LINEAR ELECTRON ACCELERATOR STUDIES

A.E.C. Contract AT(04-3)-21
(Project Agreement No. 1)

and

PROPOSED TWO-MILE ACCELERATOR PROJECT

A.E.C. Contract AT(04-3)-363

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1 July to 30 September 1961

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Project M

and

W. W. Hansen Laboratories of Physics
Stanford University
Stanford, California
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II. MARK IV PROGRAM

The Mark IV conversion program was continued during the past quarter and is now approximately 90% complete.

Essentially all the major components are in place and have been tested individually. All of the control room console instruments necessary for a preliminary beam test have been installed and final connections are being made. Modulator-ignitron pulse tests are underway using the trigger-generator source in the console.

The vacuum system and cooling-water system are operational, subject to adjustments as other portions of the accelerator are activated. As previously reported, further tests and modifications of the rf driver were found necessary and are still being carried out. A considerable amount of system-interlock wiring remains to be done and this is in progress.

The next major step toward getting a beam in the machine will be to put rf into the accelerator sections. Preparations are being made to conduct this test in October. Following this, the gun will be installed and the beam will be turned on.
III. ACCELERATOR STRUCTURE AND HIGH-POWER WAVEGUIDE COMPONENT STUDIES

A. RADIOFREQUENCY STUDIES OF THE ACCELERATOR STRUCTURE

During this period we have continued preparing facilities and have conducted the initial tests needed for undertaking the rf program of the group. At present we are concerned primarily with gathering the information, required early in the program, that underlies the later work. Areas of current activity are the determination of fabrication, processing, and handling procedures insofar as they affect rf performance; and the design of matching, tuning, and inspection techniques required in the low-level testing of 10-ft sections. The former objectives require high-power testing, whereas the latter do not.

A series of tests using short resonant lengths of accelerator structure is our initial effort in the high-power program. These tests and the equipment required were described in an earlier Status Report.¹ The necessary equipment has been gathered, modified and tested under operating conditions.

Briefly, the test set-up was as follows. A matched cavity consisting of 3 periods of the uniform structure was driven with a VA-87 klystron at a peak output power of 1.8 megawatts. This resulted in a standing-field strength within the cavity corresponding to a peak power in excess of 20 megawatts for a traveling wave in a matched structure. The pulse length of 2 μsec permitted the peak cavity fields to reach very nearly a steady-state condition with a duration of somewhat less than 1 μsec. A self-excited SAS-60 amplifier with a TS-270 echo box in the feedback loop, as used earlier in the Mark IV driver, was found to be sufficiently stable for this use.

An L-3460 cw magnetron also was used to feed the cavity with 500 watts. This tube is expected to deliver 750 watts, which will correspond to an average power dissipation of three-fourths of the maximum dissipation expected in a 10-ft section operating at full power. The tuning control and stability of the magnetron were sufficiently good to allow the cavity to be easily excited and tracked.

The enclosure for low-level measurements has been completed, and sufficient equipment is on hand to begin this portion of the program. A room temperature control of 75⁰ ± 3/4°F has been obtained. The relative

humidity has varied about $\pm 3\%$ and thus becomes the major contribution to changes in the propagation constant of the accelerator structure.

B. ELECTROFORMING

The small facility for electroforming 10-ft lengths has been completed except for the fixture for holding the 10-ft length horizontally, as described in previous Status Reports. This fixture has been designed and is now under construction.

C. BRAZING

The furnace previously described, for brazing 10-ft lengths of accelerator section, is virtually completed. The first tests with the furnace are expected to be carried out in late October.

D. PARTS FABRICATION

The boring machine and associated equipment have now been installed, and the machine is about to undergo acceptance tests. A constant-temperature system for controlling the cutting oil used on the machine has been completed and holds the temperature within $\pm 1/4^\circ C$. The room temperature is controlled to about $\pm 1^\circ C$.

E. WATER JACKET

A study is being made to determine the optimum method of maintaining the desired accelerator-tube temperature. A method is being sought that will meet the temperature-control requirements for either the constant-gradient machine or the uniform-structure machine with the same basic cooling-jacket design. Some of the more promising methods considered to date are reduced pressure boiling, cross flow, and parallel flow with variable flow rate.

A small-scale test system for the reduced-pressure boiling method of cooling has been designed and is currently being assembled. Testing is expected to begin in October. The tests will provide the necessary data to determine the feasibility of this method of cooling the disk-loaded waveguide.

A small-scale test has been planned to determine the required number of water jets for the cross-flow water-jacket design for the constant-gradient section. The test will be carried out with a simplified copper model of the accelerator section. The model is being made by putting
copper ribs, simulating the copper disks, on one side of the plate. On the other side, the water chamber is formed by a second plate that has an experimentally variable spacing. The heat input to the accelerator will be simulated by strip heaters attached to the rib side of the plate. The objective of this experiment is to provide a uniform-heat input to the under side of a copper plate and to measure the temperature distribution on the other side of the copper when water is flowing across the surface under varying conditions. With the data from this preliminary experiment it will be possible to make a test set-up with an actual short section of accelerator to check the results of the data from the sample experiment.

F. HIGH-POWER WAVEGUIDE COMPONENTS

1. Waveguide

A study is being carried out to establish the specifications for the waveguide to be used between the klystrons and the accelerator sections. The two most likely cross sections are the standard S-band waveguide (1 1/2 in. x 3 in.) and a waveguide having a cross section of 3.900 in. x 1.950 in. Radiofrequency performance of the two waveguides may be compared as follows.

<table>
<thead>
<tr>
<th></th>
<th>S-Band</th>
<th>3.900 in. x 1.950 in.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase shift in degrees/°C change in temperature per 50 ft of length</td>
<td>1.25</td>
<td>1</td>
</tr>
<tr>
<td>Attenuation</td>
<td>6.24 x 10^{-3} dB/ft</td>
<td>3 x 10^{-3} dB/ft</td>
</tr>
<tr>
<td>Heat input per cm² of waveguide-wall surface with 20 kw in the waveguides</td>
<td>.01 cal</td>
<td>.003 cal</td>
</tr>
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2. Waveguide-Wall Thickness

Preliminary calculations and a check test have been carried out to determine the deflection of a waveguide wall of OFHC copper, under vacuum, as a function of thickness.

The calculations of the deflections were simplified to elementary beam theory by taking advantage of the double symmetry of the cross section. The calculated deflections for an S-band waveguide with 1/8-in. wall, which were
carried out assuming the copper to be elastic within this range, are plotted as curve A in Fig. 1.

The values used in the plot are

\[ p = \text{inches of mercury vacuum} \]

\[ \Delta = \text{maximum deflection of each side of the waveguide in 0.001 in.} \]

To check the calculated values, deflections were measured as a function of pressure on a 2-ft long piece of annealed copper S-band waveguide with an 1/8-in. wall thickness. Curve B in Fig. 1 was obtained by plotting measured deflections at different pressures for this waveguide. As seen from curves A and B, there was good agreement between the computed and the experimental deflections in the range where Hooke's Law applies.

The curves C, D, E, and F, which represent the deflections of a 2 in. x 4 in. (nominal dimensions) waveguide with, respectively, 3/16 in., 1/4 in., 5/16 in., and 3/8 in. wall thicknesses, were all obtained from curve B by the use of relationships established through the theory of structural similitude.

A slight variation of the proportional limit from one fully-annealed waveguide to the other will give great variations in deflections in the nonelastic region, while more uniformity can be expected if the stresses stay well below the elastic limit.

The 2 in. x 4 in. waveguide will be tested for deflection as soon as it is available, and creep tests will be made when the final cross section is established.

