Critical Design Issues of High Intensity Proton Linacs*

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Abstract

Medium-energy proton linear accelerators are being studied as drivers for spallation applications requiring large amounts of beam power. Important design factors for such high-intensity linacs are reviewed, and issues and concerns specific to this unprecedented power regime are discussed.

1. INTRODUCTION

This paper focuses on the important characteristics and critical design issues of high-intensity proton linacs intended for driving spallation-technology transmutation[1] applications, including destruction of nuclear waste, plutonium disposition, production of nuclear materials, and generation of fission power. Such accelerators span the energy range 600 MeV to 1600 MeV, and the (average) current range 10 mA to 300 mA. Pulsed H^- linacs for next-generation neutron research facilities[2,3] share some of the same design concerns as transmutation accelerators, at a lower average power level, but have different performance requirements arising from their role as ring injectors. High-intensity deuteron linacs for fusion materials research also overlap the same design space, but are missing the high-energy accelerator that dominates the economic equation for transmutation drivers.

For very high power transmutation applications (> 100 MW beams) a CW RF linac based on conventional copper cavities provides the only near term practical option, in terms of demonstrated technology or reasonable extensions of existing systems. At lower power levels, the accelerator options increase. At 50 MW, the near-term solution would most likely be a pulsed high-duty copper linac, but a CW superconducting RF (SRF) linac[4] could offer operating cost (and possibly performance) advantages, pending further development of the technology base. Below 10-MW, advanced cyclotron designs[5] may enter the competition.

2. KEY ISSUES, PARAMETER SELECTION, COST MODELS

High-power transmutation linacs represent very large capital investments (several $Billion), use a lot of electricity to produce the beam (several hundred MW), and need a high availability for production (>75%). Great weight has to be given, therefore, to minimizing the life-cycle cost (including construction and operating costs), and to assuring the operability and availability of the system. Minimizing the operating cost means maximizing the electrical efficiency, especially that of the high-energy coupled-cavity-linac (CCL). The critical factor affecting operability is attainment of very low beam losses, for assurance of activation levels low-enough for hands-on maintenance. High availability is dependent on the lifetime and serviceability of key accelerator components, especially the RF generators. These top-level system issues translate to layers of interdependent design factors, including 1) choice of current vs. energy to provide the needed neutron source strength with high electrical efficiency, 2) accelerating structure and gradient choices for high efficiency, current capability and beam emittance control, 3) architecture, focusing system, frequency, and structure choices for beam-loss minimization, 4) stability and control of the strongly-coupled beam/cavity/RF-power system, and 5) reliability and serviceability of critical components.

Simple cost models provide initial guidance on values for the principal linac parameters that will place the design near a life-cycle cost minimum while also fitting within physics and engineering constraints.[6] These models are typically based on the use of unit cost factors for RF power, accelerating structure, electric power, etc., as well as target-yield energy dependence, and other key parameterizations.

3. REFERENCE DESIGNS; ARCHITECTURES

Several different linac concepts have been proposed by different laboratories to satisfy the high-power transmutation beam requirements. Some initial work has been done towards developing an analytic design optimization framework based on key criteria such as aperture-to-beam-size ratios, but the underlying relationships remain elusive.[7] In the absence of such optimization guides, the high-intensity linac design space is currently best explored through a combination of reference designs and parameter-trade scoping studies. While the development of detailed reference ("point") designs is demanding of time and resources, it enforces the discipline of producing integrated and self-consistent concepts that can be measured in terms of specific performance objectives.

Most of the debate about high-intensity linac architectures is focused on the low-energy region, below 100 MeV. Above that energy there is general agreement on using a high-efficiency high-frequency CCL, although different design groups favor different specific structure types. The critical factor affecting the low-energy (front-end) design is the balance between current limit and rms-emittance growth in the lowest energy accelerating structure, conventionally an RFQ. Higher frequencies provide better emittance control but lower current, with the relationship reversed for lower frequencies. The use of a low-frequency RFQ also leads implicitly to larger longitudinal acceptance transitions downstream (to reach the high CCL frequency). Funneling offers an escape from the RFQ's emittance vs. current constraint, but adds complication and has not been demonstrated in a full operational sense. A new low-energy structure (HILBILAC) under development at MRTI,[8] consisting of a solenoid-focused interdigital-line DTL, could offer another option for higher currents at high frequencies. Available H^+ ion-source current limits and injector performance (at 100% duty) further constrain the choice of

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front-end architectures. The performance lead is held by the electron-cyclotron-resonance (ECR) source, demonstrated at CRL and now operating at Los Alamos. This source is capable of 100-mA output into a 0.02 π cm-mrad emittance.

