

# SLAC: The Accelerator



*The Stanford two-mile linac produces up to six beams. The unusually high current and high energy can be doubled by future expansion.*

*by Richard B. Neal*

LAST MAY, APPROXIMATELY four years after construction started at the Stanford Linear Accelerator Center, a beam traveled the entire two-mile length of the accelerator from an injector at the west end to a beam dump at the east end. This machine is distinguished not only by its length and high energy (20 GeV); it also produces high current (30 microamperes), exceeding by a factor of 100 that of any other machine operating with an energy greater than 10 GeV. Moreover the design permits future expansion (from stage I to stage II) that will double both energy and current by adding radiofrequency sources along the length. Details of the design evolution appear in references 1-5.

During the first full-length operation the accelerator ran at 10 GeV with 24 of its 30 sectors contribut-

ing at reduced power. In subsequent tests we increased the energy to 20.16 GeV (in January).

## GENERAL DESCRIPTION

The SLAC site is about 3-km west of the main university campus. It is 300-meters wide along most of the accelerator length and increases to about 900 meters at the target end to allow space for laboratories, shops and experimental facilities.

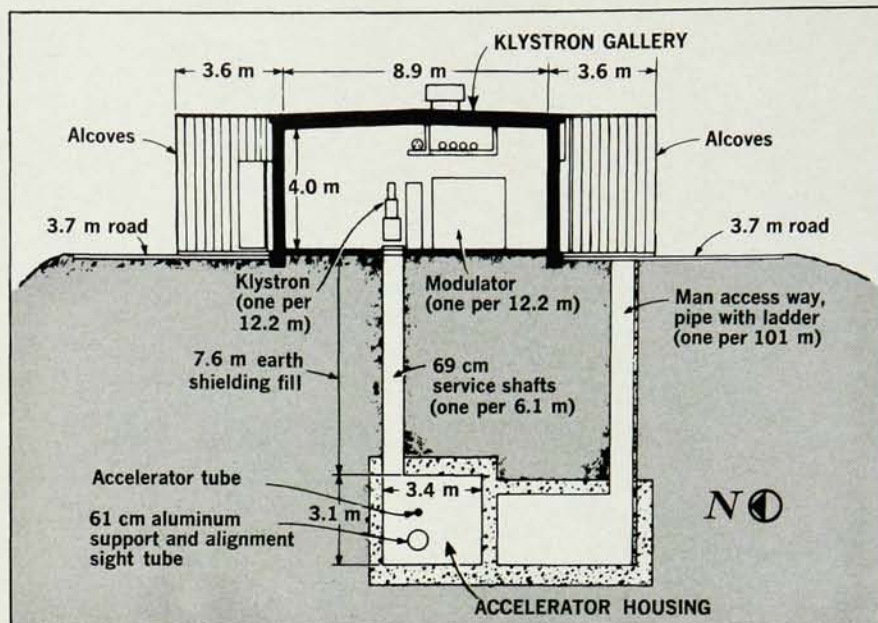
The underground accelerator housing and the above-ground klystron gallery (figure 1) are separated by 8 meters of earth for radiation shielding. An interconnecting service shaft every 6 meters carries utilities, vacuum manifolds, instrumentation and control cables, and radiofrequency waveguides between the two levels. A personnel access way is provided once in each 102-meter sector.

The beam switchyard at the target end (figure 2) is a large underground housing, approximately 300-meters long, that contains beam-transport systems and instrumentation to analyze and select beam characteristics and direct the beam into various experimental areas.

Beyond the switchyard is the research area consisting of two large buildings and many smaller structures on about 80 000 square meters (20 acres) of land. The larger of the buildings, having a floor area of 2300 square meters and walls 21 meters high, will be used primarily for electron and positron scattering experiments and for photoproduction studies. The smaller building has an area of 1600 square meters and will be the center of activity for experiments involving secondary particles.

Figure 3 shows the principal components and systems of the accelerator. Most of these units are repeated many times in the entire accelerator length. For example, there are 960 three-meter-long accelerator sections, 245 klystrons, 245 modulators, 30 subbooster klystrons, 30 power substations, 30 vacuum systems, etc. The

CROSS-SECTION of linac housing and klystron gallery. —FIG. 1



instrumentation-and-control system is spread over the entire accelerator length, although the machine can be operated from a single central-control room.

The table on page 39 is a summary of accelerator specifications.

#### Accelerator structure

The accelerator proper is a cylindrical copper disk-loaded structure<sup>6</sup> in which an axial electric accelerating field is set up when the structure is excited with 2856-MHz microwave power. The structure is designed to produce a constant axial electric field over the length of each independently-fed 3-meter section. This constant-gradient characteristic is achieved by suitable variation of the modular dimensions of the section. The shunt impedance of the structure is approximately 53 megohms per meter, which results in an electron-energy gain in a 3-meter section of about  $10P^{1/2}$  (MeV) where  $P$  is the input radiofrequency power to the section in megawatts.

The accelerator structure was fabricated by a brazing technique from basic disk and ring elements. These parts were independently machined to accuracies of  $\pm 5 \times 10^{-3}$  mm. They were then carefully stacked and clamped together on a stainless-steel mandrel passing through the disk apertures. Brazing was accomplished in a special flame furnace that provided a reducing atmosphere both inside and outside the structure to prevent oxidation. Figure 4 shows a completed 3-meter section.

Four 3-meter sections, mounted on a 12.2-meter aluminum girder, 61 cm in diameter (figure 5) form a modular length of the accelerator for support and alignment purposes. The aluminum girder serves dual purposes as support for the accelerator and as a "light pipe" for alignment.

#### Klystrons

The radiofrequency sources are high-power klystron amplifiers. A basic tube having a design capability of 24 MW peak and 22 kW average power was developed at SLAC.<sup>7</sup> Four commercial companies also developed tubes meeting the same basic specification as the SLAC tube. All of these tubes have permanent-magnet focusing and are electrically and mechanically interchangeable.

The general arrangement of the klystron, the connecting waveguides and the accelerator sections is shown

in figure 6. The power from each klystron is divided four ways (stage I) and is used to supply power to the four 3-meter sections located on a single 12.2-meter girder. Waveguide feeds to the accelerator connect to opposite sides of successive sections to compensate for deflecting forces due to residual coupler asymmetries. The provision of a waveguide valve just above each klystron allows the klystron to be replaced without affecting the accelerator vacuum or interfering with beam operation. If stage II is later authorized, the number of klystrons will be increased to 960 so that each klystron feeds a single 3-meter section.

