# LINACS OF THE FUTURE

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Before attempting to probe into the future I should like to set the stage by reviewing a few recent developments.

First I note the well-known facts that linacs find applications as injectors for synchrotrons, second as research tools, and third, as industrial or medical instruments. For all of these applications the linear accelerator whether for electrons, protons or heavy ions is a very satisfactory device. It can make available an intense beam of good emittance, it has no problems of beam extraction and it can be very reliable in its performance.

During the past two years notable progress has been made in our understanding of linac performance. The worst and most mysterious problems associated with the interaction between the particle beam and the accelerating cavity have yielded to the analytical skill of such experts as Nishikawa, Lapostolle, Hereward, Gluckstern, and many others. Many new designs due to Giordano, Knapp, Carne, and other inventive people have made it possible to make designs for linacs of almost any desired energy. One major drawback remains – the linac is a very expensive accelerator. Costs have been reduced to some extent by the new designs but still they are very high; the two-mile linac at Stanford is by far the most expensive accelerator built anywhere and proton linacs for energies in the GeV range would be even more costly.

The high costs are primarily associated with the very high power levels required for a linac of reasonable length. The Stanford linac needs about 250 megawatts per GeV, of which virtually all goes into rf cavity losses. A 1-GeV proton linac of conventional design using somewhat lower fields would require between 50 and 100 megawatts for tank excitation. This sort of operation is economical only for very high currents. If, for example, the 1-GeV proton linac were to deliver a current of 100 mA, the power required for the beam would be 100 megawatts and the efficiency of the operation would become better than 50 percent.

The high cost of linear accelerators has inspired the development or invention during the past few years of a number of competitors, particularly for use as synchrotron injectors, and the lower cost of at least some of these devices will probably result in their use in applications where formerly the linac seemed to be the natural choice. For example, the AGS conversion program originally included a 200-MeV linac to be extended in a later phase to 500 MeV. Now it appears that the linac will not be used for energies above 200 MeV; the second phase will probably involve a booster synchrotron with an output at about 1 GeV, expected to cost less than the 200 to 500 MeV linac extension. Evidently our inventors need to concentrate on linacs of materially cheaper design.

The booster synchrotron to be used for the AGS conversion would be a synchrotron of large aperture capable of accelerating all of the charge required for the AGS – some $10^{13}$ protons. It would have a circumference one-twelfth of that of the AGS and its beam would be extracted over twelve revolutions. This sort of machine has come to be known as a slow-cycling injector since it is pulsed only once per AGS pulse. Other synchrotron types considered as injectors include "rapid-cycling" synchrotrons of smaller aperture having a circumference 1/n times that of the machine into which they inject; these machines would be cycled n times, as fast as possible, each time with single turn extraction, to fill the larger ring. Still another ingenious device is an interlaced ring system in which three or four equilibrium orbits exist, each making double use of each of a ring of magnets. At CERN, for esoteric reasons, these are known as TARTS; another variety evolved at LRL is known as a QUART. In addition to these gadgets, FFAG accelerators and synchrocyclotrons are receiving consideration as injectors. One of the most formidable competitors appears to be the separated-orbit cyclotron or SOC, which is a sort of curled up linear accelerator in which a spiral orbit passes several times through each of a set of radial accelerating cavities. This is expected to result in lower rf losses and hence in better efficiency. The SOC has some as yet unsolved problems associated with interactions between beams passing through different holes in the same resonator. Perhaps the SOC should not be considered to be in competition with the linac; rather it can with equal validity be considered to be a linac variation.

Not one of these competing injectors has yet been built and used but all are under active study.

With this much background I should like now to turn to specific plans for new injectors for large proton synchrotrons in increasing order of synchrotron energy.

For the 3-GeV Saturne accelerator at Saclay a design study has been made for a 20-MeV linac to replace the 3-MeV electrostatic machine now in use. We should like to have done the same for the Brookhaven Cosmotron but I am sorry to report that this ancient and honorable machine is to be shut down at the end of this year.

At the Rutherford Laboratory the 7-GeV synchrotron (Nimrod) now has a 15-MeV linac injector. It is proposed to raise the injection energy to 70 MeV; at present a separated-orbit cyclotron is favored for this application.

For the 12.5-GeV ZGS a new injector is proposed to give a material increase in intensity. Under study are a 200-MeV linac, a 500-MeV rapid-cycling synchrotron and a 500-MeV FFAG accelerator both presumably to use 50-MeV linac preinjectors. Attention, with somewhat less enthusiasm, is also being given at the ZGS to synchrocyclotrons, separated-orbit cyclotrons, slow-cycling synchrotrons, interlaced synchrotrons and linacs in the 500-MeV range.

