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# ACCELERATOR TECHNOLOGY FOR LOS ALAMOS NUCLEAR-WASTE-TRANSMUTATION AND ENERGY-PRODUCTION CONCEPTS*

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## ABSTRACT

Powerful proton linacs are being studied at Los Alamos as drivers for high-flux neutron sources that can transmute long-lived fission products and actinides in defense nuclear waste, and also as drivers of advanced fission-energy systems that could generate electric power with no long-term waste legacy. A transmuter fed by an 800-MeV, 140-mA cw *conventional* copper linac could destroy the accumulated $^{99}$Tc and $^{129}$I at the DOE's Hanford site within 30 years. A high-efficiency 1200-MeV, 140-mA niobium *superconducting* linac could drive an energy-producing system generating 1-GWe electric power. Preliminary design concepts for these different high-power linacs are discussed, along with the principal technical issues and the status of the technology base.

## BACKGROUND

Present U.S. plans for disposal of high level defense wastes, namely vitrification and long-term storage in deep geologic repositories are meeting with public skepticism and opposition. A principal concern is that migration probabilities for the long lived fission products ($^{99}$Tc and $^{129}$I) in these wastes may not satisfy long term confinement criteria for the environment of the proposed repository. Current studies at Los Alamos[1] suggest that an accelerator driven intense *thermal* neutron source could transmute all the $^{99}$Tc and $^{129}$I accumulated at the DOE Hanford site (about 2000 kg) to stable or short-lived products within about 30 years, eliminating them from the waste stream, and overcoming a serious environmental objection to the repository plans. Higher actinides, such as $^{237}$Np and $^{243}$Am, could also be rapidly burned by such a system if desired. Neutron sources driven by high power proton accelerators have been studied previously for waste transmutation and other nuclear process applications,[2] but the technology base has only recently reached the point that the feasibility of such machines is assured.

In the Los Alamos scheme[1] for accelerator transmutation of waste (ATW) a heavy metal target is used to produce a high flux of spallation neutrons with an incident medium energy high

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current proton beam. The primary neutron spectrum is moderated to yield an intense thermal flux ($10^{15}$ to > $10^{16}$ n/cm$^2$-s) in a $D_2O$ blanket surrounding the target. Material to be converted is transported through the neutron field by continuously flowing aqueous or molten-fluoride-salt carrier loops. Precision chemical partitioning removes transmuted material from the carrier flow while the residue is returned to the blanket for continued irradiation. The Los Alamos scheme differs from other transmutation ideas in that it employs a *thermal* neutron spectrum. Other schemes, both reactor-based and accelerator-based, have relied on a *fast* spectrum which is inefficient for burning fission products. With the right fractional loading of actinides, the tranmuter can generate enough fission emergy to power the accelerator. Details of the Los Alamos ATW scheme and its advantages in comparison with previously described systems are discussed in several companion papers in these proceedings.

If fertile material ($^{232}$Th or $^{238}$U) is added to the $D_2O$ blanket, the ATW concept can be configured as an accelerator-driven subcritical converter/burner. The fertile material is converted by neutron capture to fissile fuel ($^{233}$U or $^{239}$Pu), which is then burned directly in the blanket to produce power. Preliminary studies reported at this meeting[4] suggest that such a system has the potential to generate electricity at competitive prices, while producing enough excess neutrons to convert its own high-level waste to stable or short-lived products. This concept could lead eventually to a new safe fission-energy system fueled by abundant fertile resources and requiring no off-site waste management.

Driver accelerator requirements for a defense-waste transmuter and for an advanced energy production system are somewhat different, both in terms of performance goals and development needs. Because disposal of defense wastes is a near-term concern, we consider conventional linac technology as the appropriate design approach for an ATW. By conventional we mean a linac in which the radiofrequency (RF) accelerating cavities are fabricated from copper and are water cooled. For an energy production accelerator, on the other hand, preliminary studies show that high power efficiency will be critical, and that a more advanced approach would be the best solution. For this longer-range but potentially higher impact application, we consider a design in which the high energy portion of the linac is made up of superconducting (niobium) cavities where RF losses are negligible.

