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COMPARISON OF CONVENTIONAL L AND S-BAND ELECTRON LINACS AS PION SOURCES SUITABLE FOR RADIOTHERAPY

J. Haimson and B. Mecklenburg

Haimson Research Corporation
Burlington, Massachusetts

and

C. Williamson

Massachusetts Institute of Technology
Cambridge, Massachusetts

Summary

A discussion on target configuration and negative pion yield, supported by high power electron beam experimental data, establishes 250-330 kW at 500 MeV to be desirable beam parameters for an electron linac which, in combination with a Stanford carrousel type pion spectrometer, would provide a practical source of π^- mesons suitable for radiotherapy applications.

A preliminary analysis confirms that peak current limitations imposed by cumulative beam breakup may be avoided by adopting specific microwave design procedures, which minimize higher order mode transverse shunt impedances in potentially troublesome zones of individual waveguides, and which introduce higher order mode stop bands at specific locations along the beam centerline, similar to the techniques used for the MIT and IKO high duty factor linacs.

Introduction

The 1964 Rutherford Memorial Lecture by P.H. Fowler[1] "π Mesons versus Cancer" provided a strong stimulus for the initial investigation of electron linear accelerators capable of producing beams of π^- mesons at radiotherapeutically acceptable intensities. Also the completion in June 1964 of a comprehensive design study for a high duty factor electron linear accelerator (400 MeV, 500-1000 μA) to be installed at Saclay, France provided technical information which supported the feasibility of this approach. As pointed out by Fowler, an electron linear accelerator of the Saclay type "would provide intense sources of π mesons, at least 10 times as intense as would be required for biological work" (biological as distinct from clinical radiotherapy). Preliminary physical experiments conducted at UCRL, Berkeley, California, and published[2] in 1965, also indicated the possible radiotherapeutic advantages (and some of the dosimetry problems) associated with negative pion beams.

In the decade which followed these initial investigations, and with the advent of several important technological advances (and a considerable change in the medico-political environment), increasing interest has been directed at negative pion producing machines such as an electron linear accelerator constructed specifically for installation in a busy radiotherapy center.

Relevant technological advances in recent years include the achievement of very intense electron beams in the energy range of 300 to 500 MeV, the successful avoidance of beam instabilities in long multi-section traveling wave linear accelerators (cumulative beam breakup), the routine demonstration of lifetimes in excess of 5000 hours for high RF power klystrons, and the development of a new beam transport system, which will capture, momentum select, and deliver to the treatment room a considerably larger fraction of the total yield of negative pions from a cylindrical target than was previously possible.

Target and Yield Considerations

Because of the short mean free path of pions in nuclear matter, pion production tends to be a nuclear surface phenomenon, and the photoproduction cross section varies[3] as $A^{2/3}$ (A = atomic mass). However, the number of nuclei/unit length varies as ρA^{-1} (ρ = density); therefore, the pion production/unit target length varies as $\rho A^{-1/3}$. Two considerations place limitations on the length of the pion production target: (1) The optics of the transport system and/or the desirability of spatial resolution at the irradiated site places an upper limit, L, on the target length. (2) Little additional pion yield will be realized by making the target longer than one radiation length, λ, and the cooling problems will be considerably aggravated due to the buildup of the electromagnetic shower. Thus, the length of the target should either be L, or the length corresponding to one radiation length, $\lambda\rho^{-1}$. In mathematical formulation, a useful figure of merit, M, for target materials is

$$M = \rho A^{-1/3} L \qquad \text{for } \lambda/\rho \geq L,$$

$$M = \lambda A^{-1/3} \qquad \text{for } \lambda/\rho < L.$$

A target with L = 2.5 cm is reasonable, and the figures of merit for several possible materials are given in Table I. For this geometry, Ti is a good choice of target material, and a preliminary study indicates that the heat transfer requirements of a 1 to 2 cm diameter × 2.5 cm long Ti cylindrical target can be met using conventional water cooling techniques. It is worthwhile to note that pion and positron production targets have been used at the Saclay linac[4] with beam currents up to 300 μA.

Photopion yields have been measured by Colin, et al.[5] at Saclay and by Boyd[6] at Stanford. In particular, Boyd has measured the photopion yield for 500 MeV electrons for a 1 cm diameter × 2.54 cm long cylinder of Ti [Figure 1(a)]; and in what follows, it will be assumed that such a target will be the pion source.

