THE STANFORD MARK III LINEAR ACCELERATOR AND SPECULATIONS
CONCERNING THE MULTI-BEV APPLICATIONS OF ELECTRON LINEAR
ACCELERATORS

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(presented by R. B. Neal)

I. Introduction

In the history of the use of particle accelerators in high-
energy physics, many different machines have contributed
valuable results. It is, in fact, the multiplicity of results
made possible by machines of diverse characteristics that
has, in a few short years, led to at least a semi-quantitative
understanding of an entire new field of physics: what is
now called ‘classical’ pion physics. Let us briefly examine
this process.

Pions were produced, first, by heavy-particle machines
and some of the systematics of production studied. How-
ever, real progress in the understanding of pion phenomena
was attained when (a) the heavy-particle machines became
sources of pions for scattering and absorption experiments,
and (b) the production processes of pions were studied in
the electron (x-ray) machines. The reason for this se-
quence is easy to understand: the larger cross sections
for new particle production by heavy particles make pro-
ton accelerators more copious sources of such reaction
products. On the other hand, the production process of
new particles by photons is basically a simpler one to ana-
lyze since the final state in photopion production is just
the nucleon-pion system, while in heavy-particle reaction
we have a three-body interacting complex. This dis-
cussion is just an example of the utility of diverse machines
in attacking a given system. We are convinced that in the
future diversity of incident particle, beam geometry, beam
currents, beam energies, and beam programming in time
will continue to be a more fruitful approach than the search
for a ‘best’ machine for all purposes.

It is very unlikely that the relative suitability of electron
and heavy-particle machines will continue to come into
play in the same specific manner as it has in its application
to pion physics. On the one hand, the multiple-production
processes will make the complexities of photon-induced
and heavy-particle-induced processes comparable. On
the other hand, the utility as new-particle producers
depends primarily on attainable currents; in this respect,
electron accelerators are becoming highly competitive and
will become more competitive as energy is increased. In
addition to these considerations, there is a further point
that emerges principally as the result of work with the
Stanford Mark III linear accelerator: The electron is an
ideal tool for exploring the shape of nuclei and nucleons since
one explores an unknown structure with a known (electromagnetic)
interaction. Elastic electron
scattering explores nuclear structure; inelastic scattering
leading to the production of new particles leads to a study
of such production processes, both as a function of energy
and of momentum transfer.

One of the basic reasons for pushing electron machines
to higher and higher energies is the study of the electro-
magnetic interaction itself. This requires formally not
only a high energy, but specifically a high ‘collisional
momentum’, i.e., a high momentum transfer in electro-
magnetic interactions. This means that such studies
require the investigation of electromagnetic processes at
large angles where the cross sections are very small; hence
high current becomes again a very important matter.

As a result of these and similar considerations, we believe
that in any future very-high-energy machine program,
both heavy-particle and electron accelerators should be
included. It is for these general reasons that the Cam-
bridge Accelerator Project is proceeding with a design of
a strong focusing electron synchrotron that would push
that type of machine to its practical limit. Where this
limit is precisely is still subject to further study and experi-
mentation and is also to some extent set by economic
considerations; suffice it to say here that it appears at
present that the coupling of quantum fluctuations in the
emission of radiation of a particle traversing a circular

* The research reported here was supported under contracts with the Office of Naval Research and the U.S. Atomic Energy Commission.
TABLE I
Characteristics of electron accelerator types

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Linear electron accelerator</th>
<th>Circular electron accelerator</th>
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<tbody>
<tr>
<td>1. Attainable energy</td>
<td>Unlimited</td>
<td>7-8 Bev</td>
</tr>
<tr>
<td>2. Attainable electrons per pulse</td>
<td>Depends on choice of frequency; 10^{13} epp at λ = 10 cm.</td>
<td>Function of injection, primarily; might become as high as 10^{13} epp.</td>
</tr>
<tr>
<td>3. Repetition rate</td>
<td>Limited by economic considerations; 60 cps used now; 180 cps is reasonable.</td>
<td>Limited by economic considerations.</td>
</tr>
<tr>
<td>5. Operating cost</td>
<td>At present, linear-accelerator operating costs are about twice circular-machine costs. Will be reduced as r-f sources become cheaper.</td>
<td></td>
</tr>
<tr>
<td>6. Pulse length</td>
<td>~ 1 μsec., or less.</td>
<td>Essentially as long as desired at expense of energy spectrum. Short pulse possible by means of special devices.</td>
</tr>
<tr>
<td>7. Variability of energy</td>
<td>Excellent.</td>
<td>Fair.</td>
</tr>
<tr>
<td>8. External electron beam</td>
<td>Available and free from contamination.</td>
<td>Has not been achieved in high-energy machines.</td>
</tr>
<tr>
<td>9. X-ray beam</td>
<td>Available at high yield.</td>
<td>Available at yield limited by scattering out of internal target.</td>
</tr>
<tr>
<td>10. Energy spectrum</td>
<td>ΔE/E = 2-4 percent unless energy analyzed. Can be improved by adequate design.</td>
<td>Very narrow unless long pulse is needed.</td>
</tr>
<tr>
<td>11. Multiple-target arrangement</td>
<td>Very flexible.</td>
<td>Limited unless beam can be extracted</td>
</tr>
</tbody>
</table>

orbit to the betatron oscillation will probably set a limit of 7-8 Bev. For this reason, the electron linear accelerator offers the only known solution for accelerating electrons to energies above this value.

The merits of various kinds of electron accelerators for experiments in physics research depend on many factors, summarized in Table I. Clearly, such a table will tend to over-simplify some of the questions involved, but it will serve to give a general impression. Of the factors presented here, the outstanding disadvantage of the linear accelerator is the short pulse length; the outstanding advantage is the unlimited energy and favorable beam geometry.

Experience at Stanford has shown that although the short pulse length of the linear accelerator is in general a disadvantage, it can be overcome by proper design of experiments. A good duty cycle is primarily desirable to achieve discrimination in time by coincidence methods or to avoid pile-up of pulses that interferes with discrimination by pulse height. The use of double-focusing magnet systems makes it possible to shield the detectors from the sources of background radiation without large sacrifice in solid angle; hence, time discrimination and pulse-height discriminations are possible despite the small duty cycle. The short pulse length can be turned to advantage by the use of decay periods of artificially-produced unstable particles to count the decay products after the beam pulse of the machine. Also, 'time-of-flight' measurements are possible by counting after the beam pulse. In these cases, the duty cycle is not important, but a high repetition rate remains highly desirable.

We conclude, therefore, that the high-energy electron linear accelerator is at present the only machine known
to be capable of accelerating electrons above the synchrotron limit. Its operating characteristics are such that high-energy physics research even with very small cross sections is very successful. However, the techniques used in such experiments must be adapted to the small duty cycle of the machine.

II. General considerations

There seem to be no fundamental difficulties barring the extension of linear electron accelerators to the range of energies of 10 to 25 Bev. The design of certain features becomes more critical as we go to higher energies, and it is our purpose to discuss these and to give an account of some possible solutions. At the outset, we can state confidently that an accelerator capable of producing thirty times the energy of the Mark III accelerator (designed to produce 1-Bev electrons) can be built and made to work. Our concern is not with theory but with practical questions having to do with cost of construction and maintenance of the completed machine.