## ATW ACCELERATOR REQUIREMENTS

Neutron transport calculations suggest that the primary source strength for a defense waste transmuter should be approximately $2 \times 10^{19}$ n/s, based on a plan for destroying Hanford site wastes within 30 years. Figure 1 plots the calculated neutron yield versus energy for protons axially incident on a 0.5 m diameter, 2 m long cylindrical lead target. Also shown are the proton current and beam power needed to produce this neutron source strength. The required beam power is nearly constant at 100 MW above 1000

MeV, so that current can be traded inversely for beam energy. Below this energy the neutron yield drops rapidly, and more beam power is needed. The relations in Fig. 1 provide inputs to a simple cost model that has been used to help select the linac parameters that would produce a minimum-cost ATW system.

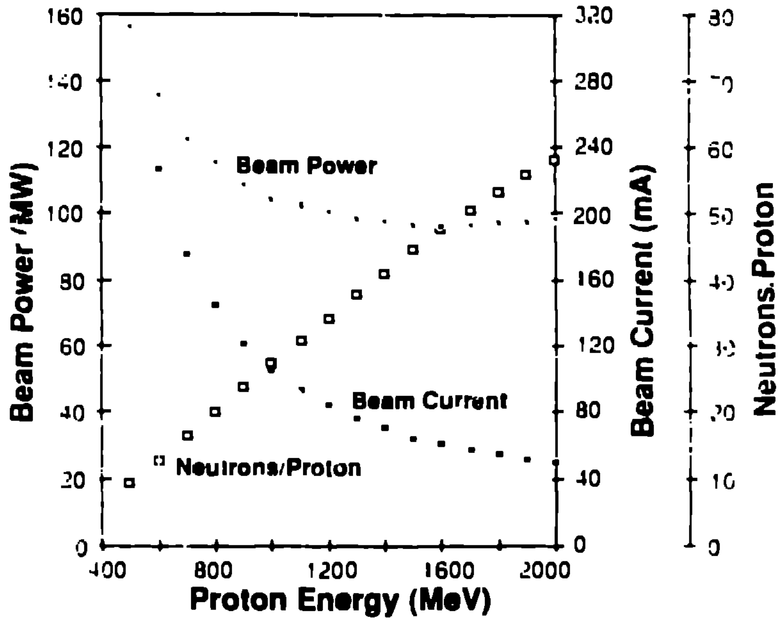

Fig. 1. Energy dependence of neutron yield from lead target. Also linac beam power and current for specified ATW source strength.

## COST/PERFORMANCE MODELING FOR ATW

A linac for ATW will be similar to the concept developed in the recent study of an accelerator for production of tritium (APT).[5] Parameters for APT were 1600 MeV and 250 mA, cw. At that high current level much more RF power is delivered to the beam than is lost in the accelerating structures, resulting in a high RF efficiency - nearly 0.8 in the high-energy portion of the linac.

Since the ATW beam power requirement is only 1/5 to 1/4 that of APT, the current, energy, and duty-factor tradeoffs must be re-examined to determine the best design space. Power-efficiency is critical because of the very high cost impact of the RF power system. This criterion could lead to either: 1) a lower energy high-current cw machine; or 2) a pulsed high-energy machine with high peak current. In order to obtain a first-order quantitative comparison of these two possibilities, simple accelerator cost models have been constructed[6]. These models assume a common machine architecture similar to APT, with dual RFQ/DTL, 350-MHz beam inputs funneled into a 700 MHz CCL. Because most of the accelerator cost is contained in the CCL, these models treat the linac front ends simply as fixed sums, and focus on algorithms

