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Medical Linac Design Possibilities

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ABSTRACT

During the last five years a dramatic expansion of the uses of accelerator-generated radiations in medicine has become possible. The application of resonant standing wave accelerator technology to conventional medical linac systems has brought them within the reach of hundreds of cancer treatment centers throughout the country. In addition the construction of meson factories will allow the use of secondary particle beams for cancer therapy. A brief discussion of the LAMPF linear accelerator is provided, including the properties of the side coupled accelerator system. Some design criteria for possible dedicated meson producing accelerator systems for hospital use are described.

I. Introduction

Medical science has benefited greatly over the last 80 years from accelerator produced radiations. Soon after the discovery of x rays in 1895 pictures of human skeletal structure were obtained. Therapy of various diseases with x rays and other radiations has also been practiced throughout most of this century. However, it is only recently that the radiation therapy of cancer has become a highly successful medical specialty with impressive cure rates documented for several previously fatal diseases. This success has occurred for a variety of reasons including: the availability of increased x-ray energies for treating deep seated diseased regions, the ability to precisely delineate the treated volume, the development of sophisticated treatment planning, and the accumulation of experience concerning the response of tumors to the high energy radiation delivered.

Recently a family of small linear accelerators for electrons based on the side-coupled cavity principle[1] developed at the Los Alamos Scientific Laboratory has become available commercially from several U.S. and foreign manufacturers.[2] These commercial units are in general extremely reliable, simple to use, and inexpensive. At the present time several of these manufacturers are developing new units, based on the same accelerator principle, which will achieve electron energies of 15-25 MeV, extending conventional radiation therapy again in terms of capability of precisely controlled radiation delivery to diseased tissue. Several hundred accelerators of these types exist in the world today, and their number is growing every month.

The success of conventional x-ray radiation has naturally led to the consideration of several other radiation types for cancer therapy. Other radiations

*Work done under the auspices of the U. S. Atomic Energy Commission.

have specific properties which might make them extremely effective in cancer therapy applications. The most accessible of these new radiations is the fast neutron beam achievable from cyclotrons, D-T generators, or perhaps from deuteron linear accelerators. Neutrons interest therapy physicians for the reason that the damage produced in tissue is of a more catastrophic type than that achieved by x-ray irradiation, resulting in less cell recovery from damage. Unfortunately, the neutron beam is not easily localized in the region of the disease as it is extremely difficult to collimate and the radiation falls off rapidly with depth. Several clinical trials with neutrons are underway at present both in the U.S. and abroad.[3]

Protons have been considered for therapy applications, and in fact trials of protons for therapy have been underway in the USSR for several years.[4] Recently proton therapy studies have been started in the United States.[5] Protons do not provide the degree of lethal damage that neutrons provide, but do provide a vastly superior localizability of effect. A proton beam can be tailored to irradiate a precisely defined volume with borders only a fraction of a cm wide.

Heavy ions provide a more localizable beam than x rays and also have a more damaging impact on cells than to x rays or protons. They are being developed for therapy applications at Berkeley, California[6] and hold a great deal of promise for the future.

Finally, an unstable particle, the pi-meson, or pion, is being used in preliminary studies at the Los Alamos Scientific Laboratory.[7] These particles are highly localizable, do heavy cellular damage in the region where they stop, and produce little damage to living tissue on their traversal of the body to the tumor site. In many ways they are an ideal radiation for cancer therapy, if they can be produced and delivered cheaply enough for widespread use.

The subject of the remainder of this paper is the production of the above radiations by linear ion accelerators at a reasonable cost and with a machine size compatible with the cancer centers in the United States today. Table I provides a summary of the accelerator requirements needed to meet normal therapeutic beam intensities for the neutron, proton, and pion therapy applications. Heavy ion production at present does not look attractive in terms of linear accelerator technology.

TABLE I

Therapy Beams

Therapy Beam	Primary Beam	Average Accelerated Current	Energy
neutron	deuteron	30 μA	50 MeV
proton	proton	1-10 μA$^{(1)}$	200 MeV
pion	proton	30-300 μA$^{(2)}$	500 MeV
pion	electron	1000-10,000 μA$^{(2)}$	500 MeV

(1) Depends upon desired radioisotope production capability.

