

APPLICATIONS OF LINEAR ACCELERATORS

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SUMMARY

Recently the possible applications of linear accelerators have dramatically diversified with several new uses for linacs in applied physics and the commercial section being pursued very actively. This Conference deals with several linac applications explicitly both in papers and in this session and other sessions dealing exclusively with the individual applications. It is my belief that some of these applications will become extremely important in the near future. We are facing an era of expanded accelerator utilization, and the future is very exciting indeed.

INTRODUCTION

I would like to review with you some applications in which linear accelerators are used today, and some of the possibilities which these scientific tools have for the near future. By applications I mean use for other than basic science, for which most of the concepts for these machines were developed and where the leading edge of technological development still resides. A cursory look at the program for this Conference indicates the magnitude of the interest now developing for applications of linear accelerators. I will include both electron and ion linacs in this review. Electron linacs, being considerably simpler to build and operate, comprise the bulk of the accelerators available commercially in the world today. However, I believe that we are at the beginning of an era where ion linear accelerators will be applied to many non-research problems, and will also become readily available commercially.

I will break my presentation down into several subdisciplines of applications--viz.,

1. Medicine
2. Radiography
3. Nuclear Fuel Breeding
4. Radiation Damage Neutron Source
5. Heavy Ion Fusion
6. Other Possibilities

Each topic is certainly not covered exhaustively, but I do hope I can convey the aspects of the application and the unique features of linacs which lead to their application and success in the field.

1. Medicine

Electron linear accelerators have effectively monopolized the field of high energy x-ray beam production for cancer therapy in the last few years. More than 500 electron linacs, 4 MeV to 35 MeV, are in service in hospitals and clinics around the world, and have a record of

excellent trouble-free service providing optimum beams for radiotherapy of cancer. Slide #1 shows a typical accelerator system in use in a clinical setting--not looking much like a linac as most of us know the term, but still truly a linac inside. Typically, 4 MeV electron linacs of the standing wave, side-coupled variety, which are by far the most numerous systems in the field, can be operated by hospital personnel with no resident engineer to oversee the operation and with a typical down time of no more than 1 to 2 days per year. These are essentially one-button machines--e.g., on-off, and they really work well. For a typical 4 MeV machine, the microwave power source is a 2 MW S-band magnetron, and the accelerator guide is about 27 cm long to yield a 150 mA, 4 MeV, .0005 duty factor electron beam on an internal tungsten target. Higher electron energies are desirable and are being achieved in the newest units offered. Eighteen to twenty MeV units with 1.5 M. accelerator guides drive by ~5 MW power sources are available. The medical application of electron linacs is by far the biggest application of linear accelerators today. Linacs have displaced other accelerator types by considerations of reliability, beam quality, and cost.

A possible future application of ion linear accelerators in the medical area arises from the neutron, heavy ion, and pion therapy research programs underway at various centers around the country. It appears that these different radiations, or "modalities," as they are referred to in the medical jargon, may be more effective for certain cancer types than x-rays, and sources need to be developed for economically producing these radiations. The proton linac, in a rather modified form from that used in typical basic physics use, appears to hold a great deal of promise for this application. We, at Los Alamos, have a program, "PIGMI," funded by the National Cancer Institute, Division of Cancer Research Resources and Centers, Department of Health, Education, and Welfare, to investigate new directions in linac technology development which lead to the application of these machines to medical use. This program is just getting underway and some reports will be given later in this meeting on PIGMI. A low duty factor, low cost proton linac could find application in a number of areas if it is possible to develop such a machine.

For the medical program associated with pion therapy, the desire is to design a proton machine to feed pions into a collector system capable of irradiating deep seated tumors of up to 1 liter volume at a dose rate of > 50 rad/min. The problem of designing a pion collector to have optimal efficiency (energy spread and solid angle acceptance) is certainly nontrivial. In fact, it is almost as difficult as designing the accelerator system

itself. Several solutions appear feasible, however, and a high solid angle (0.5 sterad) large momentum ($\pm 6\% \Delta P/P$) pion collector is under test at Stanford University. Also, in the Soviet Union at JINR, Dubna, there is in use a solenoidal lens collection system for pions with large solid angle and momentum acceptance. While neither of these systems necessarily satisfied all of the clinical requirements for pion therapy in an optimum way, it appears that acceptance figures for these channels are reasonable for sizing an accelerator for pion therapy.

To satisfy the dose rate requirement for pion therapy, a ~ 650 MeV, 50-100 μ A proton beam is required. Duty factor is not important for medical applications and for economic reasons should probably be made as low as practical. Length is of major concern since the machine should be a part of a hospital complex where space is usually at a premium. Simplicity and reliability of operation are essential for the hospital application. The PIGMI (Pion Generator for Medical Irradiation) Program at LASL will be described in detail later in this Conference. The thrust of the program is to develop a low cost, compact pion generator by investigating various extensions of proton linac technology. Higher gradient operation, at higher R.F. frequencies, with baked surface conditioning will be investigated. Alternating phase focusing and low energy injection will be tried to reduce the cost of the low energy part of the drift tube linac. Various microwave manifold schemes are being considered to increase operation reliability. Permanent magnet focusing is being investigated, and, finally, new fabrication techniques leading to excellent vacuum and surface conditions will be used. Hopefully, a pion generator for medical application can be built for less than \$10M.