At this time, the Mark III linear accelerator is the highest-energy linear accelerator in operation, so that any decisions concerning future machines must rest heavily on the performance of the Mark III installation.

A. Description of the Mark III accelerator

The design features of the Mark III machine have been fully described in a recent publication. We will summarize the design here in order to make the discussion of performance intelligible.

The accelerator consists of 21 individual accelerator units, each 10-ft long and fed from its own power source. The units are entirely independent with the exception of the mechanism of a common drive for the amplifiers feeding power to the units.

The electrons are injected into the first section at an energy of about 80 KeV. Excepting for the first 2 ft., in which about 4 Mev is reached, all remaining sections are identical since operation is completely relativistic.

Each accelerator section consists of a waveguide operating in a TM mode periodically loaded such that the phase velocity is c while the group velocity is about 0.01 c. Since the particles are completely relativistic, their velocity is essentially c also, and continuous acceleration results. No phase stability in the usual sense exists; since the structure is highly dispersive (the fractional change in phase velocity is 100 times the fractional change in operating frequency), the correct phase velocity is determined by the frequency setting. We assume here, of course, that the accelerator is designed and constructed to sufficiently high tolerance that the same frequency will give essentially the same phase velocity for all sections (see ref.3, p. 144). Each 10-ft section is fed separately from phase-adjustable sources; hence, the frequency tolerance is defined by the phase slipping permissible in each 10-ft section.

In completely relativistic operation, there is no radial stability or instability in the sense that the radial magnetic and electric forces cancel. Hence, the radial momentum of the particle is a constant of the motion while the longitudinal momentum increases linearly. The angular divergence thus varies inversely as the axial distance and the beam diameter spreads logarithmically.

Each 10-ft section is fed through a coupler that transmits r-f power from a standard waveguide, but at the same time cuts off the power from the previous section. The feeding waveguide is connected via a ceramic window to the output guide flange of a high-powered pulsed klystron.

The operating frequency of the klystron driving source is 2356 Mc/sec., and the klystron beam power is pulsed on 60 times per second for a duration of 2 μsec. The accelerator structure will fill with r-f energy in a time \( t = l/v_g \), where \( I \) is the length of each section and \( v_g \) is the group velocity; this number is here 1.0 μsec. Thus only one half of the applied ‘klystron-on’ time is useful for acceleration. The end of each 10-ft section is not terminated; hence a reflection from the end of each section will reach the klystron just at the end of each pulse; ideally, then, the klystron sees a matched load throughout its pulse time. The attenuation length is such that the power lost by not utilizing the r-f energy remaining at the end of each section is about 10%.

The klystrons are ideally operating at powers up to 30 Mw peak; actual performance will be discussed below. The klystrons have a power gain of about 1000. They are driven with a common coupling guide from a 1-Mw klystron amplifier. This tube in turn is driven at present by a cavity-stabilized magnetron.

The first two feet of accelerator are not sufficiently relativistic in operation such that the above remarks concerning the beam behaviour apply. In the sub-relativistic region the magnetic and electric forces do not quite cancel; hence a set of external magnetic lenses is used for focusing. The first section (buncher) is operated phase stable; the resultant phase oscillations are damped; the result is an acceptance r-f phase angle of about 200° ‘bunched’ into a phase angle of about 20°; the phase spread remains constant in the relativistic part of the machine.

The gun consists of a bombarded tantalum hollow cathode in a focusing structure pulsed directly by a line-type pulse generator to a voltage of 80 KeV and a pulse length variable from 0.05 to 0.6 μsec.

B. Operating performance

Table II presents the operating record during the last 22 months when records were kept. During this time and the two preceding years the machine has been used in physics research to the extent indicated. Note that the time useful to physics research has been steadily increasing.

The time not used for physics research is divided among tune-up of the machine and actual down time due to
TABLE II
Summary, Mark III operation

<table>
<thead>
<tr>
<th>Period</th>
<th>Total operating hours</th>
<th>Experimental time</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Hours</td>
</tr>
<tr>
<td>May 1954-October 1954 (6 months)</td>
<td>2314</td>
<td>1329</td>
</tr>
<tr>
<td>November 1954-April 1955 (6 months)</td>
<td>2304</td>
<td>1764-1/₄</td>
</tr>
<tr>
<td>May 1955-October 1955 (6 months)</td>
<td>2331-1/₁₄</td>
<td>1789-1/₂</td>
</tr>
<tr>
<td>November 1955-February 1956 (4 months)</td>
<td>1582-1/₄</td>
<td>1246</td>
</tr>
<tr>
<td>Total, period May 1954 through February 1956</td>
<td>8532-1/₈</td>
<td>6129</td>
</tr>
</tbody>
</table>

breakdowns of various kinds. It can be stated as a general comment that essentially all causes of lost time are attributable to insufficient maintenance or to minor engineering defects; no troubles of a fundamental nature are encountered. In particular, the process of adjusting the phases of individual sections has not given any difficulty and is not anticipated to give increased trouble for a longer length. The reason for the operating voltage failing to reach the design value is not attributable to phasing errors.

The life of the r-f sources imposes the most serious concern. The klystron amplifiers now being used on the Mark III accelerator have an average operating life of about 1000 hours. Figures 1 through 4 show our tube life experience on the Mark III accelerator to date. The remarkable thing is that the life in 'elapsed time' has remained constant as the operating life has been improved. We attribute this phenomenon to an effective 'shelf life' of the tube. This life is probably terminated by contami-

Fig. 1. Operating hours per month, Mark III.
nation of the oxide-coated cathode by oil vapor from the diffusion pumps. We are encouraged to believe that a sealed off version of this tube will remove this source of ultimate failure. It is the uncertainty in the future life improvements on the klystrons that makes the prediction of the operating costs of a multi-Bev machine difficult at this time.

One of the primary causes of imperfect performance is the r-f contacts between single (2-ft. long) accelerator sections. These cause arc-over and consequent gassing at high levels and also give rise to reflections. These reflections change the impedance seen by the klystrons as a function of time and thus the energy output is not entirely constant during the beam pulse. It is this mismatch due to imperfect r-f contacts that is principally responsible for the disparity between the useful klystron power in the Mark III machine (about 10-12 Mw on the average) and the performance of the tubes when working into a matched load.

There are several other imperfections that broaden the spectrum: among these are (a) frequency modulation of the primary frequency source (pulsed magnetron); (b) lack of uniformity of pulse height applied to the klystrons during the pulse; (c) imperfect buncher action. All these matters could be improved under sufficient incentive. The spectrum at present is about 3/4 wide at half-maximum current; the double-deflecting system fixes the energy and energy band actually used by the experimenters.

The beam current available is generally a μamp unanalyzed beam, or 10¹¹ electrons per pulse. The beam actually available to the experimenter is less than this depending on the amount of energy analysis required. The beam is limited essentially by the loading characteristic of the first section. It is a matter of interest to note that the number of electrons per pulse decreases slower than linearly as the pulse length is decreased from 0.6 μsec. to 0.05 μsec.; this implies that the loading of the first section is related to the energy storage in the accelerating
field and not to the power flux fed into the accelerator. The result is of practical interest since it gives favorable conditions for time-of-flight work and work with short meson decay periods.