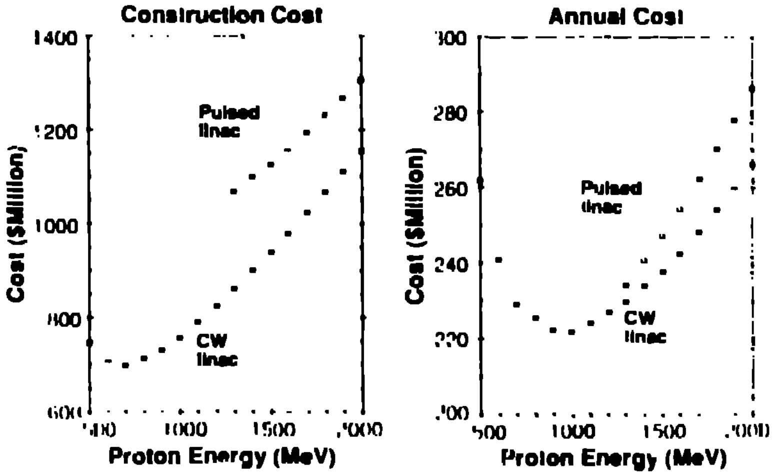

Fig. 2. ATW construction cost and annual cost versus proton energy, for cw and pulsed linac models.

that parameterize the CCL costs. While the models are incomplete in terms of structural detail, the principal cost factors are included, along with the usual multipliers for contingency, project management, ED&I, etc. Results are displayed in Fig. 2, which shows the estimated construction cost and annual cost versus beam energy for cw and pulsed linacs.

Table 1 lists values of the key model parameters for each kind of linac. Average accelerating gradient for the cw linac was chosen as 1.0 MV/m, a value that is close to minimizing construction cost, but slightly above the annual cost minimum. The pulsed linac duty factor was taken as 0.25 at 1600 MeV, which would require 240 mA peak current. The cost-optimized gradient for a pulsed machine with that duty factor is about 1.5 MV/m. An RF system (installed) capital cost of $2/watt was assumed for a cw machine, based on about 85 2-MW power modules. For a pulsed machine, with the high duty factor and pulse length that would be required to keep peak current at or below APT levels, the capital cost (per average watt) was doubled, based on preliminary comparisons of cw and pulsed RF system costs.

Table 1
ATW Linac Cost Model Parameters

| | CW | Pulsed |
|---|---|---|
| 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 |
| Time on fraction | 0.75 | 0.75 |
| Number of operating staff | 200 | 200 |
| Power conversion efficiency (rf/ac) | 0.60 | 0.60 |

Figure 2 shows that construction costs for a cw linac minimize near 700 MeV, while annual costs minimize closer to 1000 MeV. Annual costs are dominated by electric power (at $0.05/watt) and the capital charge (at 10%/year). 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, and RF power unit cost shift the cost minimum less than 50 MeV.

For a pulsed linac the energy cannot be decreased much below 1400 MeV without incurring excessive peak current levels in the CCL (> 300 mA) or duty factors greater than 30%. Figure 2 shows that at 1400 MeV the construction cost of a pulsed linac would be significatnly higher than for an 800-MeV cw machine, but the annual cost is nearly the same as that for a cw system, within the credibility of the model. This cost result, which on balance favors the cw system but not overwhelmingly, leaves the real choice to technical considerations. A cw linac would simplify RF control aspects, eliminate modulators and energy storage from the RF system, and permit substantially lower peak currents in th accelerator, with lower resultant beam-losses. These are important advantages. We therefore propose that a linac for the ATW application should be a cw machine, with energy and current selected as 800 MeV and 140 mA.

## ATW ACCELERATOR POINT DESIGN

A first approach to a point design for a cw ATW could be based on the APT architecture,[6] and would thus consist of a beam launcher (comprising two dc injectors, two 350-MHz RFQs, and two 350-MHz DTLs) funneling beams at 20 MeV into a 700-MHz CCL. Figure 3 sketches the configuration. For the beam parameters selected above, each leg of the ATW beam launcher would provide a 70-mA beam,.