(2) Depends on collection efficiency of magnetic channel.

The requirements that these accelerators must meet are significantly different from those met by the existing proton or light ion linacs in the world. In particular reasonable cost, compactness, reliability, and simplicity of operation must be emphasized. It seems likely that considerable advances can be realized with certain changes in design philosophy and design criteria based upon the new capabilities of proton linear accelerators that have been achieved during the last 5 years. These advances could lead to a practical family of new medical accelerators which could be built to provide the therapy, currently under experimental investigation, to cancer victims throughout the world.

II. Present Proton Linear Accelerator Technology

Within the last 5 years three major new proton linear accelerators have been completed[8,9,10] and a fourth project started.[11] Three of these machines are to be used as injectors for larger research machines. The Los Alamos Meson Physics Facility (LAMPF) accelerator is a research tool in itself. Some of the parameters of the completed accelerators are listed in Table II. While these parameters (some of which are common to all of the machines), may be suitable for the purpose for which these machines were designed, they are probably not optimum for medical applications. Some of the characteristics of the new accelerators are discussed below:

a) Operating Frequency

The initial drift tube part of all of the proton linacs built during the last few years operates at very near 200 MHz. This frequency is chosen partly as a result of historical precedent, partly by available radiofrequency equipment, and partly by the physics of particle acceleration. Historically, Luis Alvarez at the University of California at Berkeley built the first proton linear accelerator in 1948 using surplus radar transmitters developed during World War II. These transmitters were limited to an upper frequency of approximately 200 MHz - so the choice for the first machine was dictated by this consideration. Even today high power transmitter tubes are available at 200 MHz but not in the region between 200 MHz and about 400 MHz where klystrons are available. An excellent triode for this service at 200 MHz is available at the present time and has been used in the three new U.S. proton accelerators. Finally, the injector voltage used (750 keV) and the proton beam size available from these injectors imply a beam aperture which, when coupled with acceleration gap spacing, limits the maximum frequency to about 200 MHz in these linear accelerators.

b) Acceleration Gradient

All of the modern proton linacs are designed to accelerate protons at about 1.5 MeV/m. Several years ago studies at MURA[12] were done to establish the maximum gradient allowable in drift tube linac tanks, but unfortunately the results were inconclusive. A general criterion for resonant cavity breakdown potential was derived by Kilpatrick[13] but this also was before modern vacuum technology had been developed. In the existing accelerator tanks the most critical area is in the injection region; that is, breakdown usually occurs in the first tank which is difficult to condition to hold full fields.

c) Duty Cycle and Pulse Length

While the duty cycle of the four new proton linacs varies with the application, in all cases the pulse length is quite long, 200-500 μs. These pulse lengths are dictated by the operating frequency (200 MHz), service requirements (multi-turn injectors into synchrotrons or direct experimental applications with requirements for high duty factor), and available RF system capabilities. High duty factor capability is a major contributor to the cost of the proton linear accelerator at LAMPF.

d) Quadrupole Focusing System

All of the modern linacs use quadrupole magnet focusing with great success. These are electromagnets which are operated either pulsed or D.C. In the case of the modern linacs, the quadrupole system provides a radial restoring force to counterbalance the defocusing action of the accelerating electromagnetic field, and acts as a band-pass channel providing a wide latitude in permissible field parameters. Usually the magnets are arranged in a +-+- configuration, although older accelerators have utilized the +--++-- configuration successfully.

e) Radiofrequency Power System

All of the modern proton linear accelerators utilize triode final amplifiers in the power chain, using plate voltage modulation for power output control with phase control provided by low power electronic phase shifts on the input signal. These power systems are quite complex but have proven satisfactory in the modern linac.

f) High Energy Section

In the special case of the Los Alamos Meson Physics Facility linac the final energy is 800 MeV, achieved with drift tube linac acceleration to 100 MeV and acceleration with a new type of structure, the side coupled linac structure,[1] from 100 MeV to 800 MeV. The side coupled cavity structure is a long series of individual cavity resonators coupled to one another via small additional resonators located beside the main chain. The proton beam passes through the primary chain of cavities receiving energy gain in each one. The side cavities serve to couple radiofrequency energy from one individual cone-like cavity to the next in an extremely precise manner, allowing accurate control of the acceleration process to be exercised. In earlier accelerator designs the radiofrequency power and the proton beam placed competing requirements on the beam channel hole. Because the RF energy is now coupled outside this beam hole, the cavity shape can be chosen to provide extremely high efficiency in converting radiofrequency energy into proton particle energy. These properties of the side coupled accelerator structure have made the LAMPF proton accelerator possible and have also made this system extremely attractive for electron acceleration as used in conventional radiotherapy megavoltage sources.