At CERN a PS improvement program is under way similar in many respects to the AGS conversion except that a new injector will probably consist of an interlaced-orbit synchrotron fed by a relatively low energy linac. This system has the vigorous support of W. Hardt, the inventor of the interlaced TART scheme, but other booster synchrotrons are also under study.

In Japan a 40-GeV synchrotron is under design. My latest information is that its injector will be at least a 125-MeV linac delivering a current of 100 mA. Space will be left for a future booster synchrotron to reach higher injection energies if this is desired later.

The largest proton linac now under construction is beginning to be installed at Serpukhov in the USSR. This is the 100-MeV linac injector for the 70-GeV synchrotron. Tests on this machine should be beginning during 1967. Also in the USSR a 20-MeV quadrupole-focused linac has just been completed for the 7-GeV synchrotron at the Institute for Theoretical and Experimental Physics in Moscow. The first operation of this linac gave rather low intensity due to some minor difficulty in the focusing system; this should soon be remedied and a material improvement in 7-GeV intensity is expected. This machine will replace a 4-MeV electrostatic injector.

The injection systems for the American 200-GeV and the European 300-GeV accelerators are in a state of wild disarray. At LRL a total of fourteen combinations of linacs, rapid-cycling synchrotrons, slow-cycling synchrotrons and interlaced-orbit synchrotrons have been studied thus far with quite inconclusive results. So complicated has become the situation that it has become necessary to represent the various synchrotron types by the symbol $M_P^E$, where M is the number of interlaced rings, E is the number of turns ejected per ring per pulse, and P is the number of synchrotron pulses required for the injection process.

The two most ambitious linac projects are, of course, the Los Alamos meson factory and the intense neutron generator at Chalk River. I shall not presume to discuss the local project except to say that we at Brookhaven have been much impressed by its rapid progress and by the ingenious ideas that have gone into its design. The Chalk River project is certainly one to excite the imagination – aimed at producing a thermal neutron flux of $10^{16}$ neutrons per square centimeter, an order of magnitude higher than the flux from the high-flux beam reactor at Brookhaven. Until last July this machine was to be a separated-orbit cyclotron; then it was changed to become a cw linac almost a mile long and accelerating 65 mA or protons to an energy of 1 GeV. The Chalk River group has been impressed by the "$\pi$/2-mode" structures evolved here at Los Alamos and at Brookhaven and also is encouraged by the progress in amplitron development. The average field of about 700 kV/meter is low enough that the beam power is about three times the tank losses. A year ago such a ratio would have made people nervous about control of phase, but such a ratio has been approached at CERN in the PS injector and can now be faced with some confidence. It seems that this should be a very efficient machine. But controlling 65 megawatts of beam power should present some formidable problems.

Another meson factory design project is in progress in France at Strasbourg with the collaboration of the linac experts at CSF. Like the Los Alamos linac this would have a final energy of 800 MeV. Initially it would have a 5 percent duty cycle and a peak current of 4 mA. This machine differs from conventional linacs in that it is proposed to inject at 1 MeV into a drift tube section operating at about 400 Mc and with drift tubes of length $2\beta\lambda$. A one-meter model of the injection end of this section will reveal any difficulties associated with this technique. After a section with $\beta\lambda$ drift tubes, also operated at about 400 Mc, a change will be made at 200 MeV into a final section operated at about 1200 Mc. Although this design study is reasonably complete, construction of the machine appears to be rather remote since it is not included in the French five year plan for science covering the period up to 1971. Further study is contemplated including studies of cryogenic operation.

Another vigorous European linac group is located at Karlsruhe in Germany. Two projects have occupied the attention of this group – a superconducting linac for approximately 5 GeV and a more conventional synchrotron with high enough energy to give K-beams comparable in intensity with that of the linac. A decision between these machines is expected in 1968. The final project is to be comparable in size and cost with the DESY synchrotron. Present work at Karlsruhe is concentrated on experiments with superconducting rf cavities.

Interest in heavy ion accelerators continues at a fairly high pitch; the heavy ion machines at Yale and LRL continue to produce interesting results for nuclear chemists and interest is increasing in possible medical applications. A heavy ion linac for higher energies is under study at Heidelberg where Schmelzer's group would like to reach an energy of 6 to 7 MeV per nucleon for uranium ions. This figure sounds even more impressive when multiplied by the atomic weight of uranium to give a figure for total energy of about 1.5 GeV. To attain a high value of charge to mass ratio 2 or 3 strippers will be used. To avoid charge exchanges with residual gases the pressure in the linac must be about $10^{-7}$ torr.

