted !

2 ACCELERATOR DESIGNS

- The US APT project - Among several high-intensity CW linacs studied around the world, the design of the 170 MW beam power APT linac is without any doubt the more advanced one [4]. The choices made by LANL was arrived at after extensive beam dynamics simulations including error studies. The layout of the 1.7 GeV - 100 mA linac is given in figure 3 and table 1. The design of the front end is based on a 75 keV ECR source and a 350 MHz RFQ up to 6.7 MeV. This high output energy can be achieved in the 8 m long structure thanks to the segmented coupled RFQ concept developed by Lloyd Young at the beginning of the 90's [9]. The ability to have higher RFQ output energy is very useful. Mechanical construction of the structure that follows the RFQ becomes easier and use of EM quadrupoles in a DTL structure becomes feasible even with a jump in frequency. This allowed the APT linac to use only two RF frequencies (350 and 700 MHz) with a jump of only a factor of two at 6.7 MeV. This avoids a strong bunch compression which is always a source of mismatch and halo formation. The use of a 700 MHz Coupled Cavity Drift Tube Linac (CCDTL) after the RFQ also gives the possibility to funnel two front ends to increase the beam current if needed. The 100 MeV CCDTL is followed by a 700 MHz Coupled Cavity Linac (LAMPF-type CCL room-temperature cavities) up to 211 MeV. This transition energy to the superconducting RF (SCRF) cavities has been determined after beam dynamics error studies which showed that beam losses could happen if SC cavities are used at lower energies.

LANL has initiated a substantial ED&D (Engineering Development & Demonstration) program on the $\beta < 1$ SCRF cavities. Recent studies done at CEA-Saclay and LANL demonstrated that the superconducting properties of the niobium cavities are not affected by beam losses as high as 10^{16} p/cm^2/s. In 1997, four 700 MHz single-cell niobium cavities (2 with $\beta = 0.48$ and 2 with $\beta = 0.64$) were built and tested at LANL. They achieved more than twice the field and Q_0 required for APT with no sign of any multipacting. A five-cell cavity has been built in house and should be tested very soon. At the same time, four 5-cell cavities have been ordered from outside vendors and are expected to be delivered at the beginning of 1999. Efforts are also being directed towards the fabrication of specific cryomodules and to the design of the high power couplers. Emphasis will be given on the RF testing of the couplers in FY99. It must be stressed here that the reliability criteria imposed on APT is drastic, leading to an extremely conservative choice of parameters. For example, the maximum accelerating field achieved in the tests is in excess of 13 MV/m compared to the design value of 5.5 MV/m. That was achieved without any heat treatment of the cavities which should enable to reach even higher gradients.

- NSP in Japan - High intensity proton accelerators are being developed at JAERI since 1988 for the OMEGA project (Option Making Extra Gain from Actinides and fission products) and in recent years for the multipurpose Neutron Science Project (NSP) [10]. The NSP is aimed at exploring nuclear technologies for nuclear waste transmutation based on proton induced spallation neutrons. The accelerator facility (fig. 4) could also be used for basic research in various fields. As an example, such a linac in combination with a high intensity proton storage ring could be useful in condensed matter research. A high-intensity proton and H^- accelerator with an energy of 1.5 GeV and a maximum beam power of 8 MW has been proposed (see table 1 and fig. 4). This linac will be operated in a pulsed mode as a spallation neutron source in the first phase (1 mA average, 16.7 mA peak, 2 ms at 50 Hz). It will be upgraded to 5.3 mA CW and 5.3 mA average, 30 mA peak for engineering tests in the second stage. Tremendous R&D work has been carried out for the components of the accelerator front-end consisting of proton and H^- ion sources, 200 MHz RFQ and DTL. A

"Separated-type DTL" (SDTL) has been studied for the 50 - 100 MeV energy range. A SC linac composed of 8 different β sections (see fig. 4) has been designed and developed as a major option above 100 MeV. As the SC cavities will operate at 600 MHz, a frequency jump of 3 is made at 100 MeV. The conceptual design study for the storage ring has also been performed.