The fabrication techniques used for this system were very innovative and used the inherent large frequency error tolerance of the structure to full advantage. A system of stepped temperature brazing was used in which as many as seven separate assembly operations were performed on the accelerator tanks. A simple klystron RF system was developed for this section which utilized this type of tube for the first time in high duty factor, long pulse accelerator service. This system has proven exceptionally reliable and manageable in actual operation.

III. Innovations in Linac Technology for Practical Medical Machines

It seems clear that to optimize the proton linac for medical use it must be made simpler to operate, more compact, and more reliable than existing machines. Several innovations in the design and fabrication of proton linacs appear possible when the average current is reduced substantially from the requirements of the LAMPF accelerator, and in addition there are no stringent duty factor requirements to meet. Several areas in which it seems possible to make major design changes which could lead to practical medical machines are discussed below.

TABLE II

Proton Linac Parameters

	NAL Injector	BNL Injector	LAMPF
Energy (MeV)	200	200.3	100
Injection energy (keV)	750	750	750
Injection emittance (mmm-mrad)	50	50	10
Peak accelerated current (mA)	100	110	16
Average accelerated current (mA)	0.2	0.4	1
Pulse length (μs)	200	400	500
Pulse rep. rate (pps)	10	10	120
Duty factor (%)	0.2	0.4	6
No. tanks	9	9	4
No. drift tubes	286	286	165
Stabilizing system	post coupled	multi-stem	post coupled
RF power (peak MW)	45	37	10
Accelerator length (m)	145	145	63
E. gradient (MeV/m)	1.4	1.4	1-1.9
Beam quality (mmm-mrad)	5	5	0.6
$\Delta E/E$ (%)	0.5		0.1
Max. quadrupole gradient (kg/cm)	10	6.9	8
Quadrupole power supply	pulsed	pulsed	D.C.
High Energy Section			
Energy (MeV)			800
Injection energy (MeV)			100
No. tanks			45
No. cells			∿ 5000
Accelerator gradient (MeV/m)			1.25
Peak RF power (MW)			∿ 45
Average RF power (MW)			2.5
Structure			side coupled tank
No. RF amplifiers			45
Length overall (m)			727

a) Increased Gradient

In order to make the medical accelerator more compact an increase in the energy gradient seems mandatory; such an increase seems possible from experience with existing electron accelerator structures. The energy gradients achieved in several accelerators are listed in Table III.

TABLE III

Energy Gradient in Several Linacs

Accelerator	Particle	Structure	Energy Gradient (MeV/m)
LAMPF	proton	post coupled drift tube	1.5
LAMPF	proton	side coupled	1.25
SLAC	electron	traveling wave	7.5*
VARIAN/SHM/ARCO Commercial linac	electron	side coupled	>12

*tested at > 10 MeV/m.

The technology which allows such high gradients to be achieved in the standing wave electron linac case involves (1) a high temperature baked system, (2) highly polished cavity surfaces, and (3) higher frequency operation. It is well known in electron linac waveguide production that baking out the residual gasses on the copper surfaces reduces the time for RF processing to high field levels dramatically. In the commercial linac tanks there are short capture section cavities which demonstrate that gap length is not a critical phenomena leading to the high gradients observed. It is likely that a baked cavity structure for both the post coupled drift tube linac and for the side coupled linac would allow operation up to 10 MeV/m in a linac for medical applications.

