SLAC-PUB-1914
March 1977
(A)

ELECTRON LINAC DESIGN FOR PION RADIOTHERAPY*

G. A. Loew, K. L. Brown, R. H. Miller and D. R. Walz
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305

D. A. Pistenma†
Stanford University Medical Center, Department of Radiology
Division of Radiation Therapy, Stanford University, Stanford, California 94305

Summary

The electron linac provides a straightforward, state-of-the-art method of producing the primary beam required for a hospital-based multiport pion radiotherapy facility for cancer treatment. The accelerator and associated beam transport system described in this paper are capable of generating an electron beam of about 250 kW and delivering it alternately to one of several pion generators and treatment areas. Each pion generator, a prototype of which now exists at the Stanford W. W. Hansen Laboratory, would contain a target for the electron beam and sixty separate superconducting magnet channels which focus the pions in the patient. The considerations which enter the design of a practical linac are presented together with a possible layout of a flexible beam transport system.

Introduction

The electron linac design work described in this paper summarizes and updates SLAC's contribution to a proposal submitted in early 1976 by the Stanford University Department of Radiology to the National Cancer Institute to build a hospital-based multiport pion radiotherapy installation for cancer treatment. Following extensive review, authorization of the project was deferred for at least two years but funds were granted to the Stanford Radiology Department for the interim period to pursue its studies of the radiobiological effectiveness of negative pions. Indeed, there continues to be considerable interest in irradiation with pions and charged heavy particles because of the improved dose distribution achievable with these particles as compared to X-rays and neutrons, and the relative confinement of their increased radiobiological effectiveness (RBE) and oxygen enhancement ratio (OER) to the designated treatment volume. The history of involvement[1] in the field at Stanford goes back several years. A cylindrical geometry, one-steradian solid angle acceptance superconducting pion channel (SMPG, for Stanford Medical Pion Generator) designed specifically for a hospital-based therapy facility has been constructed and has undergone preliminary testing (see figure of combined SMPG and beam transport at the end of this paper). In order to achieve the desired pion dose rate of 30 rad/min in a 1000 cc volume, it is necessary to bombard the primary target of such an SMPG with 12 kW of ~600 MeV protons or 300 kW of ~600 MeV electrons. At first glance this power ratio would seem to favor strongly the proton machines. A committee under J. P. Blewett met in the summer of 1975 to examine the relative merits and costs of proton synchrotrons, proton linacs and electron linacs to perform this task. The committee concluded (a) that the proton synchrotron should be dropped from consideration because of complexity, cost and marginal performance for this application, (b) that the proton linac may in the long run be the best candidate if a number of technical and cost problems can be overcome, and (c) that the electron linac was at the time the simplest, cheapest, state-of-the-art candidate. There is ample experience with design, operation and maintenance of this type of accelerator in universities, hospitals and industry.[2] Its relative disadvantages, i.e., higher power consumption and broader energy spectrum are manageable.

While these conclusions were subject to change with time and new developments, they are still felt to be valid today. The SLAC linac design work which was done in response to the Radiology Department's request has been kept up-to-date and might serve as a useful foundation if a pion radiotherapy facility were to be authorized in the future.

*Supported by the Energy Research and Development Admin.
†Presently at Varian Associates, Palo Alto, Calif. 94306.

Design Parameters

The starting point to determine the main parameters of the electron linac is the pion yield vs. incident electron energy obtained from measurements on a titanium target with the Stanford Mark III linac.[3] These yield measurements were made at only three points, namely 400, 500 and 600 MeV and were found to lie on a straight line given by:

$$N_{\pi^-}/\mathrm{mA/sr}/1\%\Delta p/p = 4.125\times10^{5}\,(V_{\mathrm{MeV}}-200) \qquad (1)$$

Tentative calculations made to check these yields and extend them to higher energies differ from the straight line given by (1) in that the yields seem to increase less than linearly above 500 MeV. However, they are based solely on single-pion and not on double-pion photoproduction which should not be neglected and might extend the straight line yield up to 800-1000 MeV. The accelerator design curves given below are based on the straight line approximation. A minor change in the computer program can accommodate any other curve. An experiment and calculations to be done in the future should put the yield question on solid ground.