Maximum beam energy available thus far is 660 Mev. We believe that this figure can be substantially increased if the r-f contacts referred to above are improved.

The Stanford Mark III accelerator should not be considered as a prototype or pilot model for a multi-Bev accelerator. To expedite the completion of a machine capable of producing electrons in the range of several hundred Mev, the design of the Mark III machine was frozen before sufficient experience had been obtained with lower-energy accelerators either in the United States or abroad. Consequently, some of the auxiliary components constitute temporary solutions that served to expedite initial operation of the machine. Some of these components have been improved or replaced over the past five years; others are systems so interwoven with the over-all design of the machine that replacement or substantial improvement is involved and costly, and these remain essentially unaltered. Certainly, a new and higher-energy machine should not duplicate those features of Mark III that are considered inadequate.

Other design features that are perfectly satisfactory for the Mark III accelerator will prove to be unsuitable for a longer, higher-energy machine. Considerable engineering effort will be necessary to simplify the operation and maintenance of such a machine. The field of automation will have to be called on to handle such functions as vacuum controls and interlocks, beam steering, degaussing, electron-energy and -current control, electrical connection and removal of klystrons, and so forth. At the same time, the control system must be kept simple enough that reliability and maintenance need not be impaired.

Since a multi-Bev accelerator will differ in many engineering details from the Mark III machine, it is difficult to extrapolate costs and in particular operating costs to a multi-Bev structure. The increased need for automation and reliability of components will increase the unit cost; on the other hand, the large number of identical components needed for a large machine can be produced at a lower unit cost. Since the quantitative balance of these two factors has not been evaluated, we will resist the temptation to estimate detailed cost figures of a multi-Bev machine by simply extrapolating Mark III performance; however, we will discuss technical features of such a machine.

III. Technical considerations

A. Power-to-length ratio

The energy electrons from a linear accelerator is given by

$$V = (P L R')^{1/2}, \quad (1)$$

where $P$ is the total peak power applied to the machine, $L$ is the total length, and $R'$ is the total effective shunt impedance. The term $R'$ differs from $R$, the total shunt impedance, because of the non-uniform excitation due to the use of the accelerator itself as a feed structure. From the form of (1), it has been pointed out that the most economical design of a linear accelerator occurs when the cost of the equipment and components pertaining to the supplying of r-f power (e.g., power supply, pulsers, kly-
strons) is equal to the cost of times depending on accelerator length (e.g., building, site, accelerator tube, vacuum system, radiation shielding). To be meaningful, these cost figures should cover not only construction but also a period estimated to be the useful life of the machine. In almost every case, this will increase the power-proportional costs much more than the length-proportional costs. Fortunately, the cost curve has a broad minimum so that for fixed electron energy it is not disastrous to deviate slightly from the above rule.

The form of the cost equation is

\[
\frac{C}{C_{\text{min}}} = \frac{1}{2} \left( \left( \frac{C_p}{C_L} \right)^{1/3} + \left( \frac{C_L}{C_p} \right)^{1/3} \right),
\]

where \(C/C_{\text{min}}\) is the ratio of actual to minimum cost (excluding fixed costs), and \(C_p\) and \(C_L\) are the costs of power-proportional and length-proportional components, respectively. A plot of this equation is shown in fig. 5. If \(C_p/C_L\) (or \(C_L/C_p\)) equals 4, the value of \(C/C_{\text{min}}\) becomes 1.25; that is, for fixed energy, the length (and power) can deviate from the optimum value by a factor of 2 with only an increase of 25% in the machine cost.

Another observation is that a reduction in the cost of either power or length by a certain factor \(F\) (by, say, simplified design or mass-production methods, will result in a reduction in the over-all cost by the square root of the factor, provided length cost and power cost are kept equal. On the other hand, if the machine length is fixed and the reduction by a factor \(F\) in power cost is made subsequently, the over-all cost is reduced by a factor \(2F/(F + 1)\).

As shown above, a moderate deviation from the economically optimum power-to-length ratio does not add greatly to the cost of the machine. However, the added convenience resulting from the reduction in machine length, from, say, 2 miles to 1 mile, might be worth the 25% increase in cost. There are other disadvantages of a high power-to-length ratio: (1) The beam optics problems become somewhat simpler as the energy gradient is increased; (2) The expected reduction in power (replacement) cost over the years should make the machine design tend toward the optimum power-to-length ratio; (3) A machine with a higher power-to-length ratio can be more heavily beam-loaded (the current is proportional to the square root of the power per unit length for a given degree of beam loading).

However, there are cogent arguments supporting the adoption of a power-to-length ratio equal to or less than the economically optimum. (1) There should be less difficulty with r-f breakdown in such a machine than in one more heavily powered; (2) Maintenance of the machine and down time should be reduced since components in the ‘length’ column require less maintenance than those in the ‘power’ column; (3) A future reduction in power-related costs should make feasible an increase in energy of the machine if r-f fields are originally well below the breakdown level; in a ‘power-heavy’ machine, however, an increase in energy is more difficult. Presumably, more power cannot be added without increasing length because of electric field limitations; it may be quite costly to increase length because of site limitations.

The maximum power per unit length that can be used is determined by the maximum value of electric field that can be achieved in the accelerator without resulting breakdown. The Mark III accelerator now operates with an average gradient of 3 Mev/ft. It is now known that an average gradient at least twice this value can be maintained. Means of attaining higher gradients will be discussed in a
later section. The maximum gradients now attainable are on the high-power side of the optimum design based upon present-day cost analysis of the Stanford accelerator. Nevertheless, these gradients are economically within the range of feasibility and are therefore of current interest.

B. Beam dynamics

Previously, we have discussed beam dynamics as referred to the laboratory system, pointing out that an angular beam divergence at the origin produces a logarithmic rather than a linear displacement. The situation may also be regarded from the electron system. In the electron frame of reference, the length of the accelerator $l_0$ is much less than the length $l$ in the laboratory system. The ratio of these lengths is given by

$$l_0/l = \ln \gamma / \gamma - 1,$$

where $\gamma = (m_e c^2 + V) / m_e c^2$, and $V$ is the final kinetic energy of the electrons. In fig. 6, we have plotted the foreshortened length $l_0$ against final energy for several values of the average energy gradient $k = V/l$. For the Stanford Mark III accelerator, $l = 210$ ft., and $V = 650$ Mev; the contracted length $l_0 = 14$ in. When the electron reaches the 5.6-ft. mark in the laboratory system, it has gone half the total distance in its own system. A machine having 30 times the length and energy of the Mark III machine would have a contracted length of 20.9 in. and the half-length in the electron frame would lie at 32.3 ft. in the laboratory system. Thus, the effective length is increased by only a factor of 1.5 while the machine length and energy increase by a factor of 30. The effective half-length lies at the position where the energy is one half of one percent of the total energy in a 20-Bev machine.

For a given final energy, the effective length is inversely proportional to the energy gradient. This suggests making the machine as short as the electric-breakdown and cost considerations will permit. If cost or other considerations discourage a high gradient over the entire machine length, it would still be very beneficial to make the gradient high over the first 1 or 2% of the machine length.

While the relativistic length of the accelerator in our example is less than 2 ft., the transverse dimensions of the aperture are relativistically unaltered. This explains why we can speak confidently of transmitting an electron beam through an aperture of less than 1 in. over a distance of a mile or more.