b) Higher Frequency Operation

If the operating frequency of the post coupled drift tube accelerator section could be doubled to 400 MHz, several rather significant improvements in fabrication techniques and performance could be achieved. First of all, a tank diameter of 40 cm rather than the 80 cm diameter required at 200 MHz immediately greatly simplifies the tank fabrication problem. Of course this brings a penalty - there are now twice as many drift tubes required - but this is not an insurmountable problem and will be addressed in the next section. A smaller tank section allows fabrication techniques compatible with high temperature bakeout which is necessary for the high gradient operation mentioned previously. The requirements of beam aperture and drift tube spacing imposed by the physics of the capture section of the linac probably require somewhat higher energy injection - perhaps greater than 2 MeV. An extensive series of calculations on this problem must be performed. It appears that by using a combination of higher injection energy and beam emittance tailoring the drift tube aperture and spacing restrictions can be satisfied.

c) Permanent Magnet Focusing

A major cost item in the fabrication of the new proton linacs are the quadrupole electromagnets located within the drift tubes. In the case of the Los Alamos linac the set points used for these magnets are exactly those indicated by calculation, and it is clear that if a scheme of permanent magnet quadrupoles could be developed considerable cost reduction could be realized in the fabrication of each drift tube. These magnets either must be cooled or capable of withstanding a high temperature bakeout cycle. Several new materials have been recently developed which should meet the requirements of the majority of the magnets needed; perhaps only a few quadrupoles at the very beginning of the machine would require gradients high enough to demand operation as electromagnets. So with this innovation costs should remain reasonable even if the number of drift tubes is increased.

d) Coupling

Several years ago the RF structures group at Los Alamos proposed a scheme of accelerator tank coupling which might increase system reliability substantially.[14] In this system the entire side coupled linac for a high energy proton accelerator is coupled together with bridge couplers and then driven at several discrete points by high power RF amplifiers. This system could, if properly implemented, reduce the phase and amplitude sensitivity of the side coupled linac system markedly while perhaps removing the requirement of 100% RF system reliability for accelerator operation. This proposal is clearly speculative but certainly merits study.

e) Manufacturing Methods

The LAMPF accelerator was built using several innovative construction techniques which may point the way toward lower fabrication costs of a future medical linac. The step brazing techniques used may be applicable to manufacture of 400 MHz linac components. Certain forging and coining techniques seem appropriate for low cost fabrication of the side coupled linac system, but will require considerable development. In any case it seems possible to reduce structure costs substantially by careful engineering development.

f) Power Sources

Experience at LAMPF and elsewhere strongly indicates that the klystron power source is ideal for applications where several tank systems have to be phased together and operated under stringent amplitude control requirements. There are available at the present time high power 400 MHz klystron tubes capable of peak powers of 15 MW and average powers of 75 kW - i.e., a duty factor of 0.5%. This duty factor is adequate for medical applications and such an RF system would considerably simplify the accelerator for medical use.

IV. Example of a Medical Pion Linac

With the assumption that all of the developments described above are successfully implemented, a basic accelerator design may be outlined which illustrates the possible result of such innovations. A hypothetical linac designed for medical pion production could consist of a drift-tube accelerator followed by a side coupled cavity structure with a total length of about 80 m. Two sets of parameters for such a linac are listed in Table IV corresponding to average current capabilities of 30 μA and 100 μA. In either case a relatively large solid angle acceptance pion channel is required. For the 30 μA linac the collection and delivery system should provide an acceptance of about 1 sr. Such a system is currently being evaluated at Stanford University.[15] The higher current machine could utilize a more conventional channel. It is desirable, however, that the delivery system possess an efficiency which allows the proton current to be less than about 30 μA or significantly serious induced radioactivity problems will increase the expense of the facility substantially.

TABLE IV

Pion Producing Medical Linac

Energy (MeV)	500	500
Average current (μA)	30	100
Duty factor	0.005	0.005
Peak current (mA)	6.0	20
<u>Drift Tube Section</u>		
Injection energy (MeV)	2	2
No. tanks	3	3
Length (m)	40	40
RF power in tanks (MW)	35	35
RF power in beam (MW)	1.2	4
Total peak RF power (MW)	37	40
No. drift tubes	158	158
No. RF systems	3	3
Accelerator gradient (MeV/m)	5	5
<u>Side Coupled Section</u>		
Transition energy (MeV)	200	200
No. tanks	6	7
Length (m)	40	40
RF power in tanks (MW)	62	62
RF power in beam (MW)	1.8	6
Total RF power (MW)	65	67
Focusing	doublets along beam	
No. RF systems	6	7
Accelerator gradient (MeV/m)	7.5	7.5

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