- TRISPAL project in France - TRISPAL is a project for tritium production using spallation neutrons. The conceptual design that started in 1992 has been completed [5]. No studies are planned in the next ~ 5 years. One of the main directives to the design team was to be as conservative as possible in the choice of structure types and parameters. Figure 5 gives the layout of the TRISPAL 600 MeV 40 mA CW proton linac. The 24 MW beam is produced using 4 types of RF structures all working at 352 MHz to minimize bunch compression. The front end is composed of an ECR source at 95 kV and a ~ 8 m long LANL type RFQ up to 5 MeV. This is the minimum energy where EM quadrupoles could be used in the drift tubes. Beam dynamics (including errors) and accelerator parameter studies have been completed up to the end of the DTL at ~ 30 MeV. A SDTL structure which is mechanically simpler to build was chosen for the medium energy range (30 - 85 MeV) , followed by LEP-type copper cavities up to the final energy (600 MeV). Linear analysis of the beam dynamics for this part of the linac looks good but more detailed simulations including error analysis could lead to adjustment of the transition energies. In the present TRISPAL design, each cavity is fed through a coupler handling a maximum power of 125 kW. A quadrupole doublet focusing lattice is chosen. The cavities are built in β families (7 for the SDTL, 8 for the CCL) and the RF power is supplied by forty-nine 1 MW klystrons. An option that uses superconducting cavities at higher energies will also be presented along with this basic design.

Table 1

APT (3-kg/yr) LANL, USA	NSP JAERI, Japan	TRISPAL CEA, France
170 MW Protons 100 mA CW 1.7 GeV	Up to 8 MW Protons and H^- Up to 5.3 mA CW 1.5 GeV	24 MW Protons 40 mA CW 600 MeV
ECR source 75 keV	Volume source 70 keV	ECR source 95 keV
350 MHz RFQ 6.7 MeV	200 MHz RFQ 2.0 MeV	352 MHz RFQ 5.0 MeV
700 MHz CCDTL 100 MeV	200 MHz DTL 50 MeV	352 MHz DTL 29 MeV
700 MHz CCL 211 MeV	200 MHz SDTL 100 MeV	352 MHz SDTL 85 MeV
700 MHz SC cav. 1700 MeV	600 MHz SC cav. 1.5 GeV	352 MHz NC CCL 600 MeV

Increased R&D efforts in recent years have lead to three high-power linac projects. Three prototypes, BTA in Japan, LEDA at LANL and IPHI in France are currently funded to make performance test on front-ends of high-current linacs [12]. The experience to be gained in this difficult part of the accelerator is very important to optimize the whole linac in terms of performance, cost and reliability/availability. For example, they will give precious data related to the compromise between peak-surface electric field, beam loss in the structure and cavity length for the RFQ. R&D studies in several laboratories, not directly devoted to the linac front end are also important. The INFN TRASCO program in Italy is an example. Beside the tremendous effort by the APT team, β < 1 SCRF cavities are also being developed in Japan, Italy, Germany, and France (program scheduled for 1999-2003). CERN is also very active in this field ; 352 MHz single-cell β = 0.48, 0.6 and 0.8 Nb/Cu cavities have been built and tested. The construction of a five-cell β = 0.8 cavity is in progress.

3 SCRF CAVITY LINAC

The strong R&D effort on SCRF cavity development is justified by its potential advantage, the most obvious one being cost-benefit. The high RF to beam power efficiency (almost 100%) significantly reduces the operation-cost when the initial investment cost is nearly the same. SCRF cavities with considerably higher gradients than classical copper cavities may also allow linac length reduction. Based on the experience gained so far from the APT ED&D program, an evolution towards higher gradients can be reasonably expected. This would further reduce the linac-length and cost. However, the design and integration of a full cryomodule with its cavities, couplers and cryogenic box is not a straightforward task. Prototypes are definitely needed before construction in order to debug unpredictable problems.

Larger beam apertures can also be used to decrease the risk of beam loss. However, this point is not as obvious as it may appear at the first sight :

- The focusing period is often longer with SCRF cavities and RT quadrupoles located outside the cryostats. This leads to larger beam size and higher sensitivity to errors. Comparison must be made on the beam size to cavity-aperture ratio for ideal as well as with various error-condition scenarios (see the APT design).
- The argument does not apply to particles that lost the phase synchronization. These particles will be lost on the accelerator wall regardless of the aperture-size.
- The designer must avoid strong radial - longitudinal coupling which can enhance the number of particles lost in the longitudinal phase plane.
- The aperture increase is often achieved at the expense of an increase in the number of cavities. The average energy gain per cavity is less and the maximum electric field limits the accelerating field.

