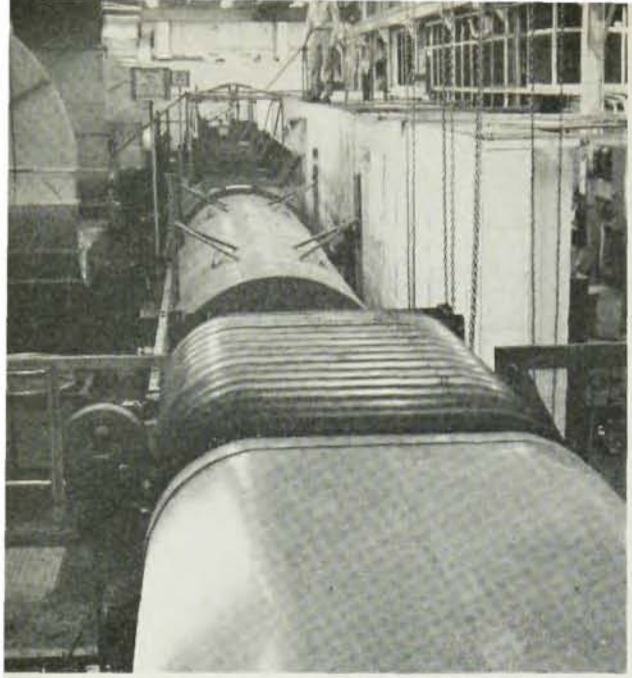

Above: the University of Minnesota's 70-MeV proton linac.

LINEAR ACCELERATORS for HIGH ENERGIES

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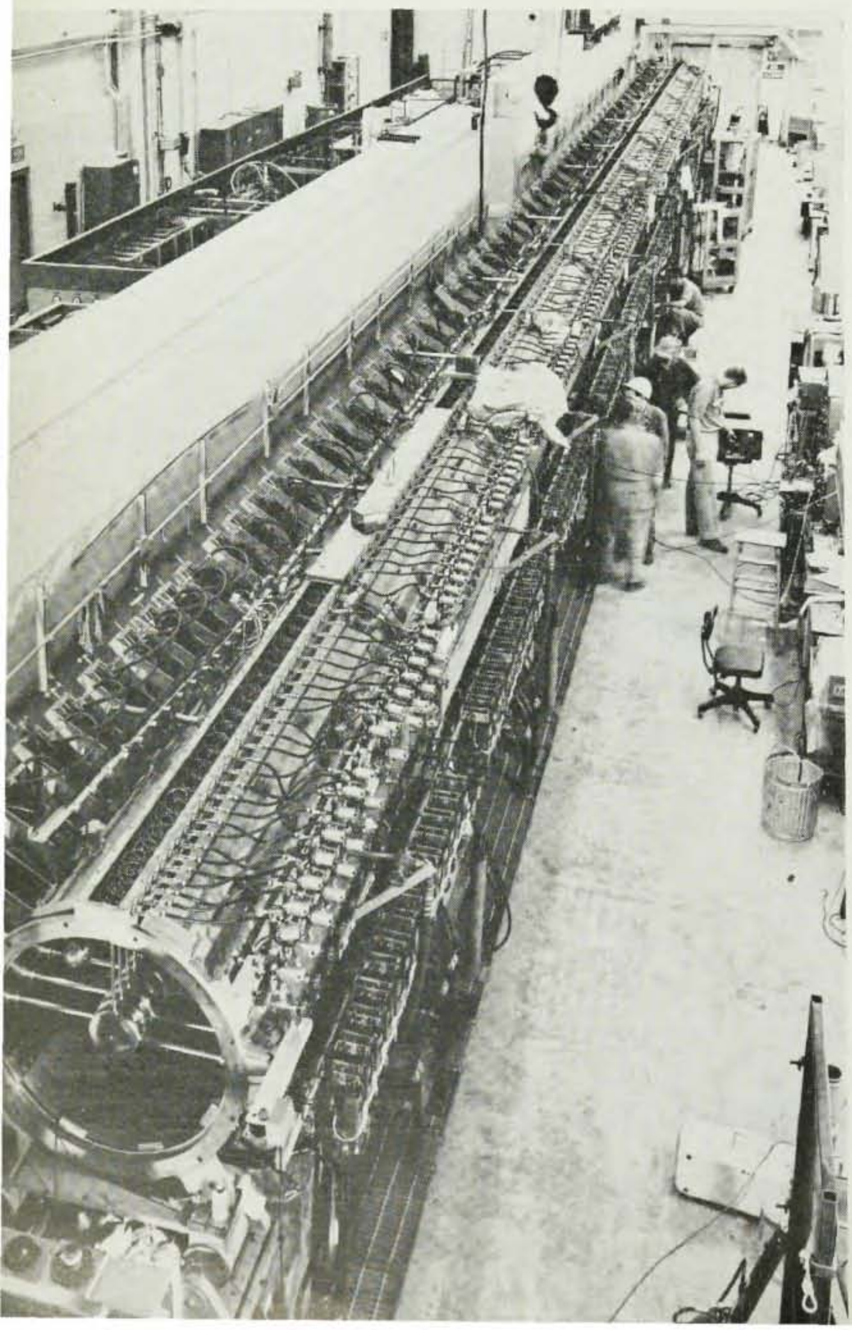


