APPLICATIONS OF LINEAR ACCELERATORS*

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Our first essays into the linear accelerator field were, by present standards, quite tentative and amateurish. Things have changed and we are now participants in an operation recognized as really advanced science and engineering.

For example, I bring to your attention a conference on "Applications of Intense Charged-Particle Beams" starting in a couple of weeks. To go to this conference you need two things: some familiarity with engineering or physics and $510. It is really not a conference, but a course designed for managers of industrial and technical projects. I mention it only to emphasize the fact that no longer are we long-haired scientists occupied exclusively with subjects primarily having only academic objectives.

Introduction

The histories of electron linear accelerators and ion linear accelerators diverged from the start,although the modern histories of both machines began immediately after the end of World War II. Both programs were based on wartime developments of high powered radio-frequency sources. But electrons are light as feathers and are easily made to fly in the electromagnetic wind inside the rf cavities of a linear accelerator. Protons are more like billiard balls and heavy ions are like bowling balls and require considerable pushing of a more specialized type to get them moving.

The result of all this was that electron linacs were much more speedily "reduced to practice" than were ion linacs and, indeed, found applications early in the 1950's in medical and engineering fields as well as in high energy physics.

At this point I digress to note that I shall pay very little attention to applications of either electron or proton linacs in the field of high energy physics. To this audience I think I can assume that this field is well known. Briefly, electron linacs from the Stanford Mark III through the machines at Orsay, SLAC and Kharkov have made major contributions to high energy physics including Nobel Prize discoveries by Bob Hofstadter. Proton linacs have served as injectors for the high energy synchrotrons at Brookhaven, Fermilab, Argonne, Berkeley, CERN, Serpukhov and elsewhere. Only now are other applications appearing for proton machines. No heavy ion linacs, to my knowledge, are important in high-energy studies.

So much for the moment for high energy physics.

It is interesting to look back forty years and to appreciate the fact that, although microwave rf sources were not available for use at high power levels, their possible uses were appreciated by many forward-looking scientists and engineers. The best known story is that of Bill Hansen and the Varian brothers who, in 1937, were exploring the possibilities of what came to be known as radar. While they were studying the potentialities of the klystron, other groups were also in the field. I mention a couple of cases with which I was personally acquainted,with the caveat that there must have been many others. At the General Electric Company in Schenectady, Chester Rice had built a primitive magnetron, had received echoes from cars in the GE parking lot and had observed Doppler effects from their velocities. In the same laboratory, Bill Hahn and Si Ramo (now the "R" in TRW) were developing a "velocity modulation" tube which was essentially the same as a klystron. My contribution to this effort was to dissuade Hahn and Ramo from using the abbreviation "VEMO" for their tube since this was already the name of a popular deodorant.

The other group , with the same appreciation of possible use of microwaves in the national defense,was at the Naval Research Laboratory. In those days--perhaps still for all I know--the Navy was by far the most imaginative and forward-looking of our military services. In any case, they were,in 1937,or so,already sponsoring experimental programs on reflection of microwaves from ships and aircraft.

So there it was, even then,--the germination process for the microwave power sources that, a decade later, made linear accelerators possible and practical.

Electron Linacs

The first sucessful operation of an electron linac came in 1947,both at Stanford and at the Telecommunications Research Establishment in England. Magnetron rf sources developed during the wartime radar effort were the first used to supply rf power, later to be supplanted by the klystrons developed at Stanford. Parenthetically, I note that I had considerable experience with klystrons during the war. These were little tubes that you could hold in the palm of your hand and were used only as local oscillators in radar receivers. It took an enormous amount of courage, again post-war at Stanford, to extrapolate these little devices from milliwatts to megawatts of output.

With the first post-war success, the Stanford group pushed toward high energy for physics research. The British, on the other hand, began

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building linacs for cancer therapy. Their first machine operated in 1952 at Hammersmith Hospital in London at 8 MeV and has operated for almost three decades providing treatment for cancer patients.