TABLE I

Comparison of Materials for a Pion Production Target*

Material	A	Atomic Number	ρ (g/cm^3)	λ (g/cm^2)	M
C (Graphite)	12	6	1.9-2.3	44.6	~2.2
Al	27	13	2.70	24.5	2.25
Ti	47.9	22	4.54	16.3	3.13
Fe	55.8	26	7.8	14.1	3.68
Co	58.9	27	8.90	13.7	3.52
Ni	58.7	28	8.90	13.2	3.40
Cu	63.5	29	8.96	13.1	3.28
Mo	95.9	42	10.22	9.8	2.15
Ta	180.9	73	16.65	7.0	1.24
W	183.8	74	19.3	7.0	1.22
Bi	209.0	83	9.75	6.5	1.09

* All symbols in headings are defined in text.

For efficiency purposes, the pion transport system should have a very large solid angle acceptance, a momentum range of several percent, and a flight path as short as possible to reduce the loss of pions due to decay in flight. The following discussion assumes that the negative pions are carried from the target to the irradiation site by the Stanford carrousel transport system[7] which appears to fulfill all of the above requirements satisfactorily with a solid angle acceptance of 1 steradian, a total flight path of 6 meters, and a triangular distribution of momentum acceptance up to a maximum of ±6.3%. The negative pion flux available at the irradiation site as a function of pion energy for incident electron energies of 400, 500 and 600 MeV, is shown plotted in Figure 1(a).

Negative pion depth-dose calculations performed at Oak Ridge[8,9] and Stanford[10] indicate that the peak absorbed dose toward the end of the pion range is approximately 2.5×10^{-7} rad-cm^2 per incident pion. (This is more than a factor of four higher than the entrance dose.) Delivering a dose of 300 rads in 10 minutes to a volume 10 cm × 10 cm × 10 cm thus requires 6.5×10^7 pions/second per percent of pion momenta per steradian.

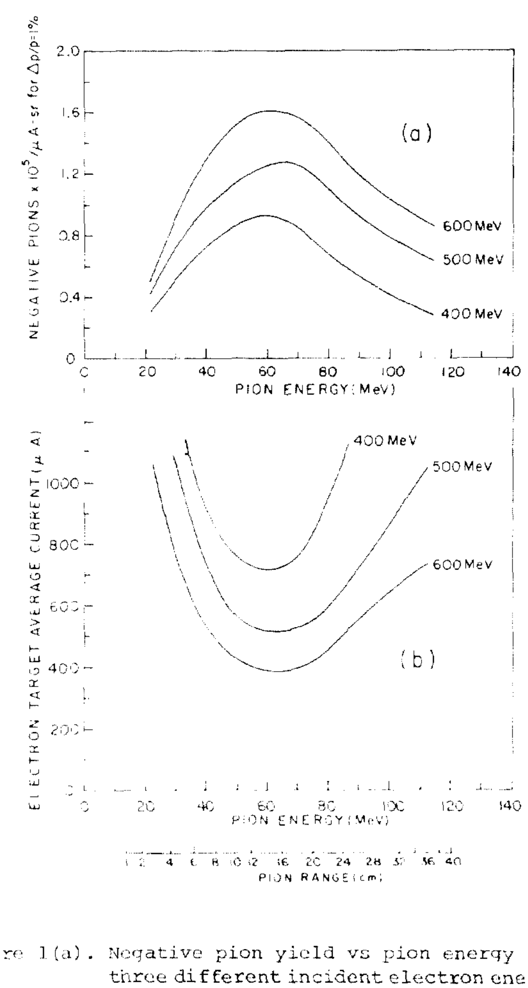

Figure 1(a). Negative pion yield vs pion energy for three different incident electron energies at the end of a 6-meter flight path. These data were taken from Ref. 6.

(b). Incident electron beam current required to deliver a negative pion dose of 300 rad in 10 minutes to a 10 cm × 10 cm × 10 cm volume vs pion energy and range.