At left is shown the 50-MeV linac now being constructed at Argonne National Laboratory as an injector for the Zero Gradient Synchrotron.

Stanford University's one-BeV Mark III linac (shown in photo at right) accelerates electrons.

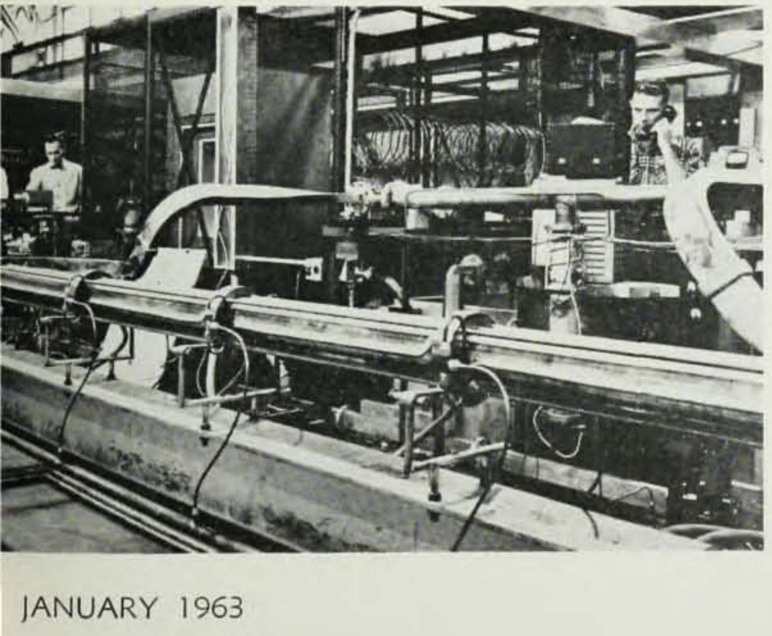
eport on the 1962 Brookhaven Conference

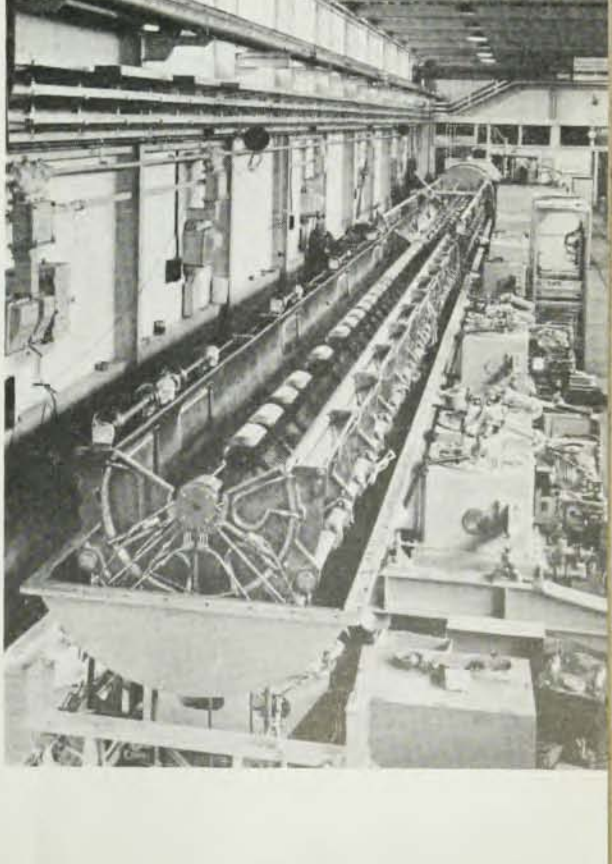
THE linear accelerator was invented very early in the history of particle accelerators, but it has been one of the latest accelerators to be exploited. This is principally because of the very large quantities of radio-frequency power required to attain respectable energies in a reasonable distance. Radar developments during World War II resulted in production of the necessary megawatt oscillators or amplifiers, and linear accelerators, both for electrons and positive ions, are now operating in several centers. The electron linear accelerator has been extended to billion-volt energies, and in the Stanford two-mile version it will soon set new energy records between 20 and 40 BeV. The proton linear accelerator has had a less spectacular history. The highest energy yet achieved in a proton linac is about 70 MeV (at the University of Minnesota). Smaller proton linacs are in use as injectors for proton synchrotrons, but no machine has been built or is under construction for the range above 100 MeV. This is because synchrocyclotrons for this energy range are much cheaper and have been preferred for this reason, in spite of the fact that the beam from a synchrocyclotron cannot be nearly as intense or as well collimated as the beam from a linear accelerator.

