Compact Linacs for Positron Emission Tomography*

D. Raparia and S. Machida
University of Houston
Houston, Texas 77204-5504
and
Texas Accelerator Center
4802 Research Forest Drive, Building 2
The Woodlands, Texas 77381

Abstract

Compact 14 MeV Proton and 7 MeV deuteron linacs for use in positron emission tomography (PET) have been studied, and conceptual designs for low energy beam transports (LEBT), radio-frequency quadrupole (RFQ) and drift tube linacs (DTL) have been achieved. The machines are compact and simple enough to be operated in hospitals. The LEBT consist of two Einzel lenses and are about 25 cm long. The 425 MHz proton RFQ is designed for 50 mA peak current, and the 425 MHz deuteron RFQ is designed for 25 mA peak current. Both 850 MHz DTLs use permanent quadrupole magnets and have high acceleration field of 15 MV/m with a peak field of twice the Kilpatrick limit.

Introduction

Positron Emission Tomography (PET) uses radiation emitted from injected radioisotope tracers within the body to provide tracking of blood flow in soft tissue areas such as the cardiovascular system and brain where structural abnormalities do not always accompany physiological deficiencies. The most common tracers are $^{11}C,^{13}N,^{15}O$, and ^{18}F which are produced by reactions $^{14}N(p,\alpha)^{11}C$, $^{16}O(p,\alpha)^{13}N$, $^{15}N(p,n)^{15}O$, $^{14}N(d,n)^{15}O$ and $^{20}Ne(d,\alpha)^{18}F$. The energy required for these reactions are approximately 14MeV for protons and 7 MeV for deuterons.

At present the most common particle accelerating device used in the production of these tracers is the cyclotron. Cyclotrons are commercially available. Several manufactures even offer compact cyclotrons dedicated to PET isotopes production, and most have programs to further simplify and automate these machines. However, the high beam current, compactness, and ease of operation, required in the clinical environment, make linacs attractive for this application. Because of the present high energy linac size and unavailability from a commercial source, the medical community believed their only option was to purchase a commercially available medical cyclotron. With recent progress in the linac technology, it is possible to design a compact linac, that is cost effective and simple enough to operate in hospitals for this purpose.

Design studies have shown that it is possible to construct a compact proton/deuteron unit which shares a common rf system. A layout of the linacs is presented in Fig 1. The key features of the design are compactness and simplicity. These linacs would provide 14 MeV protons with a peak current of 50 mA and 7 MeV deuterons with a peak current of 25 mA. The linac tanks would be about 25 cm in diameter and the lengths including the ion source (IS), low energy beam transport (LEBT), 425 MHz radio-frequency quadrupole (RFQ) and 850 MHz drift-tube linac (DTL) would be about 3.3 meters.

Ion Source and Low Energy Beam Transport

One of the most commonly used and reliable proton and deuteron sources is the duoplasmatron. These sources will operate at a very manageable voltage of 30 kV. Since the beam from the source is relatively large in radius and divergence, lenses are required to focus the beam into the RFQ.

Electrostatic axisymmetric Einzel (unipotential) lenses are selected for the LEBTs because of their simplicity and compactness. The buildup of plasma and charge neutralization cannot occur in electrostatic lenses, as in case of magnetic lenses, since the electron-ion pairs produced in collision between beam particles and background gas are swept out of the beam region by the electric field between the electrodes. Furthermore, magnetic focusing is particularly ineffective at low beta because of the velocity term in the force equation. Electric focusing, on the other hand, has no such velocity term in the force equation and should be a prime candidate for the focusing role at low velocities. The main problems in the electrostatic focusing is breakdown and aberrations. The problem of the breakdown can be overcome by providing lower but spatially continuous focusing forces, as in the helical electrostatic quadrupole (HESQ) described below, instead of spatially discreet but higher focusing forces as in a FODO structure. The spatially continuous focusing forces also help keep the beam size smaller all the time, thus minimizing aberrations. Each LEBT consists of two Einzel lenses. The two lenses were chosen to provide two degrees of freedom to match the RFQ acceptance. (Two degrees of freedom are sufficient for the matching requirement.) The present design provides 5 cm of space between the lenses for a steering magnet and beam diagnostic elements. Typical particle trajectories through these lenses are shown in Fig. 2 for deuterons.(for protons see reference 1). Calculations were made using the program AXCEL[2], which includes space charge and ion image effects. These lenses are about 7 cm long and have a voltage of 30 kV. The gap between the high voltage electrode and ground electrode is one centimeter, which is large enough to prevent breakdown. Because of the spherical aberrations in electrostatic lenses, only about 90 % of the beam can be focused into the RFQ.