High-intensity linac architectures proposed by three labor-atories are illustrated in Fig. 1. The top diagram shows a 200-mA, 1-GeV concept representative of Los Alamos designs,[9] using two 350-MHz low-energy linacs with beam funneling at 20 MeV. Following the funnel is a 700-MHz bridge-coupled DTL (BCDTL), with focusing elements only between the short tanks, that increases the beam energy to 100 MeV. The high-energy linac consists of a side-coupled linac (SCL) employing short accelerating modules and an FD focusing lattice. Each module is powered by a 1-MW klystron. A rather complete reference design has been carried out for this architecture, with end-to-end beam simulations and error sensitivity studies. An important design feature is the very large aperture factors (ratio of structure aperture to rms-beam-size at the quadrupoles), increasing with particle energy from 13 to 26 in the SCL. This is an essential criterion for assuring ultra-low beam losses, and is obtained by using both a large physical aperture (5 cm in the CCL) and a high quadrupole density. The structure gradient in the SCL is 1.3 - 1.5 MV, and the overall accelerator efficiency is 0.79.

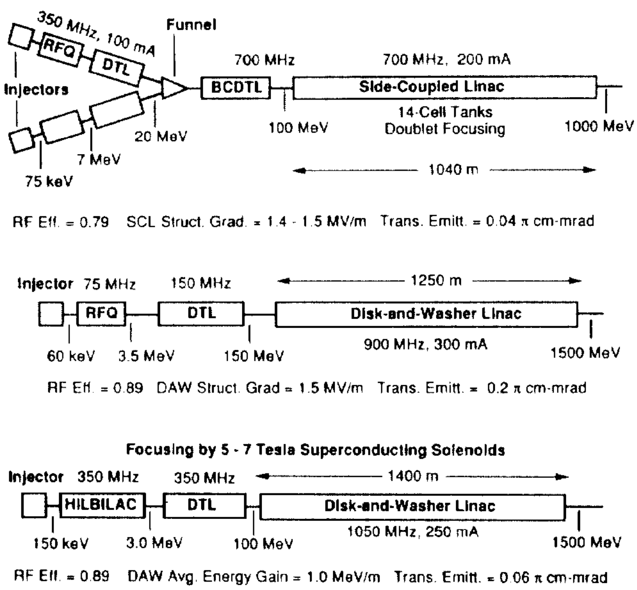

Fig. 1. Representative high-intensity linac architectures.
Top: LANL Middle: ITEP Bottom: MRTI

The ITEP transmutation linac design[10] for a 300-mA, 1.5-GeV system avoids funneling by using a low-frequency RFQ (75 MHz) that can accelerate the current in a single channel. A 150-MHz DTL accelerates the beam to 150 MeV, and a 900-MHz disk-and-washer (DAW) CCL takes the beam to 1.5 GeV. Because of the low RFQ frequency, only one out of every 12 RF buckets in the CCL contains a bunch, so the charge per bunch is an order of magnitude greater than in the LANL design. The CCL gradient is comparable to the LANL choice, but because the current is higher, the overall RF efficiency is greater, 0.89. Based on the acceptance of the CCL, the aperture factors are estimated to range from 5.5 to 8.7.

MRTI has proposed a novel linac architecture[11] based on the use of 5 - 7 Tesla superconducting solenoids external to the accelerating structures to provide beam envelope control, thus completely separating the accelerating and focusing functions. The low energy linac begins with a 350-MHz HILBILAC accelerating a 250-mA beam to 3 MeV. This structure is followed by a conventional 350-MHz DTL accelerating the beam to 100 MeV, and finally a high energy DAW CCL operating at 1050 MHz. The external focusing scheme offers advantages in terms of beam dynamics and overall efficiency, but the superconducting solenoids could introduce operational complication.