One can now combine the above considerations to arrive at the electron beam current and energy necessary to produce the required pion flux. The results are shown in Figure 1(b) where the beam current required to produce 30 rads/minute in the 10 cm × 10 cm × 10 cm volume is plotted against pion energy and range for the three incident electron energies shown in Figure 1(a). The data indicates that a 500 MeV electron linear accelerator producing a target current of 660 μA (330 kW) would meet the above dose rate requirements over a wide range of tumor depths. In fact, for π^- meson ranges extending from 10 to 20 cm depths, there is a reserve capacity of approximately 25%. This is an important practical advantage because of the more complex treatment geometries which are encountered in clinical applications, and because of the desire to maintain treatment capability even if 1 or 2 klystrons become inoperative.

Choice of Machine Parameters

As in the case of previously constructed multi-section electron linear accelerators, a final choice of design parameters is influenced, not only by the required beam energy and current, but also by the availability of suitable high power RF tubes, the desired operational stability and system reliability, the economics of operation, and the probability of encountering current limitations due to beam breakup. (This latter aspect is of prime importance and is discussed in a concluding section of this paper.) The excellent operational history of large multi-section high power electron linear accelerators such as the Stanford Mark III,[11] Karkov,[12] Orsay,[13] Frascati[14] and SLAC[15] machines - and, more recently, the high duty factor Saclay[16] and MIT[17] accelerators - has thoroughly established the practical feasibility of operating such systems with a high degree of reliability. Furthermore, because of the programs originally associated with these large machines, a wide variety of reliable high power RF components have been developed, which are directly applicable to the machine designs presented in this paper. Of particular relevance are the commercially available high power L-band (1300 MHz) and S-band (2856 MHz) klystrons which present sound technical and economic arguments upon which to base the design of a radiotherapeutically acceptable meson producing electron linear accelerator (e.g., SLAC and industrial accelerator operational histories have shown that today's cost of replacement of 20 MW S-band klystrons is approximately \$2.50 per hour of operation compared with 1965 estimates of approximately \$5.00 per hour).

In comparing existing multi-section electron linear accelerators, as used for nuclear physics high energy experiments, with those required for meson therapy, a beam energy of 500 MeV is a comparatively modest figure, but, the desired 660 μA of average target current represents an order of magnitude increase. There are two conventional methods of achieving target currents of this magnitude with present day technology.

One technique is to make use of a high duty factor accelerator which can provide 660 μA of target current at, say, 2½% duty with a peak current of only 26.4 mA. Because machines of this type are comparatively long (approximately 200 m) and require special klystrons, transmitters, and water cooling systems, we considered this high duty approach to be unsuitable for hospital installations.

An alternate technique makes use of conventional duty factor systems which require accelerated peak currents of between 400 and 880 mA, depending on choice of RF transmitter and klystron, to achieve an average target current of 660 μA. Electron linear accelerator systems of this type, making use of existing technology and components which operate at L and S-band frequencies are compared in the discussion which follows. The well-proven $2\pi/3$ mode traveling wave structure has been selected for this comparison, and the system analyses have been based on conservative designs which take into account practical aspects such as RF transmission losses, video pulse rise and fall times, guide fill time, etc. The L-band waveguide performances are based on a peak RF input power of 22 MW and a beam duty factor of 1.65×10^{-3}, i.e., 660 μA average and 400 mA peak current. The S-band waveguide designs are based on a beam duty factor of 0.75×10^{-3}, i.e., 660 μA average and 880 mA peak current, and a peak RF input power of 26 MW (ITT tube type 8840).

The influence which the choice of accelerator waveguide attenuation parameter (τ) has on the total length of the machine, and the required number of sections (one klystron per section) for L and S-band systems are shown in Figure 2 — the data being based on single section, single klystron injectors having loaded energies of 20 MeV and 10 MeV for the L and S-band accelerators, respectively. The curves show how trade-offs can be made between the length of the accelerator and the number of required klystrons to achieve 500 MeV at the rated current. Additional information related directly to the operational aspects of the various system designs, such as conversion efficiency, and phase stability, are shown listed in Table II.

