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AUTHOR(S) G. P. Lawrence AT-DO

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HIGH-POWER PROTON LINAC FOR TRANSMUTING THE LONG-LIVED FISSION PRODUCTS IN NUCLEAR WASTE*

G. P. Lawrence
MS H811, Los Alamos National Laboratory, Los Alamos NM 87544

Abstract

High power proton linacs are being considered at Los Alamos as drivers for high-flux spallation neutron sources that can be used to transmute the troublesome long-lived fission products in defense nuclear waste. The transmutation scheme being studied provides a high flux (> 10^{16}/cm^2-s) of thermal neutrons, which efficiently converts fission products to stable or short-lived isotopes. A medium-energy proton linac with an average beam power of about 110 MW can burn the accumulated Tc99 and I129 inventory at the DOE's Hanford site within 30 years. Preliminary concepts for this machine are described.

Background

High power proton linacs driving intense neutron spallation sources have been studied for four decades for various nuclear process applications including nuclear waste burning (transmutation). Present plans for disposal of defense (and commercial) high-level nuclear waste, namely vitrification and long-term storage (10^4 to 10^5 years) in deep geologic repositories are meeting with public skepticism and opposition. A principal concern is that projected migration rates for long-lived fission products in these wastes (Tc99 and I129) will not satisfy the standards for long-term confinement within the geochemical environment of the planned high-level waste repository (Yucca Mountain, NV). Ongoing studies at Los Alamos suggest that an intense thermal neutron source driven by a high-power proton linac would be able to transmute all the Tc99 and I129 inventory accumulated at the DOE Hanford site (about 2000 kg) to stable products within about 30 years, eliminating them from the repository feed, and overcoming a critical objection to repository plans. Higher actinides, such as Np237 and Am242, can also be rapidly burned in such a system if desired.

In the Los Alamos defense-waste transmuter scheme, summarized in Fig. 1, a stopping Pb target is used to generate a high flux of spallation neutrons with an incident medium energy high-current proton beam. The primary neutron spectrum is moderated to produce an intense thermal flux (10^{15} to 10^{16} n/cm^2-s) in a D_2O blanket cylindrically surrounding the lead target. The material to be transmuted would be transported through this neutron field by a continuous flow of aqueous or molten-fluoride-salt carrier loops. Precision chemical partitioning methods would remove transmuted material from the carrier flow while the remainder is returned to the blanket for continued neutron irradiation.

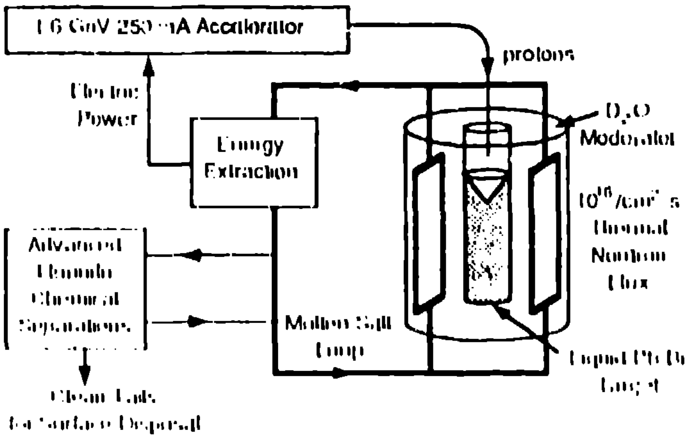

Fig. 1. Los Alamos waste transmutation scheme

Previous accelerator-based transmutation schemes have been based on a fast neutron spectrum in the conversion region. With thermal neutron flux levels in the 10^{16} n/cm^2-s range (100 times greater than in typical thermal reactors), significant technical advances are possible. The higher actinides (e.g. Np237) can be converted by neutron capture to daughter products that are fissioned rapidly by a second neutron interaction before they can decay to non-fissile isotopes. High thermal fluxes of neutrons (where cross sections are large) also permit rapid and efficient conversion of fission products (Tc99 and I129) to stable or short-lived species. Because of the high thermal flux and high cross sections, the blanket concentration of materials to be transmuted is very dilute in the Los Alamos scheme (< 0.1%), providing a system with an extremely small working inventory of dangerous materials. This provides significant safety and environmental advantages.