The CCL would be a 1-km-long 800-MeV side-coupled linac, carrying 140-mA cw current . It would be divided into six sections, each made up of modules consisting of n accelerating cells, a quadrupole magnet, and a diagnostic station. The number (n) of coupled cells per module increases from 2 to 10 as the proton energy increases from 20 MeV to 800 MeV. The average accelerating gradient is relatively low 1 MV/m to minimize RF structure power losses, and the CCL aperture is large (3 cm to 7 cm) to achieve a very high ratio of aperture to rms beam size (9 to 22). This high ratio assures the extremely small fractional beam losses (< $10^{-8}$/m) required for hands-on maintenance. The CCL cavities are somewhat more efficient than those in the APT design, providing an RF efficiency of 0.70. Because of the lower beam current and smaller beam size in ATW, smaller CCL apertures may be tolerable, which could push the RF efficiency up to 0.75.

Table 2 lists design values for the RFQ, DTL, and CCL. Other features of the design, including the avoidance of permanent magnets in the DTL drift tubes (because of the radiation threat), tran sition to a CCL structure at the low energy of 20 MeV, possible use of emittance filtering, and strong transverse focusing are similar to those in the APT study, and are discussed in Ref.6.

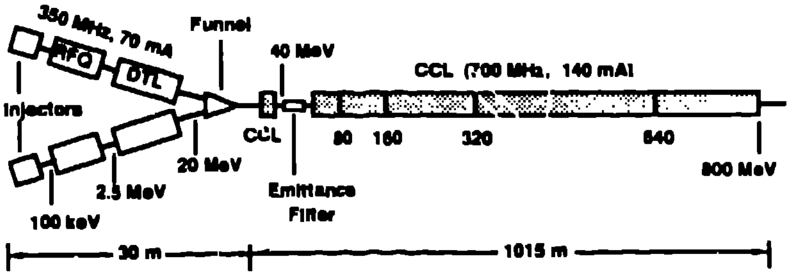

Fig. 3. Reference cw linac concept for ATW

### Table 2
### ATW Linac Parameters

| | RFQ | DTL | CCL |
|---|---|---|---|
| Frequency (MHz) | 350 | 350 | 700 |
| Energy (MeV) | 0.1 to 2.5 | 2.5 to 20 | 20 to 800 |
| 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) | 150 to 140 | 140 | 140 |
| Length (m) | 3.4 | 11.3 | 1015 |
| Accel. grad. (MV/m) | | 1.1 to 3.1 | 1.0 (avg) |
| Copper power (MW) | 0.4x2 | 1.3x2 | 47.6 |
| Beam power (MW) | 0.2x2 | 1.2x2 | 108.9 |
| Total power (MW) | 1.2 | 5.0 | 156.5 |
| Beam loading | 0.33 | 0.48 | 0.70 |
| No. of klystrons | 2 (1-MW) | 6 (1-MW) | 82 (2-MW) |
| Accel. structure | 4-vane | 2βλ | side-coupled |
| T emit. (π mm-mrad) | 0.21 to 0.24 | 0.29 to 0.61 | 0.65 to 0.72 |
| L emit. ($10^{6}$ eV-sec) | 0.0 to 1.5 | 1.7 to 3.2 | 3.2 to 4.7 |

For the nominal ATW current specification, funneling is not an absolute requirement. A current of 140 mA could be obtained from a single 350-MHz RFQ and DTL, which would simplify the accelerator front end. However, funneling allows a significantly lower emittance in the CCL for the same total current, and reduces the charge-per-bunch by a factor of two. This can be translated into smaller cavity apertures and improved CCL RF efficiency. The cost of RF power (both capital and operating) dominates the transmitter facility cost to such a degree that there is a premium in designing for as high an efficiency as practical. This factor alone appears to outweigh the extra complication introduced by funneling. In addition, the ion-source current demand would be reduced by a factor of two in a funneled sytem.

RF power for the ATW RFQs and DTLs would be provided by existing, commercially available, 1 MW cw 350-MHz klystrons; eight tubes are needed. For the CCL, it would be necessary to develop a new high power RF amplifier tube at 700 MHz. In order to reduce capital costs and improve system reliability, we propose a power level of 2 MW per unit or greater.