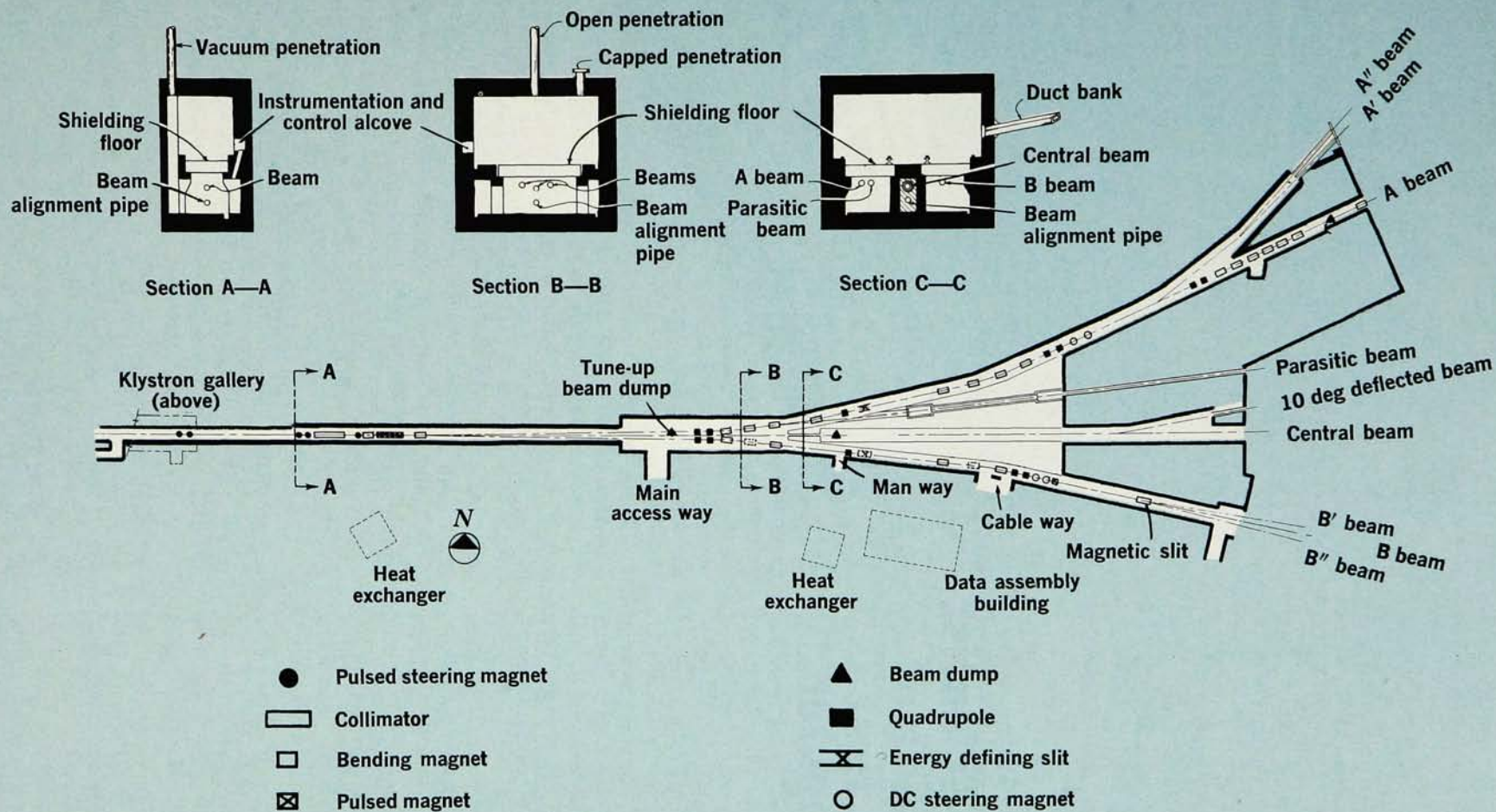
#### Drive and phasing system

The klystron amplifiers must receive coherent low-level signals at 2856 MHz for the rf waves in the accelerator sections to have correct frequency and phase relationships with individual bunches of electrons passing through the accelerator. The rf drive system consists of (a) a master oscillator providing 476-MHz cw power, (b) a main booster amplifier that increases the 476-MHz cw power to 17.5 kW, (c) an 8-cm-diameter main drive line, 3.2 km (2 miles) long, (d) couplers and varactor frequency multipliers at each 102-meter sector, which remove a small portion of the main drive signal and multiply the frequency by six to 2856 MHz, (e) a pulsed subbooster klystron at each sector, which amplifies the 2856-MHz power by 60 dB, (f) a 4-cm-diameter coaxial line that transmits 2856-MHz drive power to the vicinity of each of the high-power klystrons in the sector and (g) couplers that remove approximately 300 W peak to drive each klystron.

The main drive signal is transmitted at the subharmonic frequency, 476 MHz, since the low loss at this frequency ( $\sim 0.82$  dB/100 meters) permits transmission over two miles without series boosters, which, if used,

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BEAM SWITCHYARD contains transport systems and instrumentation for analyzing, selecting and directing beams. —FIG. 2

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would lead to phase shift and reliability problems.

The rf phasing system<sup>8</sup> uses the phase of the accelerator electron bunches as reference. The system is based on the principle that the wave induced by the bunched electron beam in an accelerator section is 180 degrees out of phase with respect to the wave from a correctly phased klystron supplying power to the section. Phasing is accomplished automatically (within  $\pm 5$  degrees) by sectors at the initiation of the operator.

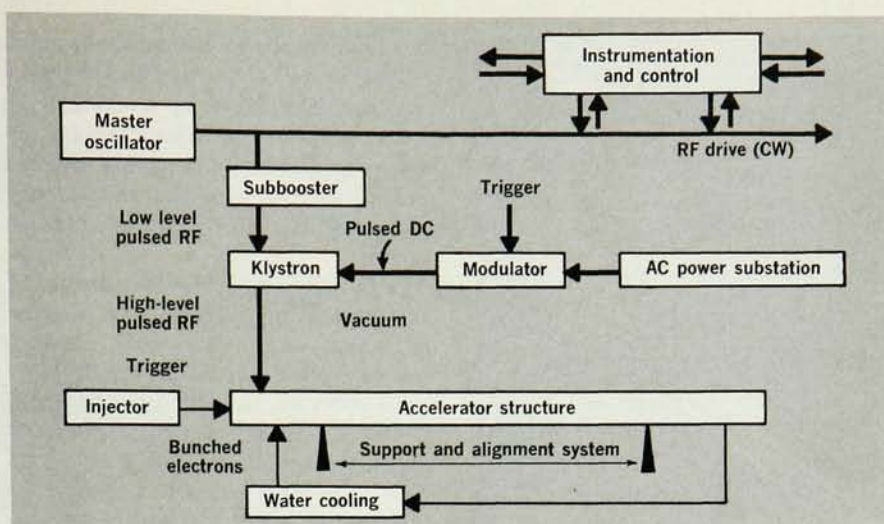
### High-power modulators

Each klystron amplifier is provided with a line-type modulator<sup>3</sup> rated at 65 MW peak and 75 kW average power, a pulse length of 2.5  $\mu$ sec, and a maximal pulse repetition rate of 360 pps. The pulse-forming network in the modulator discharges through a single hydrogen thyratron capable of handling the entire peak and average power requirements. The voltage of the modulator output pulses is increased by a factor of 12 with a pulse transformer, and the resulting pulses at 250 kV (maximum) are then applied to the associated klystron.

Each modulator is provided with a de-Q'ing circuit that compares the charging voltage of the pulse network during each charging cycle to a reference voltage. When the charging voltage reaches the reference level, the energy stored in a charging transistor is dumped into a dissipative circuit through a silicon-controlled rectifier switch. This effectively clamps the charging voltage at the reference level and thus stabilizes the output pulses from the modulator to  $\pm 0.1\%$  even with significant ( $\pm 5\%$ ) variations in the ac line voltage.

### Injector system

The main injector<sup>9</sup> (figure 7) is designed to inject a well bunched (5 degrees) and well collimated beam of electrons into the accelerator. Since the energy gain of an accelerated electron is proportional to the cosine of the phase angle it occupies with respect to the peak of the traveling radiofrequency wave, good bunching of the electrons is essential to attain a narrow electron-energy spectrum at the output. The triode-type electron gun, which operates at 80 kV, permits the



PRINCIPAL COMPONENTS are repeated along two-mile length.—FIG. 3

pulse length and beam current to be selected on a pulse-to-pulse basis from any of three predetermined sets of values. This feature of the injector, together with the ability to trigger the klystrons in the various sectors in time with or after the beam (or at various repetition rates), permits carrying on several simultaneous experiments in the research areas at different incident energies, pulse lengths and intensities.