To obtain the desired dose of 30 rad/min, it has been determined that 7.42×10^{7} $\pi^-/\mathrm{sr}/1\%\ \Delta p/p$ must be generated by the target. From this, one can derive a relationship between the necessary electron energy and current:

$$V_{\mathrm{MeV}}-200 = \frac{0.18}{i_{A,pk}D_b} \qquad (2)$$

where $i_{A,pk}$ is the peak current in amperes and D_b is the beam duty cycle. The energy of a multisection constant-gradient linac is given by[4]

$$V = n(1-e^{-2\tau})^{\frac{1}{2}}(P r \ell)^{\frac{1}{2}} - \frac{i_{pk} r \ell n}{2}\left(1-\frac{2e^{-2\tau}}{1-e^{-2\tau}}\right) \qquad (3)$$

where P is the peak RF power into a section of length ℓ, attenuation τ and shunt impedance r, n is the number of sections, and i_{pk} is the peak current. Combining Eqs. (2) and (3), we get expression (4)

$$n(1-e^{-2\tau})^{\frac{1}{2}}(P r \ell)^{\frac{1}{2}} - 200 - \frac{n i_{pk} r \ell}{2}\left(1-\frac{2\tau e^{-2\tau}}{1-e^{-2\tau}}\right) = \frac{0.18}{D_b i_{pk}} \qquad (4)$$

which together with the expression for RF-to-beam power conversion efficiency

$$\eta = \frac{i_{pk} V D_b}{n P D_{RF}} \qquad (5)$$

where D_{RF} is the RF duty cycle; is programmed and used to optimize any practical design.

Choices for accelerator design may be somewhat subjective but must consider criteria such as availability of reliable, reasonably priced klystrons, minimization of total accelerator length and RF power, practical RF pulse length, minimization of risk of beam breakup and overall economy. The klystrons that were investigated included two 2856 MHz tubes (SLAC-RCA-ITT, 30-36 MW pk, $D_{RF}=0.001$ and Varian VA-938, 4 MW pk, $D_{RF}=0.025$) and two 1300 MHz tubes (Litton L-5881, 30 MW pk, $D_{RF}=0.0025$ and Litton L-3661, 20 MW pk, $D_{RF}=0.0015$). Using these specifications, a large number of curves such as those shown in Figs. 1a and b were obtained and explored. Accelerator section lengths of 2, 3, 4 and 7 m were considered for various cases. The attenuation per section τ and the number of sections n were used as parameters. The value of shunt impedance, of the order of 50 MΩ/m for S-band and

(Contributed to the 1977 Particle Accelerator Conference, Chicago, Illinois, March 16 - 18, 1977)

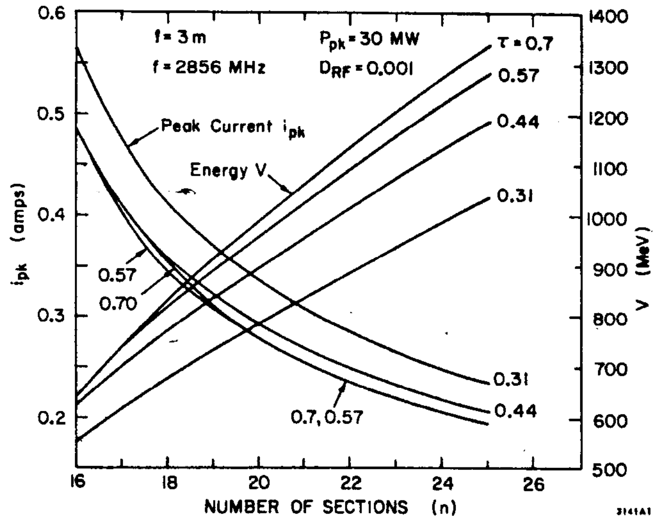

Fig. 1a. Energy V(MeV) and corresponding peak current i_{pk} (A) vs. number of sections n for accelerator capable of producing desired electron beam for pion generation.