4. FUNNELING

Funneling combines beams longitudinally from two low-energy linacs, thus doubling the intensity with minimal increase in rms emittance. An additional advantage is that it fills all RF buckets in the high-energy linac, reducing rms emittance and beam size. While the demonstration of this technical option is incomplete, tests were conducted several years ago that lend confidence in the method.[12] Beam measurements showed 100% transmission, no increase in transverse emittance, and only a small increase in longitudinal emittance. A remaining concern is the effect of the transverse distortion of the longitudinal tails caused by sinusoidal deflection of the (finite-length) bunch in the RF deflector, which could cause beam halo enhancement and downstream losses. There is also concern about control of the relative energies of the two beams at the combining point. In the 200-mA reference design, the rms bunch width at the deflector is narrow (5°) so the divergence in the longitudinal tails should be minimal. Also, the bending system approaching the combining point is achromatic, and the bend angle in the RF deflector is only 1°, minimizing deflection errors caused by energy fluctuations between the input beams.

5. BEAM PHYSICS

In high intensity transmutation linacs, the main physics design goal is to accelerate the beam with extremely low loss and transport it to nearby targets. Control of the beam loss is clearly the primary issue. The advances in theory and control of (rms properties) of high-current beams achieved in the past decade (based on high frequencies, strong focusing, ramped gradients, etc.) provide a rational starting design framework,[13] although equipartitioning must be violated somewhat because it is not practical to ramp the accelerating gradient in the high energy linac. The results of this approach are seen in Fig. 2., which summarizes simulations of the LANL 200-mA reference linac design. The figure displays the transverse and longitudinal rms emittance as a function of energy, with measured emittances of the LAMPF 17-mA (peak) proton beam provided for comparison. The LAMPF linac was designed nearly 30 years ago, and there are significant transitions and mismatches in longitudinal and transverse space that account for the rapid emittance growth. The improvement resulting from modern design is readily apparent from the comparatively modest emittance growth in the 200-mA linac simulation.

Transmutation linacs must achieve extremely low beam loss, in the range 0.1 nA/m to 1 nA/m (depending on proton energy) to assure maintainability without the use of remote handling. This translates to 10^{-8}/m to 10^{-9}/m fractional beam loss allowances. To reach such a minuscule loss levels, the

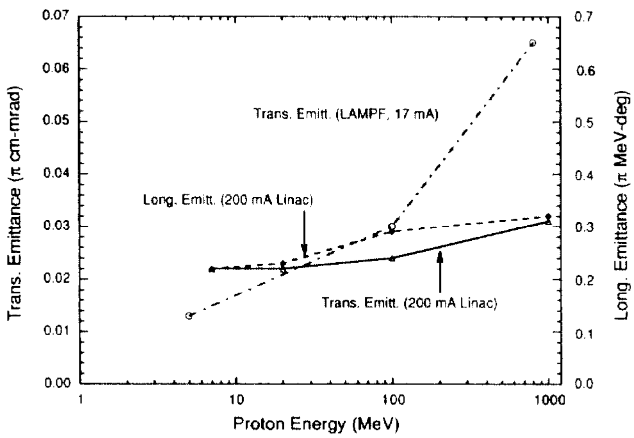

Fig. 2. Comparison of emittance growth for LANL 200-mA high-intensity linac design and in LAMPF linac.

apertures in the accelerating structures and focusing elements must be large enough to contain not only the beam core but also the tails of the beam distribution (the halo) out to very low particle densities. One measure of this containment is the aperture factor mentioned earlier. In the LANL reference design this ratio is very large, increasing from 4-5 in the DTLs to 13-26 in the CCL. In LAMPF, for comparison, the ratio is 6.3 at the end of the CCL. Because of our present ignorance of the detailed intensity distribution in the halo, the design philosophy is to use the largest possible aperture factors consistent with maintaining reasonable efficiency in the accelerating structures and practical quadrupole pole-tip fields. When better beam "clearance" criteria become available, it may be practical to reduce the aperture factors significantly.