## TECHNOLOGY ISSUES AND TECHNOLOGY BASE

Accelerator technology improvements in the past few years and advances in understanding of high-current beam behavior provide high confidence that a machine of the ATW power level can now be built and operated. The major technical concerns for a high-power proton linac are 1) beam-loss activation of machine components, threatening hands-on maintainability; 2) RF system efficiency and capital costs; 3) reliability and longevity of components; and 4) operability of an integrated cw system.

The APT point design study addressed the above technical issues in detail [5] for a 4 x more powerful machine. It included complete beam simulations with matching errors, a machine configuration layout, engineering assessment of critical components, and an analysis of off-normal conditions and beam/target safety issues. The design codes have been benchmarked in the relevant energy and charge-density regimes through simulation of high-current behavior on the Los Alamos NPB Accelerator Test Stand (ATS), and by an end-to-end simulation of LAMPF that predicts measured emittance values as well as beam loss locations and approximate magnitudes.

A number of accelerator systems have operated at or near ATW-level parameter values. Existing ion source designs appear capable of delivering the needed proton current with the desired brightness. Performance requirements are not as demanding as those for the NPB program. A 267-MHz 0.6-MeV proton RFQ at CRNL has operated at 70 mA cw, [7] and peak $H^-$ currents of 100 mA have been demonstrated in a 7-MeV ramped-gradient 425-MHz DTL at Los Alamos. Beam funneling in the relevant current and frequency range has been successfully demonstrated at Los Alamos.[8] A coupled-cavity accelerating structure at NIST has operated cw with a 1-MV/m gradient, at 4 x the ATW frequency.

Experience with existing research linacs that have operated for years with high availability as beam "factories" has provided a strong foundation for making extrapolations to the ATW performance regime. Because of its high average current (1 mA), operational experience at LAMPF is especially relevant, and also directly addresses the important beam-loss issue. For most of the LAMPF CCL length, the beam loss fraction is estimated to be $< 2\times10^{-7}$/m, and radiation levels after shutdown allow unlimited-access hands on maintenance. Because all CCL RF buckets contain charge in the ATW concept and the duty factor is 1.0, compared with LAMPF's 1-in-4 bucket filling and 0.06 duty factor, the charge/bunch in ATW is only 2.5 times greater than in LAMPF. Therefore, even though the average beam power is 140 times greater in ATW, the beam dynamics in a well-understood range. Given the very large aperture to beam-size ratio in the ATW CCL and the high quality input beam, we can be confident of achieving the low fractional beam loss (1/10 that of LAMPF) needed for hands on maintenance

## RF TECHNOLOGY: RF SYSTEM COST IMPACT

High power cw RF tubes (klystrons) in the 0.5 to 1.0-MW class are available at frequencies near 350, 500, and 1000 MHz. Operating lifetime information for 1-MW cw tubes is sparse, but vendors are confident that 50,000 hours is a reasonable expectation. The tube longevity is somewhat addressed by LAMPF operating statistics, which show the average lifetime of the 1.25-MW peak-power 805-MHz klystrons (up to 12% duty factor) as > 50,000 hours, with many tubes surviving for > 80,000 hours.

Major leverage for reducing the cost of an ATW linac could come from reducing the unit capital costs of the CCL RF power system, and/or from development of higher efficiency RF generators. The capital cost (per watt ) of installed RF capacity is expected to scale inversely as the square root of the module output power, so there should be an advantage in going to larger tubes than the 1-MW cw generators now available. A smaller number of tubes should also improve overall accelerator reliability. Candidates for ATW use are the klystron, klystrode, and the magnicon

The klystron, which operates by velocity modulation of an electron beam, represents mature high-power technology. Development of a new 1-MW cw klystron for service at 700 MHz would be well within the explored design space and a straightforward enterpise. It is thought that 2 MW is probably the practical upper power limit for klystrons at this frequency. The klystrode, a relatively new device, produces RF power through amplitude (grid) modulation. Pushed by SDI program requirements, high power klystrodes (up to 0.5 MW) are being developed at ATW-relevant frequencies. The power limit is thought to be about 1 MW, due to grid heating, but the tube has the advantage of compactness and retains high efficiency (0.70) over a large output range. Although there is no lifetime data for the new high power tubes, experience with the 50-100 kW klystrodes widely used in television transmitters is good. The magnicon, a new RF tube invented in the USSR, produces RF power by using circular deflection of the electron beam to produce a rotating electromagnetic wave.[9] It may be capable of generating 4 MW cw at very high efficiency. However, a cw high power version not been demonstrated and a significant development program will be needed to assess the promise of this technology.