C. Power sources

The most logical power source remains the klystron amplifier. These are the only tubes available at this time with the necessary power ratings and stability.

The klystron amplifiers used with the Stanford accelerator have produced peak powers of more than 30 Mw when run into a dummy load. When operating with Mark III, their maximum output has been limited to the range of 10-15 Mw by the onset of gassing within the accelerator and waveguide structures. Under better conditions they have supplied somewhat more than 20 Mw.
into the Mark IV accelerator,* again being limited by load gassing. These tubes have been operated only at 60 pps and at pulse lengths of 2 μsec.

The average operating life of these tubes is now around 1000 hours. In addition, they have a life of 4-5 months that seems to be independent of operating time. It has been postulated that the limitation of shelf life is due to the gradual contamination of the klystron cathode by vapors from the diffusion pump that escape capture in the liquid-nitrogen trap. This conjecture has not been proven, but further light should be shed on this subject in the near future by comparison of the life of sealed-off and continuously-pumped tubes. Several klystrons have been successfully sealed off independent of vacuum pumps and have given good service. It is too soon to estimate the operating life of these tubes, but the shelf life already shows promise of improvement. Only sealed-off tubes have been used with the Mark IV accelerator, and most of the experience so far obtained with these tubes has been with this machine. It is planned to run some of the sealed-off tubes on the large accelerator to afford a more direct comparison with the continuously-pumped tubes under similar operating conditions.

Duty cycle. — While the Stanford high-power klystrons have been run at a low duty cycle (1.2 × 10⁻³), it is believed that this figure could be materially increased. The maximum peak current density from the oxide cathode is 4-5 amp/cm², which is conservative. A smaller 2-Mw sealed-off klystron developed at Stanford with approximately the same current density has been run at pulse lengths up to 10 μsec with good life. It should be remarked that the shelf life of this smaller tube has also been good, some performing normally for periods of well over a year and several thousand hours of actual operation. In almost all cases, the life of these smaller tubes was terminated by their becoming gassy, not by emission failure. As far as the cathode is concerned, we see no reason why the high-power tube could not be operated with an increase in repetition rate and pulse length by a factor of 5 each, giving a duty cycle of 0.003. It would be necessary to redesign the collector of the tube to prevent overheating. Sweeping the beam after it has passed the last cavity so that it is spread out over a large, well-cooled collector is one method by which the residual beam power could be handled. The drift tube and cavities would have to be redesigned and vulnerable, difficult-to-cool parts hidden to prevent beam interception and melting of the structure. In the present tube, 10% of the beam is intercepted before passing through the output cavity. Instantaneous heating is the most difficult to combat and for this reason a higher repetition rate could probably be more successfully achieved than a longer pulse length. Moreover, it would probably be more economical in other ways: an increase in repetition rate can likely be made without increasing the size of the pulse-transformer core, whereas an increase in pulse length would require a larger and much more expensive core. The same holds true with the pulse line condensers: the existing condensers could be run at several times the present repetition rate without overheating; however, the number of condensers would have to be increased proportionally to the increase in pulse length.

The problem of window failure will have to be better understood before the development of high-power, high-duty-cycle tubes can be undertaken with confidence. Indeed, it remains the most serious problem with tubes of the present design and seems to be one of the most important factors limiting the further extension of tube life. Window life was greatly increased by locating the window to prevent a line-of-sight path between output cavity and the window. This prevented bombardment of the window by stray electrons from the tube. The cause of current window failure is not understood. It is not known whether breakdown is due mainly to peak power (i.e., high fields), average power (i.e., excessive heating), bombardment by γ-rays, or field-emission electrons, or to some other phenomenon. Higher duty cycle would, of course, affect window life little or considerably depending upon which phenomenon is acting. If higher duty cycle is considered all-important in the design of a high-energy accelerator, it is always possible to use multiple windows per tube, but this is a complication one would like to avoid.

Maximum power per tube. — There are some advantages to using a smaller number of tubes with higher peak power per tube. Maintenance should be less complicated as the total number of tubes powering the accelerator is decreased. Over a considerable range in power, the cost of manufacturing a tube is roughly independent of its power rating since the total number of operations involved in manufacture is approximately constant with variation of power rating, and labor not material largely governs the cost of a tube. Similarly, reprocessing costs do not vary rapidly with tube size and power. As far as tube costs are concerned, the important factor is life in megawatt-hours, and if two tube types are equivalent on this basis they should be approximately equal on a cost basis for use with accelerators.

A practical limit in the useful power output from a single tube source is reached when the power becomes too high to be handled in the accelerator. Of course, the power from a tube can be divided by a hybrid junction and sent to two or more accelerator sections in order to keep the power handled by a single section less than any desired value. The difficulty with this scheme is that it would be necessary to use high-power phase shifters to adjust the phase of the r-f power entering each section. These are vacuum devices and are more complicated, cumbersome, and expensive than the low-power phase shifters suitable for use at the input to the klystrons. The maximum power

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* The Mark IV accelerator is a 20ft machine powered by two klystrons. It is designed as a test vehicle for the improvement of accelerator performance.
that can be handled in an accelerator section is roughly proportional to the group velocity in the structure if electric field is the limiting factor. There seems to be no reason why powers in the range of 50-100 Mw could not be accommodated in an accelerator structure if the group velocity is made sufficiently high, say, 0.1 c. The machining tolerances become less stringent in this case, since they vary as the square root of the distance between feeds. The disadvantage of using higher group velocities is that the shunt impedance falls off: for example, the electron energy drops to 80% if the group velocity increases from 0.01 c to 0.1 c for fixed power and length.

There are three ways in which the tube power might be further increased: (1) increased efficiency, (2) increased perveance, and (3) increased beam voltage. The Stanford tubes now have an average efficiency of 35%, a perveance of $1 \times 10^{-6}$ amp/volts$^{3/2}$, and a beam voltage of 400 kV. The efficiency could be increased to around 40% by improving beam transmission. Increasing perveance is possible since the cathode emission density is on the conservative side; however, this will require a closer cathode-anode spacing or a larger cathode button. Each of these changes involves design ramifications that cannot be dealt with here. Increasing beam voltage involves some of the same problems (i.e., increased voltage gradient), and in addition means increased drive power due to relativistic reduction in the velocity-modulation coefficient. For example, increasing the beam voltage from 400 to 600 kV calls for an increase in r-f drive power by 95% if the drift distance remains constant. With any method of increasing the output r-f power, the window problem will have to be confronted. In spite of formidable difficulties, there seems to be a good chance that the power from klystron amplifiers can be substantially increased. A reasonable increase in all three parameters will likely be found most feasible.

Even if klystron tubes of increased power are not considered feasible for multi-Bev accelerator applications, experience with higher-power tubes constructed for other purposes should contribute to the increased reliability and life of lower-power tubes.

D. Injection

The problem on injecting electrons into the accelerator is essentially the same regardless of length. It is important that the injected beam be of small diameter and that it be aimed correctly. The displacement errors at the end of the accelerator are proportional to the original errors and inversely proportional to the energy gradient in a machine of fixed energy. Injection should not be a serious problem in a multi-Bev linear accelerator.