An alternative scheme for the higher current is to use the HESQ in the LEBT. The HESQ is nothing but a continuously twisted electrostatic quadrupole (see Fig 3). The HESQ lenses provide stronger first-order focusing in contrast to weak second-order focusing of Einzel lenses. Again the choice of the HESQ avoids beam neutralization. The HESQ provides an axial symmetric beam which is necessary for the RFQ matching. Being a spatially continuous transport system, the HESQ provides stronger focusing than the FODO type. The HESQ must satisfy several constraints given in reference 3 for an electrostatic quadrupole and an additional constraint for helical channel[4], namely the ratio of the period of the helix to aperture must be greater than 20. Preliminary results which include lin-

---

*This work was supported by U. S. Department of Energy under grant No. DE-FG05-87ER40374.

CH2669-0/89/0000-0987$01.00©1989 IEEE

ear space charge effects show that it is possible to match the proton beam of 100 mA, into the RFQ entrance in a length of about 25 cm with an increasing voltage of about 5 to 8 kV and a rotation of 54 rad/m. (see Fig. 4)

Radio Frequency Quadrupole

The 30 keV proton beam with peak current of 50 mA is focused, bunched and accelerated up to 3 MeV by 425 MHz RFQ in 1.3 m, and a 30 keV deuteron beam with peak current of 25 mA is focused, bunched and accelerated up to 1 MeV by another 425 MHz RFQ in 1.9 m. Each RFQ has four sections; radial matching, shaper, gentle buncher and acceleration sections. The design recipe for first three sections is conventional. The design criteria for the acceleration section have been changed to make it shorter in length without losing the beam qualities. In the acceleration section, it is customary to keep modulation and phase angle constant. In the present design[5] the modulation is increased in order to keep the transverse current limit more than double the design current. This results in the same transmission efficiency and emittance growth, but a 50 % higher accelerating field. The performances of the RFQs were analyzed with the RFQ-linac design and simulation codes RFQSCOPE and PARMTEQ. The main parameters and simulation results of the RFQs are shown in Table 1.

The RFQ structure is four-rod cavity[6]. The design is much simpler to fabricate than four-vane and is smaller than conventional four-vane or four-rod structures. It also has no unwanted dipole mode like a four-vane design. The peak rf power required for each RFQ is about 550 kW. A small (5' x 6") 425 MHz Eimac TV tube can be used for RFQs.

Table I: RFQ Parameters

	Proton	Deuteron
Energy (MeV)	0.03-3.0	0.03-1.0
Frequency (MHz)	425	425
Number of cells	134	266
Length (cm)	122	187
Bravery Factor*	2.4	2.4
Bore radius (cm)	0.3	0.25
Final modulation	3.0	3.0
σ_{0t} (deg/cell)	40.0	30.0
Transmission	94(%)	93 (%)
Emittance growth	20 (%)	20 (%)

* [illegible]

Matching the RFQs to DTLs

Matching the RFQ to the DTL is approximately the same for both proton and deuteron machines. The beam from the RFQ should be matched to the DTL acceptance for the design current in all three planes. Four quadrupoles are needed to match the beam transversely. The RFQ operates at 425 MHz and DTL at 850 MHz. Two rf buncher are needed to match the longitudinal acceptance. The matching sections are about 25 cm long for both cases and use permanent magnet quadrupole with the same pole tip field as in the DTLs.

Drift Tube Linac

By selecting a DTL frequency of 850 MHz, the DTL's dimensions have been significantly reduced. Since the tank radius is inversely proportional to the resonant frequency in the transverse direction, the choice of 850 MHz reduces the DTL diameter to 24.4 cm. This is approximately the same diameter as the 425 MHz RFQ. A focusing lattices of FFDD with a bore radius on 0.5 cm in the proton DTL and 0.25 cm in the deuteron DTL, provide enough transverse acceptance and reduce the quadrupole magnetic field strength necessary for beam focusing.