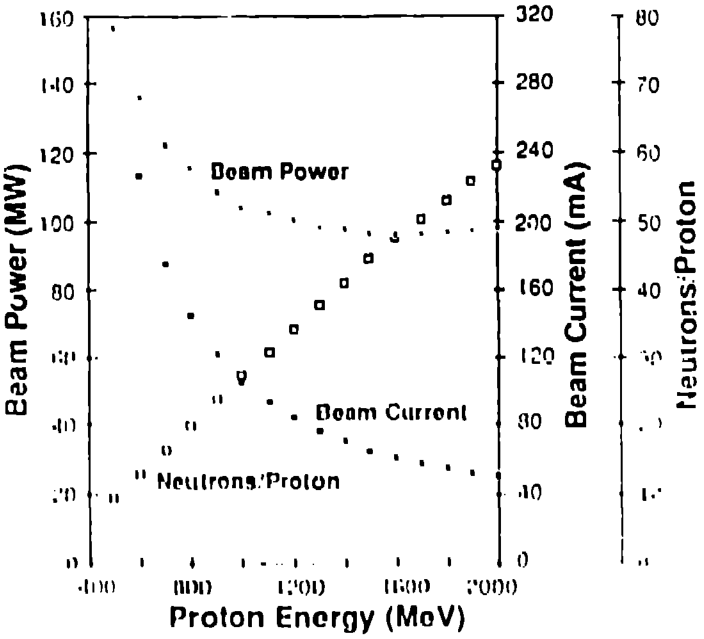

Fig. 2. Energy dependence of neutron yield from Pb target, and of proton current and beam power for ATW neutron production

Neutron transport calculations suggest that the required primary neutron source strength for a defense waste transmuter

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should be approximately 2x10^{19} n/s. Fig. 2 plots the neutron yield (calculated with HETC)[1] versus energy for medium energy protons axially incident on a 50-cm diameter, 200-cm-long Pb cylinder. Also shown are the energy dependence of the proton current and beam power required to produce this neutron source strength. The required beam power is nearly constant at around 100 MW above 1000 MeV, so that beam current can be traded linearly against output beam energy. Below this energy additional beam power is needed, reaching nearly 60% more at 500 MeV. Within the constraints of peak power deposition in the target, the transmuter accelerator parameters can be selected to provide the system with lowest lifetime facility costs.

Cost/Performance Optimization

Our approach to a rational design for a transmuter linac is to start from the concept developed in the recent APT (Accelerator for Production of Tritium) study.[2] Parameters for this machine were 250 mA (cw) at 1600 MeV. From Fig. 2 it is apparent that 60 mA (avg.) would satisfy the transmuter requirement at 1600 MeV. However, in comparison with APT, a 60-mA linac would be very inefficient, because of the relatively low beam loading. Two options can be considered for a more efficient configuration: 1) a cw linac design with lower beam energy and higher current, and 2) a pulsed linac with high peak current. In order to obtain a quantitative assessment of the optimum parameter choices for these two approaches and to compare them, a simple cost model for the linac has been constructed. It assumes a machine architecture similar to the APT linac, with dual RFQ/DTL 350-MHz beam inputs funneled into a 700 MHz CCL. Since funneling takes place at a low energy (20 MeV), for the reasons given in the APT design,[2] most of the cost of the accelerator lies in the CCL. Our cost model therefore represents the ATW linac front end as a lump sum and concentrates primarily on parameterizing the CCL.

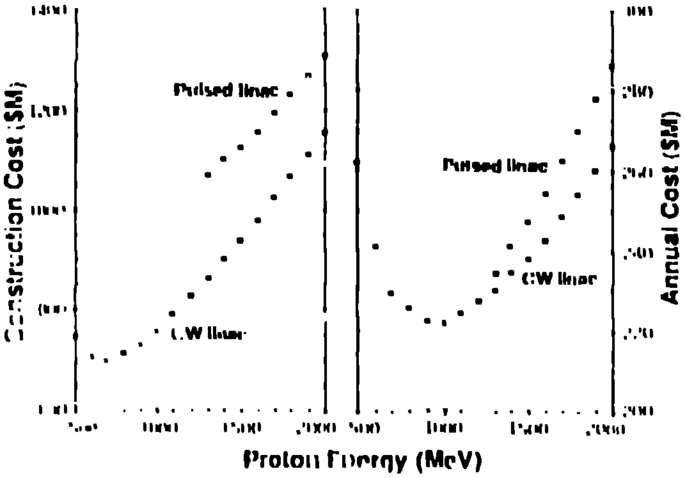

Fig. 3 ATW construction and annual cost versus proton energy for cw and pulsed linac models.