The American effort on application of the electron linear accelerator to cancer therapy was, in large part,due to a collaboration between Henry Kaplan of the Stanford Medical Department and Ed Ginzton of Stanford. Patient treatment by the machine that resulted from this joint effort began in 1956. The successes of this effort inspired many developments elsewhere and now the electron linac is by far the favored machine for radiation therapy of cancer.

Medical Applications

For medical applications electron energies are required up to about 20 MeV. Very severe requirements are imposed on the machine. First of all, it must be reliable; it must perform at the push of a button day and night; treatment schedules must not be interrupted by machine failures. It must have high intensity to hold down patient exposures. It must be possible to rotate the source around the patient so that doses can be concentrated on internal tumors. This is vastly preferable to rotating the patient since internal organs move rather surprisingly when one is turned over.

Other severe restrictions are placed on a medical machine. These seem to have been met very satisfactorily by machines now industrially available. These machines are compact, easy to operate and pleasing in appearance.

Varian Associates have pioneered this development in the United States. Worthy followers include the High Voltage Engineering Corporation and other manufacturers of electrical equipment.

We note in passing that electron linacs have an enormous advantage over ion linacs in that a section of the electron machine can fail and the machine will still work. This is not generally true of ion machines. Keep this in mind when you buy your next linac.

At present, almost a thousand electron linacs are in use in hospitals for cancer therapy. Of almost a million new cancer patients per year in the United States, about half are treated with electron linear accelerators.

Radiography

Here, also, electron energies of up to 20 MeV are favored. With the X-rays generated by electrons of a few million electron-volts, one can see through almost anything of interest. This includes big castings, machinery, pipeline sections, all sorts of welds, rocket motors and what have you. Double photographs in which either the source or the object is moved a short distance can provide stereo views of the insides of engines, rotating machines or clocks and can tell you in a moment why the object malfunctioned. Stereo X-rays give a picture that cannot be described; to appreciate this technique you must yourself look at stereo X-rays of an engine or other complex mechanism.

Probably the most extensive use of linac-generated X-rays in the field of radiography is in monitoring of welding processes. Here the X-ray pictures can be used to detect cracks, incomplete fusion, slag or oxide inclusions, porosity or many of the other disasters that occur when the welder turns his back or when he is furnished with inadequate materials.

An upper limit to the penetrating power of million-volt electron generated X-rays is set by the onset of photon pair-production. This happens generally in the energy range around 20 MeV; from this energy upward the penetrating power of the X-rays goes down. This happens, for example, in steel, at a depth of about 1.3 inches which, at this energy, is the depth where the X-ray intensity has been reduced by a factor of two.

Other Uses for Electron Linacs

Recently much interest has been evinced for the possibility that the beam from an electron linac can be directed back to its input and sent through the linac again, emerging with twice its energy. This possibility has been tested at several places including Stanford and the University of Illinois. Indeed this process can be repeated to multiply the linac's energy capability by several fold.

A possiblity for using the recirculating linac idea is found in the "free electron laser" in which the beam from an electron linac passes through achromatic bends, through a magnetic wiggler (in which transverse magnetic fields alternate in polarity) and may or may not be returned to be reaccelerated by the linac. In the course of passage through the wiggler, the electron beam has interacted with a light beam, the interaction resulting in transfer of energy from the electrons to the light beam. The reasons for this laser action are beyond the scope of this lecture but are already generously documented. High-powered, easily tunable free electron lasers can have revolutionary uses in photochemistry, purification processes and isotope separation.

An electron storage ring, like the ones that we plan for the National Synchrotron Light Source here at Brookhaven, can provide the return path for a wiggler included in one of the straight sections. We plan to try a free electron laser in one of our storage rings. It has the beautiful feature that its wavelength can be shifted over a range of a factor of ten or more merely by changing the magnetic field in the wiggler, or by changing the electron energy.

So much for electrons.