Deflections in the waveguide wall are of importance because the phase shift per unit length is determined by the waveguide cross-sectional dimensions. The total allowable variation in phase shift from one waveguide feed to the next has been set at 2°. Hence, the waveguide wall must be mechanically stable and temperature controlled to insure that any change that may occur will fall within allowable limits. The specification for these limits is now being formulated.
A 1/8" wall, S-band Hooke's Law 4.3 lb/ft
B 1/8" wall, 1\frac{1}{2}" x 3" ID measured 4.3 lb/ft
C 3/16" wall, 2" x 4" ID nominal 9.0 lb/ft
D 1/4" wall, 2" x 4" ID nominal 12.2 lb/ft
E^* 5/16" wall, 2" x 4" ID nominal 15.6 lb/ft
F 3/8" wall, 2" x 4" ID nominal 19.1 lb/ft
G 3/16" wall, 1\frac{1}{2}" x 3" ID 6.6 lb/ft

FIG. 1--Maximum deflection of each broad side of a waveguide vs inside pressure. (All copper waveguides annealed in hydrogen at 900° for 1 hour)

Also applies for 7/32" wall in 1/2" x 3" 7.75 lb/ft
IV. BEAM DYNAMICS

A section on beam dynamics of the Project M accelerator was written for a paper given at the Brookhaven Conference on High-Energy Accelerators.2

The question of beam-steering by a strong-focusing quadrupole system has been re-examined. The present tentative conclusion is that the strong-focusing system could guide the beam through somewhat larger misalignment than was thought previously. For example, in the case of systematic misalignment (constant curvature of the accelerator axis) it appears that misalignments of the order of 10-15 cm could be handled. (A figure of 2-3 cm was quoted previously.)

The quadrupoles in the above example would have to have a strength of ~5000 gauss (e.g., a gradient of 500 gauss/inch and a 10-inch length). The limitation on maximum quadrupole strength (and maximum tolerable misalignment) still appears to be imposed by chromatic aberration.

---

V. INJECTION SYSTEM

A. MARK IV CONVERSION PROGRAM

The Mark IV gun modulator has been tested with a resistive load. The pulse-forming networks have been adjusted. Some slight readjustment of the pulse lines will be required after the gun is installed.

The modulator was tested at repetition rates from 60 pps to 360 pps in multiples of 60 pps. At repetition rates above 120 pps it was necessary to reduce the grid-pulse voltage below the nominal operating voltage to avoid exceeding the rating of the grid-modulator power transformer. A replacement transformer adequate for 360 pps operation has been ordered.

B. BUNCH MONITORING

During the past quarter the problem of providing a direct monitor of the injector bunching was studied. Although the electron-energy spectrum can provide a measure of the bunch size, the spectrum width measured depends also on the phase of the bunch, on the variation of any of the primary machine parameters in the interval during which the spectrum is measured, and on the velocity modulation introduced by the buncher.

For turning on and tuning the injector it would be desirable to have a monitor that is sensitive to the bunch size, but relatively insensitive to phase and beam energy. Any device that is sensitive to the harmonic current in the accelerator might fill this need. The most obvious approach is to let the beam pass through the rf structure so that a particular harmonic of the accelerator rf will be generated. If we consider the accelerator bunch to be rectangular with a phase interval of $\theta$, the rf current at the $n$th harmonic is

$$I_n = 2I_0 \frac{\sin (n\theta/2)}{n\theta/2}$$

where $I_0$ is the dc current. Squaring and differentiating with respect to the bunch size $\theta$, we obtain

$$\frac{dP_n}{P_n} = \frac{d\theta}{\theta} \left(1 - \frac{n\theta}{2} \cot \frac{n\theta}{2}\right)$$
For good sensitivity we would like to have the fractional change of the harmonic power be of the same order as the fractional change in bunch size. Thus

\[ \frac{dP_n}{P_n} \gtrsim \frac{d\theta}{\theta} \]

which is satisfied for

\[ n\theta \geq 150^\circ \]

If the injector produces a $5^\circ$ bunch, we should monitor about the 30th harmonic whose wavelength is 3.5 mm. The magnetic undulator\(^3\) can readily be used to extract power in this wavelength range from a relativistic beam.

With an undulator 1 meter long, an aperture of 1 cm, magnetic fields of about 500 gauss, and 50 milliamperes beam current, it should be possible to generate 100 milliwatts of the 30th harmonic. The magnetic fields can be turned off when the injector is not being tuned to avoid deterioration of the beam optics.

C. INFLECTION SYSTEM

The feasibility study of injecting into the accelerator at an angle is being continued. It is possible to design an achromatic deflection for which the path length through the system is independent of momentum to first order in $\Delta p/p$. With such isochronous systems it appears feasible to inject at $90^\circ$ from the accelerator axis. This will make it possible to locate the electron guns in or adjacent to the klystron housing for ease in maintenance.

D. ACCELERATOR ENERGY SPECTRUM

The electrons that enter the first section of accelerator may be divided into four groups: (1) electrons that will form the $5^\circ$ bunch and hence will be within the desired energy spectrum; (2) electrons that may be expected to travel a considerable distance along the accelerator with an asymptotic phase outside but near the $5^\circ$ bunch; (3) electrons with an asymptotic phase so far from the bunch (and the wave crest)

that they may be expected to get lost before attaining high energy; (4) electrons that are not bound to the wave at all. It is, of course, desirable to maximize the number of electrons in group (1). It is also important to minimize the number in group (2), since these electrons contribute to the radiation along the accelerator and at the end station. The number of electrons in groups (3) and (4) is probably of less importance, but it is certainly desirable to keep their number small since they contribute to beam loading and probably to gassing in the first section of the accelerator. A preliminary calculation was performed to estimate the populations of these groups for the following two buncher configurations: (1) a single-cavity buncher followed by a uniform accelerator section with \( \beta_w = 1, \alpha = 3.63 \); (2) a uniform waveguide buncher with \( \beta_w = 0.5 \) followed by an accelerator section with \( \beta_w = 1, \alpha = 3.63 \). The parameters of the bunchers were chosen to maximize the current within a 5° bunch, assuming a 1% gun-voltage ripple. The results of the calculation are given in Table I. The fraction of injected electrons contained within a 0.1% intrinsic spectrum (5° bunch), 10% spectrum, and 100% spectrum (all bound electrons whose velocities are never negative) are listed for the two types of bunchers. It is assumed that the electrons within a 10% spectrum must be expected to travel a considerable distance along the accelerator. The minimum velocity attained by any electrons in the 10% spectrum is two-thirds the injection velocity, so their probability of attaining high energy before getting lost is considered excellent.
<table>
<thead>
<tr>
<th>Intrinsic Spectrum</th>
<th>Cavity Buncher</th>
<th>Uniform-Waveguide Buncher</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Current Within Spectrum Expressed as Fraction of Injected Current</td>
<td>Current Within Spectrum Expressed as Fraction of Current in 0.1% Spectrum</td>
</tr>
<tr>
<td>0.1%</td>
<td>.57</td>
<td>.67</td>
</tr>
<tr>
<td>10%</td>
<td>.70</td>
<td>.79</td>
</tr>
<tr>
<td>100%</td>
<td>.77</td>
<td>.86</td>
</tr>
<tr>
<td>Not bound</td>
<td>.23</td>
<td>.14</td>
</tr>
<tr>
<td></td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td></td>
<td>1.23</td>
<td>1.13</td>
</tr>
<tr>
<td></td>
<td>1.35</td>
<td>1.28</td>
</tr>
<tr>
<td></td>
<td>-</td>
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</tbody>
</table>
VI. MICROWAVE CIRCUITS

Because of a recent reorganization, the work separately reported on rf studies, drive systems and phasing studies will now be consolidated under this section.