Results of this model are displayed in Fig. 3, which plots estimated construction cost and annual operating cost versus linac output energy for both a cw linac scenario and a pulsed linac. The costs are very approximate at this stage and cover only the accelerator itself; no costs are included for the transmuter target/blanket or chemical separations facilities. Table 1 lists nominal values for the key parameters entering the model for each kind of linac. For the cw linac, the average accelerating gradient was chosen at 1.0 MV/m. A search of parameter space indicates that this is close to minimizing construction cost and somewhat above minimum annual cost. For a pulsed linac (25% duty factor), these costs optimize at a higher average gradient, close to 1.5 MV/m. An rf capital cost of $2/watt was assumed for a cw system (based on about 100 1-MW power modules). For a pulsed system with the high duty factor required (25%, 120 pps, 2 ms pulses at 1600 MeV) to keep peak current at or below ATW levels, the capital costs per average watt were taken as $4/watt.

Table 1
ATW Linac Cost Model Parameters

CCL real estate gradient (MV/m)	1.0	1.5
Duty factor	1.0	0.25
RF unit capital cost ($/avg watt)	2.0	4.0
CCL structure cost (M$/m)	0.100	0.100
CCL shunt impedance, avg. (Mohm/m)	32.5	23.8
Cost of electric power ($/kWh)	0.05	0.05
Avg. RF power per klystron (MW)	1.0	1.0
Avg. klystron lifetime (1000 hrs)	50	50
Time-on fraction	0.75	0.75
Number of operating staff	200	200
Power conversion efficiency (rf/ac)	0.60	0.60

Figure 3 shows that construction costs for a cw linac minimize near a proton energy of 700 MeV, whereas annual costs optimize near 1000 MeV. Annual costs are dominated by electric power ($ 0.05/watt), which contributes 60% of the total. We select 800 MeV as the nominal optimum operating energy, a value that has the advantage of allowing relevant measurements to be made at LAMPF withoug extrapolation and permits use of a well-established accelerator database. The corresponding proton current is 140 mA. The position of the annual cost minimum is remarkably insensitive to moderate variation of the principal model parameters. Fifty percent changes in accelerating gradient, average CCL shunt impedance, CCL structure cost, rf unit cost, etc. shift the minimum less than 50 MeV.

For a 25% duty pulsed linac Fig. 3 shows construction costs move down as the final energy is lowered. However, the energy cannot be decreased much below 1400 MeV without incurring prohibitively high peak current levels in the CCL (> 300 mA) or duty factors greater than 30%. At this energy the construction cost of a pulsed linac appears to be at least 30% higher than for a cw machine while annual cost is essentially the same as that for a cw approach, within the plausibility of the model. Given these results the selection can be made on the basis of technology preference. A cw approach would simplify control aspects, eliminate modulators from the rf system, and would allow substantially lower peak currents in the accelerator. For the remainder of this paper we assume a cw approach, with the energy/current parameters selected as 800 MeV/140 mA.

Accelerator Design

A first approach to a cw ATW linac design could start from the design of the APT accelerator described in reference 2. This concept contains a beam-launcher (front end) consisting of two dc injectors, two 350-MHz RFQs, and two 350-MHz DTLs funneling proton beams at 20 MeV into a 700-MHz CCL. Each leg of the beam launcher carried a 125 mA beam, and could be powered by existing 1-MW cw klystrons. The CCL was a 2-km-long 1600-MeV coupled cavity linac, carrying 250-mA cw current with an RF efficiency of 0.78. The APT CCL was divided into 7 sections, each made up of modules consisting of n (side-coupled) accelerating cells, a quadrupole and a diagnostic station. The number (n) of coupled cells per module increased from 2 to 10 as proton energy increased from 20 MeV to 1600 MeV. Average accelerating gradient was 1 MV/m to minimize RF structure losses, and the aperture in the CCL was chosen very large (3 cm to 7 cm) to maintain a very high aperture/beam-size ratio (9 to 22). Such a large ratio assures the extremely small beam losses required to permit contact maintenance of the accelerator. Given the very large beam power, the low average structure shunt impedance (23.8 Mohms/m) resulting from this decision imposed an acceptable structure-loss penalty. Beam power was 400 MW and structure loss about 100 MW.

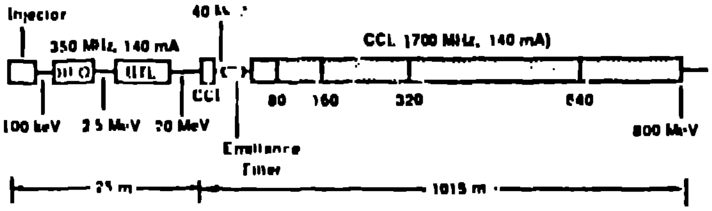

Fig. 4. ATW cw linac concept without funneling.