The prebuncher consists of a velocity-modulation cavity. The bunching section in which the phase velocity is 0.75  $c$ , is 10-cm long, and disk-loaded. It reduces the phase spread by a factor of 2 (while doubling the momentum spread) and increases the beam energy to 250 kV. A 3-meter constant-gradient accelerator section increases the energy to approximately 30 MeV. For phase synchronization, the prebuncher, buncher and 3-meter accelerator section are all driven by power from the same klystron, which is conservatively run at half to two thirds of its power capability to give good life stability.

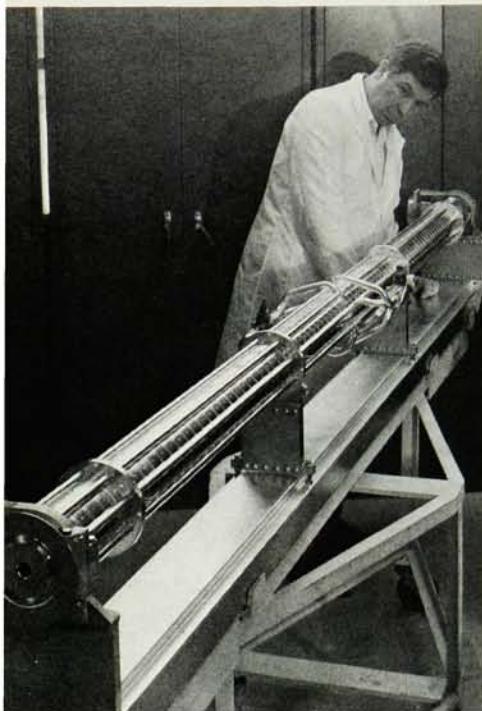
### Positron source

A positron beam is desired at a point 2/3 along the accelerator for injection into a proposed positron-electron storage ring<sup>10</sup> and at the main experimental station at the end of the accelerator for positron-scattering experiments. The positron beam is created at the 1/3 point by inserting a converter and reversing the rf phase of the first third of the accelerator. With 100 kW of

incident electron-beam power, it is predicted that approximately  $2.5 \times 10^{10}$  positrons per pulse can be accelerated in an energy band of about 1% and a transverse phase space of approximately 0.15 MeV-cm/c.

The positron-source system is shown in figure 8. Either of two separate radiators can be inserted into the beam. A radiator has a thickness of about 3.5 radiation lengths and consists of one layer of gold, two of silver and eight of copper with cooling water passages between. Each layer is approximately 3.2-mm thick. A wand radiator is provided for intermittent positron pulses at rates of one per second or less. It is a small target about 13-mm wide driven across the beam line on command in a time equivalent to about five machine pulses (at 360 pps). The center pulse of this group results in a positron pulse; the other four are caused to be blank by gating the main injector. All other pulses can be the electron beam, if desired. The second radiator is in the form of a rotating water-cooled wheel. It is used to obtain continuous positron production.

A magnetic lens system is used to improve the match between the source emittance and the accelerator phase-space acceptance. The radiator is located in a 20-kG axial magnetic field that decreases rapidly to 2.4 kG about 60-cm downstream of the radiator and then remains constant for the next 7.6 meters. Acceleration begins 76 cm downstream of the radiator, and the



**3-METER SECTION.** Constant-gradient characteristic is achieved by varying modular dimensions.—FIG. 4

**BASIC MODULE, 12.2 meters in length,** consists of four 3-meter sections mounted on an aluminum girder that is 61 cm in diameter.—FIG. 5

positron energy at 7.6 meters is about 75 MeV; at this point the solenoidal focusing is replaced by a series of 13 quadrupole triplets whose spacing increases with energy until this focusing system merges with the regular machine triplet system at the end of each sector.

A pulsed rf deflector downstream of the converter produces an angular deflection of positron and electron beams. Since the beams are 180 degrees apart in phase, they are both deflected by the same angle; depending on which beam is needed, a magnetic dipole can then be used to restore the direction of either the positron or the electron beam to the axis while deflecting the other even farther.

#### *Guidance and diagnosis*

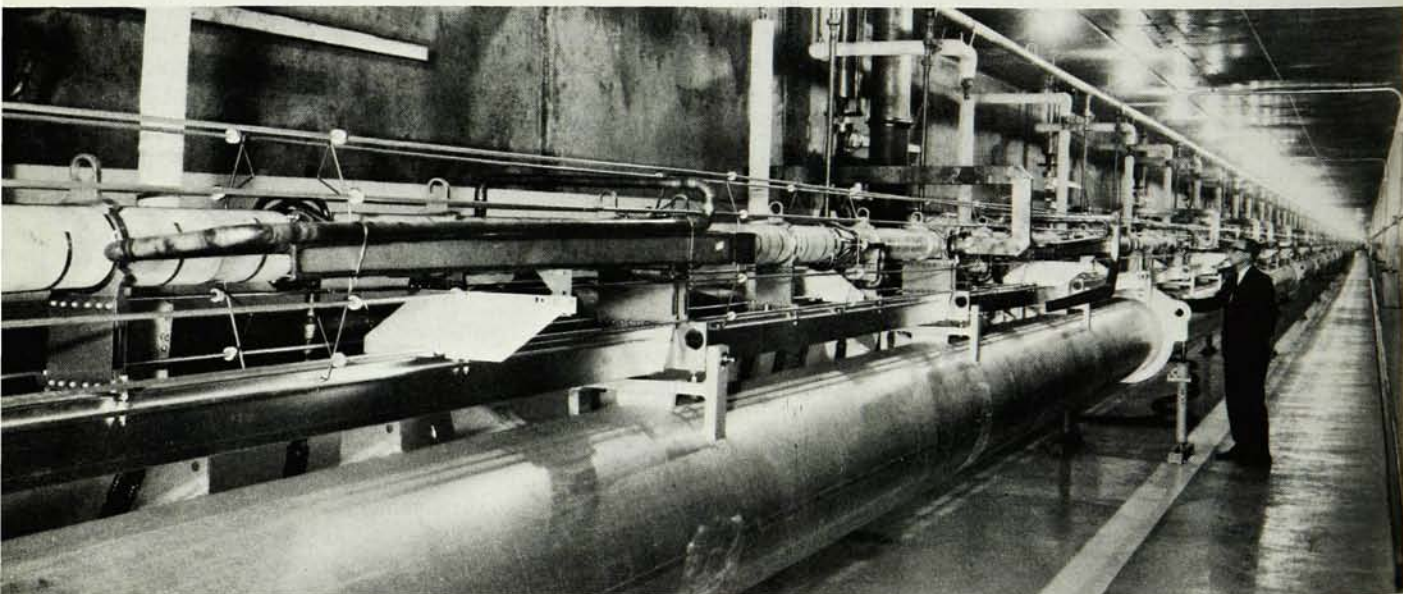
To compensate for the earth's magnetic field and for stray ac and dc fields along the machine, parallel degaussing wires and concentric magnetic shielding reduce the average fields to less than  $10^{-4}$  gauss.<sup>11</sup> Degaussing currents are independently adjustable for each sector. The magnetic shielding material, 0.15 mm of moly-permalloy, results in a local shielding factor of about 30 and an overall effective value of about 10, considering unavoidable gaps.

