RADIOISOTOPE-PRODUCTION LINAC*

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Summary

A 70-MeV proton beam would open a new family of medical radioisotopes (including the important ^{123}I) to wide application. A 70-MeV, 500-μA linac is described, based on recent innovations in accelerator technology. It would be 27.3 m long, cost ∿$6 million, and the cost of power deposited in the radioisotope-production target is comparable to existing cyclotrons. By operating the rf-power system to its full capability, the same accelerator is capable of producing a 1140-μA beam, and the cost per beam watt on the target is less than half that of comparable cyclotrons. The technology to build such a linac is in a mature stage of development, ready for use by industry.

Sources of Medical Radioisotopes

Nuclear medicine is a major medical specialty that provides cost-effective, noninvasive, dynamic-function information that is clinically useful in diagnosing human diseases. Although reactors have produced radioactive isotopes of practically every element, studies of reactor-produced isotopes by biomedical investigators have demonstrated the major disadvantages of a low specific-activity dose (plus useless beta-decay radiation) in diagnostic applications. Clever techniques have been developed for recovering the high specific-activity products from uranium fission (^{99}Mo, ^{131}I, and ^{133}Xe) and from fast-neutron-induced (n,p) and (n,α) reactions (^{43}K, ^{54}Mn, ^{58}Co, ^{67}Cu, ^{132}Cs, etc.). Although ^{133}Xe and ^{99m}Tc (formed from the radioactive decay of ^{99}Mo) continue to occupy major roles in nuclear medicine, in recent years there has been a definite shift from reactors to accelerators as a principal source of radioisotopes for innovative medical applications. Some of the accelerator-produced nuclides gaining in importance include ^{201}Tl, ^{67}Ga, ^{111}In, ^{68}Ge, ^{123}I, and ^{127}Xe.

To achieve the highest possible specific activity for charged-particle-induced reactions, a nuclear reaction is chosen so that the desired radionuclide is a chemical element different from the target. Isotopically enriched targets are usually employed to minimize radionuclidic impurities. The excitation functions for the chosen reaction (and competing nuclear reactions) must be known to optimize irradiation conditions (maximize the product and minimize impurities). This optimization generally leads to a limitation on the target thickness, resulting in lower product yields. As the energy of the accelerated ion increases, a wider range of nuclear reactions is possible, and a greater variety of radionuclides can be made.

In the United States, low-energy accelerators (energies less than 45 MeV) are generally used to prepare medical radioisotopes. A few medium-energy accelerators (100 MeV to 1 GeV) have medical-radioisotope efforts as part of their total programs. There are now 10 accelerators operating (or being installed) in medical institutions in the United States. There are also 5 university-based accelerators that devote some beam time to preparing medical radioisotopes. In US federal installations, 9 accelerators are used to prepare medical radioisotopes, but 4 are used on an infrequent basis. The radiopharmaceutical industry has a total of 13 operating or planned accelerators. Therefore, in the United States alone, 37 accelerators are used for medical-radioisotope preparation.

A number of useful nuclear reactions require energies in excess of those available from most of the above-mentioned accelerators. Some of these reactions include ^{55}Mn(p,4n)^{52}Fe, ^{75}As(p,4n)^{72}Se, ^{80}Se(p,4n)^{77}Br, ^{80}Se(p,5n)^{76}Br, ^{85}Rb(p,4n)^{82}Sr, ^{127}I(p,5n)^{123}Xe → ^{123}I, and ^{181}Ta(p,4n)^{178}W. Even though large research-accelerator facilities produce usable amounts of these difficult-to-obtain radionuclides, it is doubtful that research facilities can routinely supply large amounts of the short-lived nuclides (half-lives of ∿10 days or less) to the medical community because of periodic or lengthy shutdowns. The present gap between the low-energy machines and the large accelerator facilities could be adequately filled by a proton accelerator at energies of 70 to 90 MeV, and capable of delivering beam intensities of 200 to 500 μA.