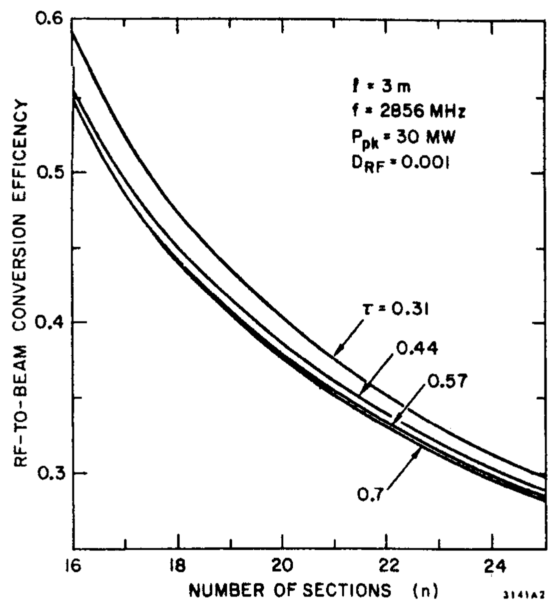

Fig. 1b. RF-to-beam conversion efficiency vs. number of sections n.

35 MΩ/m for L-band, varies slowly with τ and was adjusted accordingly. The following conclusions were drawn:

(1) The choice of L-band has the usual advantages of higher energy storage and reduced energy sensitivity to current changes, lower number of klystrons, as well as reduced risk of beam breakup because the HEM_{11}-mode gain parameter contains the term r/Q which scales directly with frequency. However, these advantages are seriously offset by the reduction in accelerating-mode shunt impedance which varies as $f^{1/2}$, which results in higher requirements in overall RF power and/or length. Also, the cost of L-band klystrons for a given duty-cycle is considerably higher. These criteria make the choice of S-band preferable.

(2) The choice of a long duty-cycle S-band accelerator similar to the MIT Bates machine (with 7.35 m sections) would have the advantage of a lower number of klystrons; however this would be offset by higher total average power, greater length, higher risk of beam breakup and higher costs for switch tubes and klystrons.

(3) Assuming SLAC-RCA-ITT klystrons and 3-meter long sections of the SLAC $2\pi/3$ constant-gradient type, one obtains the design curves shown in Figs. 1a and b. In these curves, the lowest number of sections n which is shown on the left is that below which Eq. (4) has no solution, i.e., the desired pion yield cannot be attained. With the available klystron RF duty cycle of 0.001, a repetition rate of 180 pulses per second, each 5.55 μs long, was chosen. This pulse length has been shown to be practically attainable with ordinary thyratrons, pulse transformers and PFN's. Since the accelerator will be operated between 15 and 25% beam loading, it was assumed that the beam pulse could be no longer than $(5.55-t_f)$ μs where $t_f = (2Q/\omega)\tau$. The resulting beam duty cycle is of the form $D_b = 180 \times 10^{-6}\,(5.55-1.456\,\tau)$ which is used in Eqs. (4) and (5).

(4) The choice of attenuation per section τ is influenced by conflicting criteria. Higher values of τ give higher energy and lower beam current which is more desirable from the beam breakup point of view. Lower values of τ give lower energy and higher current, decreased sensitivity to frequency changes and beam loading and shorter filling time. If one is trying to keep down the number of klystrons and sections to minimize cost and limit the peak current to, say 400 mA, then a choice of $\tau = 0.57$ and n = 18 sections seems appropriate. If cost limitations are not as stringent, then conservatism would dictate a choice of n = 20 sections with values of τ of 0.44 or 0.31. In this case, one of the klystrons and associated section could always be kept in reserve for substitution in case another one fails. Table I gives three alternate designs which take into account these diverse assumptions. Design (A) would make use of ready-made SLAC sections and would be the cheapest. Designs (B) and (C) would require some structure re-design which, given enough time, should not present any major difficulty.

(5) The question of beam breakup which is of considerable importance was considered, both theoretically and experimentally. In the absence of focusing and HEM_{11}-mode detuning, R. Helm calculated that beam breakup in such a machine would appear at currents between 400 and 500 mA. A measurement made on the first 18 sections of the SLAC accelerator with weak focusing and one-half the proposed energy gradient gave a threshold of ~400 mA for a 1.8 μs pulse, which is in good agreement. Fortunately, such thresholds can easily be doubled by using a combination of focusing and HEM_{11}-frequency detuning. The focusing system proposed would consist of quadrupole doublets every two sections with a betatron phase shift of $\pi/2$ over that length. The effect of HEM_{11} detuning was calculated for several cases with, e.g., the first and second sections both detuned by

Table I : Parameters for three possible electron linac designs for pion radiotherapy.