Beam monitoring, steering and focusing devices are provided in a 3-meter drift section at the end of each 102-meter accelerator sector. The layout of a standard drift section is shown

in figure 9. This section includes a quadrupole triplet, steering dipoles (X and Y), a phase-reference cavity, beam-position monitors (X and Y), and beam-intensity monitor, a beam-profile monitor and a beam scraper (collimator). The beam position monitors consist of two rectangular cavities that are excited in the  $TM_{120}$  mode by an off-axis beam. Since the phase of the excitation depends on the direction of beam deviation from the axis, the sense of the deviation can be detected by comparing the phase of the wave from the beam-position-monitor cavities with the phase of the wave from the phase-reference cavity, which is excited in the  $TM_{010}$  mode. Beam positions accurate to less than 1.0 mm from 30 such systems are presented at central control.

#### *Trigger system*

Although the basic repetition rate of the accelerator is 360 pps, the trigger system permits operation of various accelerator sectors and other subsystems in a very flexible manner so that up to six beams having distinct energies, currents and destinations in the research area can be programed. The repetition rates of these beams can be adjusted to any value between 1 and 360 pps. The trigger system is illustrated in figure 10. 400-volt clock pulses at 360 pps are sent over the entire two-mile length along a single 4-cm-diameter coaxial cable. A small amount of power is removed from the





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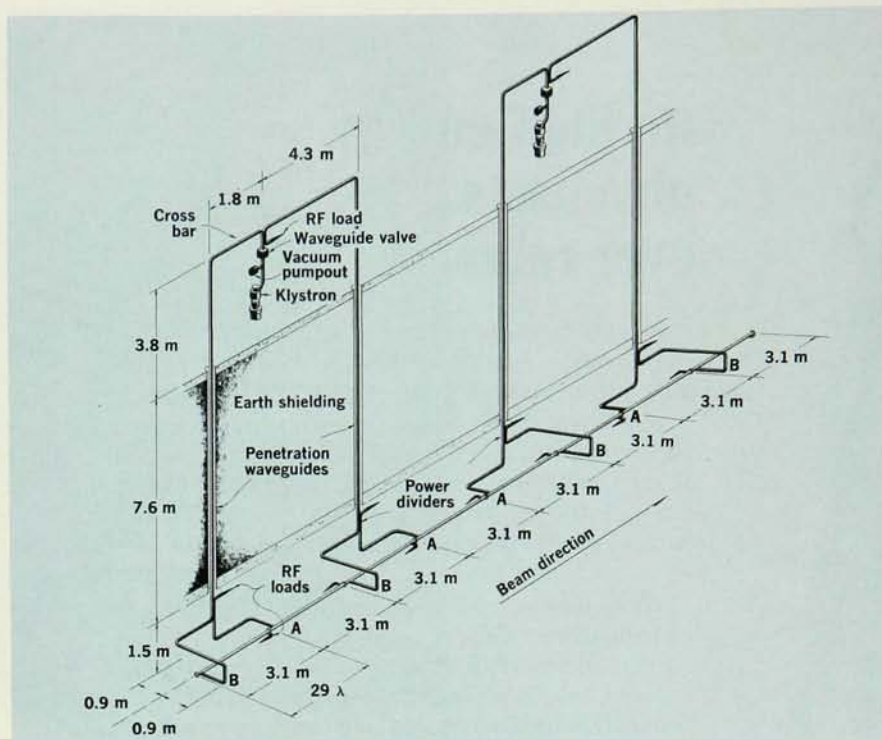
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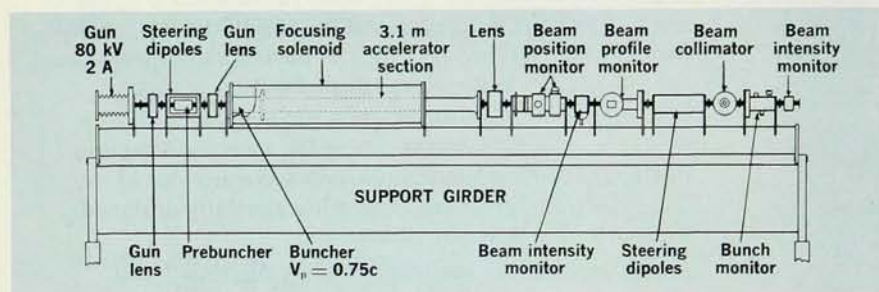
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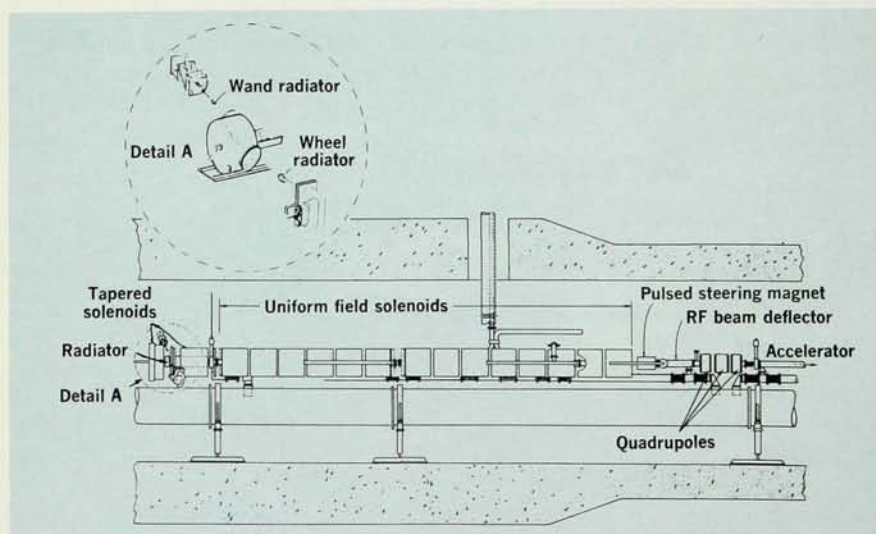




WAVEGUIDE FEEDS connect klystron to four 3-meter sections.—FIG. 6



INJECTOR produces a well bunched and collimated beam. —FIG. 7



main line by couplers at each station (injector, accelerator section, positron source, etc.) and is sent to the local trigger generator. A gating pulse is sent to each local trigger generator from the pattern generator in central control. Since the timing precision ( $\sim 25$  nsec) is inherent in the clock pulses, the gating pulses do not have to be very precise and can be transmitted on ordinary wire pairs.

In figure 10, the pattern-generator pulses are shown gating the clock pulses admitted to the klystron modulators of each sector. If a particular sector is not to contribute to the energy of a particular beam, the pattern gating signal causes the modulators to be triggered approximately  $25 \mu\text{sec}$  late, after the beam pulse has been transmitted through the sector. In other arrangements, the pattern signals can cause a particular sector to pulse at lower repetition rates, such as 60, 120 and 180 pps.

#### Vacuum system

The all-metal high-vacuum system<sup>12</sup> capable of maintaining the accelerator and waveguides at less than  $10^{-6}$  torr is shown schematically in figure 11. One such system is provided for each 102-meter sector. Four 500-liter/sec getter ion pumps located in the klystron gallery evacuate the accelerator and waveguides through interconnecting stainless-steel manifolds. A pump can be removed for servicing without interference with accelerator operations by closing the associated 15 cm valve. Similarly an individual klystron can be replaced by closing the 8-cm valve connecting it to the pumping manifold and the waveguide vacuum valve in its output rf system.

Separate pumping systems are provided for rough-pumping the accelerator, for the 61-cm light pipe, and for the beam switchyard.