E. Space-charge forces

The space-charge forces have practically the same dependence on $\beta$ as the electromagnetic forces. Both approach zero as $\beta$ approaches unity. In the case of the Stanford accelerator, for a peak current of 0.16 amp, we calculate that the space-charge forces are less than one fourth of the electromagnetic forces even with a rather unfavorable choice of parameters. We conclude that space-charge forces need cause us no concern since electromagnetic forces themselves produce a rather weak effect.

F. Alignment and stray magnetic fields

We are combining these two subjects here since the effects of misalignment of the machine and of stray magnetic fields are very difficult to distinguish. This fact can be turned to advantage, however, by the use of steering coils and beam detectors placed at a few points along the machine.

The fact that we believe that the effects of alignment errors and stray fields can be 'steered out' does not obviate the necessity of minimizing such effects to start with.

The accuracy to which the accelerator must be aligned does not impose severe problems, but time should be taken to engineer an alignment system that is quick and simple to use. The Stanford accelerator system is not adequate for a larger accelerator. Either a telescopic system or a stretched-wire technique should suffice. The allowable deviation from a straight-line path depends upon the location of the discrepancy along the accelerator: a lateral error of the accelerator in an early region is much more serious than the same error in the latter part of the accelerator; the resulting electron displacement is inversely proportional to $\gamma$ at the point of misalignment. This argument assumes that the energy gains in the contiguous misaligned sections are the same. In this case, the transverse momentum compensation is perfect and a net displacement exists only because the electron is less massive in the earlier section. Of course, in no place should the misalignment of an accelerator section be allowed to become large enough to cause the beam to strike the walls locally. An alignment accuracy of a few tenths of a centimeter throughout the length of the machine is needed.

In a machine of the length contemplated, the curvature of the earth must be taken into account in the design of the mounting system. The variation of the height above sea level over the accelerator length (assuming tangency to the earth at the origin) is around 32 in. for an accelerator length of 2 miles. The height difference varies as length squared for other lengths; it can be divided by 4 by making the tangency point the center of the accelerator. This problem can be dismissed as of little consequence.

Unlike electromagnetic and space-charge forces, the deflecting forces due to the earth's magnetic field and other stray fields do not vanish as $\beta$ approaches unity. The displacement of the electron field in a field of B gauss is given approximately by

$$D \approx \frac{3}{10^4} \frac{B}{k^2} \ln \frac{V}{V_1},$$

(4)
where $V_i$ is the electron kinetic energy at the starting point where the electron is assumed to be perfectly aligned, and $k$ is the average energy gradient along the machine. The allowable field (if no spot corrections are applied) is thus approximately proportional to $k^2/V$ (or to $k/L$). For a 20-Bev machine with $k = 3$ Mev/ft., the field must be reduced to about 1/3600 gauss to prevent the beam's striking the loading disks. For an earth's field of magnitude 0.5 gauss, the required shielding factor is 1800. This must be increased to permit operation at reduced gradient. The magnetic field can be reduced by shielding the entire length of the accelerator with a cylindrical shield of high permeability. It would probably not be economical to achieve the entire reduction by shielding alone. The cost can be greatly reduced by using degaussing wires. To achieve greater uniformity in field cancellation over the entire accelerator aperture, the degaussing wires should be displaced laterally from the accelerator by a considerable distance. The required current through the wires is quite reasonable ($i = 1.25 B d$ amp, where $B$ is the magnitude of the compensating field in gauss and $d$ is the separation of the degaussing wires in cm.), and if magnetic shielding is provided to give a factor of $\sim 60$, the required current regulation is around 1%.

Care must be taken to minimize stray fields from neighboring power lines. Large current loops should be avoided. Variations of the earth's field by as much as 0.002 gauss have been observed on rare occasions; this will be taken care of by the shielding, assuming a factor of 60 is provided.

Experience with the Mark III accelerator has shown that 'spot steering' can compensate for considerable alignment and magnetic errors. We therefore propose to insert 'detector sections' into a large accelerator where a fluorescent screen can be inserted remotely and the beam steered to a point on the screen. This can also be accomplished automatically by radial pickup electrodes feeding signals into the steering-coil control system.

The 'detector sections' should also incorporate a rudimentary analyzing magnet. This is necessary since 'phasing up' the machine requires cutting in the machine section by section; the beam from just the first few sections could not be expected to be detectable at the machine's end station; the magnetic shielding requirements would be excessive.

Mark III experiences has shown that only two very simple magnetic quadrupole strong-focusing lenses can produce a very small spot at the 220-ft endpoint of the machine. The quadrupoles are adjusted with reference to a beam image on a fluorescent screen. Such lenses could be adjusted for a long machine via the remotely inserted fluorescent screens.

We conclude that alignment and the control of stray magnetic fields can be accomplished without greatly improving the techniques now used. However, a system of point-steering coils and remotely-operated detector stations is necessary.

G. Energy gradient

It is our opinion that the choice of energy gradient is governed by considerations of economics, future expandability and conversions, rather than by physical limitations. We are coming to this conclusion through the realization (see Table III, No. 1) that the present Mark III machine would be more economical if the power-to-length ratio were smaller. Since operating costs are principally power-proportional, the optimum length of a specific machine will tend to increase if the operating budget of many years is taken into account.

<table>
<thead>
<tr>
<th>No.</th>
<th>Machine Description</th>
<th>Energy</th>
<th>r-f peak power</th>
<th>Length</th>
<th>Average input power (including standby)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Stanford Mark III accelerator</td>
<td>0.65 Bev</td>
<td>210 Mw</td>
<td>210 ft.</td>
<td>400 kVA</td>
</tr>
<tr>
<td>2</td>
<td>Straightforward extention of Mark III by a factor of 30</td>
<td>20 Bev</td>
<td>6 300 Mw</td>
<td>6 300 ft.</td>
<td>12 000 kVA</td>
</tr>
<tr>
<td>3</td>
<td>Version attempting to balance length- and power-proportional costs</td>
<td>20 Bev</td>
<td>2 800 Mw</td>
<td>14 000 ft.</td>
<td>5 400 kVA</td>
</tr>
<tr>
<td>4</td>
<td>High-repetition-rate version of No. 3</td>
<td>20 Bev</td>
<td>2 800 Mw</td>
<td>14 000 ft.</td>
<td>16 200 kVA</td>
</tr>
<tr>
<td>5</td>
<td>Extreme example of version No. 3 expanded by adding power to achieve a maximum gradient . . .</td>
<td>70 Bev</td>
<td>35 000 Mw</td>
<td>14 000 ft.</td>
<td>66 000 kVA</td>
</tr>
</tbody>
</table>

† Does not include power required for experimental purposes.
TABLE III (cont.)

