A COMPACT PROTON LINAC FOR POSITRON TOMOGRAPHY*

R.W. Hamm, K.R. Crandall, M.E. Hamm,
L.D. Hansborough and J.M. Potter
AccSys Technology, Inc.
1040 Serpentine Lane, Suite 208, Pleasanton, CA 94566

Abstract

The design of a compact proton linac for use in positron emission tomography (PET) has been completed, and a prototype is presently under construction. This linac is based on technology demonstrated at Los Alamos National Laboratory under the PIGMI program funded by the National Cancer Institute. The design presented here combines that technology with recent developments and new rf power sources to produce a practical and economical radioisotope production accelerator for PET.

Introduction

At present, PET imaging is primarily a medical research tool but it shows great promise as a routine clinical diagnostic procedure. In contrast with computed x-ray tomography, PET uses radiation emitted from within the body to provide detailed physiological information. In-vivo processes can be imaged using physiologically participative radiopharmaceuticals, enabling for instance, the diagnosis of diseases of the brain and heart, two soft tissue areas where structural abnormalities do not always accompany physiological deficiencies.[1] Magnetic resonance imaging (MRI) is the only other imaging technique available that offers the possibility of physiological information, but even this technique will be complementary to PET since each utilizes different elemental isotopes. PET has greater potential utility in this role because of the ability to synthesize compounds used by the body, such as glucose, from the short-lived positron emitting isotopes of carbon, nitrogen, and oxygen.

The cost of a facility to produce the desired short-lived isotopes will be a critical factor in determining the success of PET in the clinical marketplace. The cost of a PET scanner can be reduced by advances in electronics, data processing, and detector technologies, none of which is dependent solely on the PET market. However, radioisotope production is unique to nuclear medicine and the cost of such a facility is a major concern, as evidenced by a recent National Cancer Institute contract offering for the development of a compact cyclotron for PET isotopes stressing automation, ease of operation, size, cost, and minimum space and shielding requirements.[2]

PET scanners and small cyclotrons are available commercially. Several manufacturers even offer compact cyclotrons dedicated to PET isotope production, and most have programs to further simplify and automate these machines. The major simplification is acceleration of only protons, since useful yields of PET isotopes can be obtained by proton reactions on isotopically enriched targets at energies on the order of 10 MeV.[3] However, the high beam current, compactness and ease of operation required in a clinical environment make a proton linac attractive for this application.

One of the major obstacles to practical ion linacs has been the cost, size, and complexity of rf power sources. Advances in solid-state rf amplifiers have resulted in compact units for high power pulsed radar applications, with a 250 kW system being available from Westinghouse for naval shipboard radar.[4] This system has also been used to drive a high-Q resonant cavity.[5] The cost of the present amplifier modules prohibits their use as an rf power source for commercial linac applications. New amplifiers utilizing a high power silicon transistor developed by Microwave Modules and Devices[6] will reduce the present system cost and increase output power while keeping the system at a modest size. However, a lower cost rf power system can be obtained by using solid-state modules as drivers for a parallel grounded-grid planar triode amplifier being developed at Los Alamos.

The linac technology developed at Los Alamos in the PIGMI program,[7] coupled with this rf source technology makes the compact linac a cost-effective alternative to the cyclotron for radioisotope production. We have designed such a linac for PET isotope production which will be superior to a cyclotron-based system in size, weight, reliability, and ease of operation.

PET Linac System

The PET linac system described here was designed under a Phase I Small Business Innovative Research grant from the National Cancer Institute utilizing the Los Alamos PIGMI linac technology obtained through the laboratory's technology transfer policy and other advances that have since occurred. Phase II has been awarded and a prototype unit is being fabricated and assembled for testing.

A significant accomplishment of the Phase I design was the incorporation of proven linac technology from laboratories around the world. The vane coupling rings invented at Lawrence Berkeley Laboratory[8] and the C-seal rf joints developed in the White Horse project at Los Alamos[9] have been incorporated into the radio-frequency quadrupole (RFQ) accelerator. The stem rf seals used by Chalk River Nuclear Laboratory[10] and the drift tube alignment joint developed at CERN[11] have been integrated into the drift tube linac (DTL) design. The support structure and control system designs are modeled after those of the Racetrack Microtron Accelerator at the National Bureau of Standards.[12] The vacuum pumps have been chosen because of their successful use in several linacs at Los Alamos. The addition of these innovations to the basic PIGMI linac concept makes the PET linac more reliable and inexpensive.