#### Alignment system

Each of the accelerator 12.2-meter support points is aligned with respect

POSITRON-SOURCE system and focusing equipment. —FIG. 8



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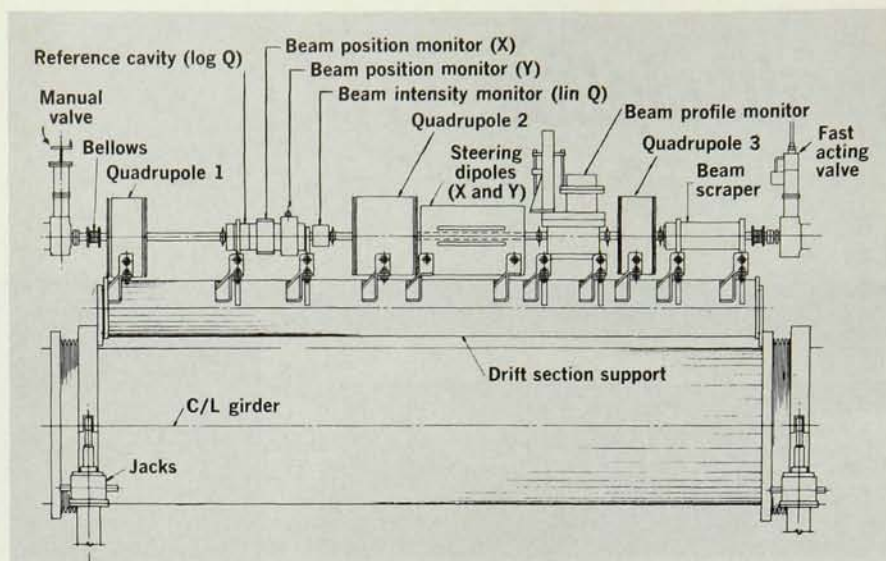
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| 0 - 40V, 0 - 500MA  | 6102A | 265.   |
| 0 - 100V, 0 - 200MA | 6106A | 265.   |

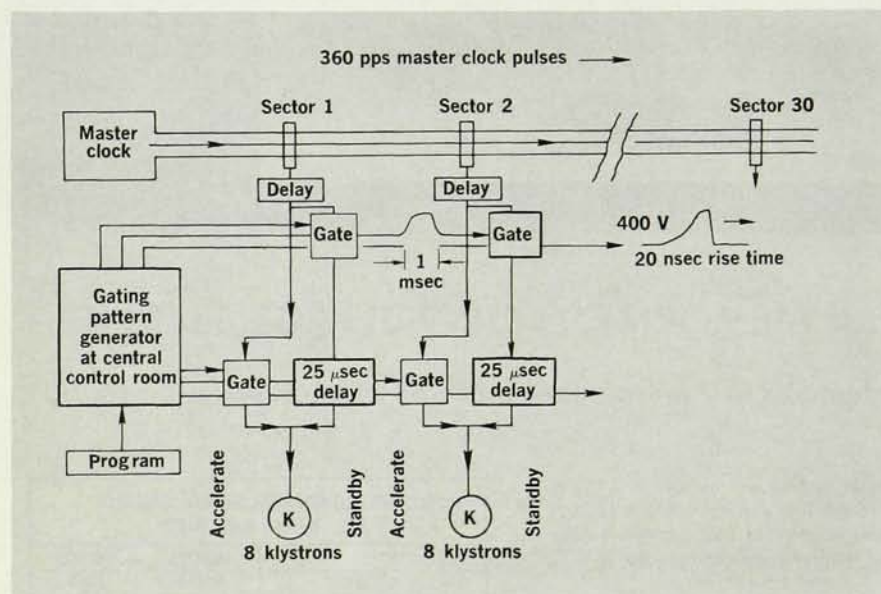
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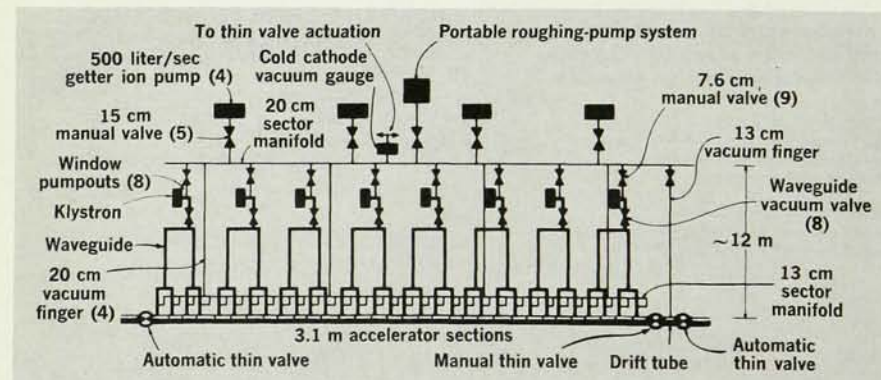
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STANDARD INSTRUMENT SECTION at each 102-meter sector.—FIG. 9



TRIGGER SYSTEM permits flexible sector operation so that up to six distinct beams can be programed at various repetition rates. —FIG. 10



METAL HIGH-VACUUM SYSTEM for each 102-meter sector. —FIG. 11

to a straight line defined by two end points.<sup>13</sup> One of the end points is a laser light source located at the end of the accelerator near the beam switchyard and the other end point is a slit with a photomultiplier detector located upstream from the main injector. The laser provides a beam that is transmitted through the 61-cm aluminum support girder. The girder (light pipe) is evacuated to about 0.01 torr to reduce refraction due to temperature gradients in the residual gas. At each 12.2-meter support point, a retractable Fresnel target, as shown in figure 12, images the light source on the detector. The transverse location of the image indicates deviation of the target from its correct position. Adjustable jacks at the corresponding support point can be adjusted to bring the target into correct alignment. Correct angular rotation of the accelerator is assured by precision level devices. The system described is able to align the accelerator to  $\pm 0.5$  mm.

#### Beam switchyard

The beam switchyard<sup>14</sup> (figure 2) is a large two-level underground structure located under 12.2 meters of concrete and earth for radiation shielding. The beam path itself is on the lower level. The upper level contains utility runs, instrumentation and control alcoves, cranes, service cars, and other equipment required in conjunction with the main beam-handling equipment in the lower level.

With a pulsed deflecting system that deflects the electrons (or positrons) on a pulse-to-pulse basis into any of three, large, dc-magnet-transport systems, several experiments can be carried out simultaneously in the research area using time-interlaced beams.

The unusually high power ( $\sim 1$  MW in stage I) carried by the incident beam has imposed difficult problems in design of beam-handling equipment. A typical example of a device capable of handling these large beam powers is the 4.9-meter-long, adjustable, energy-defining, aluminum slit<sup>15</sup> shown in figure 13. Two in-line slits of the type shown, with the second rotated 90 degrees about its axis with respect to the first, are used as an adjustable collimator at the beginning of the beam switchyard.

A small digital process-control computer (SDS 925) will be used in the beam-switchyard control system. This computer will read data from punched cards and send control information to the regulators in the magnet power supplies where a digital-to-analog converter will convert the digital information to an analog reference voltage. Slits and collimators will be adjusted in a similar way. When the operator or experimentalist wants them, data representing the parameters of a particular beam will be printed out from the computer memory for record, together with auxiliary information. The computer will scan about 100 signals from various sources every accelerator pulse (1/360 second) and about 600 signals at a slower rate. It will detect, identify and print out the time and date of any changes in the interlock and status signals in proper sequence.