Proton Linear Accelerators

Linear acceleration of protons or other ions has always been a bit of a headache because, even at energies of several million volts, proton velocities are only a fraction of the velocity of light. Slowing down the field pattern appropriately has continually been a problem. Recently, however, there have been several breakthroughs both in the Soviet Union and at Los Alamos and it seems probable that the "conventional" linear accelerator may soon be replaced by a simpler and much less expensive machine. When that happens we shall see proton and ion linacs in many new applications. I now mention a few with the reservation that probably new ideas are appearing elsewhere in the world about which we have not yet heard. Perhaps some will emerge during this conference.

Medical Applications

Many scientists and medical researchers have speculated about the advantages of using pi mesons (pions) for radiation treatment of tumors. They have the advantage of well defined ranges over which they do not do much damage, but at the end of their ranges they experience an annihilation, a sort of explosion quite destructive to the material in which it occurs. In principle this phenomenon would seem to make pions the ideal particles for treatment of tumors. Their only real disadvantage is that they are extremely expensive to produce.

A leading pioneer in the study of pion therapy is Henry Kaplan, who was for many years Chairman of Stanford's Medical Department. Several years ago we organized a committee to recommend a pion facility to be built in the Stanford University Hospital; the committee included members from the Stanford Medical Department, from the linac group at SLAC, from Los Alamos, from Varian and from Brookhaven. We studied electron linac, proton linac and synchrotron sources and finally came out with a slightly tentative conclusion. We recommended that at that time and in that location the wisest procedure would be to use an electron linac together with the accelerator skills of SLAC, virtually next door. We submitted a proposal to the National Cancer Institute which, I believe, is still under consideration.

But we qualified our recommendation with the comment that a proton linear accelerator could have important advantages--for one thing, producing pions with an efficiency 30 or 40 times higher than is possible with electrons. We condemned the proton machine only because it appeared to be much more expensive.

This was taken as an exciting challenge by the Los Alamos group who came to the discussion with two special strengths. One was that, in LAMPF, they already had a proton linac capable of producing pions in useful quantities. The second was that a new advanced accelerator development group was in the process of organization under the guidance of Ed Knapp and Don Swenson and an assembly of talent too numerous to list here.

The Los Alamos team set about exploiting both capabilities. Under Dr. Kligerman's direction a pion beam has been extracted from LAMPF with carefully controlled dimensions and intensity. Something like a hundred patients have been treated with this beam. This is a slow and somewhat frustrating experiment; with tumor treatments you are not sure that you have succeeded for five years or so. But the medical people associated with the program are encouraged by the symptoms that they observe. I simply am ignorant in this field and observe only that the treatment includes patients with tumors of the brain, head, neck, abdomen and pelvis. For more informed information, I must refer you to the Los Alamos group which is well represented at this conference.

Simultaneous with the LAMPF experiments has been a Los Alamos program on development of less expensive proton linacs. This is a very imaginative program--so imaginative to me that I find the Los Alamos people doing projects that, for a long time, I thought were impossible. I think now that I was wrong; I hope not on absolutely all points. We shall see. This is the PIGMI project--standing for "Pion Generator for Medical Irradiations." It is supported by the National Cancer Institute. You will hear a good deal more about it this week.

I shall mention two other medical projects. The favorite particle for tumor irradiation--at least measured by the number of papers presented at nuclear medicine conferences--is the neutron. The linac injector at the Fermilab is being used on the side as a neutron source for patient irradiation. Between 300 and 400 patients have been irradiated with, as I understand, considerable success. A proton beam is extracted at an energy of about 70 MeV and is used to generate the neutron flux.

We, at Brookhaven, have mounted a program using our 200 MeV linac to try to localize the end of the range of a 200 MeV proton. Protons from the AGS injector linac are injected into animals--my understanding is that pigs have been used since they seem to be as similar to people as is possible--and the proton interaction volume is indicated by activation of such positron emitters as carbon-11 and oxygen-15.