To make a compact machine, it is obvious that the accelerating field gradient E_0 should be made as high as possible. There are some factors that limit E_0, and the possibility of sparking increases rapidly above a certain value. To estimate this phenomena, there is an empirical law called the Kilpatrick limit . The Kilpatrick limit is a function of frequency, and is about 20 MV/m at 425 MHz. By selecting a 850 MHz frequency for the DTL, this limit has been increased to 28 MV/m. This allow the DTL to achieve an accelerating field of 15 MV/m, thereby reducing the length of the DTL for a 14 MeV proton system to 1.4 m and for a 7 MeV deuteron system to 0.7 m. This DTL design has a lower peak field to accelerating field ratio than conventional DTLs as shown in Fig 5. This is due to the wider gap between drift tubes. The DTL's parameters are shown in table II.

A klystrode is a suitable rf source for this design. The peak rf power for the proton DTL is 3 MW and for deuteron DTL is 0.6 MW.

Table II: DTL Parameters

	Proton	Deuteron
Energy (MeV)	3-14	3-7
Length (m)	1.4	0.7
Diameter (m)	0.244	0.244
Bore radius (cm)	0.5	0.25
DT radius (cm)	2.0	2.0
Number of cells	31	25
Gradient (MV/m)	15.0	10
Bravery factor	2.0	2.0
Focusing	FFDD	FFDD
σ_{0t} (deg/cell)	45	45
Quadrupole magnet	PM	PM*
Gradient (kG/cm)	26.5	69.6
Length (m)	1.7	1.4

* PM = permanent magnets

Conclusions

14 MeV Proton and 7 MeV deuteron linacs for PET have been studied in this paper. Each section of the system has been conceptually designed using standard accelerator codes. All components of the design appear feasible using existing technology.

Special thanks to S. Ohnuma and F. R. Huson for their encouragement and C. A. Swenson for helpful discussions.

References

[1] D. Raparia and S. Machida , ' Design Study of a Medical Proton Linac for the Neutron Therapy', to be published in the Proc. of the Application of Accelerator in Research and Industry, Denton Texas (1988) in Nucl. Instr. and Meth. B. ;Fermilab report TM-1541

[2] P. Spadtke, 'AXCEL GSI', GSI Report, GSI-83-9, 1983.

[3] M. Reiser, C. R. Chang, D. Chernin, and E. Horowitz, Microwave and particle beam sources and propagation, SPIE Vol. 873, pp 172 (1988)

[4] S. Ohnuma,' The Phase Space Acceptance of a Helical Quadrupole Channel of Finite Length',TRIUMF Rpt., TRI-69-10 (1969); R. L. Gluckstern, Proc. of the 1979 Linear Acc. Conf. Montauk, NY. pp 245

[5] D. Raparia, ' RFQ Acceleration section and Its Optimization', to be published in the Proc. of the 1988 Linear Accelerator Conference, Williamburg, VA.

[6] R. Kazimi, ' A Four-Rod Cavity RFQ', to be published in the Proc. of the 1988 Linear Accelerator Conference, Williamburg, VA.

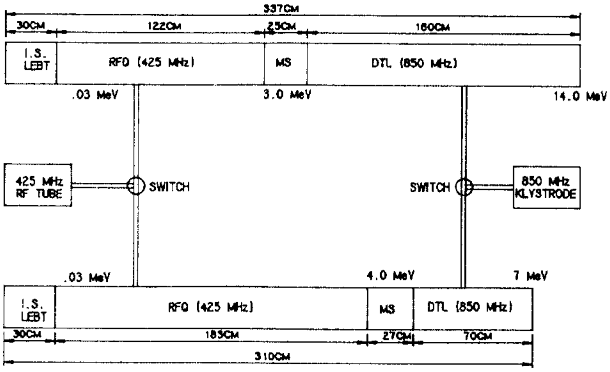

Fig. 1. Schematic block diagram of the PET linac system with common rf power sources.