A. GENERAL RF STUDIES

1. Measurement of Quality Factor Q as a Function of z in the Constant-Gradient Accelerator Structure

Figure 2 shows a graph of Q as a function of z, where z is taken in the longitudinal direction of the present constant-gradient structure design. It is seen that Q varies by about 7% over the total length of a section. A considerable improvement was obtained in the measurements by carefully electropolishing the test cavities and by taking into account the coupling coefficients of the pick-up loops. The decrease in Q will somewhat compensate for the increase of r/Q vs z reported earlier, thereby tending to reduce the increase of the electrical field over the section to about 5%, at zero beam loading.

2. Constant-Gradient Coupler Design

An output coupler for the constant-gradient structure was tested with an electroformed two-foot section corresponding to the last nine cavities of the constant-gradient section. The match appears satisfactory for the following parameters:

\[ 2a = 0.7640 \text{ inches} \]
\[ 2b = 3.1790 \text{ inches} \]
\[ \text{iris aperture} = 0.870 \text{ inches} \]

The input coupler is ready and will be tested as soon as the two-foot input sample is available.

3. Constant-Gradient Field Studies

In order to attempt a direct measurement of the field variation in a constant-gradient section, a four-foot constant-gradient sample was assembled out of available test cavities. The field variation was obtained by measuring the phase-shift variation created by a dielectric bead introduced into the section and displaced longitudinally along its axis. A graph of these results is shown in Fig. 3. It is interesting to notice that, although the
FIG. 2--Quality factor \( Q \) as a function of distance \( z \) along constant-gradient section.
FIG. 3--Field strength squared \((r/Q)\) observed along last four feet of constant-gradient section.
phase shift (and, therefore, $E^2$) undergoes oscillations as a function of $z$ every time the dielectric bead passes by a disk, the average increase in field can be measured quite accurately. Preliminary results indicate that an average increase of 7% per meter in $r/Q$ occurs in this four-foot sample. This verifies quite accurately results reported earlier on experiments done on individual cavities.

4. Conical-Disk Structure

Figure 4 shows a comparison of group velocity $v_g$ and $r/Q$ measurements done on $\pi/2$ and $2\pi/3$ conical-disk test cavities. The cavities used for the $\pi/2$ case were the same as reported in M.L. Report No. 416, where a 15% improvement was reported over the standard Stanford $\pi/2$ flat-disk case. It appears now that this early result was in error and that the conical-disk structure actually gives a lower $r/Q$ than the flat-disk structure, for both the $\pi/2$ and the $2\pi/3$ cases. Although physical reasoning had previously indicated that tapering the disk surface would increase the $r/Q$, it now is seen that in order to maintain the same frequency and group velocity, one is forced to increase both $2a$ and $2b$, thereby actually decreasing $r/Q$.

The next step is obviously to perform an experiment where the disk is tapered in the opposite direction (thinner at the wall, thicker at the hole) to check whether an improvement in $r/Q$ can thereby be obtained or whether the flat disk is actually the optimum case.

5. Measurements of Space-Harmonic Amplitude

A new series of measurements has been performed to obtain the variations of the space-harmonic amplitude $a_0$ as a function of disk thickness and group velocity. In some cases the disk edge was square, in others it was beveled. Results obtained so far are shown in the table below.

---

THREE DISKS PER WAVELENGTH \((d = 1.378 \text{ in.}, 2\pi/3 \text{ mode})\)

<table>
<thead>
<tr>
<th>Disk Thickness</th>
<th>(v_g/c)</th>
<th>(a^2/E_a^2)</th>
<th>Disk Edge</th>
</tr>
</thead>
<tbody>
<tr>
<td>.060 in.</td>
<td>.0153</td>
<td>.850</td>
<td>square</td>
</tr>
<tr>
<td>.120 in.</td>
<td>.0115</td>
<td>.837</td>
<td>square</td>
</tr>
<tr>
<td>.230 in.</td>
<td>.0057</td>
<td>.757</td>
<td>square</td>
</tr>
<tr>
<td>.230 in.</td>
<td>.0068</td>
<td>.816</td>
<td>beveled</td>
</tr>
<tr>
<td>.230 in.</td>
<td>.0115</td>
<td>.829</td>
<td>beveled</td>
</tr>
<tr>
<td>.230 in.</td>
<td>.0139</td>
<td>.839</td>
<td>beveled</td>
</tr>
<tr>
<td>.230 in.</td>
<td>.0178</td>
<td>.853</td>
<td>beveled</td>
</tr>
<tr>
<td>.230 in.</td>
<td>.0200</td>
<td>.860</td>
<td>beveled</td>
</tr>
<tr>
<td>.230 in.</td>
<td>.0215</td>
<td>.862</td>
<td>beveled</td>
</tr>
</tbody>
</table>

FOUR DISKS PER WAVELENGTH \((d = 1.034 \text{ in.}, \pi/2 \text{ mode, } 2b = 3.214 \text{ in.})\)

<table>
<thead>
<tr>
<th>Disk Thickness</th>
<th>(v_g/c)</th>
<th>(a^2/E_a^2)</th>
<th>Disk Edge</th>
</tr>
</thead>
<tbody>
<tr>
<td>.230 in.</td>
<td>.0072</td>
<td>.920</td>
<td>square</td>
</tr>
</tbody>
</table>

A few additional cases are now being measured, and a complete graph will be published in the next Status Report. It appears that previous measurements made at Stanford did not take into account more than three terms in the Fourier expansion of the field and, therefore, gave results somewhat higher than warranted.\(^5\) It can now be said that from the shunt impedance point of view, there will be a definite advantage in going to a disk thinner than .230 in. Mechanical and thermal properties may, however, outweigh the relative advantage of thinner disks.

6. Prebuncher Studies

A prebuncher design for the Mark IV accelerator has been completed, and a model has been tested. By using stainless steel and shaping the coupling loop for critical coupling, a \(Q_o\) of 530 and a \(Q_L\) of 265 at 2856 Mc have been obtained. The final unit is now being welded, and it is hoped that with this new low-Q design, no tuning will be required during accelerator operation.

\(^5\)Renée Hirel, "Space Harmonics Content of the \(2\pi/3\) Accelerator Structure," M Report No. 270, Project M, Stanford University, Stanford, California, June 1961.
FIG. 4—Comparison of $\pi/2$ and $2\pi/3$ conical disk cavities: (a) Brillouin diagrams, (b) $r/Q$. 

<table>
<thead>
<tr>
<th>t in.</th>
<th>$\pi/2$</th>
<th>$2\pi/3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>d in.</td>
<td>1.0335</td>
<td>1.378</td>
</tr>
<tr>
<td>2b in.</td>
<td>3.825</td>
<td>3.750</td>
</tr>
<tr>
<td>2a in.</td>
<td>.920</td>
<td>1.060</td>
</tr>
<tr>
<td>$\alpha$ degrees</td>
<td>11.16</td>
<td>15.72</td>
</tr>
<tr>
<td>h in.</td>
<td>.148</td>
<td>.250</td>
</tr>
<tr>
<td>$v_g/c$</td>
<td>.0103</td>
<td>.0180</td>
</tr>
<tr>
<td>$r/Q$ ohms/cm</td>
<td>37.0</td>
<td>35.0</td>
</tr>
<tr>
<td>$f$ Mc/sec</td>
<td>2857.3</td>
<td>2855.8</td>
</tr>
<tr>
<td>bandwidth Mc/sec</td>
<td>39.1</td>
<td>56.9</td>
</tr>
</tbody>
</table>

VI.
7. Group-Velocity Measurements

Report No. 5105, P.N. Robson, Metropolitan-Vickers Electrical Co., Ltd., indicates that it is possible to Fourier analyze a Brillouin diagram and to get a more accurate measurement of group velocity than is generally obtained from the graphical differentiation method (i.e., taking the slope of the curve at the used frequency). The table below shows that by using six cavities, the graphical result approaches the Fourier Series result by about 5%.