6. BEAM LOSS ESTIMATES

Operating experience at LAMPF currently provides the best hard information about the potential for achieving ultra low losses in transmutation lianas. Figure 3 shows the estimated beam losses along the LAMPF CCL following an extended production run at 1-mA average current. The losses are inferred from an activation survey made soon after shutdown, using the approximate energy dependence of neutron production, and knowledge of the integrated beam loss between 100 MeV and 800 MeV. The figure shows two areas of high beam loss, located downstream from 100 MeV and from 200 MeV. A LAMPF simulation using as-built parameter values[14] shows the same high loss regions, which are understood to be the result of sudden transitions (reductions) in both the longitudinal and transverse acceptance.

At higher energies in the SCL, beam losses are generally < 0.2 nA/m, which represents < 2×10^{-7}/m fractional loss. The corresponding radiation levels 30 cm from the linac are 5-10 mR/hr, a level that permits "unconstrained" hands-on maintenance. High-intensity linacs for transmutation applications need to achieve one to two orders of magnitude smaller frac-

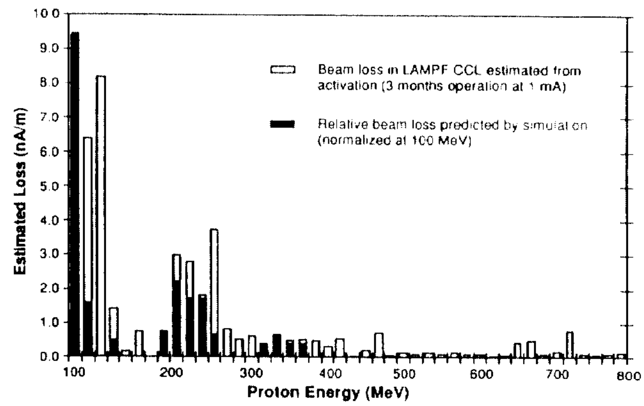

Fig. 3. LAMPF beam loss estimate and simulation.

tional beam losses than LAMPF to permit this kind of maintenance. This is a challenging objective, but one that is reachable given the much larger aperture factors that can be provided in these machines, the greatly improved understanding of matching and emittance control now available, and the greater precision of beam diagnostics and control.

7. BEAM HALO MODELING AND SIMULATION

Stimulated by the recognition that understanding and control of the beam halo could have major impacts on high-intensity linac design, theoretical investigations are underway at several laboratories.[15-17] Among the important questions regarding the beam halo are: 1) how do particles initially in or near the beam core acquire sufficient energy to move to large radii, and how rapidly does this occur; 2) does the halo grow without limit, or is an equilibrium ultimately reached; and 3) if the halo is removed (by scraping) at some point in the acceleration process, does it reappear and at what rate. Recent progress in identifying halo production mechanisms, their dependence on key beam parameters, and also in computer modeling and simulation shows promise that these questions may soon have at least qualitative answers.

Several workers are investigating a model in which individual particles interact with a beam core whose envelope is oscillating due to a mismatch in a focusing channel or a steering error. The modeling has progressed to the level of 2-D in periodic focusing channels, with emittance growth folded in, and the results show how particles initially at the edge of the core can gain significant transverse energy through resonant coupling to the core motion. For sufficiently high space-charge levels and mismatch factors, chaotic phase-space regions develop. Figure 4 shows a stroboscopic phase-space map for a case of large space-charge tune depression (k/k_0=0.5) and large mismatch factor (1.5) in a uniform focusing channel. The plot records phase-space histories of particles launched inside and outside the core with "snapshots" at each minimum of the core oscillation. Particles initially well inside the beam core remain there, whereas those just outside move on paths that take them to large radii. Particles launched at larger phase-space amplitudes orbit the core in quasi-elliptical paths. The stroboscopic plots indicate that the halo motion is apparently bounded (by KAM curves) so that particles do not move out to arbitrarily large amplitudes, but such boundaries may become leaky in 3-D simulations.[17]

Newly-available massively-parallel computing facilities (LANL CM-5) are enabling beam simulations using 10^6 to 10^7 particles, which provides a powerful new tool to perform numerical halo "experiments". Figure 5 is a 2×10^6 particle simulation in 2-D using a KV distribution launched in a uniform focusing channel, with the same tune depression and mismatch factor as above. The phase-space plot was made near a core-oscillation minimum, after 25 focusing periods. Features matching those in the stroboscopic map can be seen, including the rough outline of the separatrix surrounding the beam core, and the two-lobe distribution of halo particles. The curve representing the boundary of the resonant halo motion in Fig. 4 has been superimposed on the simulation, and it is interesting to note that no halo particles appear beyond it.