Recently, interest has developed in proton linacs for energies of the order of 1 BeV for two major applications. First, they would make ideal injectors for the 300- to 1000-BeV synchrotrons now under consideration in several centers, and second, they could be most useful as "meson factories" for production of intense beams of π and μ mesons. At Brookhaven, Yale University, the Lawrence Radiation Laboratory, the Rutherford Laboratory, the Midwestern Universities Research Association, and at CERN, studies of various aspects of linear-accelerator design are in progress. To exchange ideas and information, the groups at Brookhaven and Yale organized a summer conference which was held at Brookhaven during the week of August 20, 1962. Present were representatives from the institutions just named and from several other interested groups.

Early proton linacs were housed in large steel vacuum tanks and the radio-frequency accelerating fields were set up in copper structures supported in the vacuum tank. This type of construction is still favored in European centers, but in all three proton linear accelerators recently built in the United States, the rf and vacuum structures are combined in the form of cylindrical tanks of copper-clad steel. On the first day of the conference, reports were presented on operating characteristics of new machines of both types, with generally satisfactory performances reported in all cases. Lloyd Smith described the new Bevatron injector, a 20-MeV machine using the basic design already tested at

50-MeV proton linac at the Rutherford Laboratory (below) has recently been used in experiments to verify predictions about the mechanism of acceleration.