<table>
<thead>
<tr>
<th>Cavities</th>
<th>Fourier Series</th>
<th>Graphical Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>0.0170</td>
<td>0.0137</td>
</tr>
<tr>
<td>6</td>
<td>0.0119</td>
<td>0.0113</td>
</tr>
</tbody>
</table>

8. TM_{11} Mode Studies

Continuing the studies carried out at Stanford to examine the higher passbands present in the accelerator structure and their possible connection with the beam-breakup phenomenon observed at high currents, Brillouin diagrams were obtained for various cavities of the constant-gradient structure. Figure 5 shows the results for three different cavities. It is seen that the values of \( f_\pi \), which are approximately the frequencies at the intercept with the \( v_p/c = c \) line, vary by more than 200 Mc over a ten-foot constant-gradient length. With the mechanism presently suggested for beam breakup, where the beam induces energy to flow in the TM_{11} mode and is then deflected by it, varying the cross-sectional dimensions of the accelerator structure will prevent the oscillation from getting started at the currents usually quoted (about 300 milliamperes for a 2-microsecond pulse). The \( Q \) at the \( \pi \) mode is of the order of 13,000.

B. DRIVING SYSTEM

1. Design Studies

The whole drive system is presently undergoing re-examination and it is possible that considerable departures from the original design will be made in the next few months. The idea of eliminating the main boosters altogether and replacing the coaxial drive line by a large
FIG. 5—w-β diagrams for the fundamental TM mode at the 6½-ft point of a ten-foot accelerator section, and for the TM mode at the input, the 6½-ft point, and output. Note that the line of \( \frac{v_p}{c} = 1 \) intersects at three different frequencies.
cross-section rectangular waveguide is being examined.

2. **Radiofrequency Driver**

Tests on the rf driver for the Mark IV accelerator have continued throughout this quarter. This unit has been developed to Stanford specifications under a subcontract. Several improvements have been made, but the unit still suffers from several weaknesses. An attempt is presently being made to remedy the following problems: (1) oscillations and droop in the first three microseconds of the pulse; (2) output power instability over the 4 Mc tuning range; (3) elimination, or at least reduction, of rf power appearing in sidebands and spurious frequencies.

3. **Radiofrequency Drivers for Test-Stand Installations**

Specifications are being drafted for a total of 16 rf drivers to provide rf energy to a total of 16 test stands. These test stands are to be used to perform feasibility, performance and life-test studies of components for Project M.

4. **Drive-System Contributions to the Mark IV Conversion Program**

With the exception of the rf driver, the rf drive and phase system for the Mark IV has been substantially completed. The associated electronic components—ovens, power supplies, switching circuit, etc.—have been installed together with the necessary control wiring. Equipment for the console has been completed, with the exception of the rf-driver control. Preliminary testing of the rf system, however, can be conducted with a temporary control unit presently available. All the required microwave components have been installed, and only a limited number of rf cables remain to be laid. A complete subsystem test is contemplated immediately following acceptance of the rf driver.

5. **Sub-Boosters**

The TH-2101 klystrons on loan from the CFTH Company of France have been tested using available modulators. Their performance shows a small modulation on the beam, caused by the magnetic field of the filament. When the filaments are ac supplied, this modulation appears in the output causing the rf output power and phase to vary. At a repetition rate of 360 pps, several output levels are observed. The manufacturer is conscious of this difficulty and will try to remedy it.
Tests on these tubes will continue throughout the next quarter.

6. Coaxial Couplers

Two coaxial couplers have been received from Narda (Model 2413, 10 and 6 db, respectively). These directional couplers are to be used with an Andrew-type rigid coaxial line. Their performance has been checked, and it appears that the respective coupling factors are 10.6 and 5.7 db, with directivities of 33 and 25 db, respectively. The dispersion characteristics of these couplers were measured across the main arms, as well as across the input coupling arms, and turned out to be negligibly small over the 2856 ± 0.1 Mc range (less than 0.02° in all cases).

C. PHASE STUDIES

1. Mark III Phasing Experiments

A preliminary phasing experiment using the beam-induction technique was carried out on the Mark III accelerator. Equipment was installed to enable the phasing of four sections to be undertaken. It is difficult to draw final quantitative conclusions from this experiment, since the expected increase in beam energy and improvement in spectrum width resulting from one correctly-phased section was less than the accuracy with which these two parameters could be measured with equipment available on Mark III. It can be stated, however, that using the beam-induction technique it was possible to phase the four sections to about the same degree of accuracy as with the present technique based on beam-energy maximization.

A detector unit, previously described, was used for comparing the relative phases of the two given signals. Preliminary difficulties encountered in using this phase detector were overcome, but completely satisfactory operation was not obtained. Attempts are being made to adapt the detector so as to use it for pulsed, cw, or a combination of these inputs. More detailed experiments are to be scheduled when the improved phase-detector unit is available.

2. Beam-Energy Maximization Technique

In view of the large equipment costs involved in any method using the electron-beam phase as a reference (reactive beam loading as well as beam-induction methods), the beam-energy maximization technique is presently described in Status Report, M Report No. 260, Project M, Stanford University, Stanford, California, April 1961.
being re-examined. We are examining the problem of how to use the Mark IV accelerator in such a way as to simulate the influence of one klystron on the beam-output energy of an accelerator that uses 240 klystrons.

3. Phasing of a Nonsynchronous Section by the Beam-Induction Technique

A study of the beam-induction method applied to a nonsynchronous section, i.e., a section not operating exactly at the velocity of light, has been completed and shows that under these conditions the beam-induction method produces a phase identical to the reactive beam-loading technique. It can thus be concluded that the beam-induction method is equally satisfactory from this point of view. A separate report will be published shortly.
VII. KLYSTRON STUDIES

During the last quarter the Klystron Group completed the move into its new facilities in the Project M building. Because of this move the construction of new klystrons has been slowed down. Several beryllium oxide ceramic windows were constructed and are ready for use on the next tubes. We also have begun life testing of existing Stanford klystrons.

A. TUBE COMPLEMENT AND PERFORMANCE

The stockpile of tubes on hand has been decreased by two tubes that are now installed in Mark IV accelerator sockets and by two tubes that failed after approximately 100 and 50 hours, respectively, of life testing. During the quarter the first "short" tube was built and tested. This tube was to be operated on a permanent magnet that was received in June. The initial tube tests were performed on an electromagnet and the tube performance was adequate, although the efficiency was somewhat lower than expected. Unfortunately, during the removal of the tube from the electromagnet, a mishap in the handling equipment ruined the cathode seal and let the tube down to air. The tube has now been repaired and is ready for testing.

B. SUBCONTRACTS

At the present time both subcontractors (Sperry Gyroscope Company, Great Neck, Long Island, N. Y., and RCA, Lancaster, Pa.) are somewhat behind schedule, but the expected delivery date of six sample tubes has not been materially affected.

Sperry is testing its second klystron, which was built to accommodate reversal field focusing. They also have subassemblies for three short tubes, which should be delivered to Stanford between now and January. The permanent magnets for these tubes are manufactured by G.E. and were late in delivery.