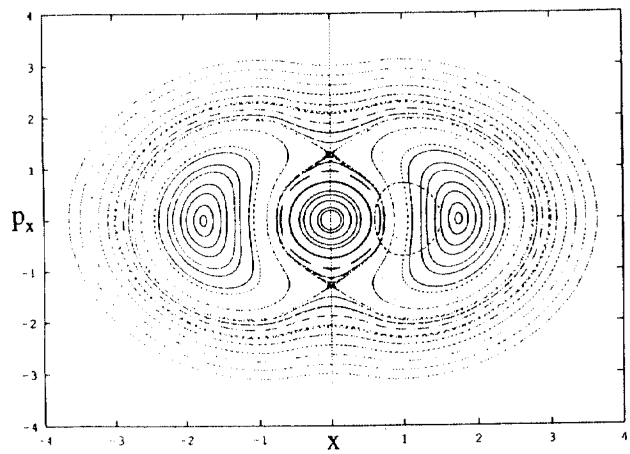

Fig. 4 Stroboscopic map for particle/core halo model, with $k/k_0 = 0.5$ and mismatch of 1.5. Scaled coordinates.

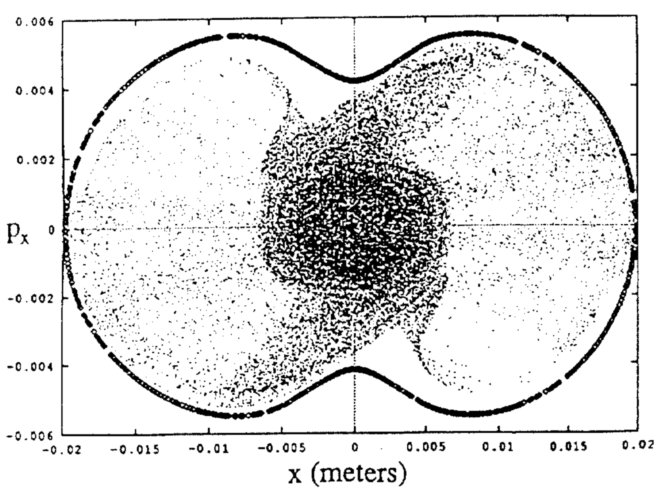

Fig. 5. Plot from 2×10^6 particle simulation of particle/core halo model, with same beam parameters as in Fig. 4.

Despite the recent progress in halo modeling and simulation, there is considerably more to be done in this field before clear strategies can be devised to guide the design of high-intensity linacs. The work accomplished to date shows qualitatively that amplitudes and growth rates depend on the degree of tune depression and initial mismatch, but has not yet determined how the underlying factors should be adjusted to minimize halo production or mitigate its effects in the linac.

8. ELECTRICAL EFFICIENCY

To minimize operating costs, the electrical efficiency of high power accelerators should be high. The wall-plug to beam efficiency can be written as:

$$\varepsilon_{tot} = \varepsilon_{ac/dc}\,\varepsilon_{tube}\,\varepsilon_{tr}\,\varepsilon_{rf/beam}$$

involving the efficiencies for ac-to-dc conversion, dc-to-rf in the RF generator, losses in RF transmission, and cavity RF efficiency (beam loading). Since cavity efficiency is simply