<table>
<thead>
<tr>
<th>No.</th>
<th>Maximum beam pulse length</th>
<th>Repetition rate</th>
<th>Ratio of power cost to length cost ( \dagger )</th>
<th>Relative cost</th>
<th>Maximum current limited by beam loading ( \dagger | )</th>
<th>Beam power</th>
<th>Ave.</th>
<th>Peak</th>
<th>Ave.</th>
<th>Peak</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1 ( \mu )sec</td>
<td>60</td>
<td>5</td>
<td>1</td>
<td>8 ( \mu )amp 130 ma</td>
<td>5200 W</td>
<td>85 Mw</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>1 ( \mu )sec</td>
<td>60</td>
<td>5</td>
<td>30</td>
<td>8 ( \mu )amp 130 ma</td>
<td>0.16 Mw</td>
<td>2600 Mw</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>1 ( \mu )sec</td>
<td>60</td>
<td>1</td>
<td>22.5</td>
<td>4 ( \mu )amp 65 ma</td>
<td>0.075 Mw</td>
<td>1300 Mw</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>1 ( \mu )sec</td>
<td>180</td>
<td>( \sim 1.65 )</td>
<td>( \approx 30 )</td>
<td>12 ( \mu )amp 65 ma</td>
<td>0.24 Mw</td>
<td>1300 Mw</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>1 ( \mu )sec</td>
<td>60</td>
<td>12</td>
<td>146</td>
<td>12 ( \mu )amp 200 ma</td>
<td>0.84 Mw</td>
<td>14000 Mw</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\( \dagger \) These are highly approximate figures based upon extrapolation of present-day cost figures over a 10-year operating period.
\( \dagger \| \) Maximum current is limited to \( \approx 1 \mu \)amp by loading in first section.

We have listed in Table III three potential 20-Bev accelerators. The first (No. 2), is simply thirty Mark III units cascaded. The second (No. 3) is a 20-Bev design modified to balance the length- and power-proportional costs. Number 4 is the same design, but operated at a higher repetition rate; this possibility would be of decided advantage to the physics program.

At this time, and probably for a considerable time to come, costs of r-f power will be highly uncertain. Hence it appears to us to be conservative to emphasize designs in which the length-proportional costs are dominant.

If it appears as the result of further extensive experience that the cost of r-f power is lessened, then it appears logical that a further expansion in energy should be attempted by increasing the input power. Machine No. 5 in Table III is an example of such an expansion applied to No. 3 without benefit of cost reduction of power.

A low energy gradient affects adversely the beam transmission properties; this can be remedied by building the first units of a low-gradient machine to be operated at a high gradient; these will thus constitute a high-current injector into the low-gradient machine. Also, there is a larger value of electron current available in the case of higher power per unit length.

Let us briefly outline the technical limitations on the energy gradient as they are known to us: The maximum energy gradient is limited by r-f breakdown inside the accelerator structure. The large Stanford accelerator now operates at an average gradient of 3 Mev/ft. The peak gradient at the input to each accelerator section is about \( 1^{1/3} \) times this value, or \( \sim 4.5 \) Mev/ft. This corresponds to an average power input of about 10 Mw per 10-ft. section, or 1.0 Mw/ft.

The average energy gradient may be increased while still remaining within an arbitrary safe limit, say 4.5 Mev/ft., by constructing a machine in which the field strength remains constant throughout. The dimensions of such a machine must vary constantly or stepwise over the length of each section to accomplish this result. In this manner, the average gradient per unit length can be increased 50%. The power required increases to 22 Mw per 10-ft. section.

It is not certain at this time that the r-f breakdown conditions that have been observed with the large Stanford accelerator are basic accelerator limitations. Present feeling is that the main source of breakdown has been poor contact between the 2-ft. accelerator subsections and at the joints in the waveguide transmission lines. Experience with the Mark IV accelerator, where more care was taken to obtain good contact between subsections, has to some extent verified this opinion. A peak energy gradient above 6 Mev/ft. has been obtained with this machine. Arcing at the waveguide flanges continues to be a problem with Mark IV, but there is good reason to believe this can be simply overcome by the use of slightly more sophisticated flanges.

H. RF drive

In contrast to heavier-particle linear accelerators, the problems in the design of a suitable drive line become only slightly more complicated as the machine length increases. There is no difficulty with phasing due to variations of particle velocity. The electron velocity is essentially the velocity of light over most of the machine length. The amount by which an electron starting from rest and accelerated uniformly to high energy lags behind a wave traveling at the velocity of light is \( m_e c^2/k \), where \( k \) is the energy gradient. For \( k = 0.1 \) Mev/cm., which is a reason-

* The lag is given more exactly by

\[
\Delta s = \frac{\mu}{k} \left( \left( \left( 1 + \frac{V_2^2}{\mu^2} \right)^{\frac{3}{2}} - 1 \right) - \frac{V_2^2}{\mu^2} \right) - \left( \left( 1 + \frac{V_1^2}{\mu^2} \right)^{\frac{3}{2}} - 1 - \frac{V_1^2}{\mu^2} \right),
\]

where \( V_2 \) is the electron energy at the origin, \( V_2 \) the final energy and \( \mu = m_e c^2 \). This equation is quite insensitive to variation of \( V_2 \) in the high energy range.
able value for accelerators, the lag is about 5 cm. Ninety-nine per cent of this lag occurs before the electron attains 25-Mev energy. Thus, there is no serious variation in the electron schedule after it passes the first accelerator section even when the energy gradient is varied over a considerable range. The only problem, then, is to provide a drive line in which the phase velocity is accurately at the velocity of light and that has negligible dispersion. The allowed velocity change in the drive line over the operating frequency range is given by

\[
\frac{\Delta v}{c} = \frac{\varphi_e \lambda}{2\pi L},
\]

(5)

where \(\varphi_e\) is the permissible phase shift at any accelerator section, which is of the order of 0.1 radian. For \(\lambda = 10\) cm, and \(L = 1\) mile, the velocity change in the drive line relative to the velocity of light must be held to one part in 10^4, but only over a frequency range of one part in 5000. The tolerance becomes tighter for an increase in length or a decrease in wavelength. An evacuated coaxial line with small supporting beads or stubs should serve the purpose. An alternative might be free-space transmission using antennas. It would not be practical to transmit the entire drive power to all the klystrons. For example, the attenuation due to conductor losses in a 77-ohm copper coaxial cable, 8-cm. in diameter, and one mile long, is about 25 db. It will be necessary to transmit a low-level signal, perhaps CW, and to provide booster amplifiers located periodically along the accelerator length. Drive requirements could be eased somewhat by using 4-cavity klystron amplifiers, which have about 20 db more gain than the 3-cavity tubes with the Stanford machines.

I. Frequency

The choice of operating frequency depends upon a great many parameters, and this will now be discussed.

The shunt impedance per unit length varies as \(\sqrt{\omega}\), which indicates that the power required to achieve a given electron energy varies as \(1/\sqrt{\omega}\) for a fixed total length. The filling time of the accelerator varies as \(\omega^{-3/2}\). Thus the total energy required to fill the accelerator varies as \(\omega^{-3}\). The total energy requirement also involves the beam pulse length, but without any frequency dependence.

Machining accuracy and frequency tolerance also have a frequency dependence. For random frequency errors, it turns out that the energy loss is proportional to \((\delta\omega)^2/l\), where \(l\) is the distance between feeds and \(\delta\omega\) is the expected machining error. The interesting point here is that this loss is independent of frequency. The required machining tolerance is seen to vary as \(\sqrt{l}\). On the other hand, the allowable fractional frequency tolerance \(\delta\omega/\omega\) relaxes as \(\sqrt{\omega}\), while the absolute machining tolerance gets closer by a factor \(1/\sqrt{\omega}\) because the physical size is reduced. The temperature tolerance has the same frequency dependence as the absolute machining tolerance. The temperature of the accelerator structure must be held within about 1-2 °C at \(\lambda = 10\) cm. As pointed out previously, the drive line dispersion must be held closer as \(1/\omega\) as the frequency increases and the same applies to the temperature regulation of the drive line.