RCA has resolved the low perveance problem experienced on their first tube. They have had a diode running at approximately 50 MW peak, 50 kW average beam power, for several weeks. Their beam tester should be undergoing tests by October 1st and they expect to have their first deliverable tube built by October 15th.
C. NEW FACILITIES

The move to the new Project M building on campus has been completed.

1. Shop

Except for the lack of gasses and chemical cleaning facilities, the tube shop is now in operation.

2. Test Area

We now have two modulators in operation, the Ling 100 Mw unit that has been used principally for life testing and the spark gap modulator that is being used for tests of special tubes (such as the short tubes). We are also adding bakeout facilities that should be completed by the end of next quarter.

3. Test Equipment

Initial tests on all-metal high-power loads have not been completely satisfactory as yet, and we are still using glass, water-filled loads in spite of the inherent dangers of loss of vacuum through glass failure.

D. LIFE TESTS

We are presently undertaking a one-socket life-test program to determine what problems besides the windows might determine end of life of our tubes. The first tube tested operated for approximately 100 hours on vacuum loads, even though the windows had been punctured much earlier. The end of life came from failure of the loads that resulted in the loss of vacuum in the tube through the punctured window. The second tube failed through a cathode-bushing puncture that was induced by gassing in the tube resulting from the loss of vacuum in the load through a punctured window. From our experience to date it appears that the windows can be blamed for the end of life of these tubes.

E. EXPERIMENTAL TUBES

As mentioned earlier, the first short tube has been tested on an electromagnet with adequate but not outstanding results. The gain was as high as the gain of a long tube, but the efficiency was somewhat lower. Another short tube will be ready for additional tests within the next month.

A complete redesign of the output system is being undertaken to accommodate the outline drawing of the production Project M klystrons.
F. PROGRAM FOR NEXT QUARTER

During the next quarter we expect to have a third high-power modulator available that will permit us to continue life testing at high-average power, to repair standard tubes, and to investigate further the short tubes and their modifications.
VIII. HIGH-POWER KLYSTRON WINDOWS

A. WINDOW-LIFE TEST STAND

During the last quarter the window-life test stand was moved to the new building where it is being used with the new Ling modulator. A Litton type-L 3302 klystron that operates up to 10 MW is on this equipment. Although the high-power section of the modulator has operated very satisfactorily, considerable difficulty has been encountered with the low-level trigger generators. We are temporarily using a jury-rigged, locally built unit to overcome this difficulty. The Ling Company is building a new trigger unit that should be available shortly. In spite of delays caused by this and by a shorted tube socket, we have operated about 160 hours on a one-shift basis. During this time one section became very gassy. The suspected window was removed and found to be peppered with punctures, none of which went through the disk that was still vacuum tight. Operation has continued with a total of six windows.

The success of the present vacuum system, which has a separate power supply for each Vacion pump, encouraged us to order supplies for the next six windows. These will be added as soon as the supplies are available. We will add additional shifts as soon as we can obtain the necessary personnel.

B. RECIRCULATOR WINDOW TESTS

Shorting plungers of a new design have been installed in the phase shifter on the recirculator. It is hoped that this will avoid the arcing that occasionally occurred on the old pair. In a few weeks use, no troubles have occurred at full power.

A series of tests has been run on 1/16-inch disks of Wesgo AL 995 and Coors AD 96 in the structure described in the last Status Report. Although these disks were run to powers in excess of 30 MW, no damage has occurred. A total of seven disks were tested, some of them several times. Tests were made at a reduced vacuum that caused some arcing but did no damage. Sudden application of power was tried to simulate the former Mark III operation (see below) without any effect. Although these results are disappointing, we will continue these tests as time permits.

---

A new RCA window with a vacuum seal made by shrinking was tested at the highest available power. During its first run it was slightly chipped. The window was rotated to place the chip at a voltage minimum. The peak power on this window was 28 MW at 60 pps. The window ran slightly warm, which accounts for the slightly lower than usual power. Tests were run to levels as high as 21 kW average power.

A window structure, similar to the J-type but having the less abrupt transitions from circular-to-rectangular guide used on the Project M klystrons, was tested to 20 MW. Except for an erratic bright glow early in the tests, operation was normal. This window is now in operation on the Mark III accelerator.

Two windows with a conductive coating applied by Eimac were tested to 20 MW. Operation was normal except for a glow that was bright green instead of the usual blue. These windows were intended for further testing on the Mark III accelerator, but both were found to leak at the metal-to-ceramic seal after the tests on the recirculator.

The low-gradient window described in the last Status Report\textsuperscript{8} was tested twice this quarter using different disks. [See Fig. 6(a)] Both assemblies ran very warm although they successfully passed more than 20 MW. The cause of this abnormal heating has not been determined.

A half-wave slab window, shown, in Fig. 6(b), has been designed and three models have been tested in the recirculator. The slight taper between the section holding the disk and the rectangular-to-circular taper enabled us to use available 3-inch tapers. The nearest measured ghost mode was approximately 50 Mc from the match frequency. This is about 17 Mc lower than our calculated value and is probably due to the effect of the taper. Three successive models of this window were punctured on one surface as shown in Fig. 7. The windows shown in Fig. 7, Nos. I and III, punctured on the load side. Figure 7, No. II, punctured on the tube side, but was reversed so that we could observe the puncturing. Arcing occurred between the pairs of puncture marks, similar to that observed on a J window.\textsuperscript{9} There was no arcing to the metal walls at any time. In each case

\textsuperscript{8}Status Report, op. cit., p. 16.

\textsuperscript{9}Ibid., p. 14.
FIG. 6--Window-test assemblies.

(a) low-gradient window assembly

(b) half-wave window assembly
failure started within a few hours operation as soon as the power had reached about 20 Mw. It was possible to observe the window through a telescope and, apparently, to see the formation of holes.

Figure 8 shows photographs taken through a telescope, of three events on the Fig. 7(III) disk after considerable damage had occurred. The area covered is about an inch in diameter in the damaged region shown in Fig. 7, No. III. A continuous series of short, thin, blue streaks move between the two patches of "stars" in Fig. 8(a). In Fig. 8(b) a diffuse white discharge is taking place to the left of the stars along a subsidiary crack discovered when the window was removed. This discharge's motion was similar to a worm. A similar "worm" occurs in Fig. 8(c) along a crack passing through some of the larger holes. The worms were quite erratic in occurrence; the stars were a fairly stable phenomena, although varying somewhat in extent and brightness. Violent lightning-like arcs also occurred across this region but were not successfully photographed.

These windows are the first type on which we seem to be able to obtain failure on every test. The holes formed are identical to those found on failures occurring on the Stanford accelerators. The pattern of holes is similar, in that there are two regions of maximum destruction. In these $\frac{1}{2}$ windows the punctured region covers a smaller area and the spacing of the two regions is closer and somewhat offset from the center of the disk. The smaller amount of damage may be due to the relatively short time of operation of each disk.

These are the first extensive observations that we have been able to make of breakdown on a disk window. While the formation of holes is still obscure, some interesting phenomena have been seen. It is apparent, as in the J-type test noted above, that all visible activity is confined to the region between and including the damage areas. Holes appear to form near or slightly below the surface, and at least one case of "eruption" has been seen. This would agree well with the ring of glass-like material surrounding some of the holes. We believe that we have seen some activity occurring at the bottom of the holes after their formation.