The present, state-of-the-art cyclotrons are not capable of producing such beams; however, in this parameter range linear accelerators appear to be an attractive solution. During the past 5 yr under the PIGMI program at Los Alamos, there have been significant advances in linac technology.[1] As a result, proton linacs are being reconsidered for a variety of applications.

Linear Accelerators

Proton linacs of conventional design require beams that have been bunched, focused, and accelerated to at least 750 keV before injection into the drift-tube linac (DTL). A high-voltage, dc preaccelerator, plus beam transport and bunching systems, are required. This equipment is costly, complex, and requires considerable floor space and ceiling clearance. This entire injection system has become obsolete since the demonstration of the radio-frequency quadrupole (RFQ) accelerator.[2] RFQ linacs can accept high-current proton beams at a very low energy (∿30 keV), then efficiently bunch, focus, and accelerate beams to energies required for injection into a DTL. In addition, by injecting into the DTL at higher than conventional energy, larger currents can be accelerated with lower beam loss.

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Conventional DTLs operate at a frequency of ∿200 MHz or lower, and have axial electric field gradients up to ∿2.5 MV/m. Field gradients as high as 9 MV/m have been demonstrated (by the Los Alamos PIGMI program) in a specially designed 450-MHz DTL structure. This implies that all future linacs will be shorter, with higher accelerating gradients, and that their physical size will be about one-half that of existing machines.

Cost Analysis

To evaluate the cost and performance of a radioisotope-production linac, designs for machines were studied that would deliver 500 μA of protons at 70 MeV. Such an accelerator based on the PIGMI design would look like the one in Fig. 1. This linac would consist of the few major components listed in Table I with their estimated cost shown in 1981 dollars.

A suitable ion source and 30-keV prototype injector has been tested.[3] The injector cost in Table I is based on the prototype component, fabrication, and assembly cost, but does not include engineering or development costs. Likewise, the RFQ structure's estimated cost is based on the actual construction cost of similar structures designed and built at Los Alamos. Because such an accelerator would be a production rather than a research facility, the requirement for computer control, although necessary, is minimal. The estimated cost of a distributed-microprocessor control system is based on the cost of a system, specially developed for linacs, that is being installed at Fermilab. This system would primarily monitor accelerator operation and would provide only a rudimentary tune-up and diagnostic capability. A traditional control room and central computer would not be required. Even conventional linacs, having numerous controllable parameters, operate essentially unattended following initial tune-up. As opposed to the requirement in research machines, beam quality would be of secondary importance. The first three components in Table I are considered to have fixed costs that comprise about 10% of the cost of the total accelerator. The total cost is dominated by (1) the cost of the DTL structure and (2) the rf-power supplies required to drive the accelerator.

The size, cost, and parameter range for practical linac designs are dictated by commercial availability of rf-power sources. The PIGMI-based design assumes use of the Litton-3694 klystron, an rf-amplifier tube produced for military radar. This tube has a peak power rating of 1.25 MW; however, reliable operation at twice the catalog rating, or 2.5 MW, is expected as long as the average power rating of 75 kW is not exceeded. The higher figure (assumed for this analysis) soon will be experimentally confirmed at Los Alamos. Two rf-power supplies have been built at Los Alamos, using the L-3694 klystron tube. The cost estimate in Table I is based on the costs of components and labor expended on the assembly of these units; it includes the klystron tube, modulator, high-voltage supply, waveguide, and all of the associated controls and instrumentation.

Table I

LINAC COMPONENT COSTS

Component	Cost
Ion source/30 keV injector	$125 K
RFQ linac (0.03 to 2.5 MeV)	$100 K
Control system	$ 75 K
DTL (2.5 to 70 MeV)	$ 66 K/m
The rf power supply (klystron)	$385 K ea

The DTL structure would be a single resonant cavity (with multiple rf-drive points). Assembled from copper-plated steel tank sections, each ∿2.5 m long, there would be 110 copper-plated drift tubes, each containing a permanent-magnet-quadrupole lens, plus 55 post couplers. The cost estimate includes procurement of these components, three rf-drive windows, the support structure, vacuum systems, and temperature-control systems. Salaries for four staff and four technicians required for assembly also are included. No engineering design or development is included in the estimate.