$$\varepsilon_{rf/beam} = I_{beam}/(I_{beam} + G/Z_{sh}\cos\phi),$$

the designer has three parameters available, the peak beam current, the cavity shunt impedance, and the structure accelerating gradient. The gradient also affects construction cost through the length factor. The simple cost models show that 1.3-1.5 MV/m structure gradient is optimum for CW operation. This is a result of the high cost of RF power systems relative to other components of the linac, as well as high power costs. Shunt impedance in principle can be increased by going to higher-frequency structures, but in practice this improvement is restricted by the need to maintain a large cavity apertures for low beam loss. For a fixed 5-cm aperture, the SCL shunt impedance vs. frequency has a dependence like that shown in Fig. 6, showing that the optimum operating frequency is between 600 MHz and 1000 MHz. The beam current should be as high as possible, within the physics constraints of the low-energy linac(s); values need to be well above 100 mA for high efficiency. Contemporary high-power klystrons have useful efficiencies around 0.55-0.60 when control margin is accounted for. With future RF generator designs there is expectation that this number could be raised as high as 0.75 (klystrode, magnicon, or advanced klystron). Thus, with all efficiencies optimized, the maximum ac-to-beam conversion efficiency that could be expected in future (conventional) linacs might be as high as 0.55-0.60, an increase of 30 to 40% over present designs. Superconducting RF technology offers still higher efficiency, as noted below.

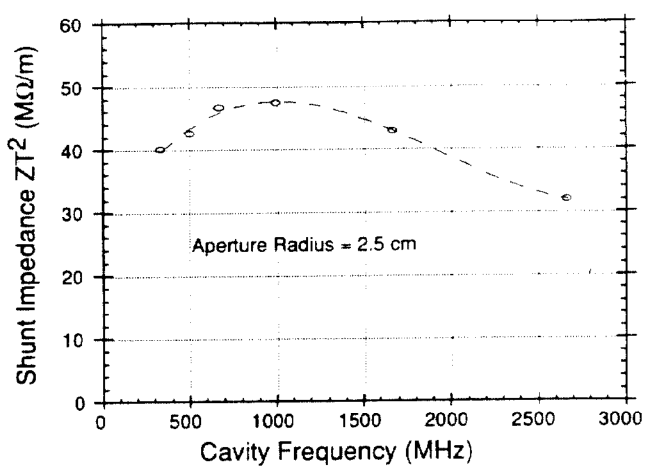

Fig. 6. Calculated SCL shunt impedance vs. frequency for fixed 5-cm aperture (without correction for coupling cells, etc.).

9. AVAILABILITY; RAMI MODELING

With the incorporation of accelerators into materials production/destruction and power generating roles, a systems assessment of reliability, availability, maintainability, and inspectability (RAMI) becomes an important aspect of the design process. The requested availability of the production plant is typically 75%, so the linac must have an availability > 85%. The use of RAMI models (based on fault-trees and component reliability statistics or projections) in system design to analyze availability is a formal discipline familiar to power plant engineers, but is new to the world of accelerators. The key elements are identification of components critical to operation, their lifetimes, reliability, and characteristic replacement or service times. For existing accelerators, some of this information is archived and available, but much of it is sketchy, anecdotal, or resident in the expert knowledge and experience of operations staffs. Nevertheless, preliminary attempts at application of RAMI techniques are showing utility in identifying components in greatest need of backups or redundancy, and in developing credible operating and maintenance scenarios that will lead to the high availabilities needed for high-intensity transmutation linacs.

RF station availability is the major concern for a linac having 300-400 klystrons. With projected tube lifetimes of 25,000 hours, we can expect failure rates on the order of 2-3 per week. Unlike electron linacs, a station fault can cause a large enough local energy deficiency to interrupt acceleration. Error studies of Los Alamos reference designs show that if the station loss occurs above some threshold energy (about 350 MeV), the beam remains in the bucket and continues to accelerate, but acquires a synchrotron oscillation resulting in $\pm$10 MeV variation in the output energy. This is within the energy bandwidth of the HEBT and operation could in principle continue. Further increases in RF availability could be obtained by diagnostic-based pre-emptive tube replacement during routine maintenance periods, and by locating switchable hot spare tubes along the linac within klystron groups.