Although the vacuum requirements for circular machines must be about two orders of magnitude more severe, another heavy ion accelerator proposed at LRL will be a synchrotron. This is aimed at much higher energies — proton energies of 1.5 GeV and heavy ion energies corresponding to the charge-to-mass ratio attained. This device, called the Omnitron, is a combination of synchrotron and storage ring with beams transferred back and forth and stripping processes included at the transfers. Originally it was hoped that the heavy ion linac could be used as the injector for this machine but, as those of you who have visited the Lawrence Radiation Laboratory will readily understand, this idea was abandoned because of the non-horizontal topography that surrounds the Hilac.

Predictions about future electron linacs must be based on a rather different situation. The electron linac is no longer in the early state of development in which the ion linacs find themselves; it has been pretty thoroughly reduced to practice. Electron linacs are available commercially and should continue to find many uses in nuclear physics, industry and medical applications. Special linacs for high intensities or high duty cycles continue to evolve in the ten to a few hundred MeV range at many places including Saclay, CSF, NBS and elsewhere. So far as I know, no one contemplates an electron linac more than two miles long — in such a case problems of beam blow-up due to transverse field modes still remain to be solved. One rather interesting electron linac application that has come to my attention is in connection with pulsed reactors. Neutrons produced by electron induced reactions can induce a reactor pulse shorter and better controlled than can be done with mechanical pulsing. Electrons for this purpose could be produced relatively cheaply by a machine like the Los Alamos PHERMEX accelerator. Still another function of electron linacs is in the production of copious beams of positrons both for experimentation and for injection into electron-positron storage rings. At SLAC the two-mile linac will be used with a convertor at about 3 GeV as a source of 3-GeV electrons and positrons for the colliding beam storage ring project now under design. At CEA an ingenious plan for use of the Cambridge Electron Accelerator for an electron-positron storage ring involves the use of two linacs in series. The present 30-MeV linac injector will be replaced by a 120-MeV linac capable of delivering over 100 mA of acceptable electrons. This will provide electrons for the CEA directly. For positron production the output of this linac will strike a convertor target and the positrons produced will be accelerated in another linac to 120 MeV. Out of this combination it is expected that a current of 500 microamps of positrons will emerge.

At the 6-GeV DESY accelerator at Hamburg a new electron linac injector will raise the injection energy from 40 MeV to 300 MeV. Not only will this increase the accelerated electron beam intensity at 6 GeV, but also it will make possible injection of positrons generated at a conversion target part way along the new linac and accelerated in the remainder of the linac structure.

The major advance that looms on the horizon is the advent of cryogenic linacs. Rf cavities do not really become superconducting but factors of the order of $10^4$ or higher are attainable in reduction of cavity dissipation. For improving the duty cycle of electron linacs this appears to be a very promising approach and work at Stanford, Karlsruhe, Urbana and elsewhere should soon result in linacs which, except for rf structure, can yield continuous beams. The part of a proton linac which consists of iris-loaded waveguide could also operate in the cryogenic regime with a virtual elimination of cavity losses. It is hard to see, however, how this would be worthwhile in a machine like that proposed at Chalk River where very high power is, in any case, required for the proton beam. Also it seems doubtful to me that cryogenic operation of the early drift tube section of a proton linac will be satisfactory. Here power is fed into the cavity by beam loss, multipactoring and dissipation from quadrupoles inside the drift tubes. Perhaps in spite of these losses it will be possible to cool a drift tube cavity but at present it seems improbable to me. Returning to the iris-loaded cavities, it may be that the first major use of cryogenics will be in rf beam separators whose present limited duty cycle is a major disadvantage. In this case there is no problem of beam loading and cryogenic operation of an iris-loaded guide can be attempted with none of the attendant complications that arise with the linac. Development of cryogenic separators is already under way at Brookhaven for use with the AGS and at Karlsruhe for use with the CERN PS. Basic studies of superconducting surfaces for use in rf cavities are in progress as a joint effort between Orsay, Strasbourg and CSF. Effects on rf behavior will be investigated of smoothness, grain structure and other significant metallurgical properties.

What of more speculative ideas? Periodically it has been suggested that the drift tube structure in a proton linac could be excited, not by external amplifiers, but by an electron beam which serves also to focus the proton beam. A similar idea has been suggested by Russell for use in separated-orbit cyclotrons. Perhaps this idea will be tested during the next decade.

Ideas for using plasma in waveguides to produce traveling wave fields and to modify waveguide geometries are brought out occasionally, usually in the Soviet Union. Perhaps some discussions between linac experts and plasma specialists might have profitable results.

In conclusion, it should be said that every year has brought new ideas and surprises to the field of linac development; this is what has made it worthwhile to hold five linac conferences in a period of five years. I am sure that many new approaches of which I have not heard will be announced at this conference. Consequently it is with considerable anticipation that I yield the stage to the people who are really making the advances in the linac art.