A layout of the linac is presented in Fig. 1. The entire system, including the injector, will be mounted and aligned on a box-like support frame. This enables it to be aligned and tested during assembly and then shipped under vacuum as a complete unit. A key feature of the design is its simplicity. The injector operates at a very manageable 30 kV, with all high voltage components shielded by lucite covers. The small ion source and single-electrode extraction gap are identical to that of the PIGMI injector.[13] A simple electrostatic einzel lens is used to focus the beam into the RFQ. The low energy transport region has a valve which isolate the ion source for maintenance and has remotely insertable beam diagnostic probes.

The 425 MHz RFQ can focus, bunch, and accelerate the 30 keV beam from the injector to 2.0 MeV in 1.59 m. It is a conventional resonant cavity RFQ with four copper-plated vanes mounted in a cylindrical rf cavity.

*This work supported by PHS Grants 1R43CA37512-01 and 7R44CA43915-01 awarded bt the National Cancer Institute, DHHS.

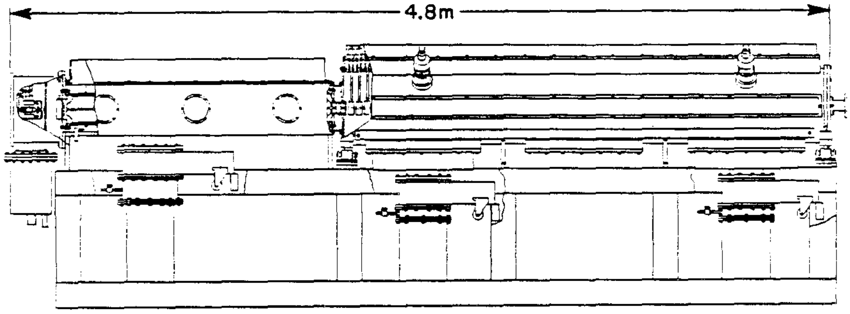

Fig. 1. Layout of PET Isotope Production Linac.

This cavity is housed in a simple vacuum container that allows easy access for inputs and monitoring, as shown in Fig. 2. The DTL is the familiar post-coupled Alvarez structure used in most ion linacs today, scaled to operate at 425 MHz. This structure accelerates the 2 MeV beam from the RFQ to 10 MeV in 2.81 m, using 38 drift tubes containing commercially built permanent magnet quadrupole lenses. The tank and drift tubes are fabricated from copper-plated steel. A cross section of the DTL is shown in Fig. 3. This system should be very reliable, requiring minimal control and monitoring during operation.

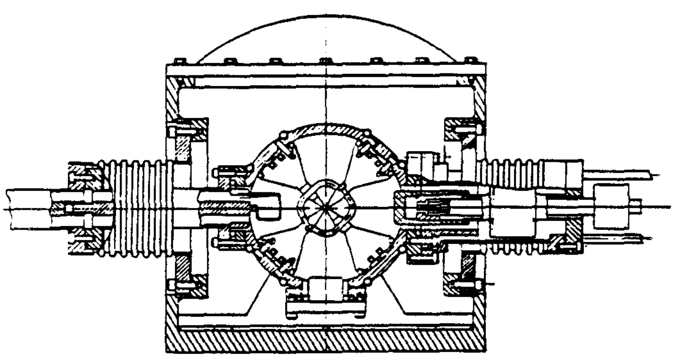

Fig. 2. RFQ Accelerator Cross Section.

The rf power is supplied by 250 kW tuned cavity amplifiers, one for the RFQ and three for the DTL. Each unit is attached to the accelerator with a 3.125 inch coaxial cable. All of the units are driven by a master oscillator, but each one has independent phase and amplitude control. The final stage of each amplifier has eighteen grounded-grid planar triode tubes on a tuned output cavity, so that a unit can operate at slightly reduced power if one tube fails, as long as the failure mode is not a short.

The entire accelerator vacuum is maintained by four commercial cyrogenic pumps which are extremely reliable and rugged. These units require periodic regeneration, but can be valved off from the accelerator for maintenance. The cooling water system is a commercial unit sized for this application.

A modest microprocessor control system based on the secondary station designed for the NBS Racetrack Microtron[12] will be used for control and diagnostics of the linac. This system will control the injector operation, the rf system, and the high energy transport system, in addition to monitoring the beam and interlock system status. There are very few active control parameters since the design has incorporated many reliable components which do not require control beyond their initial adjustments during fabrication. The overall control system design has incorporated many features of current medical electron linacs, including a computer-independent hard-wired interlock system.