We intend to continue studies of hole formation on these and similar types of windows. In addition, an increased effort will be made to explain why this particular geometry is so susceptible to this type of damage.
FIG. 8--Breakdown in half-wave window No. III, magnification approximately three times.
C. OTHER WINDOW WORK

1. Resonant-Cavity Tests

The first model of a resonant cavity has been constructed using a shrunk-in 1/8-in. alumina disk. The cavity operates in the $TE_{112}$ mode with the disk in the region of maximum field. The shrinking technique will allow us to move the window to other regions. A viewing port is provided in one end of the cavity. The cavity has a cold $Q$ of 6000. At present the unit is being powered by a type-5586 magnetron. The cavity is pumped by two Vacion 5-liter pumps. The unit has been operated for only a few days and no experimental results have been obtained to date.

2. Recirculator Power Increase

We are ordering the necessary equipment to install a larger klystron on the recirculator. With the present modulator we should be able to obtain 2 to 3 times the peak power in the ring with a suitable klystron. Either a Litton type-L 3302 or one of the M klystrons will be used, operating at much below their maximum ratings. The present tubes, Varian VA-87's, are now being used at their maximum peak-power output. This change is being made because it is apparent that the present 30 MW is insufficient to cause breakdown in most types of windows.

3. All-Metal Recirculator

We have started plans for the construction of an all-metal very high-vacuum, resonant ring. We hope to obtain a vacuum better than $10^{-8}$ on this system, which will be bakeable. The most difficult part of the design is expected to be the phase shifter, and several different types are being studied. The re-entrant nature of the ring may also give trouble in installing test pieces. At present, small inaccuracies are compensated for by a slight misalignment of the flanges. The types of metal-to-metal flanges now available will require exceedingly careful alignment and highly accurate construction. This ring should be useful in studying the effects of vacuum conditions on the operation of windows. In particular, it will allow the introduction of known contaminants into a very clean system, which is not possible on the present ring due to the inherent contamination caused by poor trapping, organic O-rings, and by not being able to bake the ring.
4. Mark III Window Failure

Since July, the failure rate of windows on the Mark III accelerator has dropped from an average of 6.6 per month to essentially none. While it is difficult to evaluate all changes on such a complex system, it now seems that this improvement was caused by one change in operating procedure. Before July, the rf power was applied at full level when the machine was turned on after a vacuum shut off. (Excessive rise of pressure in any vacuum system on the machine shuts off the rf power.) The power is now reduced approximately 50% before turn on and in 5 sec is raised to full power. It is obvious that whatever process of destruction is involved, time constants that are long compared to a pulse interval are needed if the above change in procedure is to be effective. Attempts to duplicate this effect on the ring have been unsuccessful to date.
IX. MODULATOR STUDIES

A. SUBCONTRACT SYSTEM DEVELOPMENT PROGRAM

During this past quarter the major subcontract with RCA at Moorestown, New Jersey, has continued satisfactorily. A field trip during the week of 18 September to the RCA facility confirmed that delivery of the three prototype modulators, and the 200 kw power supply for installation in Mark IV will be approximately on time.

An examination of the work in process showed that RCA has been responsive in every major respect to the statement of work called for under Subcontract S-125. In particular, we are pleased with the mechanical design of the equipment in that it reflects the amount of care they have taken to ensure that component availability is maximized for ease of maintenance and minimum down time.

During this period low-power breadboard studies at RCA and full-power studies at Stanford have confirmed that the pulse-to-pulse amplitude jitter control circuitry will perform as expected. Similar breadboard and full-power studies have shown that the pulse-shape requirements of S-125 will be met by RCA's design.

B. PROJECT DEVELOPMENT ACTIVITIES

1. Ignitron Studies During the Past Quarter

One sample of an ignitron constructed in accordance with our Drawing 504-911 has been tested in this laboratory with the following results:

a. The tube was capable of withstanding a 75 kv, rms high-potential test.

b. The tube was satisfactorily operated in a modulator circuit to a hold-off voltage of 29 kv and a pulse-current of 2000 amperes. Measurements taken during these tests confirm that the tube deionizes in the control-grid region in the time anticipated.

c. These tests showed, however, that the initial water-jacket design was inadequate. Accordingly, the water jacket was improved in our laboratory by the expedient of soft soldering the cooling pipes to the tube body.


along the entire length of the tube. After tests were resumed this improved water-cooling scheme appeared satisfactory. However, before complete confirmation could be obtained the control-grid seal ruptured.

d. Examination of this seal and conferences with the manufacturer indicate that improper care had been taken in the fabrication of all seals. The General Electric Company is now manufacturing new tubes with graded seals to accommodate the differential expansion between the alloy 304 stainless body and the Kovar seal cup. These improved tubes are now being fabricated at General Electric, Schenectady, N.Y., and should be available for testing in about four weeks.

2. Application of Solid-State Diodes

During this period silicon-junction diodes have been tested for service as end-of-line clippers, hold-off diodes and transformer-backswing clippers, and for service in the pulse-to-pulse amplitude jitter circuit. Operation has been generally satisfactory in all these applications. However, we recently have had an unexplainable failure in the transformer-clipper diode even though it had been operated satisfactorily at full power for the order of 40 hours. The cause of this failure is not known at present. We expect that the diode assembly may have deteriorated due to the high-ambient X-ray flux in the region of the assembly. We are presently undertaking tests with single cells of this type to determine whether or not such X-ray damage occurs.

3. Investigation of Solid-State Switches

We have received a developmental 5000-ampere, 2-kv switch as a consequence of our subcontract with the Shockley Transistor Corporation. However, we have been unable for various practical reasons to accomplish its test and evaluation during this period. We anticipate that complete test data will be obtained by 1 November.
X. VACUUM SYSTEM

A. MARK IV CONVERSION

The Mark IV vacuum system was completed during this quarter. The entire system consisting of two accelerator tubes, the transmission waveguide and two klystrons and waveguides has been held under a vacuum of $3 \times 10^{-7}$ torr for over a month. The accelerator tubes are a source of outgassing, so that no further improvement in the vacuum level is expected until the tubes can be outgassed by rf power or by direct heating.

B. FEASIBILITY STUDIES

A manufacturers' field-inspection trip was made for the purpose of seeing what vacuum equipment manufacturers are doing. The trip was very successful from the standpoint of observing their efforts and interests and thus establishing the areas where Project M vacuum research should be continued. Project personnel will concentrate their research efforts in certain areas and count on established manufacturers to take care of other system requirements.

C. PROBLEMS

1. The automatic bakeable ultra-high vacuum valve calculations and study has been started.
2. A new flange and metallic gasket system is under investigation.
3. Equipment for determining the pumping characteristics of sixty feet of waveguide is being fabricated.
4. Equipment for studying various material outgassing characteristics is being fabricated.

D. CONCLUSIONS

The project research and development effort has been established by consulting the latest research being done by vacuum equipment manufacturers.

The research and development studies needed for the two-mile accelerator are in various stages of investigation, engineering and fabrication. Results have been evaluated and will soon be forthcoming.

The Mark IV vacuum system has been operating successfully for over a month. Further processing is needed but must be held up until the rf power or externally applied heating can be used on the system.
XI. SUPPORT AND ALIGNMENT

A. SITE EARTH MOVEMENT STUDIES

The field work of the third precise elevation survey has been completed. The final results have not been presented as yet. The requirements that all observations of this survey be made at night and that the length of sightings be limited to 50 ft has appreciably improved the closures. Additional surveys over the same system of hubs will be repeated periodically.

Hydraulic tilt meters are being experimented with at the site. Vertical differential-movement sensitivities to one part in ten million are expected. Extensive use of this method over the entire site will depend upon the results of these experiments.

The survey plan for the precise horizontal triangulation and trilateration surveys has been established. Monuments are being placed and precision optical equipment is being purchased. It is hoped that the first survey will be completed before the middle of November.