One of the disadvantages of higher frequency is that the aperture in the accelerator is reduced for a given structural shape. The aperture can be increased somewhat by resorting to r-f feedback schemes, but the gain here is small and one would like to avoid this complication if possible. Reduced aperture means that the degaussing, steering, and alignment problems, as well as the gun optics, become more severe.

In many accelerator applications, it is desirable to put as large a fraction of the available r-f energy into beam energy as possible. The use of higher frequencies and lower power would mean a reduction in the maximum beam current available.

The maximum power available from a single r-f source varies approximately as \(\omega^{-3}\). Of course, several sources can be paralleled if desired to give any reasonable amount of power, but as already pointed out, this may not be as economical as using a smaller number of higher-power sources.

The Stanford accelerator operates in the frequency range around 3000 Mc/sec. In this range, the available powers are sufficiently high and the physical size is convenient to handle during machining and testing procedures. Consider the various advantages and disadvantages of the higher- and lower-frequency bands, it can be stated that the 10-cm. band is well-suited for high-energy accelerator applications. There seems to be no reason to recommend a change at this time.

J. Gas scattering

The root-mean-square scattering deviation of the electrons from the axis is given approximately by

\[
(\bar{y}^2)^{1/2} \approx \frac{(E_e/k)}{\sqrt{T}},
\]

(6)

where \(E_e\) is a constant equal to 21 Mev, \(k\) is the average energy gradient, and \(T\) is the accelerator length expressed in radiation lengths. The radiation length in the accelerator is approximately \((2.5 \times 10^4)\) p cm. where \(p\) is the pressure expressed in mm. of Hg. In an accelerator 6300-ft long, with \(p = 10^{-5}\) mm. Hg., and energy of 20 Bev, the rms deviation \((\bar{y}^2)^{1/2} \approx 0.05\) cm., which is on the safe side. Loss of electrons from scattering should be quite small under the above conditions. However, there would be concern in a machine ten to twenty times this long, and it would probably be necessary to improve the vacuum by an order of magnitude.
K. Improvement in accelerator efficiency

There is reason to believe that by resorting to a somewhat more complicated accelerating structure, the shunt impedance $r$ may be improved, perhaps by a factor of two or more. Any improvement here will decrease the required power as $r^{-1}$ for constant electron energy. The over-all cost would decrease as $r^{-1/2}$ for the cost-optimized machine, or the electron energy would increase by $r^{1/2}$ in case of conversion of an existing accelerator. In the latter case, the improvement might be limited by field-breakdown considerations. Higher shunt impedance will reduce the maximum available beam current as $r^{-1/2}$ for fixed power or as $r^{-1}$ for fixed electron energy.

L. Physical arrangement

Experience with the Stanford accelerator has shown certain features of the general arrangement of components and facilities to be inconvenient or unsatisfactory. The following recommendations are based upon this experience: (1) The shops and offices should not be located in the same building or closely paralleling the accelerator as is the case with the Stanford machine. This complicates traffic and increases the magnitude of the radiation-shielding problem. (2) The radiation shielding should be designed to allow easy access to the accelerator. With the Stanford machine, it is necessary to remove the shielding blocks to work on the machine. (3) Further study will be required to determine the optimum shielding configuration. The maintenance problem is involved in this decision. If it is deemed advisable to replace faulty klystrons or to repair other auxiliary components while the accelerator is operating, adequate shielding must be provided between the accelerator and the klystrons and between adjacent klystron stations. In this case, it might be advisable to locate the accelerator in a trench. Such a shielding philosophy has been used with the Stanford Mark IV accelerator. This method is illustrated in fig. 1. If it is decided to shut down the machine periodically for servicing, it seems satisfactory to eliminate shielding between the accelerator and the klystrons and to locate all of these components in the same shielded enclosure. The shielding in this case could consist of earth-works pushed up parallel to the accelerator building with periodic tunnels leading to the outer buildings. At least a part of

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Fig. 7. Possible radiation shielding plan: trench.

Fig. 8. Possible radiation shielding plan: earth shielding.
the earth-works could be obtained from material excavated for the accelerator and pulser building, as shown in fig. 8.

If the terrain is not flat, the provision of a tunnel for the accelerator may be competitive in cost with other means of housing and shielding the machine.

(4) The vacuum system should be a compromise between the extremely segmental arrangement used with the Stanford accelerator and the opposite extreme, a single pumping station. A vacuum manifold should run parallel and near to the accelerator inside the shielding for good pumping speed. The use of the recently-developed combination pumps of the continuous-gettering and ion types should be considered to avoid the expense and irksomeness of liquid-nitrogen cold traps. Refrigerated traps are a possible alternative. Valves should be provided to isolate sections of the accelerator for leak hunting. Built-in leak detectors at intervals along the accelerator would pay off in convenience and should provide greater sensitivity since long connecting hoses and pipes could be avoided.

(5) The main power supply should be segmented as much as cost will permit. This is desirable to prevent a large amount of energy from being dumped at a point of failure. Also, it will permit the voltage to be decreased locally if necessary without materially affecting the final electron energy. Ideally, to aid in the cutting in and out of klystrons, each tube should have its own pulser and a suitable high-voltage circuit breaker to connect and disconnect it from its power-supply line.

(6) The Stanford machine is constructed with a minimum of non-accelerating length. It is desirable to leave space periodically for the provision of beam monitors, and possibly for other auxiliaries such as strong-focusing quadrupole magnets, collimators, and so forth.

(7) Space should be provided for an ample number of experimental stations at the end of the machine. Because of the time involved in setting up equipment, this can greatly extend the versatility and usefulness of the accelerator. Adequate shielding should be provided between experimental stations to allow personnel to work at idle stations with the beam active at another. The desirability of intermediate stations along the accelerator length depends upon the type of shielding used.

IV. Conclusions

A. There is excellent scientific justification based on past experience for pushing electron machines into the multi-Bev region also. At this time, the electron linear accelerator offers the only technical means of exceeding 10-Bev electron energy.

B. The electron linear accelerator has many advantages and disadvantages for experimenters relative to circular machines that materially affect the choice of experimental techniques.

C. We find no basic limitations standing in the way of construction of a linear electron accelerator in the energy range of 10 to 25 Bev or higher.

D. Linear accelerators are blessed (or cursed) with an excess of parameters that one may attempt to juggle and optimize. The long discussion of this report was an attempt to establish a preliminary basis for such efforts.

E. The major efforts in the development of a multi-Bev accelerator will have to be devoted to achieving ease of maintenance and ease of operation in the completed machine. These ‘housekeeping’ problems need careful study and evaluation before reliable dollar estimates can be made.

V. Acknowledgments

The authors wish to express their appreciation to their associates, Professor E.L. Ginzton, Professor R. F. Mozley, Dr. R. J. Debs, and Mr. J. H. Jasberg, for helpful discussions of the subject matter of this report; and to Miss L. Becker and Mrs. L. Waldron for assistance with the preparation of the manuscript and figures.