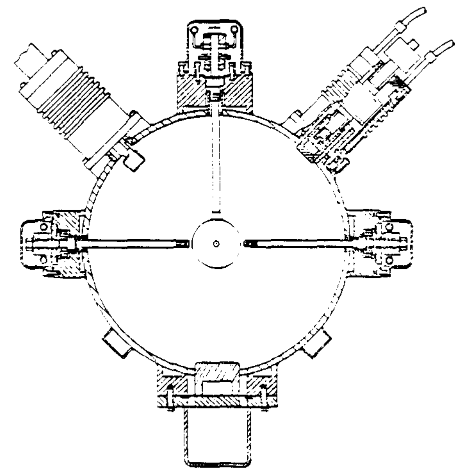

Fig. 3. Cross Section of the DTL Tank.

The calculated operational parameters for the linac design of Fig. 1 are listed in Table I. The operation of the linac with a 34 μsec pulse at 120 pulses/sec is a compromise between rf system efficiency and target window capability. A short intense pulse at a rapid rate allows the window to cool more uniformly, but is less efficient since more rf power is wasted during the accelerator cavity fill time. Measurements will be made to study the operation of the linac with a longer beam pulse. Increasing the beam pulse width and average current are however, limited by the maximum rf pulse and duty factor available from the rf system. The proposed planar triode amplifier units will operate with a pulse width up to 100 μsec at a duty factor of about 1%, so a beam pulse of 74 μsec is possible.

Table I. PET Linac Operating Parameters

Parameter	RFQ	DTL
Input Energy (MeV)	0.03	2.0
Input Beam Current (mA)	28.0	25.0
Output Energy (MeV)	2.0	10.0
Bore Radius (mm)	2.6-1.6	4.5-5.0
Length (m)	1.59	2.81
Maximum Acceleration Field (MV/m)	3.268	3.694
Final Synchronous Phase (deg)	-30.0	-25.0
Nominal Current Limit (mA)	63.0	325.0
Nominal Acceptance (πcm-mrad)	0.116	9.0
Input Emittance (πcm-mrad)	0.04	0.057
Output Emittance (πcm-mrad)	0.057	0.059
Output Beam Current (mA)	25.0	25.0
Beam Transmission (%)	90.0	100.0
Peak RF Power w/ Beam (kW)	165.0	670.0

The 10 Mev proton beam from the DTL is transported to the shielded target system for isotope production via a beam transport system using conventional electromagnet quadrupole lenses as shown in Fig. 4. This system expands the beam to reduce the target window power density and beam divergence. The calculated operating range of the system is given in the figure. The three quadrupole lenses are 15.24 cm long with an inner magnet bore of 6.0 cm, so that a 2 inch outer diameter beam pipe can easily be accomodated. The total beam line length of 1.65 m to the target window from the DTL allows adequate room for shielding the accelerator from the target area.

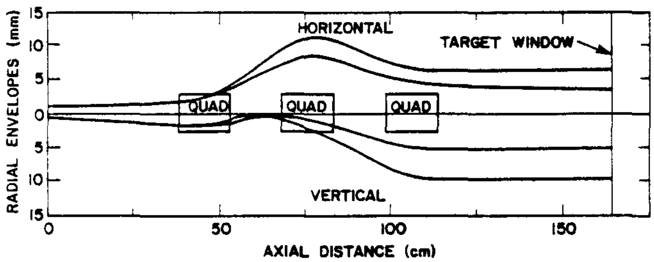

Fig. 4. Calculated Final Transport Optics.

PET Facility

The model PET facility shown in Fig. 5 illustrates the desirable features of the PET linac. The accelerator system, including target cell and shielding, occupies about 250 ft^2 and weighs around 3000 lbs. The actual layout will be determined by the particular medical complex in which it is located. The placement of the linac in the basement of an existing building could be accomplished by the addition of earthen embankments or backfill. The accelerator and target system could even be located remotely from the radioisotope processing and PET scanning facility by installing a transport system to the hot cells.

Although the beam simulations have shown 100% transmission of beam from the RFQ through the DTL, in practice there may be a small (less than 1%) beam loss in the DTL at energies greater than 2 MeV, but the radiation at angles greater than 45° to the beam is down by an order of magnitude from that of the forward direction. The shielding shown in Fig. 5 is based on calculations of the worst case beam spill and is substantially less than that required for a small cyclotron facility.[14] Hence, some medical centers could house the linac in an existing facility with the addition of stackable concrete blocks for shielding.