	A	B	C
Loaded electron energy V (MeV)	820	790	735
No-load electron energy V_o (MeV)	1065	935	900
Beam loading energy V_b (MeV)	245	145	165
ΔV/Δi (MeV/mA)	0.70	0.43	0.43
Peak electron current i_{pk} (mA)	350	335	380
Average beam power P(kW)	244	243	246
RF-to-beam conversion efficiency (%)	44	41	41
Repetition rate (pps)	180	180	180
Attenuation parameter τ (nepers)	0.57	0.31	0.44
Filling time t_f (μs)	0.82	0.45	0.64
RF pulse length t_{RF} (μs)	5.55	5.55	5.55
Beam pulse length t_b (μs)	4.72	5.10	4.90
Klystron power at accelerator P_{pk} (MW)	30	30	30
Frequency f (MHz)	2856	2856	2856
Shunt impedance r (MΩ/m)	57	52.2	57.8
Average group velocity v_g/c	0.0135	0.0247	0.0115
Section length ℓ (m)	3	3	2
Number of klystrons, modulators and accelerator sections including injector	18	20	20
Number of instrumentation drift sections	8	10	10
Length of instrumentation drift sections (m)	1.5	1.5	1.5
Number of quadrupole doublets	8	10	10
Total approximate length (m)	75	85	65

2 MHZ, or by 2 and 4 MHz respectively. Other more drastic schemes extended over more sections could easily be obtained. One simple technique would be to divide the 18 or 20 sections into 4 or 5 groups and build each group with a slightly different input group velocity, thereby staggering the resonant frequency of the first 5 or 6 cavities.

Beam Transport System and Target

Figure 2 shows a plan view of a possible beam transport system leading to an array of SMPG's. Also given is a cross section of a typical SMPG as mentioned earlier. The accelerator emittance is assumed to be $\epsilon = 0.5\pi$ mm-mr. The acceptable momentum spread of the electron beam at the target is $\Delta p/p = \pm 1\%$ and the acceptable spot size diameter at the target is ≤ 6 mm. The transport system consists of two parts. The first is a standard symmetric, achromatic system with two bends (arbitrarily set at 45°). The second consists of an achromatic switching system (not shown) feeding into a zero-dispersion vertically-deflecting bending magnet system B5X/B6X. This allows the beam to be independently delivered to one of four treatment facilities or to be tuned up in the straight-ahead tune-up area. The split-level arrangement also separates the accelerator and transport system from the patient treatment area and thus increases safety.

The pions are produced nearly isotropically in a stationary low-Z target. The residual electron beam is dissipated in a water-cooled beam dump. The target is designed to handle the full electron beam power. The photoproduction of pions per unit length varies as $\rho A^{-1/3}$, where ρ is the density and A is the atomic weight. It shows that materials such as titanium or iron are most suitable for pion production. The present investigation limits itself to a titanium target with a diameter of 10 mm and a length of 25 mm ($\approx$3/4 r.l.). For the assumed beam parameters, the power deposited in the target is ~7 kW. For a repetition rate of 180 pps, the energy deposited per pulse in the target is 40 joules. Neglecting radial beam spread and assuming a maximum allowable beam spot size of 6 mm, the temperature rise per pulse in the heated volume can be shown to be 24°C. The resulting thermal stress rise in a fully restrained body would be 220 kg/cm^2 (3120 psi). The total surface area of the target is ~9.5 cm^2. For assumed uniform power deposition, the heat flux off the surface to be cooled is ~3/4 kW/cm^2. For a small target this heat flux can be handled by boiling heat transfer to water with high subcooling. The flow channel should be ~6 mm wide. A flow rate of 0.25 1/s results in a velocity of ~1 m/s and a bulk water temperature rise of $\approx$7°C. Such a target is feasible but may not be optimum. The pion yield could probably be increased if the target were a composite of a high-Z (i.e., Au, Ta, W-Re) preradiator followed by a low-Z (Be, Al) main target.

References

1. H.S. Kaplan, H.A. Schwettman, W.M. Fairbank, D. Boyd, M.A. Bagshaw, Radiology 108, 159-172 (1973).
2. J. Haimson, B. Mecklenburg, C. Williamson, IEEE Trans. Nucl. Sci. NS-22, No. 3, 1805 (June 1975).
3. D. Boyd, P. Fessenden, G. Luxton, private communications.
4. R.B. Neal, ed., The Stanford Two-Mile Accelerator (W.A. Benjamin, New York/Amsterdam, 1968).