LIST OF REFERENCES

DISCUSSION

J. P. Blewett: I would like to make a comment on heavy ion linear accelerators for the GeV range. Concerning the advantage of relativistic shortening, one may say that protons have not this advantage, but have the advantage of phase stability.

Regarding the choice of frequency for the driving klystrons, it seems to me that the easiest problem is to obtain sufficient power. If, for example, the frequency were dropped from 3000 Mc/sec to 1000 Mc/sec, R.F. power would be increased by 70%, not including the filling time (this factor depends on ratio filling time to beam accelerating time). But machining tolerances would go down by 70% and the aperture would be much larger. The cathode area for klystrons would be raised by a factor 9. The cathode problem should be very simple.

E. G. Komar: (to M.G. White); could you explain why your accelerator weighs 8 times less than the Cosmotron?

M. G. White: The air gap is much smaller: 3" by 11", whereas in the Cosmotron it is 7" x 30"; the iron weight is up by a factor 10.

E. G. Komar: What made you choose such a small aperture?

M. G. White: This is a long story. We are now confident that a weak focusing machine of small aperture can be made to work provided one is careful with magnet design, injection and vacuum. This confidence was not justifiable when the Cosmotron was first built. Now that the Cosmotron and Bevatron and the Birmingham machines work exactly as predicted by theory we have no uncertainties regarding our ability to calculate performance. Also beam diaphragms experiments on the Cosmotron give direct proof that our pole tips of 3" x 11" will yield a large enough aperture. Our main problem is to make a very good magnet, and a vacuum of 10^-6 mm. of Hg. To reduce radial aperture requirements we depend upon running the radiofrequency on a high harmonic of the particle frequency, which reduces radial amplitude of synchrotron oscillations by \sqrt{n}, and on modulating the Van de Graaff energy such that injection is always on the equilibrium orbit, thus practically eliminating betatron oscillation due to injection errors.

R. B. Neal: I would like to comment upon the suggestion by J. P. Blewett of using a lower frequency (1000 Mc/sec instead of 3000 Mc/sec) in multi-Bev linear electron accelerators. The RF energy required during the filling time would be increased by a factor of 9 while the energy required during acceleration would increase by a factor \sqrt{3}. Thus, in a typical case where the beam is on for 1 \mu sec and the filling time at 3000 Mc/sec is 1 \mu sec the total RF energy requirement at 1000 Mc/sec would be greater by a factor of more than 5. While the technical problem of supplying this extra energy could certainly be met, the added operational cost would definitely be a drawback.

In the low gradient machine which we have described the power supplied by each klystron (located at 20 ft. intervals) is around 5 megawatts at 3000 Mc/sec. This is a conservative figure based on present day performance of these tubes which have produced up to 30 MW.

It is, of course, true that the aperture would be larger at longer wavelength. However, the aperture in the 3000 Mc/sec machine is almost 1 inch and we believe this is sufficient for good beam transmission. The corresponding lower frequency structure would weigh up to 9 times as much and would not be as easily handled during manufacture, test, and assembly.

We are not concerned with the machining tolerances at 3000 Mc/sec. Reverts due to machining errors were less than 1% during the construction of the Stanford accelerator. Also, we have had some successful experience in manufacturing accelerator structures at even higher frequencies (10,000 Mc/sec) where the required tolerances are even closer than at 3000 Mc/sec.

P. M. Zeidlitz: Two methods of phasing were described by R. B. Neal. Which one is the better?

R. B. Neal: We are still considering both of these methods. Perhaps they will be used together. For example, auxiliary guns and deflecting magnets at 250 ft. intervals might be used for initial phasing operations with the klystrons; afterward, the scheme of phase comparison between the RF wave and the electron beam could serve to maintain the proper phase conditions.

P. M. Zeidlitz: Please quote the results of the calculations of neutron fluxes by Panofsky.

R. B. Neal: With the existing Stanford machine, the neutron fluxes in an adjacent building 1000 ft. distant from the target area is somewhat more than the accepted tolerance. Preliminary calculations for a 20 Gev machine show that a shielding factor of 10^4 is necessary to make areas 1000 ft. from the target habitable.

R. L. Walker: 1) Can vacuum pumps be used to obtain 10^-10 mm. Hg? Our low temperature laboratory has experience with liquid Hydrogen pumps, but this kind of pump leads to quantities of liquid Hydrogen which are rather prohibitive.

2) Is the vacuum chamber of the synchrotron directly connected with the Van de Graaff or separated by a foil? If directly connected, how can you get the vacuum needed since a source of ions of 1000 \mu A admits cm^2/hour into the tube? In the second case, how with the foil, do you avoid processes of this type:

\[ H^- \rightarrow H^0 + e^- \]
\[ \rightarrow H^+ + e^- + e^- \]
3) What are the values of the effective cross section for the process:

\[ \text{H}^+ \rightarrow \text{H}^- + 50 \text{kV} \] in a source of \( \text{H}^- \) ions

and for \( \text{H}^- \) ions at 3 Bev before the beam is introduced into the storage ring?

\textit{M. G. White:} As a proof that it is not totally impractical to consider attaining a vacuum of \( 10^{-10} \) mm. of Hg, I remarked that I have actually seen an all metal vacuum system of 1/10 our expected volume which had been pumped down to \( 10^{-10} \) mm. of Hg by a single oil diffusion pump and a large quantity of liquid nitrogen. We believe that by use of an “Evapor-ion” pump (which uses no pumping fluid) and by making provision for outgassing all internal parts we can attain \( 10^{-10} \) mm. of Hg. without excessive consumption of liquid nitrogen.

With regard to gas flow from the Van de Graaff, the influx of gas can be controlled by passing the beam through a long, small bore channel. The big question is what will be the gas flux from the ion source at the top of the Van de Graaff. J. L. Tuck (Los Alamos) quotes a 2.2 \( \mu \)A source of \( \text{H}^- \) with a gas flow of 10 cc/hour. Weinman and Cameron \(^1\) quote 25 \( \mu \)A at 110 cc/hour. There is no question that large negative ion currents imply large gas flows and consequently difficult technical problems, but not as difficult as building a 50 Gev machine which would be needed to yield 7 Gev center of mass kinetic energy.

Certainly we cannot send an \( \text{H}^- \) beam through a foil separating the Van de Graaff from the synchrotron. The stripping cross section we assume for the range 3 Mev to 3 Bev is \( 10^{-17} \) cm\(^2\) based on extrapolation of a measured value of \( 2.5 \times 10^{-18} \) cm\(^2\) at 70 Kev.

We are aware of the fact that in the ion’s frame of reference there will be an intense electric field, given by \( E = 300 B \gamma \) volts/cm., which will tend to dissociate the ion. Rough estimates seemed to indicate stability at 3 Bev and 13,000 gauss. However, we have now performed a more nearly correct quantum mechanical calculation and find that while the neutral hydrogen atom is stable the negative hydrogen ion will quickly dissociate. An ion travelling through a field of 13,000 gauss will dissociate in 0.1 seconds at an energy in the neighbourhood of 30 Mev. It is clear that the feasibility of \( \text{H}^- \) acceleration in a magnetic field is confined to the region of a few tens of Mev.

\textbf{LIST OF REFERENCES}