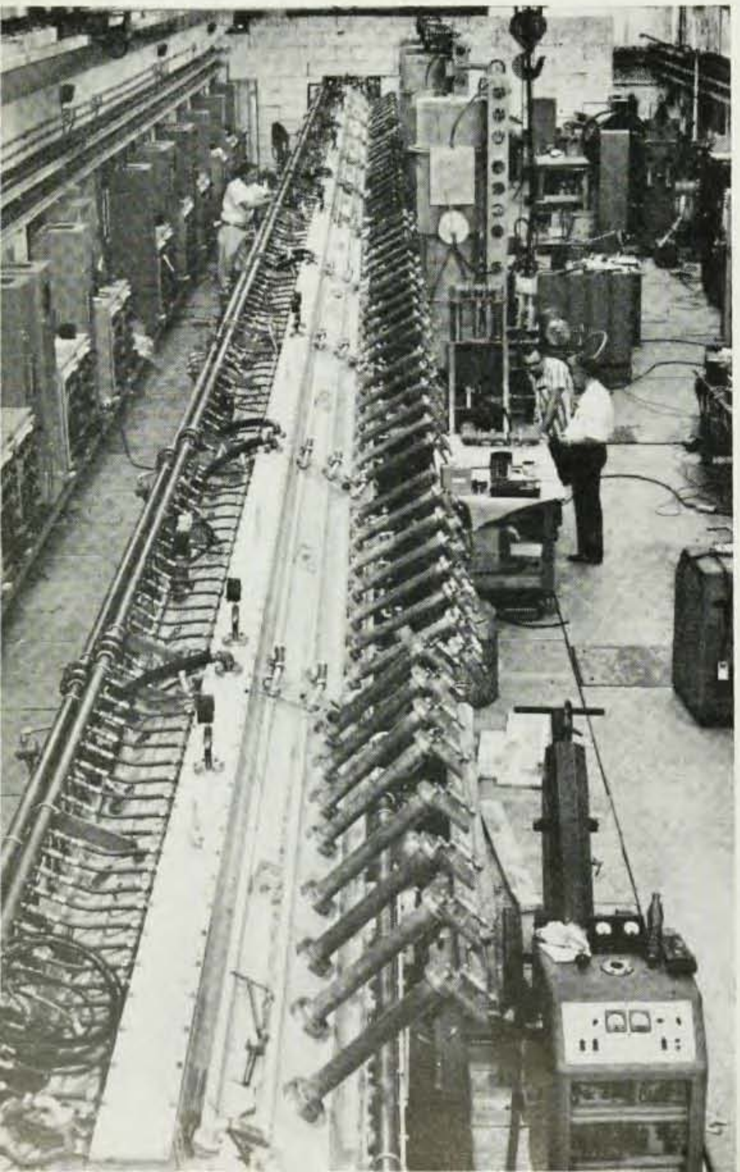




F. E. Mills, R. B. R-Shersby-Harvie, A. P. Jeudon.

K. Johnson, K. Batchelor, P. Grand, R. B. Neal, N. D. We

Brookhaven. The 25-milliampere output of this machine will make available an injected beam for the Bevatron higher by a factor of 100 than the beam from the old injector. The 50-MeV injector for the 12.5 BeV ZGS at Argonne was reported by R. Perry. This machine, also similar to the Brookhaven linac, is progressing so rapidly toward completion that the conference found it necessary to keep in touch with Argonne by telephone.



At the Rutherford Laboratory, a 15-MeV injector for the 7-BeV synchrotron has been completed and is in operation. Its characteristics were reviewed by N. West. Multipactoring difficulties in this machine have been temporarily cured by coating the drift tubes with carbon black, a procedure that horrified most of the audience but that nevertheless seems to have been effective since the linac is now delivering pulsed currents up to 10 milliamperes. The 50-MeV PLA (proton linear accelerator) at the Rutherford Laboratory has been operating for some time and, as described at the conference by K. Batchelor, has now been used for a series of beautiful experiments using refined time-of-flight techniques to verify theoretical predictions about the mechanism of acceleration.

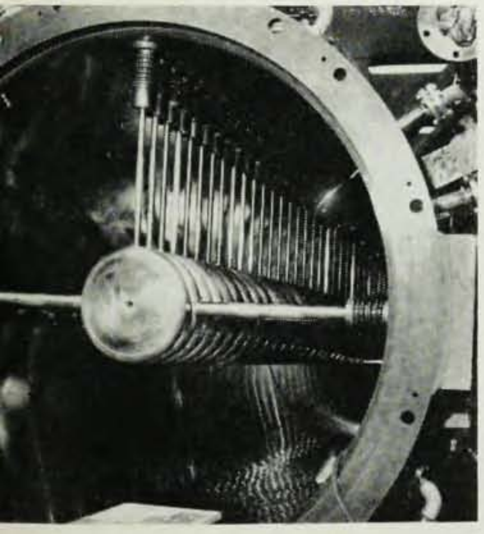
At Yale, a preliminary design study is in progress for a 500–1000-MeV linac. This study was introduced to the conference by its director, V. Hughes. The machine would have an average beam intensity of one milliampere, a beam power of over 500 kW. The accelerated beam should have an energy spread of 0.1% and should be concentrated in an area one centimeter or less in diameter. Design of target areas for this machine was discussed by W. Blanpeid and H. Knowles. It should be a very powerful tool for studies of meson physics; for example, at 750 MeV the π-meson beam at 180 feet from the target would include 4×10^8 200-MeV π^+ mesons and 2×10^8 400-MeV π^+ mesons, in both cases included in a plus or minus 1% momentum range and in a solid angle of 10^{-3} steradians. Neutrino studies also appear possible with this machine since neu-

50-MeV injector for Brookhaven's Alternating Gradient Synchrotron (left) was the first proton linac to combine the rf and vacuum structures in cylindrical tanks of copper-clad steel.

trinos in the 150–175-MeV range should give several observable events per day. Possible post-acceleration of the π beam from this machine was considered by R. Gluckstern, who showed that a second linear accelerator carrying the mesons to 1300 MeV would yield more than a thousand times the π-beam intensity now available at the Cosmotron. This project was regarded as interesting but overexpensive.