## ACCELERATOR FOR POWER-PRODUCTION

Initial estimates for an accelerator-driven power-producing system specified at 1000-MWe generating capacity call for a neutron source strength somewhat greater than required for a defense-waste transmuter, about $3.3 \times 10^{19}$ n/s. This translates to about 160 MW of beam power for proton energies in the linear spallation neutron yield range (1200-2000 MeV). To generate electric power at competitive prices, the accelerator efficiency must be as high as possible and the capital and operating costs as low as possible. Initial studies using a cost model similar to that for ATW suggest that these objectives can best be achieved with a linac whose high-energy section (above 20 MeV) consists of superconducting RF (SCRF) accelerating cavities. The ac-to-beam power efficiency could be > 0.65. The best that can be achieved with a conventional machine is about 0.45. SCRF niobium cavity technology, developed over the past 20 years, has reached a high level of maturity, culminating recently in major (electron) accelerator projects at several high-energy physics laboratories (CEBAF, CERN, KEK). Standard accelerating gradients achievable within the accelerating structures are in the range 5 to 8 MV/m, and cavity fabricatiion costs, initially high, have come down to $200K/m, with further decreases anticipated.

The simple ATW linac cost model was extended to accomodate a superconducting CCL. While RF power losses in the accelerating cavities become very small, there are significant refrigeration requirements to handle them as well as the ambient heat leaks. Table 3 lists the relevant parameters, including refrigeration assumptions, included in the model. The structure gradient was chosen as 5 MV/m, even though costs appeared to be somewhat lower at higher gradients, in order to avoid an excessively large RF drive power per unit length. SCRF (cw) linac construction and annual costs are compared in Fig. 4 with costs for a room-temperature (RT) cw linac as a function of beam energy.

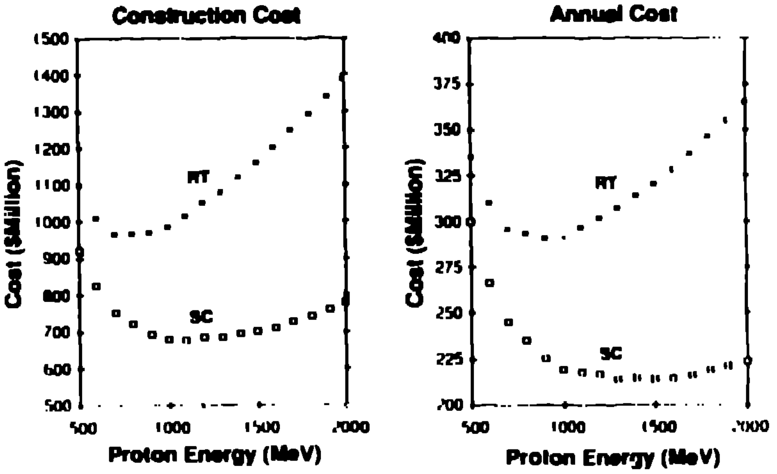

Fig. 4. Construction cost and annual cost versus proton enrergy for superconducting and room-temperature cw linac models.