For ATW, with a current specification of 140 mA cw and an output energy of 800 MeV, the funneling requirement could be eliminated, simplifying the front end, and producing an architecture as sketched in Fig.4. The injector and the 350-MHz RFQ and DTL would provide a 140 mA beam at 20 MeV, and would have essentially the same performance and design as projected for APT. Table 2 lists important design parameters. One refinement that might be made to this machine architecture would be to continue the DTL to a higher energy, say 40-60 MeV. However, because of the desirability of keeping acceptance [illegible] at low energy, to minimize the impact of halo formation, there may be an incentive for retaining the transition to the higher frequency CCL at the lowest practical energy. An average CCL gradient of 1 MV/m would be maintained, as in APT, leading to a total accelerator length of about 1050 m. Structure apertures and shunt impedance values are the same as for APT. Emittance values and beam sizes are essentially the same as in APT because charge per bunch is almost the same. Only every other RF bucket is filled.

The above concept provides a baseline ATW design that has the virtue of beam-launcher simplicity (no funnel). However, we believe a more optimum performance could be obtained with the following design modifications: 1) Employ funneling to reduce the current requirement in the injector, RFQ, and DTL to 70 mA. This allows a 30% lower emittance in these structures and smaller growth, leading to a significantly smaller beam size. 2) With this reduction in beam size, and taking account of the lower current, it should be possible to reduce CCL apertures from those used in the very conservative APT design, without compromising the beam-loss criterion. The higher CCL shunt impedance will give improved RF power efficiency. Funneling permits lowering the charge/bunch in the CCL by a factor of two compared with APT (all buckets filled), which will be beneficial in terms of halo generation and beam loss. Beam simulations and cavity design must be carried out to examine how far this path can be pushed. The cost of RF power (both capital and operating) dominates the ATW facility cost to such a degree that there is a significant premium on designing a higher efficiency CCL. The additional complexity of funneling is outweighed by this factor, and initial experiments at Los Alamos have demonstrated funneling viability.

Table 2
ATW Linac Parameters (No funnel)

	RFQ	DTL	CCL
Frequency (MHz)	350	350	700
Energy (MeV)	0.1 to 2.5	2.5 to 20	20 to 900
Synchr. phase (deg)	-90 to -37	-40	-60 to -40
Radial aperture (cm)	0.4 to 0.3	0.8	1.4 to 3.5
Beam current (mA)	130 to 120	120	120
Length (m)	3.4	11.3	1150
Accel. grad. (MV/m)		1.1 to 3.1	1.0 (avg)
Copper power (MW)	0.4	1.3	77
Beam power (MW)	0.3	2.2	106
Total power (MW)	0.7	3.5	183
Beam loading	0.43	0.56	0.58
No. of klystrons	1	5	190
Accel. structure	4-vane	2βλ	Side-coupled
T emit. (π mm-mrad)	0.20 to 0.23	0.27 to 0.58	0.61 to 0.68
L emit. (10^{-6} eV-sec)	0.0 to 1.4	1.6 to 3.0	3.0 to 4.4

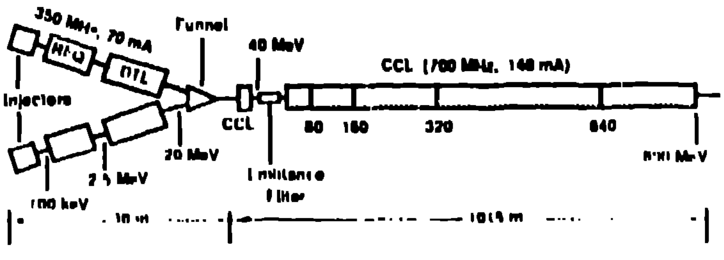

Fig. 5. High efficiency ATW; cw funneled linac concept

A transmuter accelerator for burning defense wastes would then look as represented in Fig. 5. Emittance values and apertures will be lower than in Table 1. Beam current will be 70 mA in the RFQ and DTL instead of 140. In the CCL structure RF power loss will be 52 MW, giving a total RF power requirement of 158 MW and an RF efficiency of 0.67. An additional 10 MW is required for the beam launcher.

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3. G. P. Lawrence, "New Applications for High-Power Proton Linacs," Proc. 1990 Linear Accelerator Conf., Los Alamos Report LA-12004-C, 553 (March 1991).