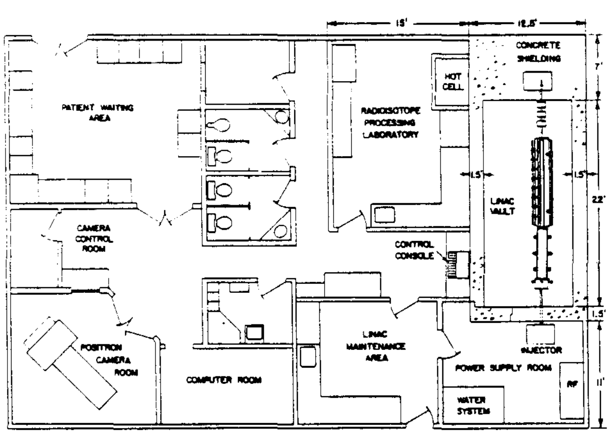

Fig. 5. Model PET Facility Layout.

The efficiency of the rf system and the low duty factor of the accelerator will also minimize the required input ac power. The projected power consumption for the complete accelerator system is 25 kW. Most of this (15 kW) is required to power the accelerator and injector, with the balance divided between the vacuum and cooling systems.

Summary

The Phase I design study has clearly demonstrated the technical feasibility of combining the PIGMI technology with other recent advances to produce a compact proton linac for the generation of short-lived radioisotopes for PET imaging. There is little doubt that the linac will operate almost exactly as predicted. The technology used for the control and rf systems is also proven and will only have to be tailored to this particular application. During the fabrication, assembly, and testing of the prototype, the major effort will be to optimize the fabrication techniques and mechanical parts of the system in order to reduce the construction cost of production units. The main objective of the prototype project is thus to successfully implement the technology in a cost-effective commercial system.

References

1. A.P. Wolf, "Cyclotrons, Radionuclides, Precursors and Demands for Routine vs. Research Compounds," Annals of Neurology, Suppl. to Vol. 15, 519 (1984).
2. "Solication of the Public Health Service for Small Business Innovation Research (SBIR) Contract Proposals," PHS 85-3, 23 (1985).
3. R.J. Nickles, J.R. Votaw, G.D. Hutchins, M.S. Rosenthal, K.M. Funk, J.S. Sunderland and M.R. Satter, "Target Telemetry in Medical Isotope Production," Proc. Eighth Conf. on Applications of Accelerators in Research and Industry, Nucl. Inst. Meth., Vol B10/11, 957 (1985).
4. K. Lee, C. Corson, and G. Mols, "A 250 kW Solid-State AN/SPS-40 Radar Transmitter," Microwave Jour. 23, 93 (1983).
5. D.R. Vaughan, G.E. Mols, D.W. Reid and J.M. Potter, "A High-Power, Solid-State RF Power Source for Accelerator Cavities," IEEE Trans. Nucl. Sci. NS-32, No. 5, 2857 (1985).
6. Microwave Modules and Devices, Mt. View, CA, Type MC-600 transistor.
7. L.D. Hansborough (compiler), "PIGMI: A Design Report for a Pion Generator for Medical Irradiations," Los Alamos Report LA-8880 (1981).
8. H.D. Lancaster, J.A. Fugitt and D.R. Howard, "Stabilized Radio Frequency Quadrupole," U.S. Patent No. 4,490,648, Dec. 25, 1984.
9. H.O. Dogliani and J.A. Farrell, "White Horse Program Review FY82," Los Alamos Report LA-9835-PR, 116 (Sept. 1983).
10. J. Ungrin, J.C. Brown, B.G. Chidley, R.M. Hutcheson, G.E. McMichael and S.O. Schriber, "Low Energy 100% Duty Factor Alvarez Linacs at Chalk River," Proc. 1981 Linear Acc. Conf., Los Alamos LA-9234-C, 12 (Oct. 1981).
11. E. Boltezar, "Mechanical Design of CERN New Linac Accelerating Structure," Proc. 1979 Linear Acc. Conf., BNL 51134, 392 (Sept. 1979).
12. R.L. Ayres, N.R. Yoder, E.R. Martin, RE. Trout and B.L. Wilson, "NBS Racetrack Microtron Control System," IEEE Tran. Nucl. Sci. NS-32, No.5, 2086 (Oct. 1985).
13. R.W. Hamm, D.W. Mueller and R.G. Sturgess, "A 30-kV Proton Injector for PIGMI," Proc. 1981 Linear Acc. Conf., Los Alamos LA-9234-C, 309 (Oct. 1981).
14. Baby Cyclotron Brochure on Model BC 168, Standard Layout on p. 5, The Japan Steel Works, Ltd. (1982).