The construction cost and annual cost dependence on beam energy for the SCRF linac appear to have considerably broader minima than those for a room-temperature system, and the cost optimum is at higher energy. This effect is due to the elimination of cavity RF power consumption in the CCL, which is only partly offset by the refrigeration requirements. The cost comparisons suggest that a superconducting linac for energy production could be 25 to 30% less expensive to build and operate than a room-temperature system. Because SCRF cavities can operate cw at higher gradients than RT copper structures, a superconducting

CCL can be much shorter than its room-temperature equivalent, even if the SCRF linac has a higher output energy. Another advantage of a superconducting CCL is that beam apertures in coupled SCRF cavities can typically be much larger than those in RT cavities of the same frequency, allowing lower beam losses. Since negligible RF power is lost in SCRF cavities, there is no design imperative to reduce apertures in order to maximize the shunt impedance. On the contrary, apertures are made large in order to provide adequate on-axis coupling for the fundamental accelerating RF mode and to prevent trapping of destructive beam-excited high-order modes.

### Table 3
### Energy-Production Linac Cost Model Parameters

| | RT | SCRF |
|---|---|---|
| CCL real estate gradient (MV/m) | 1.0 | 3.0 |
| CCL structure gradient (MV/m) | 1.3 | 5.0 |
| Duty factor | 1.0 | 1.0 |
| RF unit capital cost ($/avg. watt) | 2.0 | 2.0 |
| CCL structure cost (K$/m) | 100 | 200 |
| RF structure losses (W/m) | 72,500 | 20 |
| Refrigerator efficiency | | 0.002 |
| Cost of electric power ($/kWh) | 0.05 | 0.05 |
| Time-on fraction | 0.75 | 0.75 |
| Number of operating staff | 200 | 200 |
| Power conversion efficiency (rf/ac) | 0.60 | 0.60 |

A possible accelerator for driving an energy-producing system might have an architecture as sketched in Fig. 5. Table 4 summarizes some of the expected machine parameters.

### Table 4
### Parameters for an Energy-Production Linac

| | RFQ | DTL | CCL |
|---|---|---|---|
| Frequency (MHz) | 350 | 350 | 700 |
| Energy (MeV) | 0.1 to 2.5 | 2.5 to 20 | 20 to 1200 |
| Radial aperture (cm) | 0.4 to 0.3 | 0.8 | 10 to 15 |
| Beam current (mA) | 75 to 70 | 70 | 140 |
| Length (m) | 3.4 | 11.3 | 515 |
| Accel. grad. (MV/m) | | 1.1 to 3.1 | 3.0 (avg) |
| Copper power (MW) | 0.4x2 | 1.3x2 | 0.006 |
| Beam power (MW) | 0.2x2 | 1.2x2 | 165.2 |
| Total power (MW) | 1.2 | 5.0 | 165.2 |
| RF efficiency | 0.33 | 0.48 | 1.00 |
| No. of klystrons | 1 (1-MW) | 4 (1-MW) | 87 (2-MW) |
| Accel. structure | 4-vane | 2βλ | axis-coupled |
| Refrigerator power (MW) | | | 5.6 |

The beam launcher for this machine could be a room-temperature funneled system identical to that described for ATW. The coupled cavity linac, from 20 MeV to 1200 MeV would consist of multicell superconducting niobium cavities, with the number of coupled cells per module increasing from 2 to about 5 as the energy increases. If an average packing factor of 0.6 can be achieved (as at CEBAF), and assuming a structure gradient of 5 MV/m, the real-estate gradient would be 3 MV/m, which leads to a CCL length of only 0.5 km.

Beam performance for the superconducting linac should be very similar to that estimated for the ATW linac. Transverse and longitudinal emittance are determined essentially in the beam launcher. Only a small growth is anticipated in the CCL. The ratio of structure aperture to rms beam size in the SCRF CCL could be 2 x larger than for the RT machine, with the machine aperture limit probably determined by the quadrupole bores.

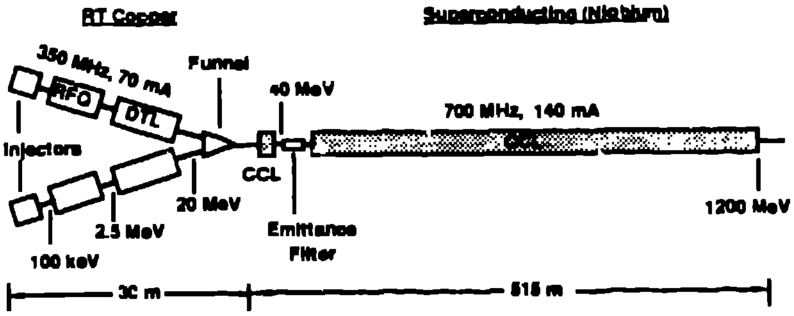

Fig. 5. Superconducting linac for energy production.