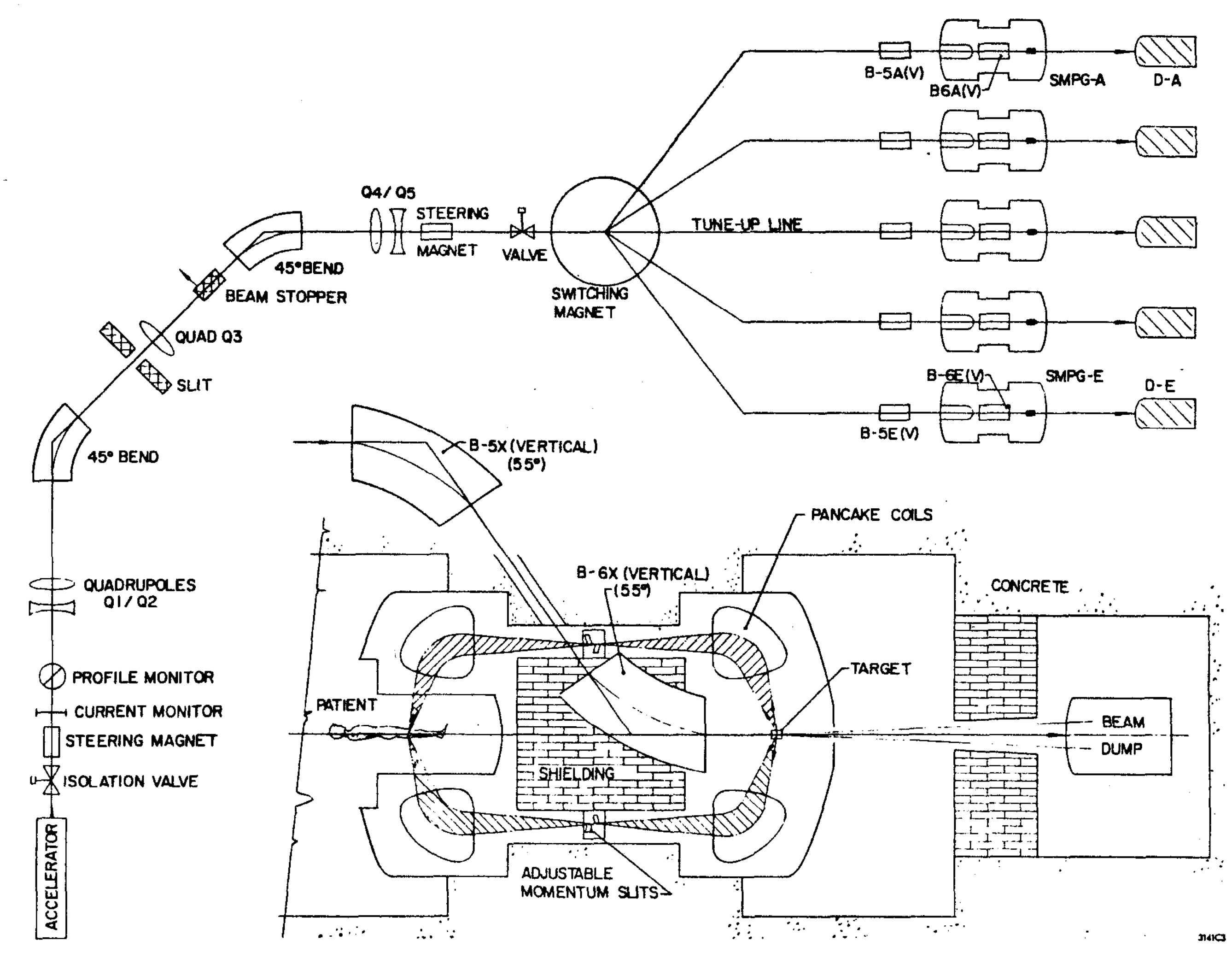

Fig. 2. Plan view of a possible beam transport system leading to an array of SMPG's and vertical cross section of a typical SMPG.