For neutron generation, it may be possible to utilize optimized proton linacs of the PIGMI type directly, at an energy of ~ 35 MeV. Figure 1 shows a possible proton linac-based neutron generator. A 35 MeV, 100 μ A proton beam incident on a thick Be target yields 100 rads/min @ 1.25 m target to skin distance. This is just about optimum for neutron radiotherapy applications. The competition for this service is a cyclotron system. I do not feel that it is yet clear what the costs of either system would be.

2. Radiography

The other well-established commercial use of linacs is in the field of industrial radiography. Several of the linac manufacturers make high energy radiographic machines to investigate thick sections of materials for flaws, weld cracks, etc. I estimate that there are 70 linac-based radiographic units in service around the United States at the present time. The requirement is for small spot size and high dose rate. Many of the newer models are adaptations of the high energy medical accelerators described previously.

3. Nuclear Fuel Breeding

The Chalk River Laboratory has for many years discussed the possibility of building a very high current, highly efficient linac system to use

as an intense neutron source for a variety of applications, including nuclear fuel production. The advent of the energy crises and the difficulties encountered in the design of the first liquid metal fast breeder reactor make this possible application of linear accelerators very interesting today. The idea is to develop a machine which is highly efficient in turning electrical power into neutrons of the proper energy spectrum which are then suitable for converting fertile material (U^{238} , Th^{232}) into fissile material (U^{235} , Pu^{239} , U^{233}) in an appropriate target-blanket assembly. Rather extensive studies have shown that one possible solution is a spallation neutron source driven by a proton linear accelerator of energy ~ 1 GeV and operating at very high beam powers. Most of the energy of the incident proton is given up in nuclear interactions, rather than in dE/dx losses in the target. The yield of neutrons per incident proton is most favorable above 500 MeV, and does not appear to change going to very high energy. There are almost an infinite number of variations on the target and blanket design and optimization, and I will not discuss these problems in detail here. The characteristics of the accelerator needed to drive such a system are quite clear, however. First of all, it must be efficient. A net conversion efficiency of electrical energy to beam power of $>50\%$ is required for reasonable system performance, with a higher figure desirable. A typical accelerator system might have a 100 mA, 1 GeV beam yielding 100 MW beam power. The major technological problem to solve is then the handling of a 100 MW proton beam with safety and precision. In my opinion, beam losses in such an accelerator must be kept low enough so "hands on" maintenance of the machine is possible, and understanding and controlling beam losses at this level (say, 10 μ A total, or 10^{-4} of the total beam) is a challenge to the linear accelerator builder of major proportion. If beam losses are allowed to get higher than this level, costs will escalate out of reason for such a system. The proton linear accelerator is the only candidate I know of which can even consider beam loss figures in this range. The Chalk River group has made significant progress in the directions needed for this application, and will report extensively at this Conference on their work.

4. Radiation Damage Neutron Source

Radiation damage in the components of a controlled thermonuclear reactor may be the limiting factor in the application of fusion power commercially in the decades ahead. Recently, there has been a strong interest in a facility to investigate the radiation damage induced by fast neutrons (~ 14 MeV) in structural materials at the neutron fluence typical of the first wall of a fusion reactor. A D-T generator is capable of providing exactly the spectrum expected from such a thermonuclear reactor, but it appears that a deuteron linear accelerator of about 35 MeV energy, 100 mA average current used in conjunction with a Li target could mock up the neutron spectrum quite well and achieve source strengths appreciably greater than those available from D-T sources and adequate to carry out the irradiations in a reasonable time.

There are four active proposals to build such a radiation damage facility based on a deuteron linear accelerator in the United States, at Brookhaven (BNL), Oak Ridge (ORNL), Livermore (LLL), and at Hanford (HEDL). The proposals are all basically similar.

A large CW linac system is designed to achieve 100 mA acceleration of a deuteron beam to ~ 35 MeV final energy. Some typical parameters (these are taken from the BNL Study) are:

Energy	35.5 MeV
Current	200 mA
RF Power	~ 10 MW
RF Frequency	50 MHz
No. Tanks	8
Length	40 m

A major consideration in these machines is the beam loss within the accelerator structure, as loss could yield unacceptable radioactivity levels within the accelerator itself. "Hands on" maintenance of these machines is essential for reliable operation at a reasonable cost.