### OPERATING RESULTS

Tests to date have confirmed the principal design parameters of the accelerator. In evaluating the operating results, we concern ourselves with energy gain, energy spectra, electron bunching, phasing, beam transmission and beam breakup.

### Energy gain

The basic equation for energy gain in a multiple-feed linear accelerator of constant-gradient design is

$$V = (1 - e^{-2\tau})^{1/2} \sum_{n=1}^N (P_n L r)^{1/2} - \frac{IrNL}{2} \left( 1 - \frac{2\tau e^{-2\tau}}{1 - e^{-2\tau}} \right)$$

( $N$  = number of independently fed sections,  $L$  = length of each section,  $P_n$  = input rf power to section  $n$ ,  $r$  = shunt impedance per unit length,  $I$  = peak beam current,  $\tau$  = rf attenuation in accelerator section in nepers). The first term in this equation is the no-load energy—the energy obtained with negligible beam current. The second term is the correction for beam loading; it is directly proportional to the beam current. Using the design parameters of the SLAC accelerator ( $N$  = 960,  $L$  = 3.05 meters,  $r$  = 53 megohms/meter, and  $\tau$  = 0.57 nepers) and taking into account the fact that each klystron feeds its power equally into four accelerator sections

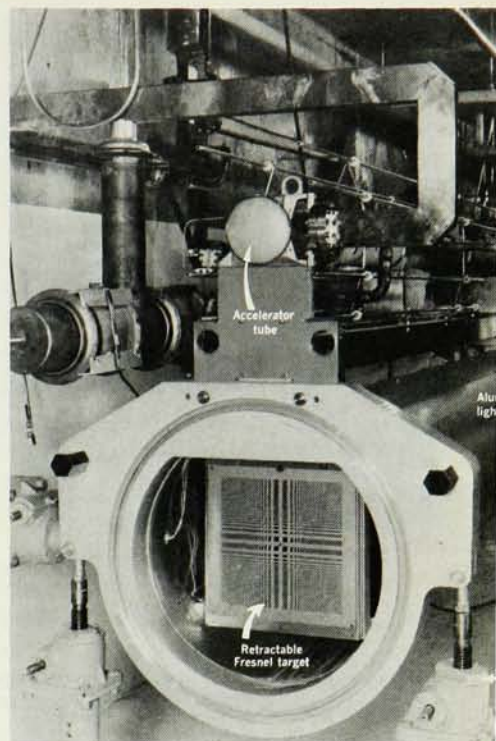
and that some of the power ( $0.54 \pm 0.1$  dB) is dissipated in the waveguides connecting the klystrons to the accelerator, we get

$$V = 0.020 \sum P^{1/2} - 0.035I$$

where  $V$  is in GeV,  $P$  in MW, and  $I$  in mA. For example, this equation states that if each of the 245 klystrons connected to the accelerator is producing 16 MW, each klystron and its four associated 3-meter sections would contribute an electron energy gain of 80 MeV and the total no-load energy in the two-mile accelerator (assuming perfect phasing) would be 19.6 GeV. Further, if the electron beam current were 20 mA, the resulting beam loading would reduce the energy by 0.70 GeV to 18.9 GeV. The coefficients in the above equation have been verified within experimental accuracy (about 2%).

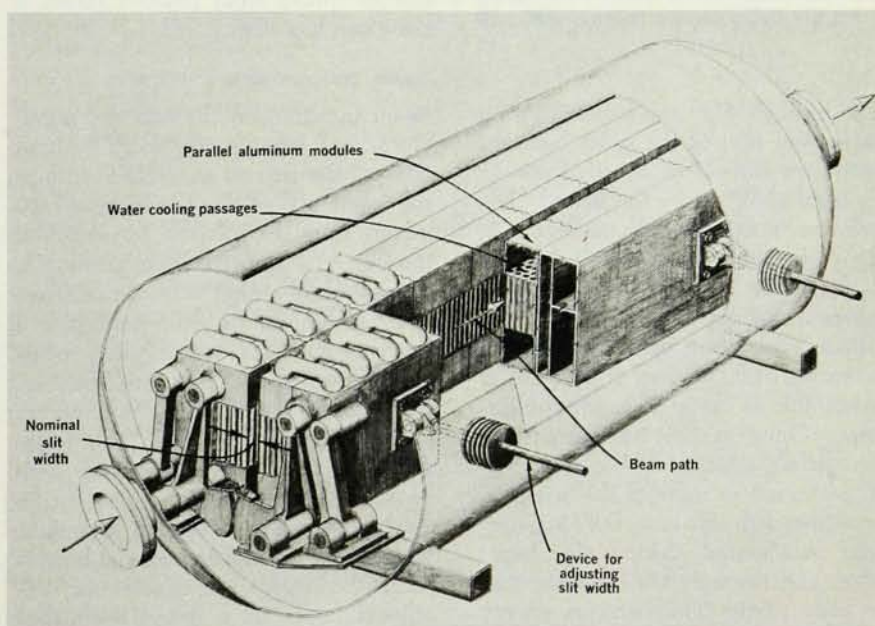
### Energy spectra

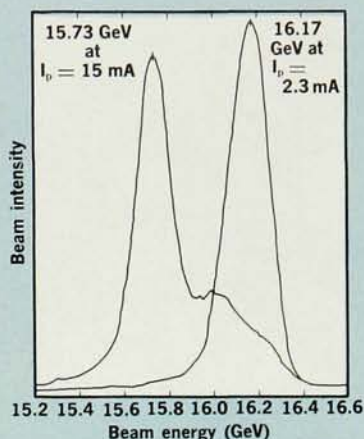
Typical energy spectra are shown in figure 14. The spectrum of higher energy was obtained for light beam loading (2.3-mA peak beam current). A higher beam current (15 mA) results in the lower-energy spectrum with 0.44 GeV less energy than the first. Note that the lower-energy spectrum contains some electrons having energies as high as the lightly-loaded spectrum. These are the electrons that



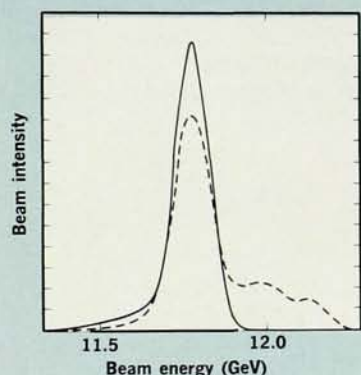
FRESNEL TARGET used every 12.2 meters in alignment system. —FIG. 12

ENERGY-DEFINING SLITS in beam switchyard can withstand unusually high beam power ( $\sim 1$  MW). —FIG. 13





ENERGY SPECTRA under different beam-loading conditions. —FIG. 14



COMPENSATION of spectrum broadening due to beam loading by trigger delay to one sector.—FIG. 15

pass through the accelerator during the earliest part of the pulse before a significant amount of stored rf energy has been absorbed by the beam. The spectrum width at half maximum is 1.3%, of which about 0.9% is attributable to the resolution of the measurement devices.

Energy-spectrum broadening with increasing beam loading (figure 14) is undesirable in many research applications. Compensation for beam loading can be achieved by delaying the trigger to one or more of the accelerator sectors. In this case, the first electrons accelerated during the beam pulse pass through some sectors that are only partly filled with rf energy

and therefore the electrons gain less energy than they would if the sectors were completely filled. The compensation achievable with this technique is demonstrated in figure 15, in which the dashed line shows the uncompensated spectrum and the solid line shows the compensated spectrum resulting from trigger delay to one sector by approximately 0.5  $\mu$ sec.