A computer program has been prepared that (based on the estimated cost of the structure and the rf-power supplies, certain electrical properties of the structure, the klystron's power rating, plus some efficiency factors and beam-dynamics considerations) can generate the first-order cost and performance characteristics for DTLs. The cost can be expressed as a function of both structure length (a continuous variable) and the required number of klystrons (a discrete variable). It would be desirable to design short linacs to save on the cost of not only the structure, but also of the

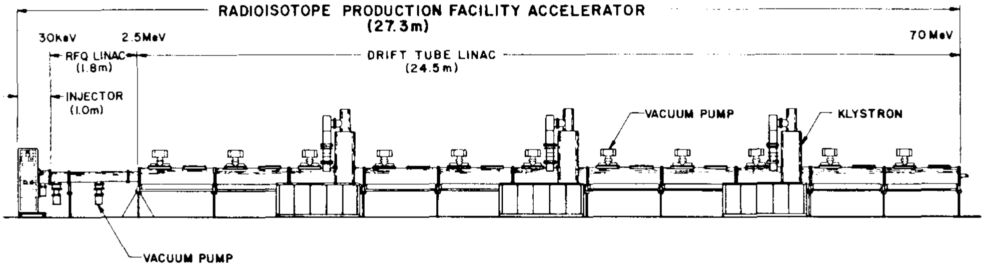

Fig. 1. PIGMI-based radioisotope production linac.

building required to house it. However, the power required is proportional to the accelerating gradient, or inversely to the structure length. Therefore, there is a cost minimum as shown in Fig. 2, a curve generated for the sample case (500 μA at 70 MeV). The cost of the optimized DTL design is $2.3 M, and three klystrons are required. This 18-m-long machine is called Case I. Coincidentally, if the linac were made any shorter, more than three klystrons would be required, and operation would be required at electric surface fields greater than 1.8 times the Kilpatrick limit, a value that is the present level of confidence for reliable operation. Families of curves were generated for PIGMI-based linacs designed to operate over a range of energies and beam currents. Figure 3 shows that an essentially linear relationship exists between cost and final energy for a fixed beam-current requirement. In addition, for a given energy, a fourfold increase in beam current can be achieved for ∿20% increase in accelerator cost.

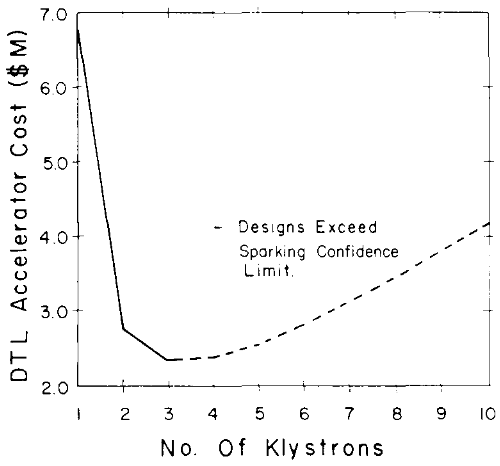

Fig. 2. DTL cost versus number of klystrons.

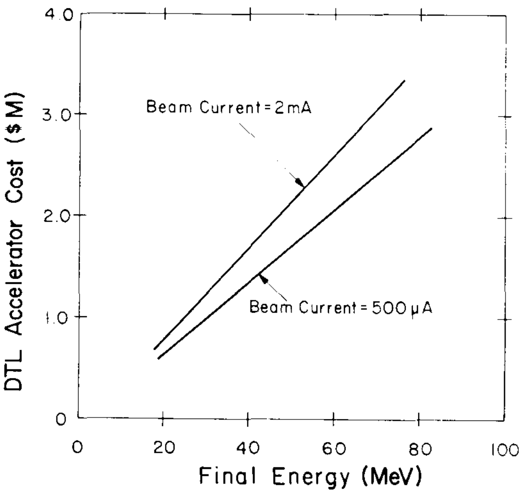

Fig. 3. DTL cost versus final energy.