10. POTENTIAL OF SRF TECHNOLOGY

The growing maturity of superconducting RF (SRF) technology provides a potentially attractive alternate approach for high-intensity proton (and deuteron) linacs. Design issues for high intensity, and outlines of linac designs have been discussed recently in Ref. 4. The advantages of an SRF accelerator would be significantly reduced operating costs because of the elimination of RF wall losses, higher gradients which could reduce linac length and capital costs, improved dimensional stability of the cavities due to zero material expansion coefficients, and much larger structure apertures, which should greatly reduce or eliminate the beam loss threat. Design concerns specific to high-intensity linacs include the greater complexity of structure assembly and maintenance, the necessity for low-temperature refrigeration systems, the lack of established medium-β structures, and the stability of RF control. In addition, it is necessary to gain experience in operation of prototype SRF cavity systems with high-current beams. The practical gradients that can be realized may be bounded by the limitations of power couplers, presently at 100-kW per unit at 500 MHz. For example, a 5-MV/m SRF cavity accelerating 100 mA would need to couple in 500 kW of RF power per meter, requiring several power couplers per meter of structure. Since very-high-current conventional linacs already have high RF efficiency, the most attractive initial application zone for SRF may be in the medium current range where conventional CW linacs would be inefficient.

11. ACKNOWLEDGEMENTS

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12. REFERENCES

1. C.D. Bowman, et al., "Nuclear Energy Generation and Waste Transmutation Using an Accelerator-Driven Intense Thermal Neutron Source", NIM in Phys. Res., (Sec. A), Vol. A320, Nos. 1,2, August 15, 1992, pp. 336-367.
2. H. Lengeler, "Proposals for Spallation Sources in Europe", Proc. 1994 European Particle Accelerator Conf., London, June 1994.
3. A.J. Jason, et al., "The Los Alamos Study for a Next-Generation Spallation-Neutron-Source Driver", ibid.
4 J.R. Delayen et al. "Design Considerations for High-Current Superconducting Ion Linacs", Proc. 1993 Particle Accelerator Conf., Washington, DC, May, 1993, pp. 1715-1717.
5. P. Mandrillon, et al., "A High-Intensity Accelerator for Driving an Energy Amplifier for Nuclear Energy Production", Proc. 1994 European Particle Accelerator Conf., London, June 1994.
6. G.P. Lawrence, et a.., "Accelerator Technology for Los Alamos Nuclear Waste Transmutation and Energy-Production Concepts", Proc. 6th International Conf. on Emerging Nuclear Energy Systems, Fusion Technology Vol. 20, No. 4, December 1991, pp. 652-656.
7. R.A. Jameson, "Design for Low Beam Loss in Accelerators for Intense Neutron Source Applications", Proc. 1993 Particle Accelerator Conf., Washington, DC, May 1993, pp. 3926-3930.
8. B.P. Murin, et al., "High-Current Low-Energy RF Ion Accelerator", Proc. 1990 Linear Accelerator Conf., Albuquerque, NM, September 1990, pp. 707-709.
9. G.P. Lawrence, "High-Power Proton Linac for Transmuting the Long-Lived Fission Products in Nuclear Waste", Proc. 1991 Particle Accelerator Conference, San Francisco, May 1991, pp. 2598-2600.
10. I.M. Kapchinsky, et al., "Linear Accelerator for Plutonium Conversion and Transmutation of NPP Wastes", Proc. 1993 Particle Accelerator Conf., Washington DC, May 1993, pp. 1675-1680.
11. V.G. Andreev, et al., "Design Problems of High-Energy CW Ion Linac", Proc. 1992 Linear Accelerator Conf., Ottawa, August 1992, pp. 621-623.
12. K.F. Johnson, et al., "The Single-Beam Funneling Demonstration: Experiment and Simulation", Proc. 1990 Linear Accelerator Conf., Albuquerque, NM, September, 1990, pp. 701-703.
13. T.P. Wangler, et al., "Linear Accelerator for Production of Tritium: Physics Design Challenges", ibid., pp. 548-552.
14. R.W. Garnett, et al., "Beam Dynamics Simulation of the LAMPF Linear Accelerator", ibid., pp. 347-350.
15. J.S. O'Connell, et al, "Beam Halo Formation from Space-Charge Dominated Beams in Uniform Focusing Channels", Proc. 1993 Particle Accelerator Conf., Washington, DC, May 1993, pp. 3657-3659.
16. R.A. Jameson, "Beam Halo from Collective Core/Single-Particle Interactions", Los Alamos Report LA-UR-93-1209, March 1993.
17. J.M. Lagniel, "Chaotic Behaviour Induced by Space Charge", Proc. 1994 European Particle Accel. Conf., London, June 1994.