### Electron bunching

Beam-dynamics studies have shown that the electron-bunch length at the 10-meter point along the accelerator corresponds to about 5 deg ( $1/72$  of the operating wavelength of 10.5 cm). A well bunched beam is essential in obtaining a good energy spectrum since the fractional energy spread  $\delta V/V$  resulting from a bunching angle of  $\alpha$  radians is  $\alpha^2/8$ . Thus  $\delta V/V$  from this cause amounts to only 0.1% in the two-mile machine.

### Phasing

The accuracy with which the rf sources are phased influences how closely maximal energy can be approached. The fractional energy deviation from imperfect phasing is  $\langle \theta^2 \rangle / 2$  where  $\langle \theta^2 \rangle$  is the average value of the square of the phasing error for the entire complement of klystrons. Measurements have shown that the automatic phasing system, which uses the electron beam as a phase reference, can achieve a  $\langle \theta^2 \rangle$  of less than 0.01 ( $\theta \leq 5$  degrees). The resulting energy spread from phasing errors is therefore less than 0.5%.

### Beam transmission

Beam transmission through the accelerator has been quite good. About 90% of the current measured close to the input end of the machine, say 10 meters from the injector, is preserved through the entire two-mile length. This favorable result arises from effective performance of beam-position and intensity monitors, steering and focusing system, and a long ion chamber. The microwave position monitors at each sector end have been able to indicate transverse beam position with respect to accelerator axis within  $\pm 0.5$  mm. The long ion chamber, which is an argon-filled coaxial line installed alongside the accelerator, enables the operator to detect beam loss-

es and, from the times of arrival of the ionization signals, to resolve their location within 30–60 meters.

The transverse phase space of the beam is an index of its optical quality and its suitability as a research tool. The phase space is given approximately by the product of the beam diameter at the beam minimum times the angular divergence of the beam. At about 10 meters downstream from the injector, 80% of the injected beam current is found in a phase space of  $1.2 \times 10^{-2}$  MeV-cm/c (expressed as a product integral of the transverse momentum in units of MeV/c and the beam displacement in centimeters). A second measurement at the beam switchyard beyond the accelerator indicates that the same fraction of the beam is contained in a phase space of about  $3 \times 10^{-2}$  MeV-cm/c. Since the beam diameter is approximately 0.4 cm at this point, the angular divergence at an energy of 10–20 GeV is less than  $10^{-5}$  radians. Thus, the natural increase in the transverse dimensions of the beam in passing through the entire 300-meter beam switchyard enroute to the research area is no more than 0.3 cm. The beam spot observed at the end of the accelerator is shown in figure 16.

As mentioned earlier, the ability to accelerate multiple time-interlaced beams is very important in that it permits simultaneous physics experiments to be carried out in several physically separated areas. Tests to date have demonstrated the feasibility of accelerating at least three beams of different energies simultaneously. The pulse length and intensity of each of these beams can be independently controlled.

### Beam breakup

During initial operation a phenomenon called "beam breakup" has been encountered. This difficulty, observed in earlier accelerators,<sup>16</sup> manifests itself as a progressive shortening of the electron-beam pulse length as the beam current is increased. Design steps (such as employment of the constant-gradient accelerator structure) that were taken in the two-mile machine to combat this phenomenon appear to have alleviated but not to have cured the problem. The attainable intensity is at present limited to about

half the design value of 30  $\mu$ A average beam current (50 mA peak current at 360 pps). Corrective measures are being investigated both theoretically and experimentally even though the achievable current is adequate for all experiments now planned or contemplated.

Beam breakup in the two-mile accelerator is attributed to the transverse fields arising from the excitation by the beam of a higher-order  $TM_{11}$ -like mode in each 3-meter accelerator section. This excitation occurs at a frequency of about 4140 MHz although other frequencies (such as 1284, 1572, 4428) resulting from beating of 4140 with the various harmonics of 2856 are also observable as modulation of the electron beam. The 4140-MHz frequency originates as a resonance in the first eight to ten cavities of each 3-meter accelerator section. There are several other nearby resonances involving other groups of cavities in the structures, but they are weaker than the 4140 resonance that seems to be principally responsible for beam breakup.

In a multiple-section machine, the beam interacts successively with the excited region of each section. The resulting transverse modulation of the beam causes an even greater excitation of succeeding sections. In a given section the later-arriving electron bunches during a pulse add to the already existing excitation. Thus, buildup of the transverse deflecting mode increases with both time and distance down the machine. Alternate electron bunches are deflected to opposite sides.

Beam breakup occurs when, at some position along the accelerator, the amplitude of the transverse displacement equals the accelerator aperture. Even at a given beam current, however, the time and position of beam breakup are not unique. When breakup occurs, the beam current first strikes the walls of the accelerator at the end of the machine. Then the continuously expanding displacement causes later regions of the injected beam pulse to strike the walls progressively closer to the injection end of the machine.

Theoretical considerations and experimental results indicate that breakup in a given accelerator structure can

be characterized by the simple expression

$$\frac{I_t z}{\partial V / \partial z} = K$$

where  $I$  is peak beam current at which blowup occurs,  $t_p$  is length of beam pulse as limited by breakup,  $z$  is distance from injector to closest position where current is lost at a time  $t$  during beam pulse, and  $\partial V / \partial z$  is average energy gradient in the accelerator. With  $I$ ,  $t$ ,  $z$ , and  $\partial V / \partial z$  expressed in units of milliamperes, microseconds, meters and MeV/meter, respectively, the value of  $K$  in the SLAC accelerator has been found to be approximately  $1.8 \times 10^4$ . For example, at an energy of 16 GeV ( $\partial V / \partial z = 5.3$  MeV/meter), the threshold current for beam breakup at a pulse length of 1.6  $\mu$ sec is about 20 mA for the entire two-mile accelerator. At 40 mA the pulse length for the entire machine shortens to about 0.8  $\mu$ sec. On the other hand, a peak current of 40 mA can exist for the entire 1.6  $\mu$ sec over the first 1500 meters of the machine.

We have observed that as the current is increased, beam breakup first occurs in a vertical orientation in the



BEAM SPOT as observed at end of two-mile accelerator. —FIG. 16

accelerator. We believe this fact is explained by the horizontal orientation of the waveguide feed, partially suppressing the horizontally oriented transverse mode. As the beam current is increased further, beam breakup occurs randomly in both horizontal and vertical planes. Threshold current for horizontal breakup is about 1.5 times threshold for vertical breakup.