B. SUPPORT

In addition to the previously discussed support methods, the possibility of using a forty-foot substructure to carry four accelerator sections is being considered. Adjustable supports in this design would be placed at an appropriate distance in from each end of the substructure so that the elastic deflection at the ends and mid-point would be equal. Operation of the adjustment mechanism would be manual but could be extended to the klystron housing if desired.

C. ALIGNMENT

An additional optical-alignment proposal has recently been submitted by Keuffel and Esser Co., Optics and Metrology Division, Hoboken, N. J. It will be considered along with the numerous other proposals previously submitted.
XII. CONTROL SYSTEM STUDIES

A. GENERAL STUDIES DURING THE QUARTER

During the past quarter the Instrumentation and Control Group has continued to pursue the following objectives.

1. General studies of the operation and maintenance policies and of the data communication costs, and technical considerations that will influence the control system design. Several reports based on these studies have been issued during the quarter.

2. Technical feasibility studies of ideas that show promise of simplifying the control system. Preliminary results from a study of magnetic beam-inflection systems are presented below.

One of the staff members attended the design study for the 300-1000 Bev accelerator at Brookhaven National Laboratory during the month of August and, subsequently, attended the International Accelerator Conference in September. A contribution was made to a chapter on instrumentation of the report published by the Brookhaven Conference (as a consequence of the design study), entitled "A Design Study for a 300-1000 Bev Accelerator," dated August 28, 1961.

Another member of our staff made a trip to Europe as a result of an invitation to present a paper at the Microwave Measurements Conference in London, England. This trip also included visits to Harwell and Orsay.

Three members of the group visited Brookhaven and Argonne National Laboratories to exchange instrumentation ideas. Particularly interesting was the proposed application of digital data techniques to the ZGS machine at Argonne. The opportunity to compare notes also provided valuable information for cost estimates in this field.

Considerable time has been spent by the group in analyzing the equipment requirements for the instrumentation of the Project M accelerator, test accelerator and test stands. Budgetary estimates and scheduling, which will represent our schedule of work for the coming year, resulted from this analysis. As a consequence of project approval the staff has been increased, and the group now will proceed to analyzing and itemizing in greater detail the manpower and equipment requirements.
B. MAGNETIC SYSTEMS FOR INJECTION

During the last quarter extensive calculations have been made on several achromatic isochronous beam-transport systems that are applicable for injecting into and extracting from electron linear accelerators. As reported at the 1961 International High Energy Accelerator Conference, we have been able to devise systems which satisfy both of these requirements and have an almost arbitrary deflection angle. A summary of these calculations is given below. A more detailed report is in preparation.

The main limitation of a deflecting system used for injection is the debunching. The path length of the electrons depends on their energy. For a zero-dispersion system that transfers a parallel beam into a parallel beam, the path length depends only on the energy of the particle.

Among the zero-dispersion systems it is possible to have (1) a non-isochronous system with small debunching; the angle of deviation will be limited by this debunching; and (2) isochronous systems; for these systems the path lengths of all the particles of the bunch are the same to the first order.

The following systems are under study.

1. Three Identical Uniform-Field Magnets (Fig. 9)

   The maximum angle of deviation is 60° and

   \[ l = \rho_0 \frac{2 \cos \alpha - 1}{\sin \alpha} \]

   The debunching is

   \[ \Delta \varphi = -360 \degree (r \sin \alpha - 3\alpha) \frac{\rho_o \Delta p}{\lambda_o p_o} \]

   For \( \rho_o = 26.6 \) cm (the radius of curvature for 40 Mev electrons in a magnetic field of 5000 gauss), the debunching for each percent of energy spread is

<table>
<thead>
<tr>
<th>( \alpha^\circ )</th>
<th>( \Delta \varphi^\circ )</th>
</tr>
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<tr>
<td>30°</td>
<td>-3.9°</td>
</tr>
<tr>
<td>40°</td>
<td>-4.3°</td>
</tr>
<tr>
<td>50°</td>
<td>-4.1°</td>
</tr>
<tr>
<td></td>
<td>-40°</td>
</tr>
</tbody>
</table>
FIG. 9 - Three identical uniform-field magnets.
This system is not acceptable for an injection device.

2. Three Nonidentical Uniform-Field Magnets (Isochronous System) (Fig. 10)

If the deviation is specified, the system is completely determined.

The maximum deviation angle for isochronism is $105^\circ$, and for $90^\circ$ the results are

\[
\alpha = 52.5^\circ \\
2\alpha' = 15^\circ \\
\rho/\rho' = 5.13 \\
\lambda/\rho' = 3.81
\]

and, for $105^\circ$

\[
\alpha = 87.5^\circ \\
2\alpha' = 35^\circ \\
\rho/\rho' = 2
\]

3. Two Bending and One Quadrupole Magnets (Fig. 11)

The conditions are

\[
\lambda = \frac{2\rho}{\tan \alpha} \\
\tan \beta = \frac{\tan \alpha}{2} \\
\frac{f}{\rho_0} = \frac{2 \cos \alpha}{\sin \alpha (1 + \cos \alpha)}
\]

The debunching is given by

\[
\Delta \varphi = 360^\circ \frac{2(\alpha - \sin \alpha)\rho}{\lambda} \frac{\Delta \rho}{\rho}
\]

The deviation angle is $2\alpha$. 
Fig. 10—Three nonidentical uniform-field magnets (isochronous system).
For $\rho_0 = 26.6$

<table>
<thead>
<tr>
<th>Deviation (Degrees)</th>
<th>$\Delta \rho$ Degrees/Percent of $\Delta \rho/\rho$</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>0.06</td>
</tr>
<tr>
<td>40</td>
<td>0.13</td>
</tr>
<tr>
<td>50</td>
<td>0.25</td>
</tr>
<tr>
<td>60</td>
<td>0.43</td>
</tr>
<tr>
<td>70</td>
<td>0.68</td>
</tr>
<tr>
<td>80</td>
<td>1.00</td>
</tr>
<tr>
<td>90</td>
<td>1.43</td>
</tr>
</tbody>
</table>

If we assume an energy spread of $\pm 5\%$, which is reasonable at the output of the first section, $60^\circ$ looks like the maximum possible deviation and $45^\circ$, a reasonable value.

a. Geometrical Tolerances

We have calculated the possible displacement of each of the three components in respect to its theoretical position.

$$
(D_H) \leq 2 \alpha d \\
(D_V) \leq \frac{4d + 8(3 - 6\alpha)}{\alpha}
$$

$$
(\Delta_H) \leq \alpha d + (3\alpha/2) \\
(\Delta_V) \leq (\alpha d/2) + 2\alpha \delta
$$

$D_H$ is the horizontal displacement of the output beam.
$D_V$ is the vertical displacement of the output beam.
$\Delta_H$ is the horizontal rotation of the output beam.
$\Delta_V$ is the vertical rotation of the output beam.
$\rho_0 d$ is the tolerance in positioning the "center" of each element.
$\delta$ is the angular tolerance in positioning the axis of the elements.

b. Adjustment of the Focal Length of Quadrupole

The center of the beam, if the focal length is not properly adjusted,

\[12\text{This center is the intersection of the input axis, the output axis for a bending magnet, and the geometric center for a quadrupole.}\]
is displaced by an amount $x$, where

$$x = \rho_o \frac{\Delta p}{p} \frac{1 + \cos \alpha}{2 \cos \alpha} \frac{\Delta f}{f}$$

For a $45^\circ$ inflection system, the following tolerance is computed.