For 70-MeV linacs, machine cost is related to design current, as shown in Fig. 4. The price starts at $2.2 M for a linac that uses all the available power just to excite the structure. These curves also show that for linacs requiring three or more klystrons, there is an inherent redundancy. For Case I, Fig. 4 shows that if one rf power supply were lost, there would be enough reserve power in the remaining two klystrons to accelerate ∿100 μA of beam. The 1.5-mA design case (requiring four klystrons and costing $2.7 M) could still accelerate over 1 mA with the loss of one klystron, and could accelerate almost 500 μA with the loss of two. In the medical-isotope business, such insurance might well be worth the extra investment.

Operating Costs

Initial-investment amortization of a particle accelerator is only a part of radioisotope production cost. Linac design Case I would require ∿660 kW of primary power, and it would be only 5.3% efficient in converting primary power into beam power. Linac efficiency can be readily improved by lengthening the structure. This reduces the required peak power, but at a substantial cost penalty. It is far more cost effective to lengthen the structure while using the full peak-power capability of the klystrons to accelerate higher peak beam currents. This reduces the duty factor required to accelerate the same average current, and it improves the conversion efficiency. Figure 5 shows that a modest increase in cost for increased structure length results in considerable operating-cost savings. The lower curve shows that the required primary power for Case I can be reduced 40% by raising the peak current from 18 mA to 30 mA.

Table II shows the basic design parameters for two different PIGMI-based linacs. Case I has been optimized for only initial cost. Case II is a slightly longer accelerator designed to accelerate a higher peak current; it is considerably more cost effective to operate at the design average current of 500 μA from Case I. Case II has two attractive additional features. In the event of one

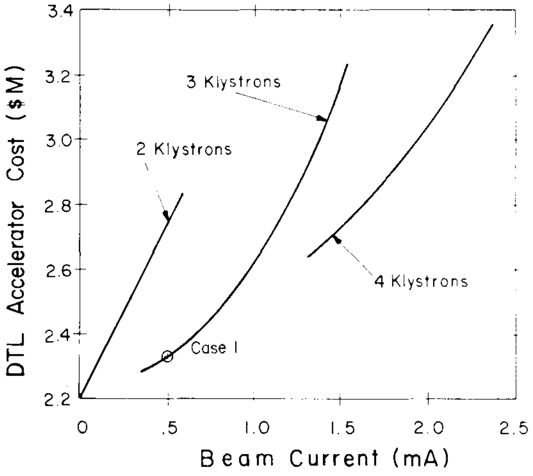

Fig. 4. DTL cost versus beam current.

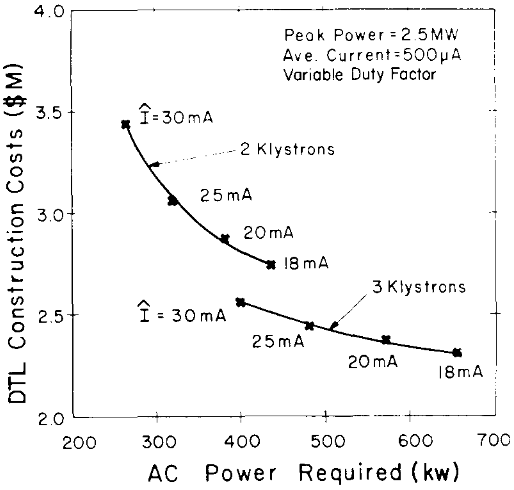

Fig. 5. Initial DTL cost as a function of operating cost.