The target systems for these facilities are very complex, and need significant development work. Typically, a flowing Li target systems are envisioned which may be the most difficult engineering problem in the entire facility. While a 7.0 MW beam power is small compared to the 100 MW discussed in the preceding topic, it is still orders of magnitude greater than current accelerator practice and deserves very careful study and a great deal of respect.

5. Heavy Ion Fusion

Recently several proposals for utilizing heavy ions to initiate an inertial confinement fusion power source have received serious consideration. Laser systems have been studied in great detail to heat a D-T pellet to igniting temperature. However, laser initiated fusion is still decades in the future. Recently several groups have come to the realization that high energy storage (>100 kJ) laser systems are very difficult to build, and that storage ring systems (such as the ISR at CERN) routinely store large quantities of energy (in the case of the ISR, >5 MJ) in circulating particle beams. For driving a fusion power system, protons are not satisfactory as they do not lose energy in a small enough volume to satisfy the criteria of the pellet fusion systems. Typically, heavy ions (say, U^{1+} of up to a few hundred MeV/nucleon) give optimum performance. Beam requirements of 1 to 10 MJ stored energy, delivered in 10 ns in a few beams directed to the pellet are typical requirements for this application.

Ion linacs could play a significant role in several areas of this research. If a storage ring is used as the source of heavy ions, a high gradient, low cost R.F. linear accelerator appears to be an optimum way of filling the ring. Programs such as the LASL PIGMI Study can have a significant impact on the size and complexion of such a conventional linac injector.

However, a major contender to replace the storage ring entirely is an induction linear accelerator directly accelerating the ions into the reaction chamber, with no storage ring involved. Such a linac is discussed later in this Conference by Dennis Keefe (LBL) and is a very interesting alternative to the storage ring approach. Problems of accelerator ion source, cost, length, and operation all need to be carefully investigated but the induction ion linac represents a new approach to this problem which deserves considerable attention.

6. Other Uses

Electron linacs have been considered in the past as possibly being used for polymerization of plastics where deep penetration into the material is required. CO^{60} is routinely used for this application, and linacs have been slow to penetrate this field. Higher dose rate or direct electron use may make linacs attractive in this area in the future.

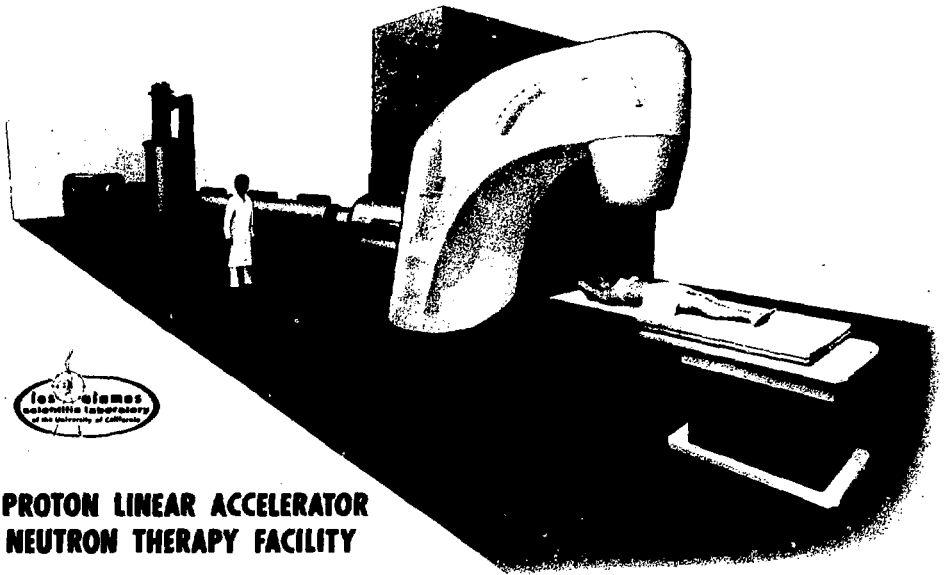
Sterilization of medical supplies is routinely accomplished with isotopic sources, and linacs may become competitive here also. Sewage sterilization with linac-generated x-ray beams has been studied. And food sterilization for room temperature storage is also possible. None of these applications is actively being pursued at present by any of the linac manufacturers I am aware of.

An interesting application which has not progressed is the possibility of lowering linac units into oilwell bore holes for logging applications. With the additional information this would make available and the cost of oil increasing rapidly, we may see this application in the future.

DISCUSSION

P. Grand, BNL: You indicated on a slide that the neutron energy spectrum from 35 MeV protons on Be is the same as from 35 MeV deuterons. Can you explain?

Knapp: These measurements were made by John Dicello of Los Alamos on the Davis cyclotron. The depth-dose curve and the microdosimetric data indicate that the radiation quality is similar for the two projectiles.



**PROTON LINEAR ACCELERATOR
NEUTRON THERAPY FACILITY**

Figure 1. Proton linear accelerator neutron therapy facility.