Extension of the proton linear accelerator to such energies will involve a change in present technique. In low-energy proton linacs, accelerating fields are maintained between drift tubes (see photos below) which serve the function of shielding the protons from the electric field while the field passes through its decelerating phase. In the early days, drift-tube dimensions were obtained from model studies, but it has now proved possible to make theoretical designs using computers. Results of such analyses were reported by G. Wheeler of Yale and D. Young of MURA, who agreed that the performance of drift-tube linacs has deteriorated badly at energies of the order of 200 MeV. At 200 MeV, about four times as much power is required per MeV of acceleration as was needed in the 50-MeV range. For accelerating fields of 2 million volts per meter, a 50-MeV linac requires about 60 kW per MeV of acceleration. At 200 MeV, between 200 and 300 kW per MeV are required and performance deteriorates even more as energy is increased. Consequently, for energies higher than this, studies are in progress of the efficacy of using iris-loaded waveguides like those used in electron linacs. At the Brookhaven conference, new data were presented by R. Neal of Stanford on the performance of iris-loaded guides for velocities less than the velocity of light. At the velocity of light, the performance of an iris-loaded linac is comparable with that of a 50-MeV proton linac, but as the velocity decreases, in contrast to the drift-tube structure, the iris-loaded waveguide efficiency decreases. At the velocity of a 200-MeV proton, the power required per MeV is up by a factor of 4 over that required at the velocity of light and deteriorates rapidly as velocity decreases still further. From these figures, many of which have just been collected during the past year, it is now agreed that a proton linac for high energy should change at about 200 MeV from a drift-tube structure to an iris-loaded guide. The happy feature of this choice is that the high-energy section of the linac will be materially cheaper per MeV than the drift-tube structure: hence, the higher the final energy of the linac, the lower will be its average cost per MeV.

Some details of design for injectors into super-high-energy synchrotrons were presented by representatives of the groups concerned. Since the intensive design studies of 1961, little progress has been made in the United States, but an authorized design study is in progress at CERN. The aid of the Rutherford Laboratory has been enlisted by CERN in its attack on the design of a possible BeV linac for injection into a 300-BeV synchrotron. A linac injector is somewhat simpler in design than a linac for use in meson research since the duty cycle of the injector will be low and, although peak power is still high, average power will be low. In basic design, however, the injector linac will be similar to the meson factory already discussed. As an injector for a proposed 10-BeV FFAG accelerator, the MURA group requires a 200-MeV linac and hence has concentrated its attention on drift-tube



At left are shown some of the drift tubes at the low-energy end of the Brookhaven linac.

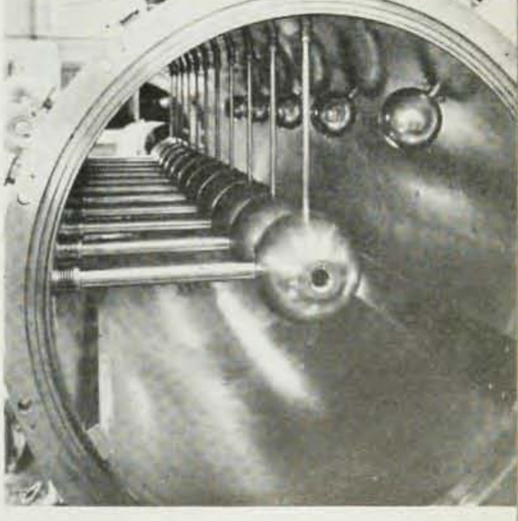


Photo at right illustrates drift-tube structure of injecting linac for Argonne's ZGS.