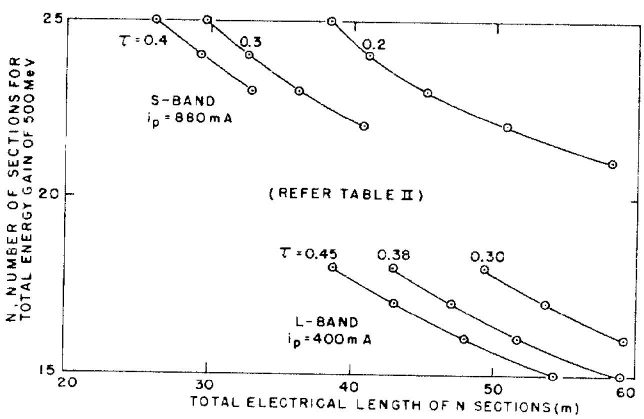

Figure 2. Influence of Waveguide Attenuation Parameter (τ) on Length of Accelerator for S-Band Designs Based on 10 MeV Injection and L-Band Designs Based on 20 MeV Injection (i.e., Total Energy = 500 MeV for All Cases).

TABLE II

[illegible]

L-Band Designs Based on 20 MeV Injection

[illegible]

Attenuation Parameter	Length of Section	Number of Sections	Energy Gain per Section (MeV)	Total Electrical Length	[illegible]	[illegible] Efficiency	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

S-Band Designs Based on 10 MeV Injection

[illegible]

[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

The tabulated values of attenuation parameter have been selected from prior experience to cover a range of practical designs consistent with the required degree of beam loading at 500 MeV. These data indicate that a suitable L-band linear accelerator would have an overall length of approximately 60 meters (including the 20 MeV injector) and would require 16 or 17 klystrons depending on final choice of section length.

At S-band, the linear accelerator would have an overall length of 45 m (including the 10 MeV injector) and would require 23 or 24 klystrons depending on final choice of section length.

The RF transmission system for both machines would be of the simplest form, since the use of single section modules allows the use of short direct runs of rectangular waveguide and avoids the need for high power RF phase shifters, power dividers, or phase compensated networks.

It should be noted that, since this application does not require a narrow energy spectrum electron beam, and because the waveguide phase stability parameters are low (less than 3/4° per kHz at L-band and less than 1/4° per kHz at S-band), the construction of the transmitter, driver and temperature control system is simplified and, therefore, less costly than similar multi-section linear accelerators used for nuclear physics research.

Although the number and type of accelerator sections can be readily determined by simple analysis, as indicated in Table II, this information, as it stands, merely results in a "paper" design which would certainly lead to failure due to the phenomenon of beam breakup (BBU).[18,19]

Results of Beam Breakup Investigations

Because the avoidance of BBU is the single most difficult design task associated with multi-section, high current linear accelerators, a comprehensive system analysis of the beam interaction with the BBU producing HEM_{11} modes is an essential prerequisite in determining the final centerline configuration and the actual manufacturing dimensions of the different accelerator structures.

A detailed description of recently developed microwave design techniques which have successfully avoided BBU in long, multi-section linear accelerators without the use of focusing elements has been presented elsewhere.[20] These techniques are based on minimizing the buildup of the HEM_{11} fields by (a) reducing the BBU mode transverse shunt impedance within individual accelerator sections, and (b) avoiding BBU signal coherency along the full trajectory of the beam. The former is controlled by suitable selection of waveguide iris dimension, number of cells within each uniform element of a particular section, type of RF transition between uniform elements, and the degree of coupling of the backward propagating HEM_{11} wave to the input rectangular waveguide; and the latter is achieved by using different waveguide designs which introduce higher order mode stop bands at specific locations along the centerline of the machine.

The present BBU studies included a variety of L and S-band beam centerline configurations, and suitable final designs were established on the basis of limiting the transverse deflection amplification below the critical beam interception value, without the assistance of magnetic focusing elements. In the interests of conservatism, an initial beam modulation of 10^{-5} cm was assumed (this is 2 orders of magnitude greater than the SLAC value); and in the absence of focusing, the objective for an upper limit of the overall deflection amplification was established at between 10^4 and 10^5.