The SCRF cavities for an energy-production linac would be cooled at 4.2 K by a refrigeration system comparable in scale to those now in use at CERN, DESY, and KEK. Estimated residual RF losses in the niobium cavities (at 5 MV/m) will be about 20 W/m. This load and the static heat load to the cryostat (also about 20 W/m) must be rejected at room temperature by the refrigeration plant, which would require about 6 MW of ac power, assuming an overall efficiency of 0.0022. This is to be compared with the 80 MW of ac power saved by eliminating CCL RF power losses.

With a 140-mA cw beam, the CCL RF power input requirement averages 700 kW/m; at the 1200 MeV point this implies a 700 kW power coupler feeding each 5-cell module. This high power coupling requirement constitutes one of the technology challenges for development of a superconducting linac. The practical level that has been reached is 100 kW per feed (at 500 MHz), but Cornell University is now developing a 500-kW coupler (also at 500 MHz). Additional areas that need to be addressed in an R&D program for high-power SCRF linacs include the sensitivity of niobium cavities to radiation damage, cavity Q-degradation due to adsorbed residual gas layers, handling of beam-excited high-order RF modes and other control issues, and development of cavitiy designs appropriate for the large range of proton velocities in the linac (v/c = 0.2 to 0.9).

## ACKNOWLEDGEMENT

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## REFERENCES

1. "A Los Alamos Concept for Accelerator Transmutaion of Waste and Energy Production," Los Alamos Report LA-UR-90-4432, December 1990.
2. G. P. LAWRENCE, "New Applications for High-Power Proton Linacs," Proc. 1990 Linear Accelerator Conf., Los Alamos Report LA-12004-C, 553 (March 1991).
3. E. ARTHUR, "A New Concept for Accelerator-Driven Transmutation of Nuclear Waste," Proc. International Conf. on Emerging Nuclear Energy Systems, Monterey, CA, June 16-21 (1991), to be published.
4. C. D. BOWMAN, "Fission Energy Without a Long-Term High-Level Waste Stream," Proc. International Conf. on Emerging Nuclear Energy Systems, Monterey, CA, June 16-21 (1991), to be published.
5. "Accelerator Production of Tritium, A Presentation to the Energy Research Advisory Board, October 25, 1989," Los Alamos Report LA-UR-90-3651.
6. T. P. WANGLER, G. P. LAWRENCE, T. S. BHATIA, J. H. BILLEN, K. C. D. CHAN, R. W. GARNETT, F. W. GUY, D. J. LISKA, S. NATH, G. H. NEUSCHAEFER, AND M. SHUBALY, "Linear Accelerator for Production of Tritium: Physics Design Challenges," Proc. 1990 Linear Accelerator Conf., Los Alamos Report LA-12004-C, 553 (March 1991).
7. G. E. MCMICHAEL, "High-Current CW RFQs," Proc. 1991 Particle Accelerator Conf., San Francisco CA, May 6-10, 1991, to be published.
8. K. F. JOHNSON, O. R. SANDER, G. O. BOLME, J. D. GILPATRICK, F. W. GUY, J. H. MARQUARDT, K. SAADATMAND, D. SANDOVAL, AND V. YUAN, "A Beam Funneling Demonstration: Experiment and Simulation," Proc. of International Symp. on Heavy Ion Fusion, Monterey, CA, December 3-7, 1990, to be published.
9. O. A. NEZHEVENKO, "The Magnicon: A New RF Power Source for Accelerators," Proc. 1991 Particle Accelerator Conf., San Francisco, CA, May 6-9 (1991), to be published.