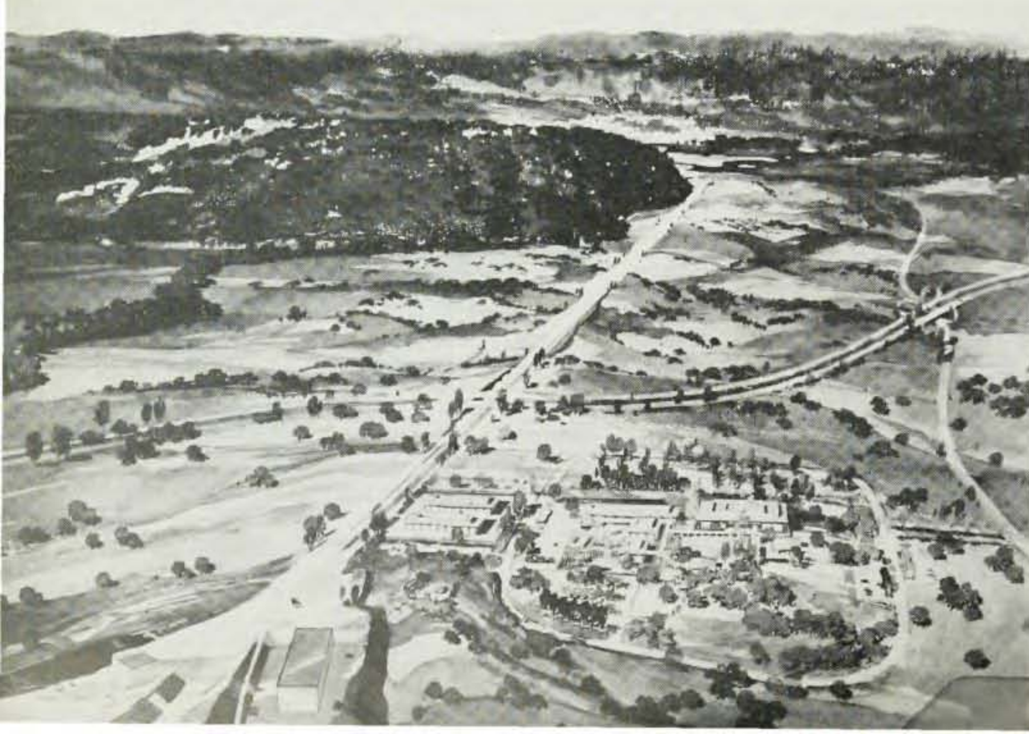
configurations. Focusing, in all of the proposed linacs, would be by quadrupoles embedded in the drift tubes of the drift-tube section. At the proton velocities involved in the iris-loaded waveguide section, focusing requirements are not so severe and possible alternations of quadrupoles and waveguide sections were presented by Lloyd Smith.

Preinjectors for proton linacs are usually of 500–750-keV energies. Recently, much progress has been made in the design of ion sources. Ten years ago, 5 milliamperes was regarded as a respectable beam. At the Brookhaven conference, R. Perry of Argonne and A. van Steenbergen of Brookhaven described studies on ion sources, particularly the duoplasmatron (a hot-cathode magnetically focused source) with output currents up to 100 milliamperes in a beam acceptable in the linear accelerator.

Rf power sources for proton linacs have been troublesome and various, although satisfactory operation seems now to be attainable. At present, operating linacs require about 5 megawatts of pulsed power at 200 megacycles per second. Homemade rf triodes capable of megawatt outputs are used at the Rutherford Laboratory, and at the University of Minnesota the linac is powered by homemade tetrodes. At the Lawrence Radiation Laboratory, the preference has been for a larger number of commercially available tubes in the 300-kW range. The CERN and Brookhaven linacs use megawatt triodes supplied by the French Thomson-Houston Company. The Argonne linac will use a single 5-megawatt triode built by RCA. More uniformity is found amongst electron linacs, which operate at 2856 megacycles per second and which, in all cases, employ klystron amplifiers. Progress in the design of commercial tubes for megawatt outputs was described at the conference by M. Hoover of RCA. Developments in the linac frequency ranges have been stimulated by military applications, and it now appears that several possible power sources of reasonable life are, or will shortly be, on the market.

A miscellany of ancillary developments was included at the conference; for example, techniques for producing beams of polarized protons were described by R. Featherstone of the University of Minnesota, and procedures for acceleration of deuterons in proton linacs were outlined by E. Courant of Brookhaven. Perhaps the most exciting of the developments described was associated with a proposal by Banford and Stafford of the Rutherford Laboratory for a superconducting linac whose inside walls would be lead-covered and which would be operated at temperatures of 4°K. In this way, the rf power requirements could be reduced to negligible proportions, and the linear accelerator could be operated continuously, instead of with a low duty cycle. Batchelor of the Rutherford Laboratory reported on model experiments now proceeding under Banford's direction, and R. Neal of Stanford described work in progress at Stanford under the direction of P. B. Wilson. At this stage it can be said only that the experiments give encouraging results, but actual design of a superconducting linac is probably several years off.

The conclusions, if any, of this conference can probably be summarized by the statement that proton linacs for BeV energies are eminently practical. Electron linacs have demonstrated capabilities in this energy range, and their success seems transferable to proton machines. Serious proposals for construction of BeV proton linacs can be expected during the next few years.



Artist's conception of the layout of the two-mile linear accelerator now under construction at Stanford university. This machine will raise electron-linac energies to the 20–40-BeV range.