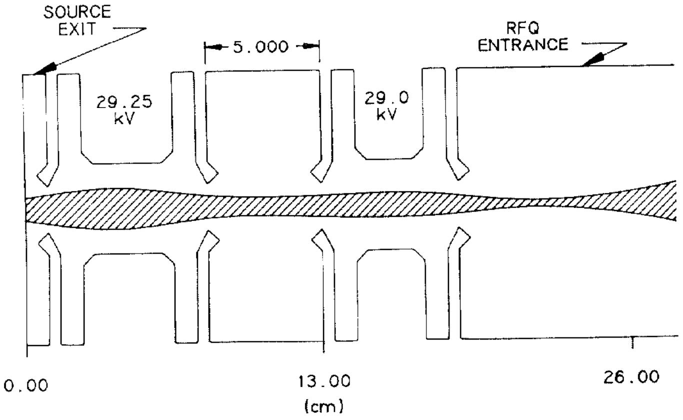

Fig. 2. Particle (deuteron) trajectories through the LEBT.

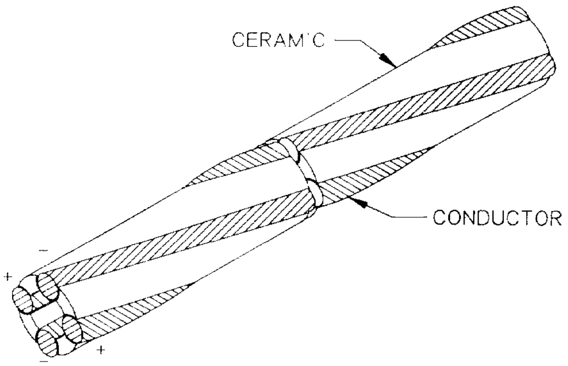

Fig. 3 A possible design of the HESQ.

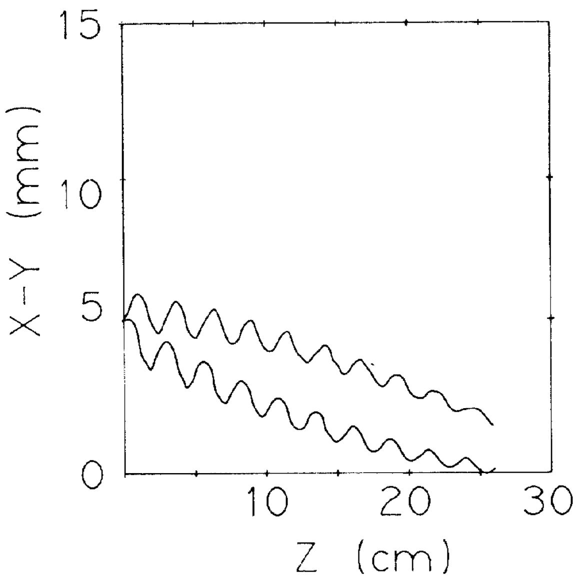

Fig. 4 Beam (proton) particle trajectory for 100 mA through the LEBT using the HESQ.

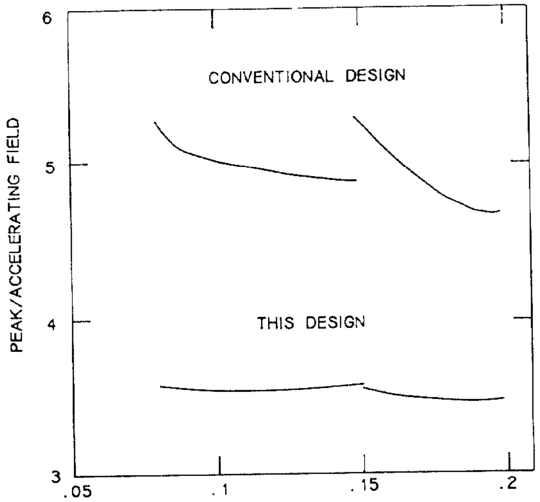

Fig. 5. The wider gap between tubes reduces the peak field ratio down to approximately 3.5 in all section of β. At $\beta = .15$, the discontinuity is due to a change of drift tube corner radius.