Table II

PIGMI DESIGN LINAC PARAMETERS

Injection energy	30 keV
RFQ/DTL transition energy	2.5 MeV
Final design energy	70 MeV
Average design current	500 μA
Frequency	440 MHz

	Case I	Case II
No. of klystrons	3	3
Length (m)	17.9	24.5
Aver. axial electric field (MV/m)	5.1	3.7
Acceleration rate (MeV/m)	3.77	2.76
Peak beam current (mA)	18	26
Peak klystron power (MW)	2.5	2.2
Average klystron power (kW)	75	43
AC power required (kVA)	658	373
DTL cost (K$)	2335	2771
Total installed cost (K$)	2635	3071

klystron failing, there would still be enough reserve power to accelerate 186 μA of beam. If more than 500 μA of beam current were desired, the full-power capability of all three klystrons could accelerate 1140 μA.

It is difficult to make an objective comparison between a PIGMI-based linac and accelerators currently available to the radioisotope industry; none are in a comparable parameter range. Table III lists the three highest energy accelerators available (all cyclotrons), their catalog rating, and price. For comparison, PIGMI-based Case II is listed for both the design current, plus for operation at its full-power capability. Any commercial-product selling price usually equals the production cost multiplied by some factor (often 2) to cover operational overhead and amortize the initial development cost. In the case of the PIGMI design, ∿80% of the development has been completed, and the technology is available to industry. Some investment would be required for technology transfer, and some risk is associated with building the first accelerator of this type. To arrive at a price (for comparison with other accelerators), a 33% contingency was added to the estimated production cost; this figure was multiplied by 1.5 to cover overhead, etc.; that is ($3 M + $1 M) • 1.5 = $6 M. The selling price divided by the maximum beam power capability was used to arrive at values for "price per installed watt." The conversion efficiency is the maximum rated-beam power divided by the primary-power requirement.

Conclusion

Nuclear medicine is a well-established medical speciality that, with increased availability of accelerator-produced isotopes, promises to hold even greater potential for diagnosing human diseases. To meet this potential, accelerators having higher energy and current capability than are currently available will be required. PIGMI-based linacs appear to be capable of meeting that need. Not only do they appear be cost effective (in terms of initial cost for performance), but also will be more efficient in operation. The

Table III

RADIOISOTOPE PRODUCTION ACCELERATOR PARAMETERS

Accelerator Type	Proton Energy (MeV)	Beam Current (μA)	Primary Power Required (kVA)	Purchase Price ($ M)	Price/Installed Power ($/W)	Conversion Efficiency (%)
Scandatronix MC-40[1]	40	250	480	2	202	2.08
Cyclotron Corp. CP-45[2]	45	200	350	2	222	2.57
PIGMI Case II[3]	70	500	373	6	171	9.38
PIGMI Case II[4]	70	1140	658	6	75	12.12
Sumitomo 930F[5]	75	100	450	6	800	1.67

1. Variable-energy, variable-particle cyclotron, internal target.
2. Variable-energy H⁻ cyclotron
3. Design case
4. Operated at full-power capability
5. Fixed energy cyclotron

PIGMI accelerator technology is in a mature stage of development, ready and available for transfer to the industry.

References

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Discussion

We don't quote building costs because they are very site dependent. The shielding, beam transport, targets, remote handling, etc., might cost as much (or more) as the accelerator itself. We haven't tried to optimize operating costs over a 10- to 15-yr period, because the uncertainties of power costs are too great.

The energy of the radioisotope production linac I describe could be varied down to 25 MeV by dropping the accelerator gradients using the post couplers. The only commercially available cyclotron at these energies is fixed energy. You could arrange to break the linac structure at several places to put in targets, but you would lose the redundant features of multiple klystron drive.

There would definitely be a payback from increasing the klystron efficiency. We are constrained to use the latest linac technology in a framework of commercially available klystrons; we would be way ahead with a more efficient tube.

In terms of technology transfer to industry, we are told that certain proprietory allowances can be given, for example about particular designs and design drawings. On the other hand, we wouldn't give proprietory rights to design codes. This could be worth a lot in getting a head start on competition.