$\alpha = 22^\circ 30' \quad x_{\text{max}} = 0.5 \text{ mm} \quad \rho_o = 266 \text{ mm} \quad \frac{\Delta p}{p} = \pm 5\% \quad \frac{\Delta f}{f} \leq 4\%$

$\alpha = 22^\circ 30' \quad x_{\text{max}} = 0.5 \text{ mm} \quad \rho_o = 532 \text{ mm} \quad \frac{\Delta p}{p} = \pm 1.5\% \quad \frac{\Delta f}{f} \leq 6.5\%$

If we replace the rotated-face magnets by n-type magnets ($n = \frac{1}{2}$) the results remain about the same with

$$l \approx \frac{\rho_o \sqrt{2}}{\tan (\alpha/\sqrt{2})} \quad \frac{1}{f} = \frac{\sqrt{2} \sin (\alpha/\sqrt{2})}{\rho_o}$$

$$\Delta \varphi = 360^\circ \frac{\rho_o}{\lambda_o} 2^{5/3} \left( \frac{\alpha}{\sqrt{2}} - \sin \frac{\alpha}{\sqrt{2}} \right) \frac{\Delta p}{p}$$

4. **Four Bending and One Quadrupole Magnets (Isochronous System) (Fig. 12)**

This system depends on five parameters ($\alpha, \alpha', l_1, l_2$ and $f$) bound by four conditions. If one free parameter remains, the best compromise seems to be

$$l_1 = \frac{\sqrt{2}}{4} \rho_o$$

$$l_2 = \frac{3\sqrt{2}}{4} \rho_o$$

$$\alpha = 55^\circ 20'$$

$$\alpha' = 10^\circ 20'$$

In this case, the compromise requires both $l_1$ not too small and $\alpha'$ not too small, which are two contradictory conditions.
FIG. 12--Four bending and one quadrupole magnets (isochronous system).
FIG. 14--Two bending and one off-center quadrupole magnets.
A. RADIATION SHIELDING

1. An attenuation measurement has been made using nuclear emulsions exposed at various depths in a large stack of concrete (baryte) shielding to the 20-Bev scattered external proton beam at the CERN accelerator. This exposure was made by Ballam, Lock, Hoffman and others at CERN. The exposure was done with three sets of emulsions, and these have been given to Stanford, Harwell, and a DESY-CERN group. The Stanford emulsions are being scanned by the emulsion group under Gilbert and Oliver at the Livermore Laboratory, and it is hoped that a measurement to an attenuation factor of about $10^5$ will be possible.

2. Clayton Zerby of the Oak Ridge National Laboratory has finished a Monte Carlo calculation of the longitudinal development of the electromagnetic cascade. The results agreed within 5% with the differential photon track length of Approximation A of shower theory for secondary energies greater than the critical energy and less than half the primary energy. These data are being combined with the photoneutron yields predicted by Dedrick using a photodeuteron model to give a source strength, and an analytic calculation of shielding attenuation is being made. The coding for this calculation is almost complete.

Zerby will also make a calculation of the lateral shower development. This will be done also in special configurations such as collimators.

3. We are continuing our calculations of the residual radioactivity inside the accelerator tunnel and, also, our estimates of the effects of ducts through the main shield.

B. ACCELERATOR HEATING

A calculation has been made by J. Muray of the heating of the accelerator structure if it intercepts the electron beam. An M report on this will be issued shortly.13

In addition, Muray and J. Cobb have equipped a two-foot length of accelerator with thermistors to allow a measurement of the heating of the accelerator disks when exposed to the 1 Bev beam of the Mark III accelerator. This measurement can be used to check the calculations.

XV. AC POWER SYSTEM

During the last quarter studies were completed of site-utilities preliminary-design features, of project-power service, and of the Test Laboratory definitive-design factors.

A. PRELIMINARY PROPOSAL FOR THE SITE UTILITIES

Electrical features of the initial utility installation were determined and included in the Preliminary Proposal for the Site Utilities. Prior to the installation of the electrical service to the project, needs will be met by engine-driven generators furnished by ABA. The first power service connection will be via a 60 kv, overhead-transmission line. This line will tap the existing Pacific Gas and Electric Company's 60-kv system near the intersection of Alpine Road, Santa Cruz Avenue and Serra Road. It will terminate at a temporary 60-kv substation located adjacent to and south of the proposed beam switchyard. The temporary 60-kv substation will feed a temporary 12-kv overhead pole-line distribution system to serve project needs. The temporary system will be replaced by 12-kv underground cables, and the 60-kv substation will be incorporated into the project master substation complex.

B. PROJECT POWER SERVICE CONNECTION

Reviews made during this quarter of the envisioned load growth are summarized in the following table.

<table>
<thead>
<tr>
<th>Description</th>
<th>Connected Load Mvamps</th>
</tr>
</thead>
<tbody>
<tr>
<td>Project support</td>
<td>1.87 1.87</td>
</tr>
<tr>
<td>Project general utilities</td>
<td>1.00 1.20</td>
</tr>
<tr>
<td>Auxiliary test and research</td>
<td>11.60 11.60</td>
</tr>
<tr>
<td>Accelerator auxiliaries</td>
<td>17.80 21.00</td>
</tr>
<tr>
<td>Accelerator operation</td>
<td>54.24 106.60</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>86.51 142.27</strong></td>
</tr>
</tbody>
</table>
C. TEST LABORATORY DEFINITIVE DESIGN

Continuing efforts in connection with the Test Laboratory requirements and load locations yielded the definitive information necessary to expand the preliminary data previously reported. Revisions were incorporated in the definitive design, such as the reduction in the high-bay illumination intensity to 50 foot candles. The special usage areas in the Test Laboratory wing will be at 100 foot candles. Also, the preliminary design was changed to include an 8 Mvamps substation appended to the building.

\[\text{--- Status Report, M Report No. 272, Project M, Stanford University, Stanford, California, July 1961, pp. 36-37.} \]
XVI. COOLING WATER SYSTEM

A. TWO-MILE ACCELERATOR

The master plan for the plant water system has been completed except for the location of the water-storage tank. The selection of a location for the storage tank is awaiting completion of development of a possible water-supply system to be operated by the City of Menlo Park to serve Project M, the Sharon Estate development and Stanford University lands adjacent to Project M.

There will be three cooling-tower stations serving the plant: one large one located about halfway along the two-mile accelerator to serve the Klystron Gallery and Accelerator Housing; a second large one located near the end stations to serve them and the beam switchyard; and a third and smaller station to serve the buildings in the laboratory area. The laboratory area station will be the first one constructed, to coincide with the construction of the Test Laboratory Building.

In the case of the two-mile accelerator, cooling-tower water will be distributed to fifteen identical heat-exchanger installations spaced about 640-feet apart along the length of the accelerator. At these points the low conductivity, closed-circuit cooling-water systems, serving klystrons, modulators, etc., will give up heat to the cooling-tower water and be pumped back to the electronic equipment. This arrangement was decided upon on the basis of ABA Report, "Heat Transfer System Study" (ABA-3).

In the case of the beam switchyard and end-station area, cooling-tower water will be distributed to heat-exchanger installations located adjacent to the major cooling-load centers, where the exchangers will pick up the heat load from the closed-circuit, low-conductivity, cooling-water systems.

The laboratory area cooling-water system is in the detailed design stage.

B. MARK IV

The cooling-water system for the revised Mark IV machine has been tested and final calibrations are being made.

C. RESEARCH AND DEVELOPMENT

See Section III., Accelerator Structure Studies, for research and development work on cooling the accelerator structure.
Detailed design of the heating and ventilating system for the Test Laboratory Building is virtually complete.

Detailed design of Utility Building A has been started. This building will house a central-heating plant, compressed-air equipment, and air-conditioning refrigeration equipment for all of the buildings in the laboratory area. Included in the design are distribution lines to the various buildings.