The results of the BBU investigations for 20 MeV injection into a 16 section L-band machine, and 10 MeV injection into a 23 section S-band machine are shown in Figures 3 and 4, respectively. The shunt impedances, Q's and resonances used in the computations were based on data obtained empirically at L-band[21] and S-band;[20] and the presentation of transverse deflection amplification data is similar to that published in previous reports.[22,23]

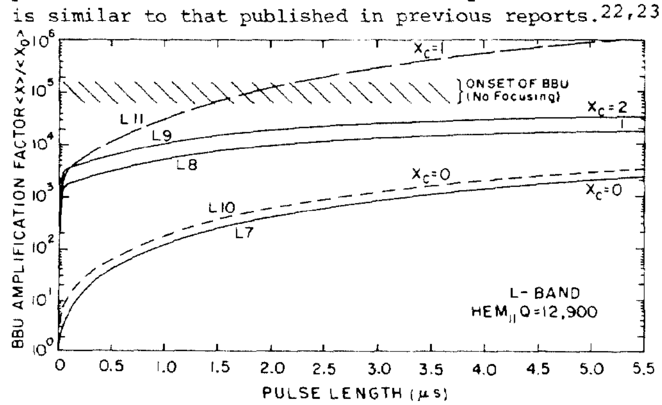

Figure 3. L-Band Comparison of BBU Amplification at 400 mA for Different Centerline Configurations and HEM_{11} Resonances, and Section Misalignments (X_c mm). 20 MeV Injection into 16 Sections (42 cells per section).

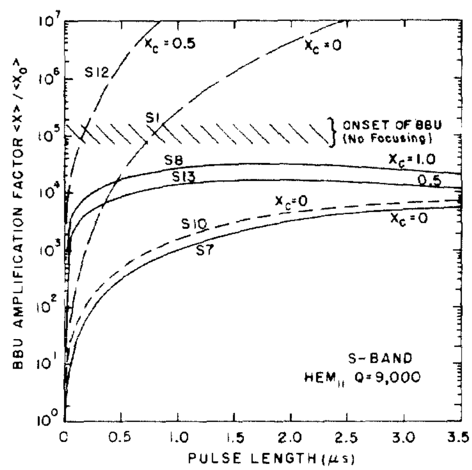

Figure 4. S-Band Comparison of BBU Amplification at 880 mA for Different Centerline Configurations and HEM_{11} Resonances, and Section Misalignments (X_c mm). 10 MeV Injection into 23 sections (50 cells per section).

Curves L11 of Figure 3 and S1 and S12 of Figure 4 show the unacceptably large amplification factors ($\langle x\rangle/\langle x_0\rangle$) which result for L and S-band accelerators, respectively, when the centerline is comprised of identical waveguide sections. Waveguide section misalignments (X_c) of zero and 0.5 mm were assumed for curves S1 and S12, respectively, and 1 mm for curve L11.

Data for an L and an S-band beam centerline configuration, comprising different waveguide designs, are also presented in Figures 3 and 4 respectively. L-band curves L7, L8 and L9 of Figure 3, and S-band curves S7, S8 and S13 of Figure 4, indicate the degree of reduction in deflection amplification that can be achieved when the beam centerline comprises a specifically grouped set of different waveguide designs with section misalignments as indicated by the X_c values. These computations took into consideration the dominant HEM_{11} resonance and the transverse shunt impedance (corrected for transit time) for each waveguide section along the beam centerline. Graphs L10 and S10 were obtained from multiple resonance computations which took into account the transverse shunt impedances and BBU resonances for individual uniform elements within each waveguide section along the centerline.

Graphs L11, S1 and S12, representing accelerator designs which use a plurality of identical sections, indicate that such accelerators would experience cumulative beam breakup at quite short pulse lengths, or at peak currents well below the desired level. The lower value $\langle x\rangle/\langle x_0\rangle$ graphs show that these BBU transverse deflection amplifications can be reduced by several orders of magnitude and that, even for the relatively high levels of current under consideration, the technique of grouping specific design waveguides at different locations along the beam centerline can be applied successfully to 500 MeV L and S-band accelerators having overall lengths of 60 or 45 m, respectively.

It should also be noted that results of BBU studies which take into consideration the presence of beam centerline focusing elements indicate further reductions of $\langle x\rangle/\langle x_0\rangle$ can be expected (e.g., for 1000 gauss solenoids or strong focusing elements, the reduction factors are approximately 3 and 12, respectively).

Conclusions

Our investigations have confirmed that, with presently available technology, both L and S-band, conventional duty factor, electron linear accelerators can be designed and constructed to operate successfully at beam intensities which are more than adequate to meet the needs of π^- meson radiotherapy applications.

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