Isotope Production and Nuclear Chemistry

At Brookhaven and elsewhere proton beams are extracted from linacs for a number of auxiliary purposes beside the medical applications just mentioned. A favorite is isotope production, mostly I believe, for medical uses. Essentially the same beam is also used to produce a copious neutron beam by stopping the 200 MeV protons in a copper target. All of this goes on at the bottom of a 30-ft. deep water tank; for many years I have lived with the fear that eventually the proton beam will bore a hole through the window through which it enters the tank. I have never had the nerve to estimate the eventual depth of water in the linac tunnel.

The first industrial linac isotope production will soon be in progress at the New England Nuclear Corporation in Massachusetts just north of Boston. They are building a 45 MeV linac for this program and are prepared also to build linacs for sale.

Far-out Schemes Using Protons

A nice idea, that so far has come to nothing, was an idea thought up by Maglich, then at Rutgers, and Macek of Los Alamos, for producing collisions between mesons, using the LAMPF facility, together with a storage ring under study there. The idea was to dump the ring as quickly as possible into a target in a magnetic field shaped so that positive mesons would precess in one direction around the target and negative mesons in the other. It was hoped that enough mesons could be produced that interactions between them could be observed. For reasons too complicated for description here, this scheme became converted into a fusion project and the meson program was forgotten.

Another idea that was explored some years ago in Canada was the construction of a cw machine in the GeV range. Back in the '50's a similar project had been started at Livermore. The idea is now being resurrected and we have given it some study at BNL. The intense neutron beam generated in some sort of heavy metal target could be used for a variety of purposes including production of reactor fuel. It would be a mighty machine, requiring something like a thousand megawatts just to turn it on.

Deuteron Linacs

The beauty of a deuteron linac is that, by dissociation of the deuterons in a target, one can produce a more or less monoenergetic neutron beam. We shall hear a number of papers at this Conference about the FMIT, a joint Hanford-Los Alamos project for production of a 35 MeV deuteron machine to produce an intense beam of about 15 MeV neutrons to simulate the neutron flux at the wall of a fusion reactor using the D-T fusion reaction. This calls for a flux of about 10^{14} neutrons per square centimeter per second, a flux that will be produced rather easily by the proposed linac. I don't mean to intimate that the linac will be built easily--we shall hear about its problems later.

Heavy Ion Linear Accelerators

The two pioneering heavy ion linacs that resulted from the joint efforts of Yale and Berkeley had distinguished careers and produced a number of significant discoveries in the field of heavy ion physics. The present, somewhat unlikely marriage between the Hilac and the Bevatron is something I never thought we should see; but it seems to be quite successful.

Heavy ion linacs for medical applications were given thoughtful study in a joint study between LBL and the Arizona Medical Center. This study covered radiation therapy, radiography and isotope production; it lasted two years, running until the end of 1977. The conclusions were, first, that heavy ions have special advantages for radiotherapy and, second, that the linac is not the best way to accelerate them--circular machines were thought to be more desirable and economical.

Heavy ions are beginning to be regarded with favor in the pellet fusion programs at LBL, Argonne and Brookhaven. They are thought by their proponents to have notable advantages over either lasers or electron beams. A clear picture of how to generate heavy ion beams has not yet emerged--the three laboratories I just mentioned all have different schemes. But heavy ion linacs to help in the generation of the required short, intense bursts are very much part of the study. You can visit our experimental program on Wednesday.

Another possible field of use for heavy ion linacs is as "after burners" for tandem electrostatic machines and they are under study in several laboratories. Here also there is not agreement that a linac is the best choice. That picture may change as we assimilate the developments of the last few years in basic linac design.

Superconducting Linacs

Although work on superconducting linacs has been in progress for the better part of two decades, they have had a somewhat troubled career and have not yet found many applications. But they have their strong supporters. A great deal of credit must be given to the unfailing optimism of Alan Schwettman at Stanford and it was his superconducting machine that was used in the first demonstration of the free electron laser.

Work on superconducting cavities and linacs is in progress at a number of laboratories here, in Japan and in Europe.

Perhaps by the time we are using superconductivity in accelerator magnets, in ore separation magnets, in power transmission and in levitated trains, the superconducting linac will be the standard particle accelerator. It will be interesting--if we live long enough to see it.