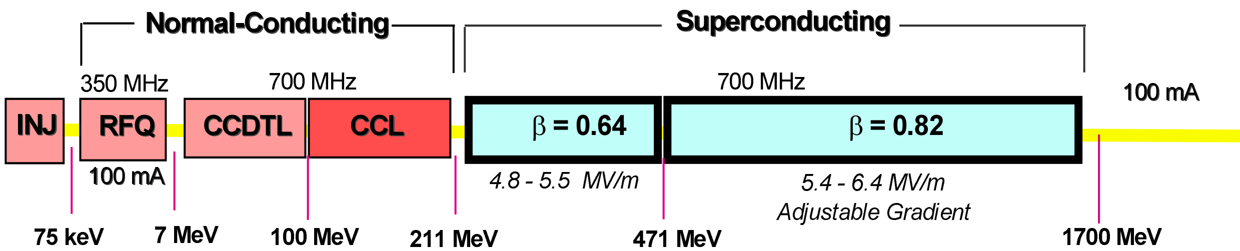

Figure 3 : APT layout for a 3-kg/yr production rate (Linac length = 1220 m)

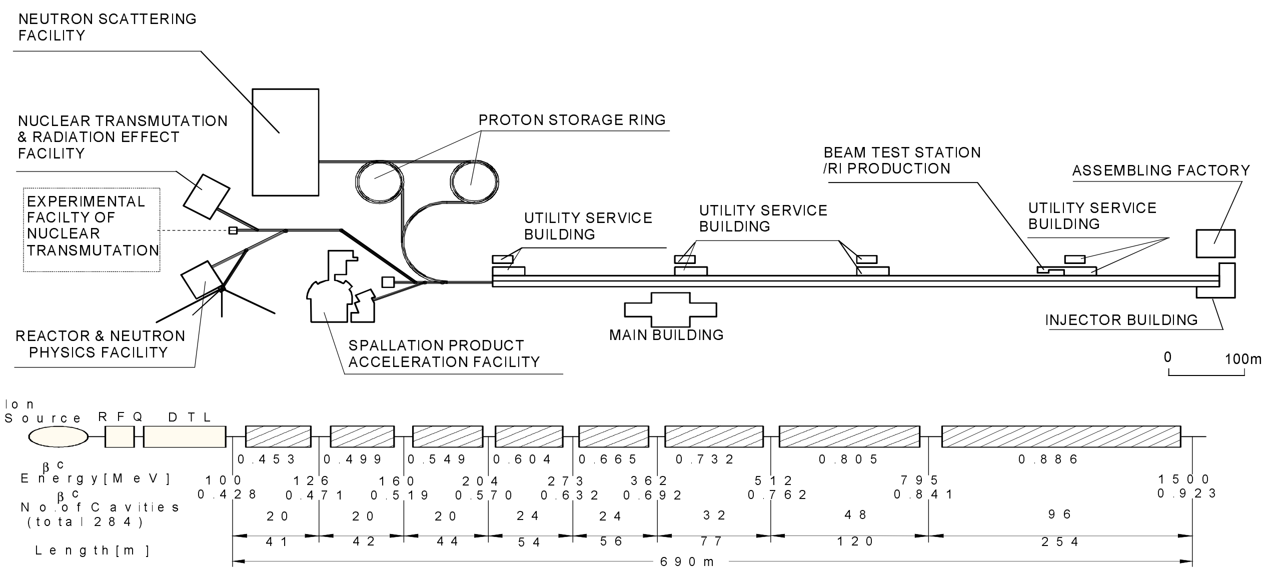

Figure 4 : Layout of the JAERI Neutron Science Project (top) and 1.5 GeV linac design (bottom) (from [11])