Various means of curing or alleviating the beam-breakup problem are

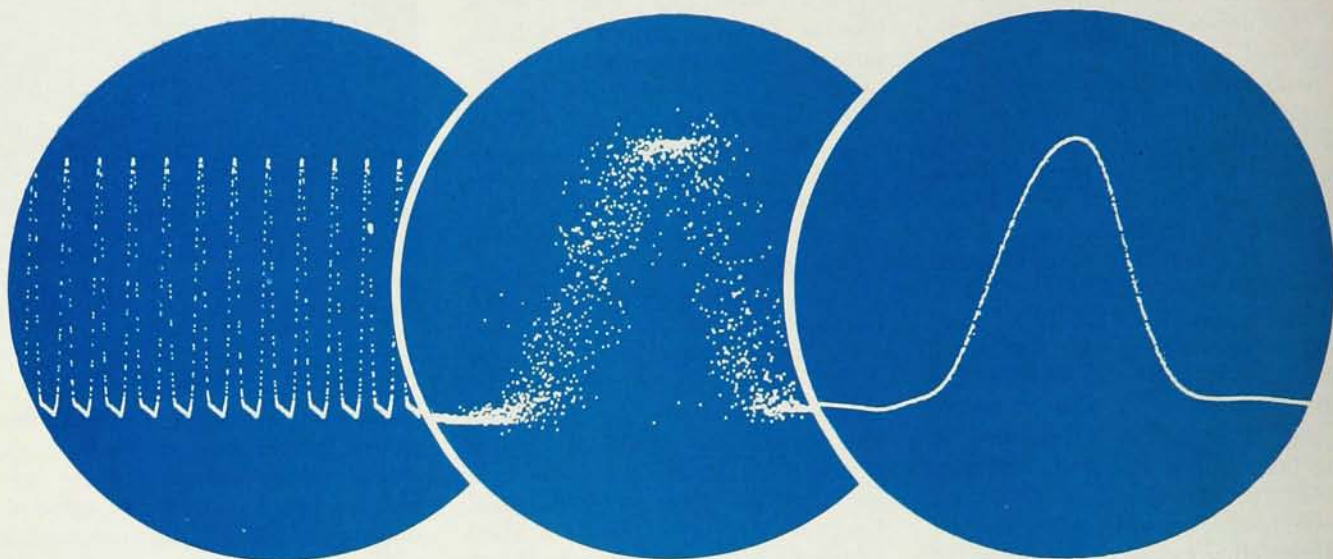
#### General SLAC Accelerator Specifications

|                                   | Stage I                                                                   | Stage II           |
|-----------------------------------|---------------------------------------------------------------------------|--------------------|
| Accelerator length                | 3 km                                                                      | 3 km               |
| Length between feeds              | 3 meters                                                                  | 3 meters           |
| Number of accelerator sections    | 960                                                                       | 960                |
| Number of klystrons               | 245                                                                       | 960                |
| Peak power per klystron           | 6–24 MW                                                                   | 6–24 MW            |
| Beam pulse repetition rate        | 1–360 pps                                                                 | 1–360 pps          |
| RF pulse length                   | 2.5 $\mu$ sec                                                             | 2.5 $\mu$ sec      |
| Filling time                      | 0.83 $\mu$ sec                                                            | 0.83 $\mu$ sec     |
| Electron energy, unloaded         | 11.1–22.2 GeV                                                             | 22.2–44.4 GeV      |
| Electron energy, loaded           | 10–20 GeV                                                                 | 20–40 GeV          |
| Electron peak beam current        | 25–50 mA                                                                  | 50–100 mA          |
| Electron average beam current     | 15–30 $\mu$ A                                                             | 30–60 $\mu$ A      |
| Electron average beam power       | 0.15–0.6 MW                                                               | 0.6–2.4 MW         |
| Electron-beam pulse length        | 0.01–2.1 $\mu$ sec                                                        | 0.01–2.1 $\mu$ sec |
| Electron-beam energy spread (max) | $\pm 0.5\%$                                                               | $\pm 0.5\%$        |
| Positron energy                   | 7.4–14.8 GeV                                                              | 14.8–29.6 GeV      |
| Positron average beam current*    | 1.5 $\mu$ A                                                               | 1.5 $\mu$ A        |
| Multiple-beam capability          | 3 interlaced beams with independently adjustable pulse length and current |                    |
| Operating frequency               | 2856 MHz                                                                  | 2856 MHz           |

\* For 100 kW of incident-electron-beam power at positron source located at one-third point along accelerator length.

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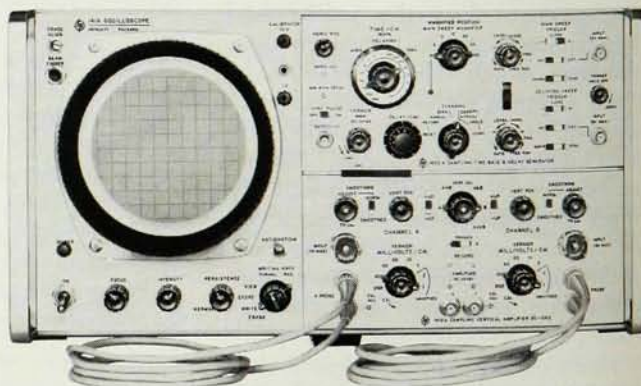
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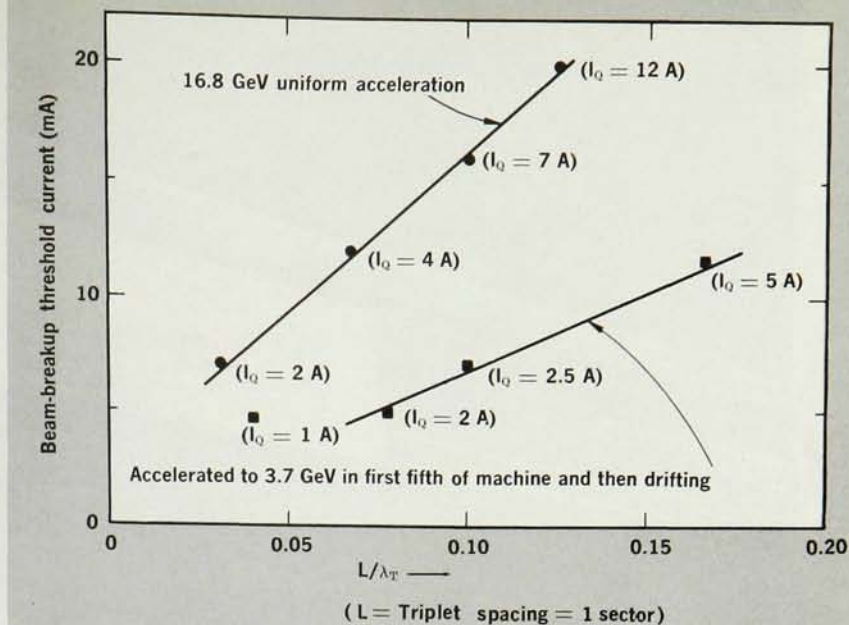
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under investigation. These include microwave suppression and feedback schemes, addition of sextupole or octupole devices, and improved quadrupole focusing along the machine. The last measure is the only one that has thus far been found definitely efficacious. The improvement in beam-breakup threshold that can be obtained with stronger quadrupole focusing is shown in figure 17. The quadrupoles used are the triplets at the end of each 102-meter sector. Effective quadrupole strength is given in terms of the parameter  $L/\lambda_t$  where  $L$  is the length of one sector (102 meters) and  $\lambda_t$  is the focusing wavelength.  $I_Q$  is the maximal quadrupole current used at any point in the machine. The current in the quadrupoles increases linearly sector by sector up to the value of  $I_Q$  at sector 30. By making greater quadrupole current (or more quadrupoles) available it appears possible to raise breakup-current threshold significantly.

Present plans are to rearrange individual quadrupoles of existing sets of triplets in the form of doublets. The shorter quadrupoles will be used as doublets in the early part of the accelerator and the longer quads as doublets in the downstream sector. Larger power supplies will be provided for



BREAKUP current threshold vs quadrupole focusing along accelerator. Quadrupole strength is in terms of effective focusing wavelength.—FIG. 17

the downstream doublets. Somewhat later additional singlet quadrupoles will be added at 12.2-meter intervals in the first few sectors of the accelerator. These steps are expected to increase breakup threshold to design current or higher.

The next article discusses the experimental research now being conducted as well as future programs. About

65% of the present running time is devoted to physics research and the remaining 35% to continuing machine testing and shakedown. By July 1967 we expect that about 90% of the running time will be committed to physics research.

\* \* \*

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