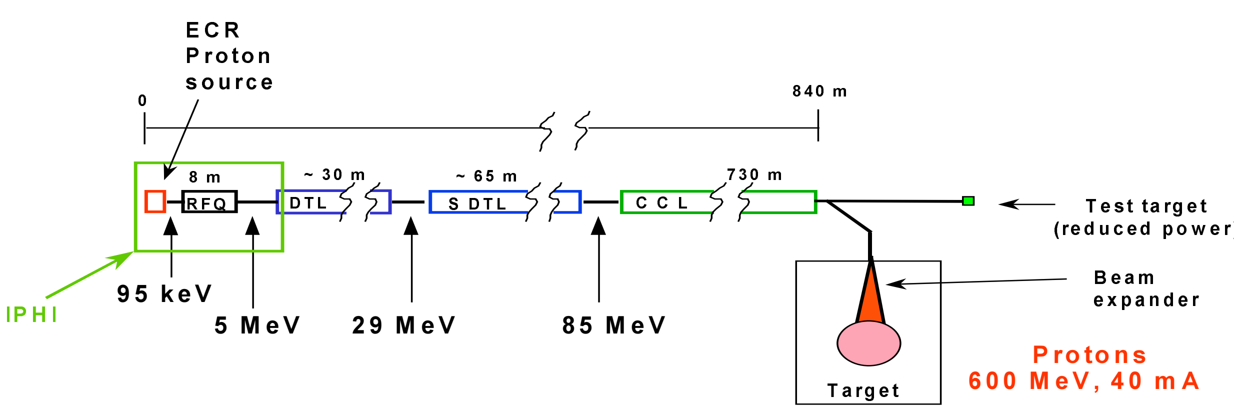

Figure 5 : TRISPAL layout

4 RF SYSTEMS

RF systems for high-intensity CW linac [13-14] have a very important role linked to the three major points listed in section I. The severe restriction on beam loss leads to the need for accurate control of the accelerating fields. The low level RF system must include both feedback and feedforward loops to maintain the amplitude and phase errors at less than 1% and 1^o. In addition, this system must allow a resonant frequency tracking for heating the cavities during the turn-on procedure and a pulsed mode operation during beam-tune up.

The reliability/availability goal will also be very difficult to achieve. To reach a linac availability of 95%, the availability of the RF system must be of the order of 97.5%. Redundancy is obviously needed but organization of the RF distribution to avoid beam interruptions longer than 100 ms is not obvious. RF systems are also major cost items from both the construction and operation point of view. Larger amplifiers have lower costs but induce higher vulnerability to a single-point failure. Several studies have shown that the construction cost is proportional to the square root of the number of amplifiers used in the system. In the frequency range under consideration, the construction cost is ~ 2 MEcu/MW for 1 MW units but reaches to ~ 2.8 MEcu/MW for 500 kW units [13][15]. The same arguments also apply to the high-voltage power supply whose cost is approximately half the total cost of the RF system. Money can be saved using large power supply powering several RF sources. They can be built either with thyristors or IGBTs.

Tetrodes can be used at low frequency (NSP 200 MHz RF systems). Higher frequency (350 - 700 MHz) systems are mainly based on klystrons able to deliver more than 1 MW CW. The LEP 352 MHz 1 and 1.3 MW RF systems give interesting reference points for this kind of use. The control system could be more effective using IOTs which can operate near the maximum output power of the tube. However, a complete cost and reliability /availability analysis must be done before considering the use of high-power IOTs at high frequency.

The other major components are the circulators, the RF windows and couplers. It is now widely accepted that circulators must be used to protect the sources and that windows and couplers can be used up to 250 kW CW.

5 BEAM TRANSPORT AND EXPANDER

In terms of lattice structure, the beam-transport sections are usually regarded as a continuation of the high-energy accelerating section of the linac. For example, the last section of the APT linac consists of a series of SC cavities arranged in a doublet focusing lattice. The transport-section continues with the same lattice.

Besides providing an achromatic bend at the end of the transport section, the other requirement of the transport section is to expand the beam in transverse dimensions (40x80 cm for TRISPAL) with an uniform density distribution on the target. One of the methods pursued in the early stages of APT and TRISPAL was to use suitably placed non-linear lenses. In spite of its relative simplicity, the expanded beam size makes the beam scrape the aperture of the second non-linear magnet under some error-condition scenarios. So the preferred and chosen option is to rastor scan the beam with a series of ferrite magnet fed by triangular current wave from IGBT modulators.

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